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Development of the fracture zone water flow level in the overburden

Zhao Bingchao[a,*], Yang Leilei[a], He Weizhong[b,c], Li Hui[b,c] and Wang Guirong[d]

[a] School of Energy Engineering, Xi'an University of Science and Technology, Xi'an 710054, China

[b] Key Laboratory of Mine Geological Hazards Mechanism and Control, Xi'an, Shaanxi 710054, China

[c] Shaanxi Institute of Geo-Environment Monitoring, Xi'an 710054, China

[d] School of Geology and Environment, Xi'an University of Science and Technology, Xi'an 710054, China

*Corresponding author. E-mail: zhaobc913@163.com

Abstract

The Guojiahe coalmine was studied to estimate the maximum water level in the fractured zone in the overburden of a thick seam in Linyou mining area, where extraction is fully-mechanized. Using a predictive model of the movement and deformation of the upper rock/soil layer in the overburden fracture zone, the free water level in the overburden was determined. Physical and numerical simulations were performed to study the development characteristics of water-flow in the fractured zone under different conditions, and the maximum water level in the fracture zone was determined. The maximum height of the fracture zone is 185 ~ 193 m from the roof of the coal seam, and the relationship between it and the distance to the working face has a step-like function, revealing the controlling effects on water level of the key strata in the overburden.

Key words: fully-mechanized mining, numerical simulation, similarity simulation, theoretical analysis, water flow in the fracture zone

INTRODUCTION

Free-water level calculations in fracture zones are usually performed using the empirical formula recommended in *Regulations of Buildings*, *Water, Railway and Main Well Lane Leaving Coal Pillar and Press Coal Mining* (State Bureau of the Coal Industry 2017). The formula applies to coal seams that can be mined in single layers of between about 1 and 3 m thick, and whose cumulative thickness does not exceed 15 m. Fully-mechanized extraction has now been implemented for thick, single coal seams, with rapid working face advance and extensive destruction of roof rock strata (Teng 2011). Consequently, the traditional empirical, predictive formula may no longer be applicable. Thus, studying the changes in the free-water level in the overburden fractured zone with respect to fully-mechanized mining is significant in coal mine safety.

There have been many studies of free-water surface level development in overburden. Kang (1998) suggested that decreasing primary mining thickness might lower the water level in the fractured zone, after studying the effects of various exploitation methods on water levels in the overburden fractured zone. Gao *et al.* (2012) used two arcs to fit the edges of the subsidence trough, and studied the relationship between fracture zone permeability and the interlayer tensile deformation of the overlying strata. In other studies the relationship was deduced between mining parameters and generalized damage factors by combining the generalized damage-factor definition of an interlayer stratum and the free water level in the fractured zone (Zhao & Yu 2010). Du & Bai (2012) elaborated the phenomena of intense static pressure, moderate dynamic pressure, and insufficient fracture

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growth to investigate the fracture mechanisms in overburden caused by fully-mechanized mining. Chen *et al.* (2006) determined the free-water level by simulating the failure of overburden caused by such mining using RFPA software. Liu *et al.* (2014) used various methods to find the free-water development level, by studying its dynamic characteristics in relation to fully-mechanized mining. Zhang *et al.* (2014) analyzed failures of overlying strata in a fully-mechanized extraction face and believed that the key stratum (KS) controlled overburden failure development. Xu *et al.* (2011) developed an empirical formula to calculate the 'two zones' height of fully-mechanized extraction faces using regression analysis. Xu *et al.* (2012, 2009) showed that the location of a primary key stratum (PKS) affected the development of the free-water level when they studied PKS impact.

EMPIRICAL CALCULATION OF THE FREE-WATER LEVEL

Guojiahe mine

Coal Seam No. 3 in Guojiahe mine is a stable coal bed, with an average thickness of 15 m. It dips at between 1 and 15° (average 7°). The working face is 235 m long, and between about 441 and 583 m below ground level. The overlying strata comprise 33 to 149 m of loess and laterite, and then about 407 to 446 m of consolidated strata. The immediate roof is dense and hard, and includes dark grey and sandy mudstones, and grey-white sandstone. Hydrogeological conditions are simple, the working face's main water source is the Luohe Formation sandstone. The principal overlying aquiclude is a sandy mudstone about 203 m above. The mechanical characteristics of the overburden strata are given in Table 1.

