

Prediction of the Height of the Water-Conducting Zone Above the Mined Panel in Solid Backfill Mining

Jixiong Zhang · Haiqiang Jiang · Xuejie Deng ·
Feng Ju

Received: 8 November 2013 / Accepted: 11 September 2014 / Published online: 23 September 2014
© Springer-Verlag Berlin Heidelberg 2014

Abstract Numerous water inrush disasters have been associated with Chinese coal mines over the past 30 years. Accordingly, solid backfill mining (SBM) has been widely adopted to extract coal resources from beneath aquifers to reduce the magnitude and scope of overburden failure. Therefore, accurate determination of the height of the water-conducting zone associated with SBM is particularly important. The primary factors influencing development of water-conducting zones within solid backfill mines have been quantified in the current study, based on overburden movement and deformation characteristics. Numerical simulation has been used to evaluate the height of water conducting zones with respect to mine heights and backfill ratios. The results have been analyzed via multiple regression, leading to the development of a predictive equation. Field trials undertaken as part of the current study indicate a high level of accuracy with the developed equation.

Keywords Water inrush · Filling ratio · Water leakage · Numerical modeling · Multiple regression analysis

J. Zhang · H. Jiang (✉) · X. Deng
School of Mines, China University of Mining and Technology
(CUMT), Xuzhou 221116, China
e-mail: hqjiang2007@126.com

J. Zhang · H. Jiang · X. Deng
Key Laboratory of Deep Coal Resource Mining,
Ministry of Education of China, Xuzhou 221116, China

F. Ju
State Key Laboratory for Geomechanics and Deep Underground
Engineering, CUMT, Xuzhou 221116, China

Introduction

The hydrological conditions in many mines are complicated in eastern China; an estimated 25 billion t of coal reserves are situated beneath surface and groundwater bodies (Zhang et al. 1997), with reserve extraction potentially threatened by these aquatic systems. Typically, three primary groundwater-associated inrush threats are considered with respect to operational mine safety (Du and Wang 2005), namely:

1. Recharge from unconsolidated (i.e. sands and gravels) aquifers comprising effective precipitation and surface water;
2. Recharge from bedrock (consolidated) aquifers comprising pore water, fracture water, and karst water;
3. Combined recharge from unconsolidated and bedrock aquifers.

According to official statistics, about 285 of China's 600 key collieries have previously reported the occurrence of water inrush problems, resulting in considerable fiscal repercussions and, in a minority of cases, loss of life (Zhang and Shen 2004). A number of significant water inrush disasters associated with coal mining operations in China are outlined in Table 1.

Coal removal and the necessary production of stopes typically lead to substantial subsurface movement and deformation, frequently resulting in the development of cracking and increased interconnectivity. Two failure zones affecting subsurface hydraulic conductivity characteristically form over the mined area, namely, a caving zone and a fractured zone (Bai and Elsworth 1990; Liu 1981a). Fractured zones have a high concentration of conductive fractures, providing preferential pathways into mined areas via significantly enhanced hydraulic

Table 1 Selected water inrush disasters associated with Chinese coal mines (Zhang and Shen 2004)

Coal field	Mine	Maximum flow rate (m ³ /min)
Kailuan	Fangezhuang	2,053
Feicheng	Taoyang Zhong No. 1	299
Feicheng	Yangzhuang	73.5
Fengfeng	No. 1	150
Jiaozhuo	Yanma	320
Jiaozhuo	Zhongmacun	105
Xuzhou	Zhangji	400
Hancheng	Magouqu	200
Chenhe	No. 2	335
Jingjing	No. 3	68
Zibo	Beidajing	566
Zhengzhou	Micun	75.2
Pingdingshan	No. 8	53.3

conductivity within these zones, also referred to as water-conducting zones (Zhang and Shen 2004). Fractures in the water-conducting zone are generally classified as tension fractures and separation fractures. Tension fractures intersect vertically or obliquely with rock strata as a result of the strata bending downward under tensile influences; separation fractures spread horizontally along bedding planes due primarily to differences in the mechanical properties of bedding layers. Fractures of both types may interconnect, permitting recharge water to enter the stope and creating the potential for water inrush accidents. In some countries, coal resources have been successfully extracted from beneath water-bearing formations via ‘partial mining’ methods, whereby large coal pillars remain in situ in the gob. The use of solid backfill mining (SBM) has become increasingly frequent in China; compared with ‘caving mining’ methods, it may be used to effectively reduce the extent and magnitude of movement of overlying strata, in concurrence with efficient waste rock disposal (Miao et al. 2010a, b).

