Environ Earth Sci (2015) 74:5653–5662
DOI 10.1007/s12665-015-4581-6

ORIGINAL ARTICLE

Simulation of water resource loss in short-distance coal seams disturbed by repeated mining

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Received: 30 August 2014 / Accepted: 23 May 2015 / Published online: 31 May 2015

Abstract Physical simulations and field measurements were performed to study the movement of overlying strata and water conductive fractures (WCF) under conditions of repeated mining in short-distance coal seams. In addition, the feasibility of water resource conservation mining (WRCM) was analyzed in areas disturbed by repeated mining. The results of the simulation showed that the aquiclude remained intact after the mining of Coal Seam 11 (the 1st main seam) in Shigetai coal mine in northwest China. According to the findings, WRCM can be conducted in this area. After the mining of Coal Seam 12 (the 2nd main seam), the WCF in overlying strata above the central section of the mined-out area will gradually compress and close. However, due to the impact of repeated mining in short-distance coal seams, WCF in overlying strata at the edge of the mined-out area are connected to the Quaternary loose aquifer and are not likely to close, resulting in the loss of the water resource. Thus, WRCM in this area would be difficult to conduct. Moreover, field observations showed that the aquifer can likely remain intact after Coal Seam 11 is mined, but the aquifer's water level will probably not fully recover if Coal Seam 12 is mined. This is consistent with the simulation results. Therefore, appropriate technical mining measures must be taken to conduct WRCM at the 2nd main seam in the shallow-buried short-distance coal seams. These research results can be used as a reference for future WRCM endeavors in the arid and semi-arid regions of northwest China.

Keywords Short-distance coal seams · Repeated mining · Water conductive fractures · Water resource conservation mining · Physical simulation

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Introduction

The arid and semi-arid regions of northwest China are ecologically vulnerable environments that lack natural water resources. The problem is made worse by environmental disruption, and resource exploitation, and coal mining operations (Booth 2006; Maximovich and Khayrulina 2014).

Technological advancements in water resource conservation mining (WRCM) are ecologically significant in China, and WRCM technology was applied during the exploitation of the 1st main seam in the western shallow-buried coalfields. Some mines have adopted coordinated methods of coal mining and water resource conservation to protect the surface environment and underground water resources (Bian et al. 2012; Zhang et al. 2010). However, due to mining constraints, studies have only been conducted on single seams (the 1st main seam), and no research has been conducted in respect to WRCM and its feasibility in the conditions of repeated mining in short-distance coal seams (Ma et al. 2013; Zhang and Shen 2004).

Based on the actual geological conditions of Shigetai coal mine in the Shendong mining area of northwest China, this paper analyzed the development process and evolvement of mining-induced water conductive fractures (WCF) in areas disturbed by repeated mining in short-distance coal seams. It subsequently researched the feasibility of WRCM under these geological conditions, providing a reference for potential WRCM in shallow-buried short-distance coal seams in the future (Zhang et al. 2013).

Coal seam occurrence conditions and hydro-geological characteristics

Coal seam occurrence and longwall face conditions

Located in Shenmu County in Shaanxi Province, the Shigetai coal mine has a production scale of 10 Mt/a in the primary mineable coal seams of Coal Seam 11 and Coal Seam 12, which are located in the center of the fifth section of the lower and middle Jurassic Yan'an Formation. The average thicknesses of Coal Seam 11 and Coal Seam 12 are 2.1 and 2.7 m, respectively, and the average depths are 78.1 and 100.2 m, respectively. The average interval between two seams is approximately 20 m.

Longwall Face 11105 is being excavated in Coal Seam 11, with a strike length of 1000 m, a dip length of 300 m, and a mining height of 2.5 m. Longwall Face 12105 is being excavated at Coal Seam 12, with a strike length of 1300 m, a dip length of 300 m, and a mining height of 2.7 m. The end of the open-off cut for Face 12105 is approximately 10–20 m internally removed from that of Face 11105, and the air-return roadway for Face 12105 is approximately 50 m removed externally from that of 11,105.

Two hydrological observation points (Hole 1 and Hole 2) are positioned on these two faces to conduct observations on the variation of the aquifer water level, as shown in Fig. 1. The column of observation holes is shown in Table 1.

Hydro-geological characteristics

The main aquifers in the coal mine are Quaternary loose aquifers. Under this, a loess layer and highly weathered fine sandstone strata make up the aquiclude.

Physical simulation and experimental design

After the simulation mining of Coal Seam 11 and Coal Seam 12, the development process and evolvement rule of WCF was obtained to determine whether WRCM could be conducted in the area disturbed by repeated mining. Based