Calculation using empirical formulae

The overlying lithology in the mine comprises medium-hard formations. According to Yu & Zhang (2010), empirical formulae (1) and (2) can be used to calculate the free-water level in the fractured zone. Xu *et al.* (2011) report that empirical formula (3) can be used to calculate the height of the water-conducting fracture zone in the overburden under fully mechanized mining.

$$H_f = 100\sum M/(1.6\sum M + 3.6) \pm 5.6 \tag{1}$$

$$H_f = 20\sqrt{\sum M} + 10 \tag{2}$$

$$H_f = 100\sum M/(0.26\sum M + 6.88) \pm 11.49 \tag{3}$$

where, H_f refers to the free-water level in the fractured zone (m), and M to the mineable thickness of the coal seam (m).

Using a mineable thickness of 15 m, empirical formulae (1), (2), and (3) yield different free-water surface maximum levels for the fractured zone – i.e., 59.9, 87.46 and 150.64 m, respectively – showing that the results from the traditional formulae for fully-mechanized upper coal extraction differ significantly. In other words, the traditional formulae do not apply to thick coal seams with fully-mechanized extraction. It is thought that both the differing lithology within the overburden and the KS locations might cause differential free-water surface level development, even at the same depth and with the same mining height. Low- and high-level key layers have different effects on free water surface development in the overburden strata. Thus, only with the correct combination of ratios of bedrock to overburden thickness (*Jz*) and bedrock thickness to mining height (*Jc*) with a KS, the maximum height of water conducting fractured zone can be estimated.

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Table 1 | Physical and mechanical parameters of overburden strata

No. of Layer	Lithology	Thickness/m	Density/(kg/m^3)	Elasticity modulus/Gpa	Tensile strength/Mpa	Compressive strength/Mpa	Poisson ratio
37	Loess layer	148.78	1.568	0.012	0.002	0.01	0.45
36	Medium sandstone	17.58	2.528	1.76	4.12	41	0.22
35	Cobble conglomerate	41.86	2.489	1.86	4.69	45	0.25
34	Coarse sandstone	34.44	2.489	1.9	4.36	43	0.25
33	Medium sandstone	16.20	2.528	1.76	4.12	41	0.22
32	Post stone	1.40	2.558	1.83	3.15	29	0.23
31	Coarse sandstone	22.29	2.489	1.91	4.36	43	0.25
30	Sandy mudstone	66.79	2.430	1.54	2.87	25	0.30
29	Coarse sandstone	9.42	2.489	1.71	4.36	43	0.25
28	Mudstone	5.93	2.450	1.44	2.57	23	0.31
27	Coarse sandstone	4.60	2.489	1.91	4.36	43	0.25
26	Sandy mudstone	17.29	2.430	1.54	2.87	25	0.30
25	Coarse sandstone	6.80	2.489	1.71	4.36	43	0.25
24	Post stone	1.70	2.558	1.83	3.15	29	0.23
23	Mudstone	21.38	2.450	1.46	2.57	23	0.31
22	Post stone	5.80	2.558	1.83	3.15	29	0.23
21	Mudstone	5.20	2.450	1.46	2.57	23	0.31
20	Pebbly sandstone	4.94	2.489	1.78	4.17	42	0.25
19	Siltstone	25.02	2.411	2.11	2.69	28	0.21
18	Coarse sandstone	4.10	2.489	1.92	4.36	43	0.25
17	Mudstone	6.90	2.450	1.45	2.57	23	0.31
16	Siltstone	1.98	2.411	2.11	2.69	28	0.21
15	Sandy mudstone	8.42	2.430	1.55	2.87	25	0.30
14	Siltstone	15.40	2.411	2.11	2.69	28	0.21
13	Medium sandstone	4.03	2.528	1.75	4.12	41	0.22
12	Mudstone	1.00	2.450	1.45	2.57	23	0.31
11	Medium sandstone	9.78	2.528	1.75	4.12	41	0.22
10	Siltstone	4.28	2.411	2.11	2.69	28	0.21
9	Coarse sandstone	2.20	2.489	1.92	4.36	43	0.25
8	Carbon mudstone	3.99	2.450	1.55	2.67	21	0.31
7	No. 2 coal seam	1.20	1.382	0.32	1.32	13	0.32
6	Sandy mudstone	1.35	2.430	1.56	2.87	25	0.30
5	Siltstone	11.87	2.411	2.12	2.69	28	0.21
4	Sandy mudstone	1.80	2.430	1.56	2.87	25	0.30
3	Siltstone	14.90	2.411	2.12	2.69	28	0.21
2	Coarse sandstone	0.80	2.489	1.92	4.36	43	0.25
1	Post stone	0.93	2.558	1.83	3.15	29	0.23
	No. 3 coal seam	15.00	1.382	0.32	1.32	13	0.32