The safe extraction of coal reserves from beneath an aquifer necessitates accurate determination of the height of the water-conducting zone (HWCZ) above a mined panel, which permits the infiltration of recharge water into the working panel. Overlying strata failure profiles and predictive equations pertaining to both caving and fractured zones induced by longwall mining have been developed, based on applied experience.

To safely extract coal reserves beneath an aquifer, it is critically important to determine the HWCZ above a mined panel that allows water inflow into the working panel (Chuen 1979; Dahl and Von Schonfeld 1976; Fawcett et al. 1986; Liu 1981a, b; Peng 1992; Peng and Chiang 1984).

Similarly, extensive in situ monitoring has resulted in the availability of extensive data pertaining to inter-burden deformation, pre- and post-mining coring, static water levels, water-inflow rates and caving, and fractured zone heights (Hasenfus et al. 1998; Hu et al. 2012; Miao et al. 2011; Styler 1984; Zhang and Shen 2004; Zhou 1991). Furthermore, numerical modeling has previously been undertaken to determine permeability changes in fractured rock as a consequence of mining under diverse conditions (Islam et al. 2009; Min et al. 2004; Tao et al. 2011; Wang 1982; Zhang and Shen 2004). Accordingly, the present study presents the derivation of a predictive equation to forecast the HWCZ under aquifers in SBM via a combination of numerical modeling with multiple regression analysis. Field trial results from the Wugou coal mine in China are presented and compared with predictions made using the aforementioned method.

Analysis of the Movement Characteristics of Overlying Strata and Their Influence on SBM

A Brief Introduction to SBM

The magnitude and scope of overlying strata failure are most significantly influenced by the mining method and roof control; roof control is of particular importance, as this determines the basic characteristics and maximum height of the strata failure zone (Liu 1981b). SBM is a relatively new backfill method that has been extensively employed for the extraction of coal resources located beneath buildings, railways, or water bodies, and for the disposal of solid wastes (such as gangue) on the surface (Bian et al. 2012; Miao et al. 2010a). In SBM, after coal extraction, waste materials (e.g. gangue, fly ash) are immediately deposited into the gob and compacted, so that the waste materials, adjacent solid sections, and coal pillars may, in combination, bear the load of the overlying strata (Zhang et al. 2010). Due to filling of the gob with compacted waste material, downward movement of the roof strata is constrained, which retards the extent and magnitude of upper strata movement, and limits ground subsidence (Huang et al. 2011a; Li et al. 2012).

A typical SBM process layout is presented in Fig. 1. Solid wastes derived from coal preparation plants or roadway extraction on the surface are crushed and screened before being transported to the subsurface mine sector via a vertical feeding hole. Typically, wastes are temporarily stored in an underground bunker connected to the vertical feeding hole before delivery to a working panel and backfilling into the gob area void space (Huang et al. 2011b; Zhang et al. 2009).