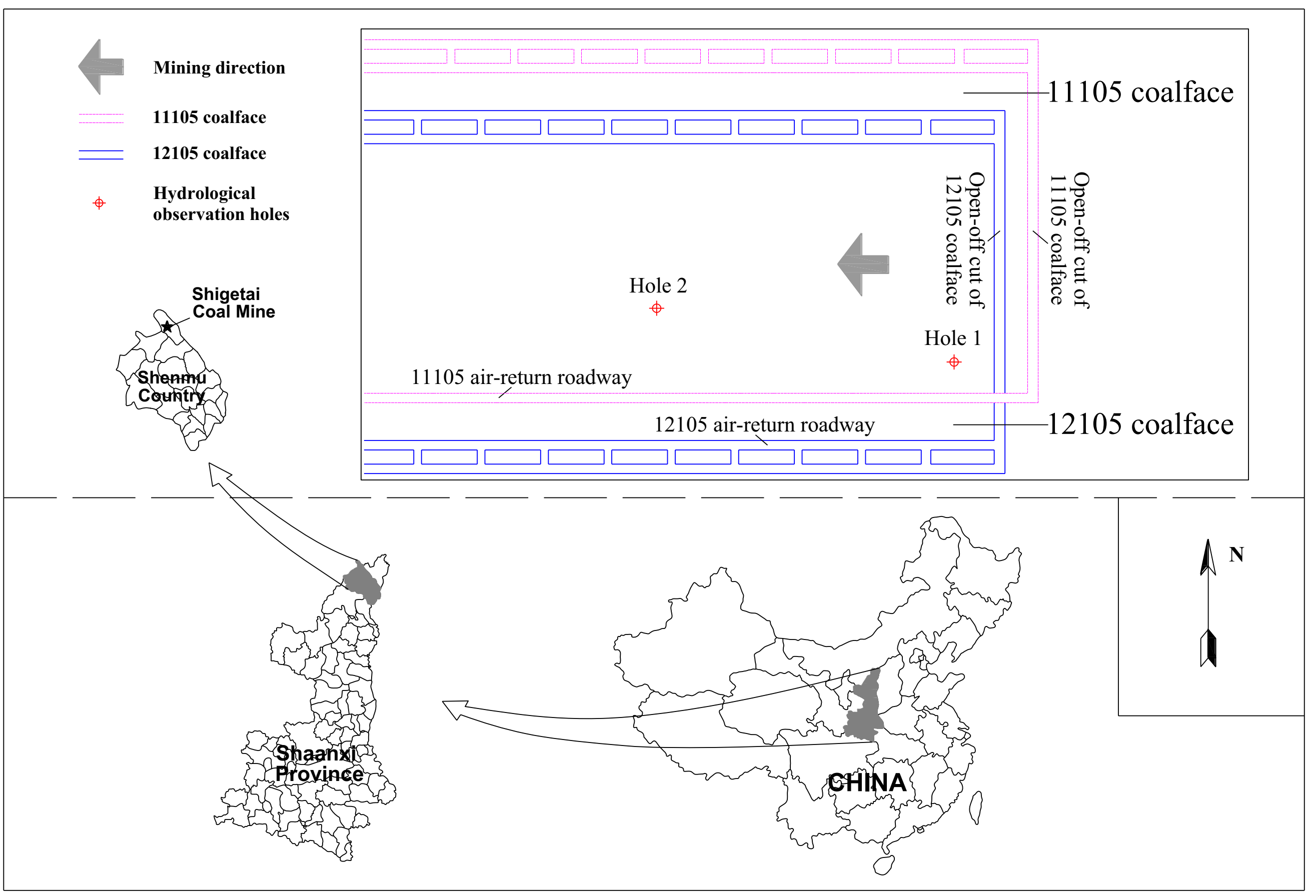

Fig. 1 Layout of water level observation holes

Table 1 Column of observation hole (relative to the Coal Seam 11)

Hydrological observation holes	Loose layer thickness			Bedrock thickness (m)
	Sand layer thickness (m)	Gravel layer thickness (m)	Loess layer thickness (m)	
Hole 1	15.68	1.51	6.34	56.37
Hole 2	17.27	1.82	5.73	61.45

on the principles of the similarity theory, the similarity ratios adopted in the experiment are as follows: The geometric similarity ratio is $\alpha_L = 1{:}100$, the density similarity ratio is $a_\gamma = 1{:}1.9$, and the time similarity ratio is 1:10. The similarity simulation model had a size of 2.5 m × 0.2 m × 1.1 m (length × width × height).

According to the criterion of similarity, the mechanical properties of the physical model keep a relationship with the prototype as follows:

$$[\sigma_t] = \frac{L_M}{L_P} \cdot \frac{\gamma_M}{\gamma_P} \cdot [\sigma_t]_P = \alpha_L \cdot \alpha_\gamma \cdot [\sigma_t]_P \qquad (1)$$

$$[\sigma_c] = \frac{L_M}{L_P} \cdot \frac{\gamma_M}{\gamma_P} \cdot [\sigma_c]_P = \alpha_L \cdot \alpha_\gamma \cdot [\sigma_c]_P, \qquad (2)$$

where subscripts M and P represent the model and prototype, respectively; σ_t and σ_c are the uniaxial tensile and compressive strength of the rocks in MPa, respectively; γ is density in kg/m^3; L is length in meter. Accordingly, the mechanical properties of each stratum in the physical model were estimated. Table 2 shows the various strata lithology and their similarity ratios with the simulation materials.

Ground water will not be drained if the aquiclude at the bottom of the Quaternary loose aquifer can keep intact during coal mining, and then WRCM can be achieved (Booth et al. 1998).

Analysis of experimental results

Development process of WCF after mining Coal Seam 11

The first weighting occurred in the main roof as soon as Face 11105 advanced 41.5 m, and WCF reached the medium sandstone stratum which is above the main roof, the peak height of WCF reached 12 m simultaneously (Majdi et al. 2012).

As Face 11105 advanced 65 m, the WCF developed continually and got connected with the bed separation fractures above the siltstone, and the maximum height of WCF reached 24.8 m.