THEORETICAL ANALYSIS OF THE FREE-WATER LEVEL IN THE FRACTURED ZONE

Prediction of free-water surface level

When the interlayer tensile deformation of the rock stratum exceeds its critical value, a transfixion crack is generated and a water-flow channel formed. Equally, if the interlayer tensile deformation

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is below the critical value, no transfixion crack is generated and water channel development in the fractured zone will stop. Thus, the fracture condition of the strata can be judged by calculating the overburden's interlayer tensile deformation, allowing the maximum free-water surface in the fractured zone to be determined. Two elliptical arcs are used in the free-water surface predictive model to fit the inner and outer edges of the overlying subsidence trough – see Figure 1. It was assumed that the arcs have the same curvature and length, but in opposite directions, and the relationship between the overburden fracture zone permeability and tensile deformation of the rock layer under full mining conditions studied. Using the geometric properties of ellipses together with trigonometric function relationships, the formulae for L_1 and L_0 are (4) and (5):

$$L_1 = (\pi l_a + 2l_b - 2l_a)/2 = \pi l_a/2 + l_b - l_a \tag{4}$$

$$L_0 = 2r(z) = 2H(z)/\tan\beta(z) \approx 2H/\tan\beta \tag{5}$$

where, L1 refers to the arc length of the curve section after bending deformation of the upper rock and soil layer in the water conduction fracture zone (m); L_0 to the straight-line length before the bending deformation of the upper rock-soil layer in the water-flowing fractured zone (m); z to the location of the upper rock-soil layer in the water-flowing fracture zone (m); $r(z)$ to the radius of influence of the upper rock-soil layer in the water-flowing fractured zone of the overburden strata (m); $H(z)$ to the distance between the upper rock-soil layer in the water-flowing fractured zone of the overlying strata and the coal seam roof (m); H to the depth of the coal seam (m); $\beta(z)$ to the displacement angle of the upper rock-soil layer (degrees); β to the displacement angle of the ground surface (degrees); l_a to the minor axis length of the ellipse (m); and l_b to the major axis length of the ellipse (m).

As shown in Figure 1, the major axis of the ellipse is twice the length of the radius of influence of the upper rock-soil layer in the free-water zone of the fractured zone, i.e., $l_b = 2r(z)$ and the minor axis length equals the maximum subsidence of the upper rock-soil layer, i.e., $l_a = w(z) = M(z)$. According to formulae (4) and (5), the tensile deformation, ε, of the upper rock-soil layer can be represented as:

$$\begin{aligned}\varepsilon &= 1000(L_1 - L_0)/L_0 \\ &= 250(\pi - 2)M\eta(z)\tan\beta/H\end{aligned} \tag{6}$$

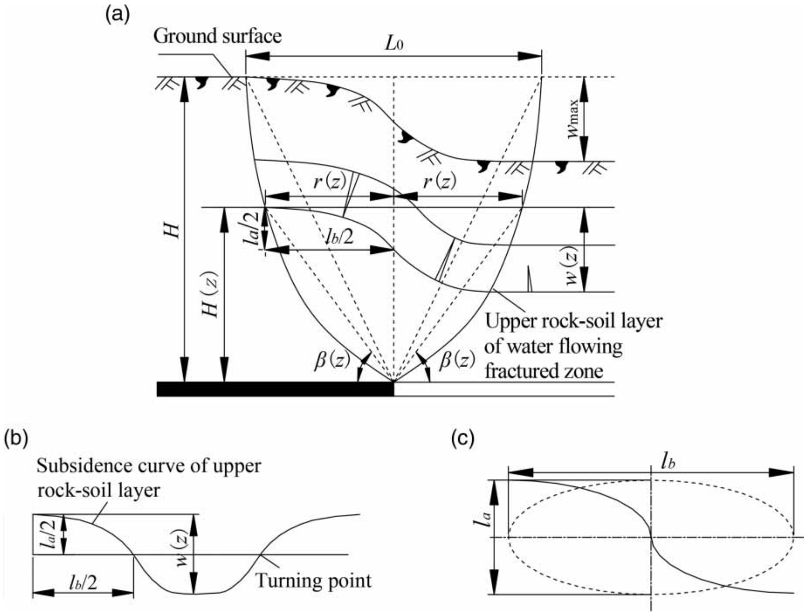

Figure 1 | Geometric model of the movement and deformation of the upper rock-soil layer in the facture zone. (a) Bending and subsidence of overlying strata. (b) Subsidence function pattern. (c) Elliptical arcs fitting subsidence function.