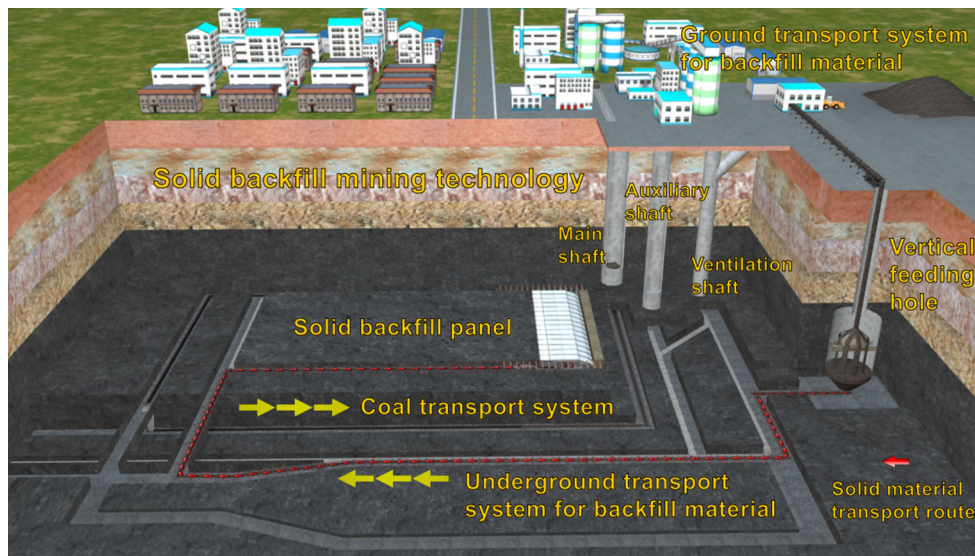


Fig. 1 Schematic of a typical solid backfill mining (SBM) process layout

Key equipment for SBM includes backfill supports, compactors, and a backfill conveyor; a specially designed backfill support comprises a front beam, back beam, six columns, a four-bar linkage, a compactor, and a support base (Fig. 2). The back beam of the support maintains void space for backfilling, while the compactor, in the rear of the support, consolidates the solid waste in the gob. The backfill conveyor encompasses unloading holes at the bottom, located beneath the back beam of the support and permitting a range of movement along the beam. Opening and closing of unloading holes is controlled via telescopic jacks (Figs. 2, 3).

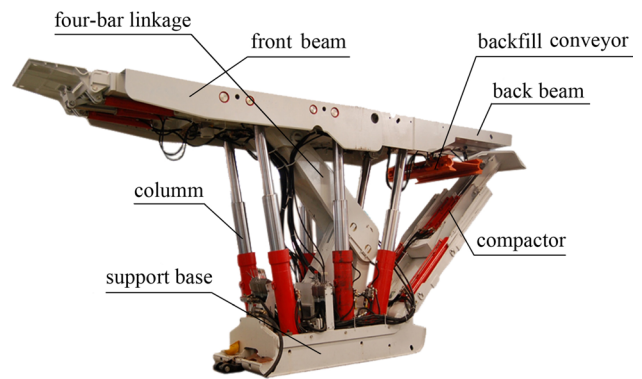


Fig. 2 Backfill support

SBM effectively combines mining and backfilling; backfilling proceeds from the tail to the head of the backfill conveyor. When fill material deposited at the bottom of the conveyor reaches a specified height, the hole is secured, followed by tamping of the fill by the compactor. The subsequent unloading hole is opened, with this process repeated until the fill has been sufficiently tamped; typically, two or three cycles are required.

General Characteristics of Overlying Strata Movement in SBM

Typically, only crack development occurs in the overlying strata when SBM is used, as opposed to caving damage; the maximum HWCZ associated with SBM is usually significantly less than that associated with the caving method (Liu 1981b). Based on previous field observations and physical laboratory simulations, the overlying strata can be divided into a fractured zone and a continuous bending zone (Fig. 4), the heights of which are influenced by the mining



Fig. 3 Backfill conveyor during operation

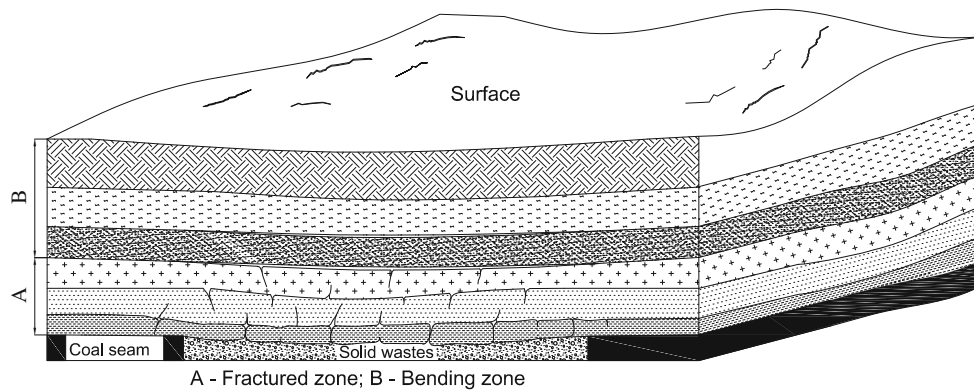


Fig. 4 Two zones of strata movement above a solid backfill panel

height and filling ratio (Huang et al. 2011a; Zhang et al. 2010).