When Face 11105 proceeded 145 m, the bed separation fractures, which were 38 m behind the working face, were gradually compressed and closed.

When Face 11105 advanced to the end (180 m), the WCF reached the medium and coarse sandstone underlying the main key stratum (MKS) (Zhang et al. 2011), and the peak height of WCF was 33.4 m after the movement of overlying strata got stabilized. Moreover, some surface cracks were also initiated in the subsided basins (Booth 2007; Palchik 2010), but they did not get connected with the WCF in the overlying strata, as shown in Fig. 2.

"Regulations of coal mining under buildings, railways and water bodies" allow a maximum WCF height of (Zhang and Shen 2004):

$$H_d = \frac{100\sum M}{1.6\sum M + 3.6} \pm 5.6, \qquad (3)$$

where H_d is the maximum WCF height in meters, and ΣM is the cumulative mining thickness in meters.

The WCF height ranged from 30.1 to 41.3 m, which is consistent with the simulation results.

The experimental results showed that after the mining of Coal Seam 11, its overlying aquiclude remained intact, so WRCM could be conducted in that area. This was consistent with the actual mining situation.

Development process of WCF after mining Coal Seam 12

When the advancing length of Coal Seam 12 was 35 m, the first weighting occurred in its main roof (the stratum between Coal Seam 12 and Coal Seam 11), and the WCF above the face connected with the floor of Coal Seam 11.

The first periodic weighting of the main roof occurred at the point when Face 12105 advanced 65 m. The WCF within overlying strata had propagated above the MKS and had a maximum WCF height of about 74.3 m, as shown in Fig. 3.

Once the advancing length of Face 12105 reached 180 m, the WCF in the overlying strata near the beginning and stopping mining line would develop through the aquiclude to the Quaternary loose aquifer, resulting in water loss. WRCM in such areas was therefore difficult to implement, as shown in Fig. 4 (Partially enlarged view).

Maximum WCF height

When the advancing length of Coal Seam 11 reached 180 m, the maximum WCF height reached 35.2 m. Thereafter, the WCF gradually compressed to a close and the final WCF height was stable at 33.4 m, as shown in Fig. 5a.

Table 2 Strata graphic column and proportioning of similar material

Stratum era			Strata	Thickness (m)	Lithology	Proportioning				Remark
System	Division	Group				Sand (kg)	$CaCO_3$ (kg)	Gypsum (kg)	Water (kg)	
Quaternary	Upper Pleistocene	Salawusu (Q_{3s})	Drift sand	1.0	Loose layer	5.80		0.85	0.4	
			Aeolian sand	4.3		33.80		4.2	3.5	Aquifer
	Pleistocene	Lishi loess (Q_{2l})	Loess	6.3		52.35		7.5	6	Aquiclude
Jurassic period	Mid (J_2)	Zhiluo (J_{2Z})	Fine grain sandstone	6.4	Argillaceous cementation	43.80	5.7	3.3	6	
			Siltstone	8.3	Argillaceous cementation	49.65	7.5	5	7	
			Medium-grained sandstone	3.6	Mainly include Feldspar	27.30	2	1.9	3	
			Fine grain sandstone	8.5	Argillaceous cementation	60.65	3.7	8.4	8	MKS
			Sandy mudstone	3.2	Gray	21.90	3.9	1.6	3	
			Coarse-grained sandstone	9.5	Feldspar	69.65	3.5	8.1	9	
			Siltstone	3.7	Horizontal bedding	24.10	2.4	5.6	3	
			Fine grain sandstone	3.5	Feldspar	23.65	1.4	3.3	3	
			Medium-grained sandstone	4.9	Feldspar	36.00	1.8	4.2	4.5	
			Siltstone	2.0	Horizontal bedding	13.20	1.3	3	1.5	
			Medium-grained sandstone	3.9	Horizontal bedding	28.75	1.5	3.3	3.5	
	Mid/lower (J_1)	Yan'an $J^5_{1\text{-}2y}$	Fine grain sandstone	6.0	Horizontal bedding	43.00	2.6	5.9	5.5	Main roof of Coal Seam 11
			Medium-grained sandstone	3.0	Feldspar	22.30	1.1	2.6	2.5	
			Coal Seam 11	2.1	Fine strip	22.30	2.6	1.1	2.5	
			Siltstone	4.5	Horizontal bedding	29.00	2.9	6.8	4	
			Medium-grained sandstone	10.5	Feldspar	77.00	6.8	15.9	10	Main roof of Coal Seam 12
			Coarse-grained sandstone	5.0	Feldspar	36.00	3	3.0	4.5	
			Coal Seam 12	2.7	Fine strip	22.30	2.6	1.1	2.5	
Triassic	Upper triassic	Yongping (T_{3y})	Fine grain sandstone	4.0	Feldspar	28.70	1.7	4.1	3.5	