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where, ε is the interlayer tensile deformation of the bent and deformed rock strata (mm/m); $\eta(z)$ the subsidence coefficient, and $\eta(z) = (M - \Sigma h(Ks - 1)\cos\alpha)/M$; Σh the vertical distance from the calculated rock stratum to the coal seam roof (m); α the coal seam dip (degrees); Ks the residual bulking coefficient of the rock strata; and w(z) the maximum subsidence of the upper rock-soil layer in the free-water zone of the fractured zone (m).

The PKS in the overlying strata is the main control on fracture zone height development. When the PKS is within the excavation zone and at shallow depth, the free-water zone of the fractured zone above develops to ground level. When it is within the fracture zone, the free-water surface is above it. On the other hand, when the PKS is in the bending subsidence zone, the top of the free-water zone is below it. Thus, determination of the PKS location within the 'three zones' of the overlying strata is crucial to any study of the free-water level. Zhao *et al.* (2015a, 2015b) and Huang (2002), report that the preliminary location of the PKS in 'three zones' was initially determined by calculating Jz and Jc, after which the water level range in the fractured zone was determined. Finally, formula (6) was adopted to calculate the tensile deformation of the rock strata within the range and to determine the maximum free water level in the fractured zone can be calculated. The detailed method is shown in Figure 2.

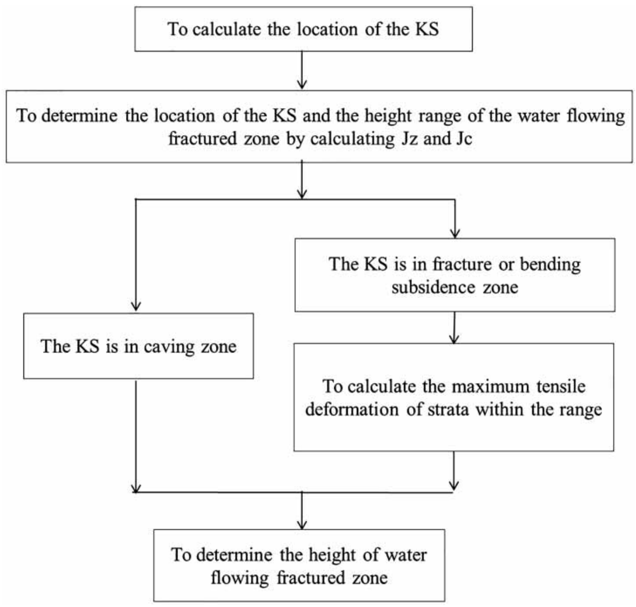

Figure 2 | Flow chart for determining the water flowing fractured zone.

Calculation of the free-water level in the fractured zone

Field measurements and calculations show that the bedrock displacement angle in working faces 1304 and 1305 in Guojiahe mine is 65°, the surface soil layer displacement angle 45°, and the tangent of the major influence angle $\tan\beta$ 1.64. The surface soil layer and rock strata above the coal seam are about 148 and 403 m thick, respectively. The average dip angle of coal seam is 7°. The comprehensive residual rock strata bulking coefficient, Ks, is 1.065; and the tensile deformation limit $[\varepsilon]$ of the overburden strata is taken as 2.9 mm/m. Using the method indicated in Figure 2, the calculated maximum thickness of the fractured zone was determined as in Table 2.

(1) According to the KS theory, No. 3, No. 5, No. 11, No. 14 and No. 19 rock strata were determined as sub key strata while No. 34 rock stratum was the PKS. The deformation and fracture parameters of key strata are as shown in Table 2.