The primary characteristics comprising the fractured zone include strata breakage and discontinuities in the stratified bedding. The magnitude and extent of fracture development gradually decreases with decreased depth below ground level, resulting in reduced permeability in an upward trajectory within this zone. The height of the fractured zone, primarily influenced by the filling ratio and the mining height, is considered to be the HWCZ, due to the aforementioned pattern of hydraulic conductivity.

The continuous bending zone, located above the fractured zone, is characterized by sustained deflection in the absence of apparent fracturing. Continuity and stratified features remain; some strata fissuring may occur due to tensile stress; however, continuity of the strata is typically retained, with minimal differential subsidence.

Main Factors Influencing the HWCZ in SBM

Where SBM is undertaken beneath an aquifer, it effectively prevents the extension of the water-conducting zone into the aquifer, providing enhanced operational safety. Based on previous studies, mining height has been shown to be a major factor affecting the height of the fractured overlying strata (Liu 1981b; Peng and Chiang 1984), because stress redistribution within the surrounding rock mass and the scope and magnitude of overlying strata failure after mining are both directly affected by mining height. Field measurements have shown that, for a single-slice extraction or for the first slice in multiple-slice longwall mine, fracture zone height is directly proportional to mining height (Liu 1981b).

Additionally, the quantity of fill deposited into the gob directly influences HWCZ. The filling ratio, η , is the ratio between fill material height after compaction by the overburden load (i.e. in situ stress) and the mining height (Zhou et al. 2012). The degree of compression exerted on the fill

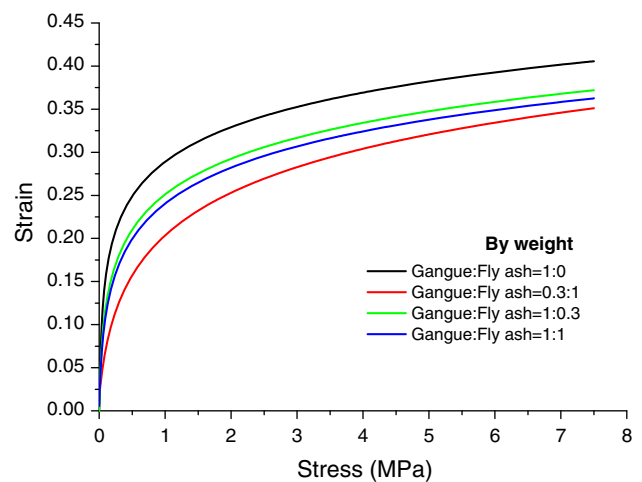


Fig. 5 The stress–strain curve of four commonly employed backfill materials

materials decreases with an increased filling ratio; accordingly, the degree of overburden failure and influence will eventually decrease due to an associated reduction of the sink of overlying strata over the gob. Fill materials such as gangue and coal ash are granular media with high porosity. Based on previous compaction testing, backfill material deformation increases logarithmically with increased stress (Fig. 5). The filling ratio can be obtained from the following equation:

$$\eta = \frac{h_0 \rho_c}{\theta h_1 \rho_s}, \quad (1)$$

where h_0 is the mining height (m), h_1 is the height of the fill material after tamping by the compaction device (m); ρ_c is the bulk density of coal (10^3 kg/m^3), ρ_s is the bulk density of the fill material compacted by the overburden load (10^3 kg/m^3), and θ is the ratio between the weight of fill material inserted into the gob and the extracted coal (unitless). The quantities h_0 , h_1 , and θ can be measured in the field, while ρ_c and ρ_s are obtained by laboratory analyses.

Numerical Modeling of HWCZ in SBM

Numerical Model

Numerical simulations of overlying strata failure due to mining operations were conducted at the Center of Mine Numerical Simulation of the State Key Laboratory of Coal Resources and Safe Mining, China, using Universal Distinct Element Code (UDEC) (Itasca 2004). Physical and mechanical parameters of the rock masses used for modeling were derived from laboratory tests (Table 2).

Numerical simulations objectified the prediction of HWCZ associated with varying mining heights and filling ratios, with two simulation schemes employed:

Simulation Scheme 1 Fixed mining height (3.5 m), simulate HWCZ caused by mining with varying filling ratios (0, 10, 30, 50, 60, 65, 70, 75, 80, and 85 %).