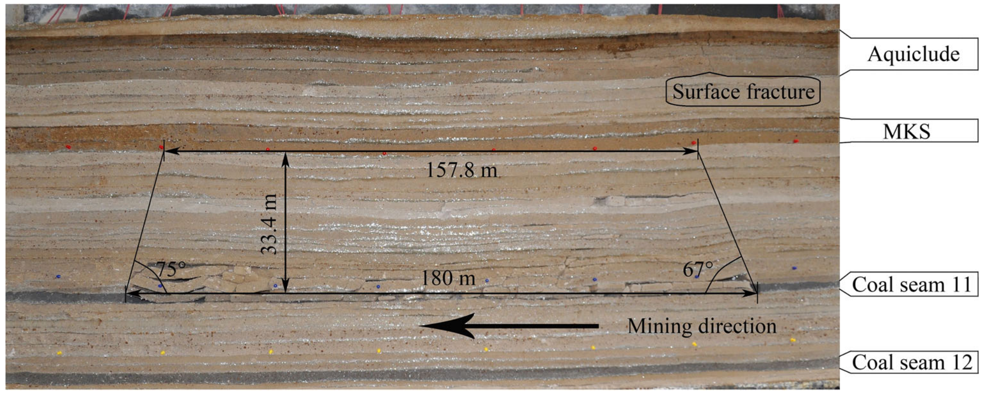

Fig. 2 Development characteristics of WCF (advancing length of Face 11105 is 180 m)

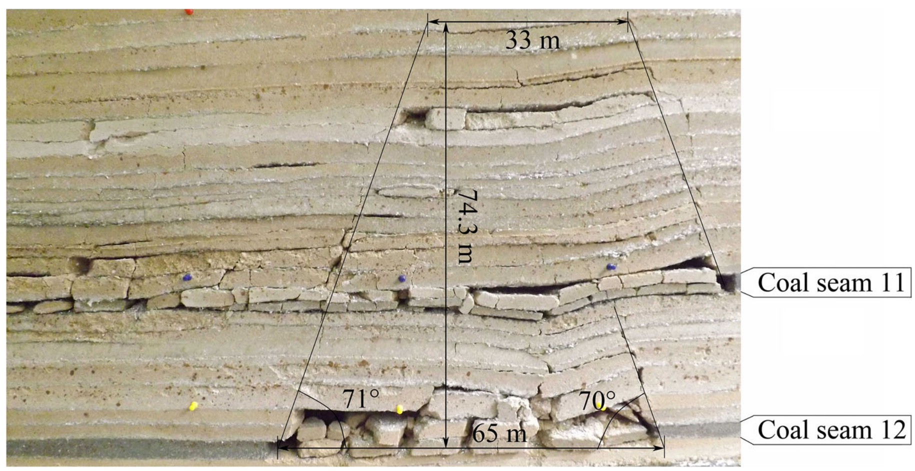

Fig. 3 Development characteristics of WCF (advancing length of Face 12105 is 65 m)

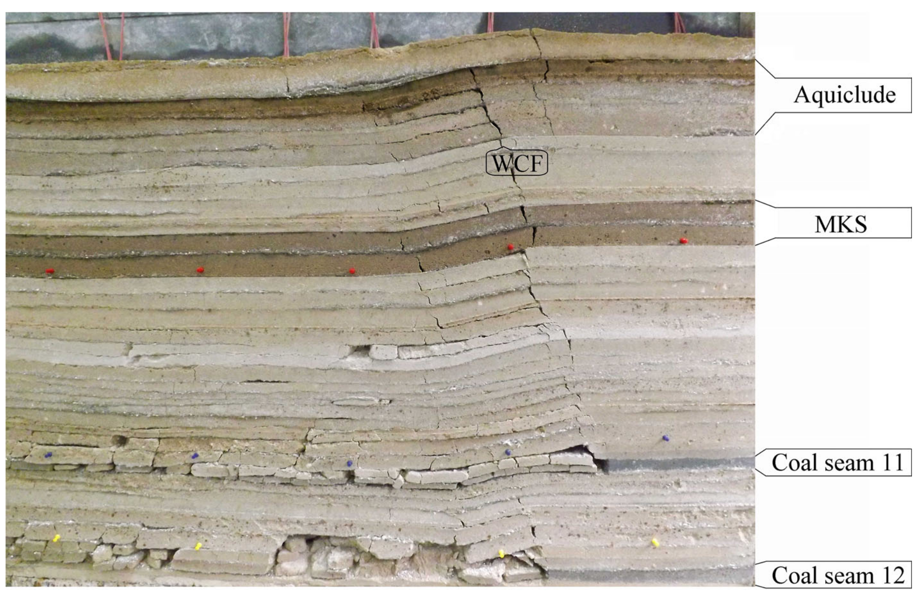

Fig. 4 Development characteristics of WCF (advancing length of Face 12105 is 180 m)

Before the mining of Coal Seam 12, the WCF height in the overlying strata of Coal Seam 11 decreased slightly because of aging effects, but the degree of decrease was minute. During the extraction of Coal Seam 12, great amounts of the compacted and closed WCF in the overlying strata during the mining of Coal Seam 11 were reactivated and then developed again. After the mining of Coal Seam 11, the WCF in the overlying strata in the area