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Table 2 | Deformation and fracture parameters of key stratum

No. of layer	Key stratum	Thickness of stratum s/m	Fracture condition	Tensile Deformation/(mm·m − 1)
34	PKS	34.44	Unfractured	–
19	Sub KS 5	25.02	Fractured	7.52
14	Sub KS 4	15.4	Fractured	9.53
11	Sub KS 3	9.78	Fractured	10.34
5	Sub KS 2	11.87	Fractured	11.7
3	Sub KS 1	14.9	Fractured	12.62

(2) The calculated ratios of bedrock to overburden thickness, J_Z, and of bedrock thickness to mining height, J_C, are: $J_Z = 403.57/148.58 = 2.71 > 0.8$, and $J_C = 403.47/15 = 26.9 > 25$. It can be inferred, therefore, that the PKS is in the bending and subsidence zones, and that the highest free-water level in the fractured zone was less than the vertical distance from the PKS to the coal seam roof.
(3) The subsidence coefficient of No. 27 rock stratum $\eta 27$ was calculated as:

$$\eta_{27} = (M - \sum h(K_s - 1)\cos\alpha)/M = 0.213$$

The total tensile deformation of the stratum was calculated as:

$$\varepsilon_{27} = 250(\pi - 2)M\eta_{27}\tan\beta/H = 2.7\text{mm/m}$$

The calculation results, $\varepsilon_{27} = 2.7$ mm/m $< [\varepsilon] = 2.9$ mm/m, and $\varepsilon_{26} = 3.65$ mm/m $> [\varepsilon]$, indicate that No. 26 rock stratum was fractured while No. 27 was not. Thus, under the geological and mining conditions of this working face, the height of the fractured zone in the overlying strata developed to the level of stratum 26, which means the maximum development height of water-flowing fractured zone in the overlying strata was 183.06 m and the thickness of the water-flowing fractured zone was around $183.06/15 = 12.20\ M$.

SIMILARITY SIMULATIONS

Design

A model 5,000 (X) × 2,000 (Y) × 200 mm (Z) was chosen to meet the experimental conditions and objectives. The geometry, volume weight, and stress similarity constants were 200, 1.56 and 312, respectively, according to similarity theory. Working faces 1303 and 1305, both with an average width of 1,225 mm, were arranged in a coal seam with 100 mm section coal pillars between them, to match the experimental similarity ratio. The working height of the coal face was 75 mm. To eliminate boundary effects, 1,225 mm boundary coal pillars were placed on both sides of the model, and were 1,095 mm tall. The rest of the overburden strata were loaded using the gravity compensation load (because the experimental model does not extend to the surface).

Analysis and experimental phenomena

Figure 3 presents the failure characteristics of the overburden strata during mining at the working face. Failures occurred periodically as the face advanced. When failure developed to the KS, an abscission space formed under it. As the KS fractured, the abscission space closed gradually and

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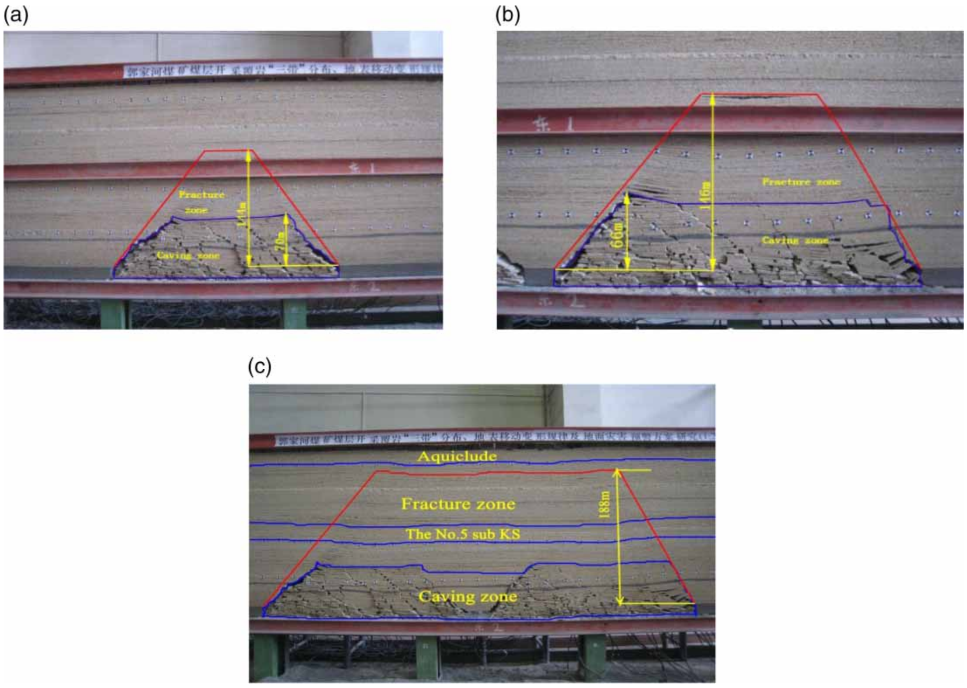