Simulation Scheme 2 Fixed filling ratio (85 %), simulate HWCZ caused by varying mining heights (1.5, 2, 2.5, 3, 3.5, 4, 4.5, and 5 m).

The Mohr–Coulomb model and the Double-Yield model were adopted for simulation of rock mass and filling material, respectively. Compaction of the fill material in the gob and the support provided to the overlying strata by the fill material were simulated using dynamic updating of the basic physical and mechanical parameters of fill materials based on the following relationship (Bai et al. 2013; Pappas and Mark 1993):

$$K = \frac{3(1 - 2\mu)}{2(1 + \mu)} G = \frac{\sigma_v}{2\varepsilon} = \frac{E_0}{2(1 - \varepsilon/\varepsilon_m)}, \tag{2}$$

where K is the bulk modulus (MPa), μ is Poisson’s ratio (unitless); G is the shear modulus (MPa), σ_v is the vertical stress (MPa), E_0 is the initial deformation modulus of the filling material (MPa), ε is the vertical strain, and ε_m is the maximum vertical strain (unitless). A flow chart of the algorithm used to represent the compaction process is presented in Fig. 6.

Feasibility Analysis

To validate the developed numerical model, laboratory testing of the compaction properties of backfill material was undertaken using a steel chamber (Fig. 7) and an MTS815.02 electro-hydraulic servo system. The stress–strain curves obtained via testing, in concurrence with the fitted curve (Eq. 2), are presented in Fig. 8. The fitted curve approximates the laboratory obtained curve well. According to the fitted curve and Eq. 2, the initial mechanical parameters required for accurate simulation of backfill material were successfully obtained (Table 3).

The stress–strain relationship of solid backfill material from the numerical model exhibited a high level of agreement with that of Eq. 2 and laboratory testing (Fig. 8). Accordingly, it may be concluded that simulation of the compaction of backfill material using Eq. 2 and the developed algorithm (Fig. 6) produces valid results.

Simulation Result

Figures 9 and 10 present HWCZ simulation results for various filling ratios and mining heights; at a fixed mining height, predicted HWCZ in the overlying strata decreased

Table 2 Physical and mechanical parameters of rock lithologies employed in numerical simulations

Lithology	Thickness (m)	Density (kg/m ³)	Bulk modulus (GPa)	Cohesion (MPa)	Tensile strength (MPa)	Internal friction angle (degrees)
Topsoil	200	1,800	0.1	0.5	0	17
Fine sandstone	20.0	2,250	1.64	2.0	1.0	32
Fine sandstone	10.0	2,200	1.63	2.5	1.1	32
Siltstone	15.0	2,615	1.87	2.0	1.0	30
Sandy mudstone	10.0	2,200	0.63	1.0	0.5	28
Mudstone	6.0	1,600	0.6	0.5	0.6	28
Siltstone	4.0	2,615	1.87	2.0	1.0	30
Medium sandstone	4.0	2,100	1.60	2.2	1.0	31
Mudstone	7.0	1,600	0.6	0.5	0.6	28
Siltstone	2.0	2,615	1.87	2.0	1.0	30
Fine sandstone	6.0	2,200	1.63	2.5	1.1	32
Mudstone	2.5	1,600	0.6	0.5	0.6	28
Coal seam	3.5	1,400	0.8	0.3	0.5	26
Silt-fine sandstone	10.0	2,600	2.5	4.0	1.4	35

linearly as the filling ratio increased (Fig. 9); an increase in the filling ratio results in a decreased level of filling material compression and subsequent downward migration of overlying strata above the gob. Thus, the predicted HWCZ due to mining operations is reduced in SBM.

When the filling ratio was fixed, the HWCZ above the gob increased linearly as the mining height increased (Fig. 10); this finding is consistent with conclusions reported by Liu (1981b) and Peng and Chiang (1984). At a fixed filling ratio, as mining height is increased, unfilled space is added, thus creating an increased HWCZ.

Development of Predictive Equation for HWCZ of SBM

Based on the simulation results described above, the level of linearity between HWCZ and both mining height and filling ratio in SBM was analyzed using SPSS 13.0 statistical software (SPSS 2004), as follows:

$$H_c = 31.96 + 2.72M - 34.555\eta, \quad (3)$$

where H_c is the HWCZ caused by SBM (m), M is the mining height, and η is the filling ratio in the gob. A correlation coefficient (R^2) of 0.981 was obtained, suggesting a high degree of fit with respect to the model.