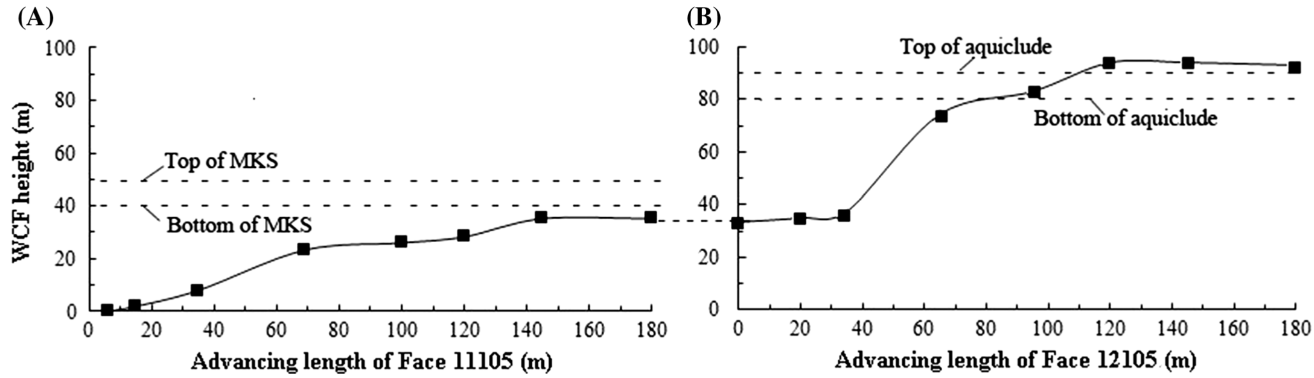

Fig. 5 Relationship between the maximum WCF height and face advancing length. **a** The maximum WCF height during the mining of Coal Seam 11, **b** the maximum WCF height during the mining of Coal Seam 12

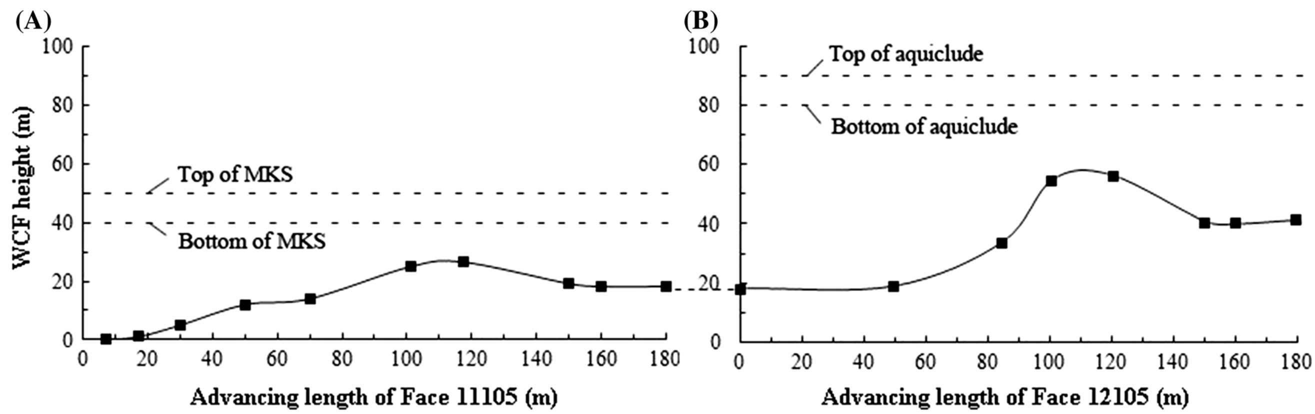

Fig. 6 Relationship between the WCF height and face advancing length in the central section of mined-out zone. **a** The WCF height during the mining of Coal Seam 11, **b** The WCF height during the mining of Coal Seam 12

of the open-off cut and the end of Coal Seam 12 ran through the aquiclude, and connected to the Quaternary loose aquifers, as shown in Fig. 5b.

Development process of WCF in overlying strata above the central section of mined-out area

During the mining of Coal Seam 11, the WCF in the overlying strata above the central section of the mined-out area experienced three stages: initial development, rapid development, and compressed closure. The maximum height reached 26.5 m and the WCF height was approximately 18.2 m after the compression closure, as shown in Fig. 6a.

During the mining of Coal Seam 12, WCF in the overlying strata above the central section of the mined-out area in Coal Seam 11 experienced three stages: reactivation, secondary development, and twice-compressed closure. The maximum height was approximately 56.5 m and the final WCF height was approximately 41.3 m after it was compressed to close, as shown in Fig. 6b.

WCF height after mining was stable

After the mining of Coal Seam 11, the MKS was not fractured but the WCF had developed into the bottom of the MKS before stopping. Moreover, as shown in Fig. 7a and c, the development degree of WCF in the open-off cut area was clearer than that in the overlying strata above the mined-out area.

After the mining of Coal Seam 12, repeated mining fractured the MKS. The final WCF in the open-off cut area at the end traveled through the aquiclude, and connected with the aquifer, as shown in Fig. 7b and d.