Figure 3 | Overburden failure forms. (a) No. 1303 working face after mining finished. (b) No. 1305 working face after mining finished. (c) Bulking failure of section coal pillar.

the gob was compacted. The periodic KS failure controlled development of the free-water flow fracture. The free-flowing fracture zone thickness variation curves that arose during mining are shown in Figure 4.

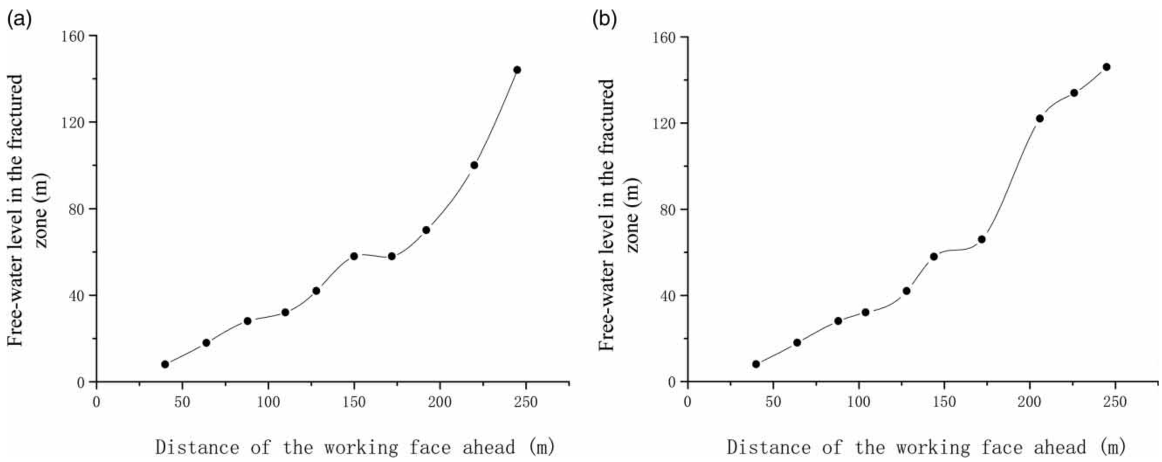

Figure 4 | Variation curve of the height of the water-flowing fractured zone. (a) No. 1303 working face. (b) No. 1305 working face.

When mining of face 1303 was finished, the failure zone and free-flowing fracture zone heights were 70 and 144 m respectively (Figure 3(a)). When face 1305 was finished, the respective zone heights were 66 and 146 m (Figure 3(b)). After failure of the section coal pillars, the fractures in the strata above them developed gradually upward during mining, and the maximum free-water level in the fractured zone was 188 m (around 12.53 M) (Figure 3(c)).

Figure 4 shows the step-like variation of the relationship between the free-flowing fracture zone thickness and the distance ahead of the working face. When overlying strata failure developed as

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far upward as the KS, fracture zone development stopped due to the KS' strength. As the working face advanced, however, the length of the suspended span of the KS exceeded its maximum unsupported capacity, and fracture zone development continued upward again. In other words, fracture zone development was retarded when the failure of the overlying strata reached KS level. The relationship between the height of the free-flowing fracture zone and the distance ahead of the working face display a step-like variation, revealing the controlling effects of the KS.

NUMERICAL SIMULATION AND ANALYSIS

Model design

The UDEC numerical model was designed to study development of the free-flowing fracture zone height in the overlying rock under sub-level extraction mining in the Guojiahe mine. The model dimensions are 275 (h) $\times$ 600 m (l). The thicknesses of the coal seam, bedrock, and coal seam floor are 15, 240, and 20 m, respectively, and working face length is 300 m. To eliminate boundary effects, 150 m boundary coal pillars were placed both sides of the working face. The model adopted the Mohr-Coulomb criterion, in which horizontal displacements are limited by the left and right boundaries, and vertical displacements by the upper and lower boundaries. The strata at the top of the model were simulated with a 6.46 MPa load, except at the boundary.

Analysis

The failure forms of the overburden during mining are shown in Figure 5. When the working face reached 70 m, the overburden failure form became conspicuous (Figure 5(a)). When it reached 150 m, the failure height was around 73 m and an abscission space formed gradually in No. 5 sub-KS (Figure 5(b)). As the working face advanced to 230 m, No. 5 sub-KS fractured. At this time the water-flow fissured zone level was around 133 m (Figure 5(c)). The mine was almost fully exploited when the length of mining face reached 300 m, the gob compacted, and the water-flow fractured

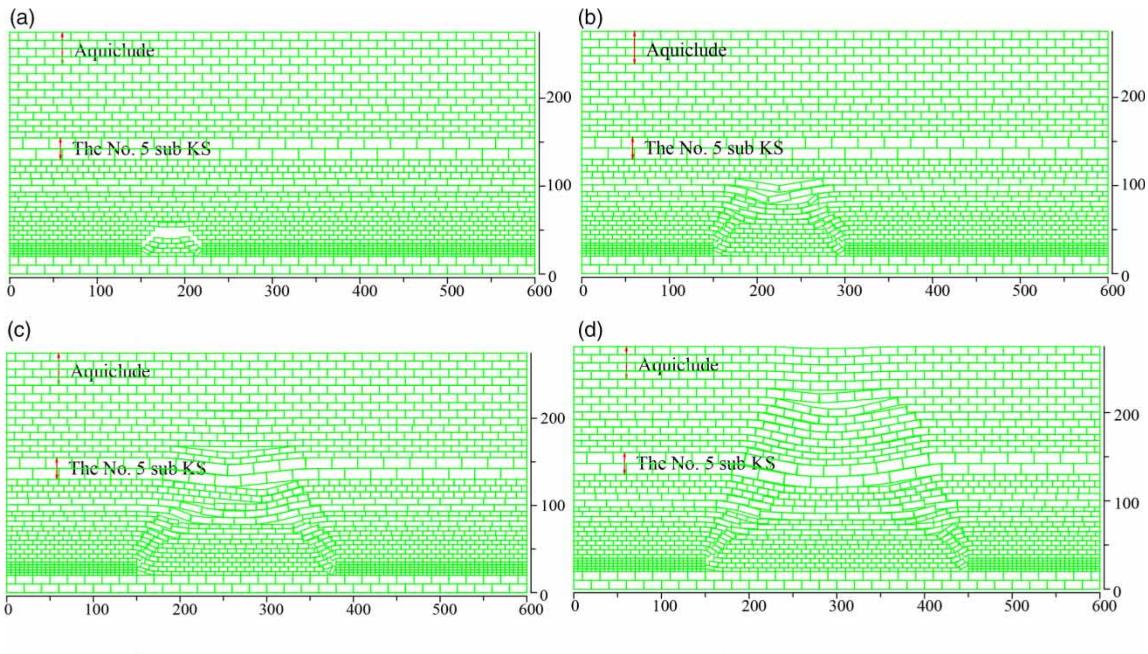

Figure 5 | Failure forms of overburden rock. (a) Working face advance distance 70 m. (b) Working face advance distance 150 m. (c) Working face advance distance 230 m. (d) Working face advance distance 300 m.

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zone in the overlying strata developed further upward; the maximum water-flow fractured zone level was 193 m (around 12.87 M) (Figure 5(d)).

COMPARATIVE ANALYSIS

The empirical formulae, predictive model of movement and deformation in the upper rock-soil layer in the water-flow fractured zone, and the similarity and numerical models all yielded different maximum heights for the water-flowing fractured zone – Table 3. The values calculated using the traditional empirical formulae differ significantly, while those derived from the other models are close and show good consistency.