Engineering practice

The mining of Coal Seam 11

Figures 8 and 9 show the water levels and the surface subsidence in Hole 1 and Hole 2 during the excavation of Face 11105, respectively. The water level in borehole 1

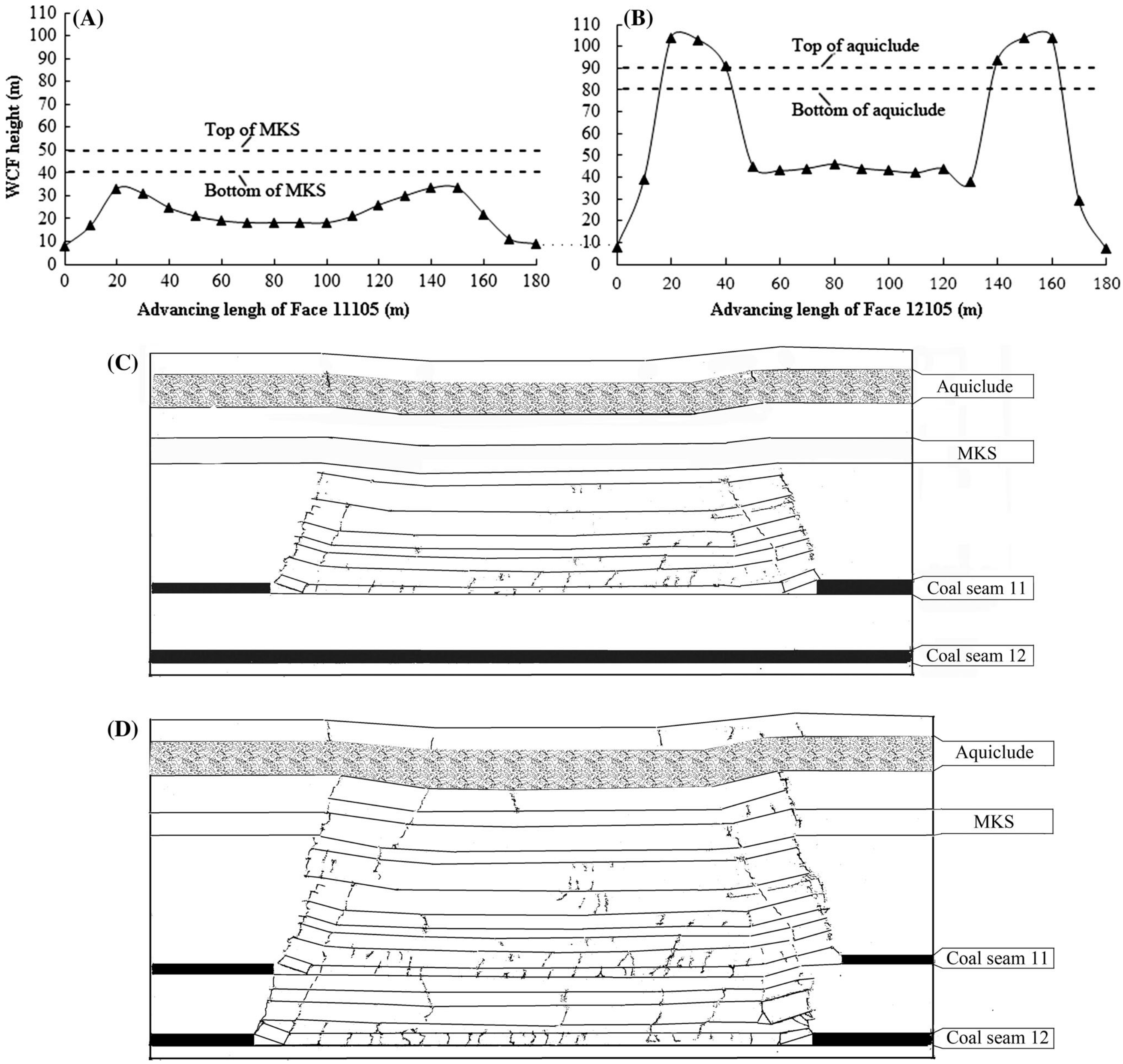

Fig. 7 WCF characteristics after mining. **a** WCF height after the mining of Coal Seam 11, **b** WCF height after the mining of Coal Seam 12, **c** distribution characteristics of WCF after the mining of Coal Seam 11, **d** distribution characteristics of WCF after the mining of Coal Seam 12

which was adjacent to the open-off cut of Face 11105 was stabilized after around one month, with an accumulative water level decline and surface subsidence of 1.22 and 0.85 m, respectively (see Table 3). The water level in Hole 2, located in the central section of Face 12105, decreased tremendously in the previous 20–25 days, then gradually slowed down and eventually stabilized, and the accumulative totals of the water level and ground subsidence decreased by 1.21 and 1.73 m, respectively.

The final water level in Hole 1 decreased less than that in Hole 2, which indicates that the development degree of the WCF in the overlying strata at the edge of the mined-out area was greater than that of the WCF in the overlying strata above the central section of the mined-out area. The water levels of Hole 1 and Hole 2 maintained a stable level after approximately 30 days, indicating that the WCF formed in the overlying strata was closed by compression between the strata. There was no reduction of the water resources of the aquifer in the loose layer.

The mining of Coal Seam 12

During the excavation of Face 12105, the levels of phreatic water and surface subsidence at the openings of Hole 1 and

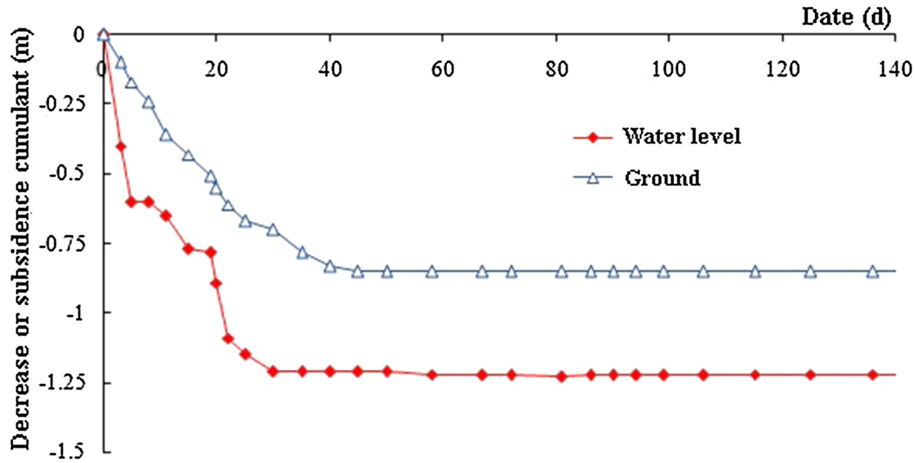

Fig. 8 Water level decrease in observation Hole 1 and the ground subsidence

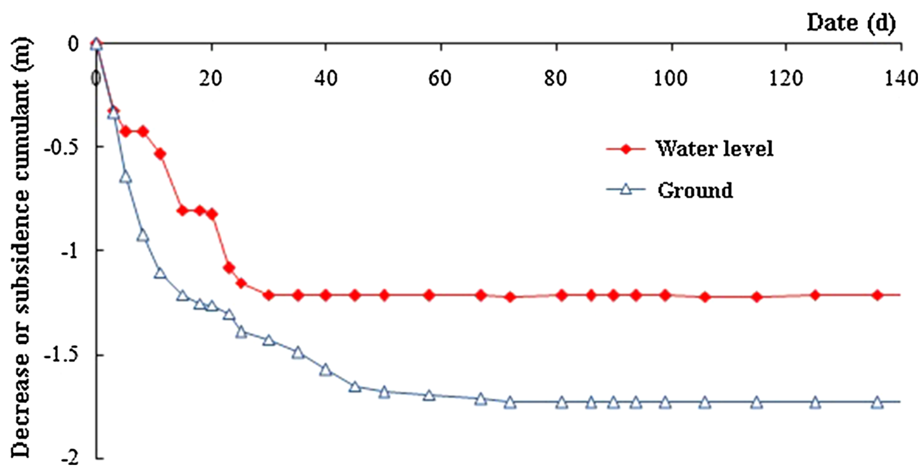

Fig. 9 Water level decrease in observation Hole 2 and the ground subsidence

Table 3 Water level of Hole 1 and Hole 2

Hole no.	Initial thickness of the aquifer (m)	Pre-mining water level (m)	Post-mining water level decrease (m)	Post-mining water level (m)	Remaining thickness of the aquifer (m)	Cumulative subsidence of ground (m)	Relative decrease of water level (m)
Hole 1	8.56	1197.3	1.22	1196.08	8.19	0.85	0.37
Hole 2	10.5	1194.2	1.21	1192.99	11.02	1.73	−0.52

Hole 2 were actively observed, as shown in Figs. 10 and 11, respectively.

When the face advanced approximately 40–50 m, the water level in Hole 1 began to decrease significantly. When the face advanced approximately 80–90 m, the water level in Hole 1 decreased to below the surface of the bedrock. The water level in Hole 1 has not recovered even after the cessation of mining.

Repeated mining of 12,105 significantly impacted the water level in Hole 1. Incompletely closed WCF at the open-off cut of 11,105 redeveloped and reached to the bottom of the aquiclude. However, because Hole 1 was a considerable distance from the open-off cut of 11,105, there was no significant impact on water level. As the WCF at the open-off cut of 12,105 reached the surface after two instances of periodic weighting, the water level in Hole 1 significantly decreased until it was below the surface of the bedrock. Unfortunately, the WCF in the overlying strata in the open-off cut area are not likely to close, so Hole 1's water level will be difficult to recover (Howladar 2013).

During the mining of the 2nd main seam, the water level in Hole 2 that decreased the fastest was within the range of 10 m in front of the face and 20 m behind the face. After the face advanced 220 m from the hole, the water level in Hole 2 decreased to below the surface of the bedrock. When the face had advanced 50–60 m, the water level in Hole 2 began to recover gradually and decreased 4.6 m compared to its initial value.