Table 3 | Calculated heights of water flowing fractured zone

Calculation method	Theoretical prediction	Similarity simulation	Numerical simulation	Empirical formulae		
				(1)	(2)	(3)
Height of the water-flowing fractured zone/m	183.06	188	193	59.9	87.46	150.64

CONCLUSIONS

(1) The predictive model of movement and deformation of the upper rock-soil layer in the water-flowing fractured zone of the overlying strata shows that the maximum height of the water-flowing fractured zone in the fully-mechanized upper coal face is 183.06 m, which is 12.2 times the mining height. In the overlying strata, periodic failures of lower level key strata control the height development of the water-flowing fractured zone, which is restrained by high level key strata.
(2) The similarity model showed that, after the section coal pillars failed in the middle of the working face, the maximum fractured zone water level was 188 m, while the numerical simulation showed that, under full mining conditions, the water level was 193 m. The relationship between the water level in the fractured zone and the distance forward to the working face varies step-wise, revealing the controlling effects of the overlying KS on water level.
(3) The maximum water level in the fractured zone, calculated by the predictive model, agrees well with results from the similarity and numerical simulations. The predictive model can yield reasonable estimates of the water level in the fractured zone above thick coal seams under fully-mechanized extraction conditions.

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REFERENCES

Chen, R. H., Bai, H. B. & Feng, M. M. 2006 Determination of the height of water flowing fractured zone in overburden strata above fully mechanized top coal caving face. *Journal of Mining & Safety Engineering* **23**(2), 220–223.

doi: 10.2166/wpt.2019.024

Du, F. & Bai, H. B. 2012 Mechanism research of overlying strata activity with fully mechanized caving in thin bedrock with thick alluvium. *Journal of China Coal Society* **37**(7), 1105–1110.

Gao, Y. F., Huang, W. P., Liu, G. L., Zhang, S. F., Zhu, Q. M. & Deng, Z. Y. 2012 The relationship between permeable fractured zone and rock stratum tensile deformation. *Journal of Mining & Safety Engineering* **29**(3), 301–306.

Huang, Q. X. 2002 Ground pressure and definition of shallow seams. *Chinese Journal of Rock Mechanics and Engineering* **21**(8), 1174–1177.

Kang, Y. H. 1998 Effects of changes in mining methods on development laws of water flowing fractured zone. *Journal of China Coal Society* **23**(3), 262–266.

Liu, Y. F., Wang, S. D. & Wang, X. L. 2014 Development characteristics of water flowing fractured zone of overburden deep buried extra thick coal seam and fully mechanized caving mining. *Journal of China Coal Society* **39**(10), 1970–1976.

State Bureau of Coal Industry 2017 *Regulations of Buildings, Water, Railway and Main Well Lane Leaving Coal Pillar and Press Coal Mining*. Coal Industry Publishing House, Beijing, China.

Teng, Y. H. 2011 Development features and max height calculation of water conducted fractured zone caused by fully mechanized top coal caring mining. *Coal Science and Technology* **39**(4), 118–120.

Xu, J. L., Wang, X. Z., Liu, W. T. & Wang, Z. G. 2009 Effects of primary key stratum location on height of water flowing fractured zone. *Chinese Journal of Rock Mechanics and Engineering* **28**(2), 380–385.

Xu, Y. C., Li, J. C., Liu, S. Q. & Zhou, L. 2011 Calculation formula and its applicability analysis of the 'two zones' heights in overlying strata under fully mechanized top coal caving. *Coal Mining Technology* **16**(2), 4–7.

Xu, J. L., Zhu, W. B. & Wang, X. Z. 2012 New method to predict the height of fractured water-conducting zone by location of key strata. *Journal of China Coal Society* **37**(5), 762–769.

Yu, X. Y. & Zhang, E. Q. 2010 *Mining Damage*. Coal Industry Publishing House, Beijing, China.

Zhang, H. W., Zhu, Z. J., Huo, L. J., Chen, Y. & Huo, B. J. 2014 Overburden failure height of super high seam by fully mechanized caving method. *Journal of China Coal Society* **39**(5), 816–821.

Zhao, B. C. & Yu, X. Y. 2010 Research on broad sense damage gene of fracture zone. *Journal China University of Mining & Technology* **39**(5), 705–708.

Zhao, B. C., Liu, Z. R., Tong, C. & Wang, C. L. 2015a Relation between height of water flowing fractured zone and mining parameters. *Journal of Mining & Safety Engineering* **32**(4), 634–638.

Zhao, B. C., Tian, S. C. & Dong, Z. K. 2015b *Report of Research on 'Three Zones' Distribution of Overlying Strata, Rule of Ground Movement and Deformation, and Ground Disaster Warning Scheme During the Mining of Coal Seams in the Guojiahe Coal Mine*. Xi'an University of Science and Technology, Xi'an, China.