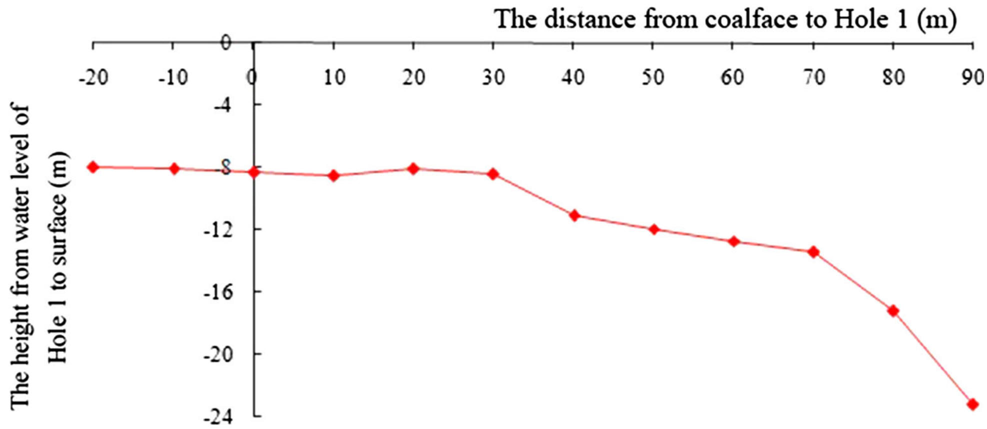

Fig. 10 Water level decrease in observation Hole 1

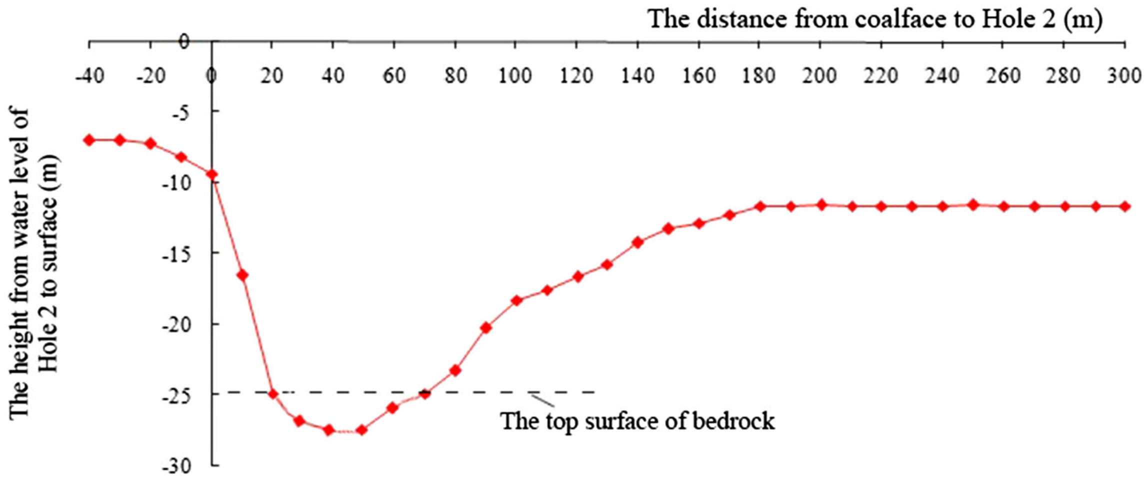

Fig. 11 Water level decrease in observation Hole 2

After the face advanced beyond Hole 2, fractures cut through the aquiclude to form WCF, causing the water level in Hole 2 to rapidly decrease to below the surface of the bedrock. After 2–3 times of periodic weighting, the mined-out area compressed and the WCF closed, and the water level in Hole 2 gradually recovered. However, the loss of the water resource was significant. Although the water level increased relatively quickly, the initial water level was never recovered, as is shown in Table 3.

Field observation revealed that after the mining of Coal Seam 11, the aquifer remained intact; after mining Coal Seam 12, the WCF in the overlying strata connected with the aquifer, and the water levels could not be recovered. This led to the loss of a water resource, and WRCM could not be conducted.

Discussions

The 1st main seam in the western shallow-buried coalfield has been or will be mined out in the near future, and mining has started in the 2nd main seam. The extraction of the lower coal seam will significantly affect the development of WCF in its overlying strata because of the narrow intervals (30 m on average) between the two primary mineable coal seams. This will not only create new mining-induced WCF in the overlying strata, but may also cause WCF that have been previously compressed and stabilized to be reactivated for secondary development. This will lead to a loss of surface water and groundwater resources that were not damaged originally or recovered after the 1st main seam mining was conducted. This situation will bring new challenges for WRCM. Consequentially, the research on WRCM mechanisms and technology in areas disturbed by repeated mining in short-distance coal is imperative. According to past research, reducing the mining height of coal seams can control the development of WCF and effectively avoid WCF from developing in the overlying strata connecting with the aquifer, thus enabling WRCM to be conducted.

Conclusions

After the mining of Coal Seam 11, the WCF noticeably developed and reached a final height of 33.4 m. The water levels of Hole 1 and Hole 2 recovered stability approximately 30 days after mining. The WCF that formed in the overlying strata were closed by compression between the strata. The aquifer in the loose layer was not damaged, so WRCM can be successfully conducted in Coal Seam 11.

During the mining of Coal Seam 12, a large number of overlying strata WCF in Coal Seam 11, which had been closed by compression, were reactivated and developed secondarily. Regional water levels in Hole 1 and Hole 2 decreased to below the surface of the bedrock. After the mining of Coal Seam 12, the WCF in the overlying strata in the area of the open-off cut at the end traveled through the aquiclude and connected with the Quaternary loose aquifers. The regional water level in Hole 1 has not recovered, and the water level in Hole 2 has not reached its initial level though it increased relatively quickly. Therefore, WRCM would be difficult to achieve in Coal Seam 12.

After the mining of Coal Seam 11, the MKS was not fractured and WCF developed into the bottom of the MKS before stopping. Repeated mining after the mining of Coal Seam 12 fractured the MKS. The WCF finally traveled through the aquiclude, and then connected with the aquifer. Reducing the mining height can be an efficient way to conduct WRCM, and the appropriate height can be determined by physical simulations.

Acknowledgments This work was supported by the National Key Basic Research Program of China (973 Program) (2015CB251600), the Fundamental Research Funds for the Central Universities (2014YC01), Qing Lan Project, and the Priority Academic Program Development of Jiangsu Higher Education Institutions.

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