Engineering Application

The Wugou coal mine is located in Huaibei City, Anhui Province. In the northeast section of the mine, an aquifer directly covers the bedrock strata overlying the coal reserves, with an overlying alluvial layer. Associated on-site bedrock thickness increases from approximately 20 m. In these geological conditions, the use of the caving method may lead to inclusion of the aquifer within the fractured zone, thus presenting a potential water inrush hazard. An SMB field trial was conducted at the CT101 working face, and the resulting HWCZ was measured.

Mining and Geological Conditions

The surface elevation of the CT101 face is 26.79–27.20 m above ordnance datum, with the main coal seam located 292–339 m below the ground surface, with a mean thickness of 3.5 m and an average inclination angle of 6°. The immediate roof is comprised of siltstone and fine sandstone with high associated wet and dry strengths and a mean thickness of 5.8 m. Weak, fine-grained, highly plastic sandstone with a low permeability coefficient and a large proportion of interior argillaceous rock overlies the immediate roof. The immediate floor comprises 1 m thick mudstone underlain by a band of fine sandstone. The 7.1 m

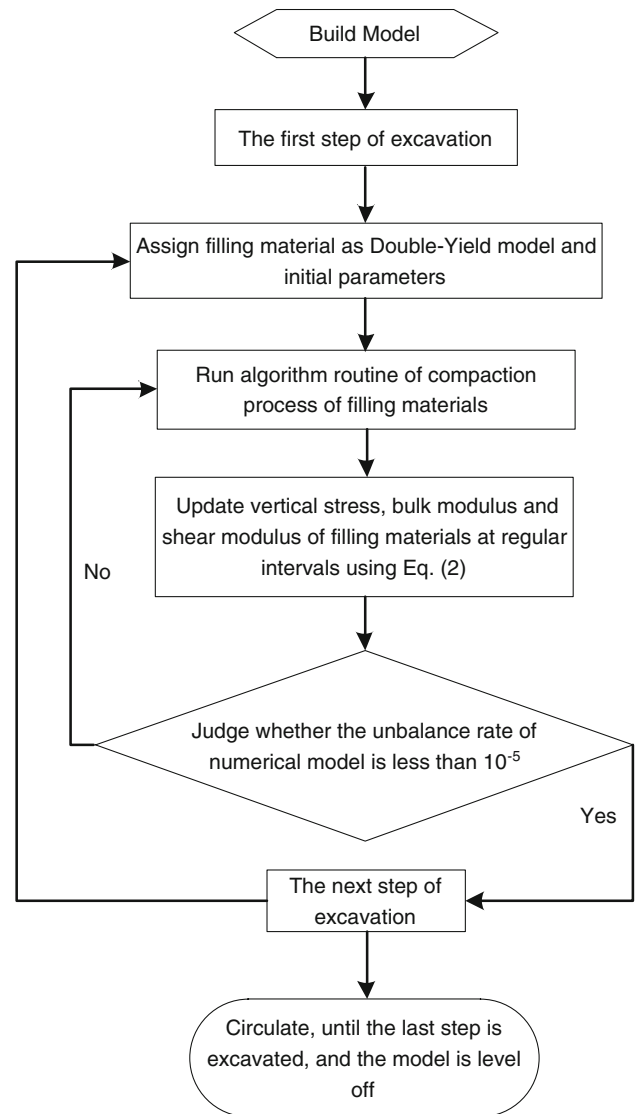


Fig. 6 Algorithm schematic for filling material compaction of the filling material in the gob

thick aquifer is mainly comprised of gravel, clayey sand, and coarse and medium sand, and is not highly productive. The layout of the CT101 working face is shown in Fig. 11. Above the CT101 starting cut, the distance between the CT101 working face and the aquifer is 21.8 m (Fig. 12).

HWCZ Measurement in SBM

The drilling water leakage method for measuring HWCZ uses a water tank of fixed volume (1 m³), with water levels measured before and after drilling, permitting determination of leakage during the drilling process based on water leakage per unit time or unit length. HWCZ and fracture development in the overlying strata can be ascertained based on observed changes in water leakage during the drilling procedure (Zhang and Li 2011).

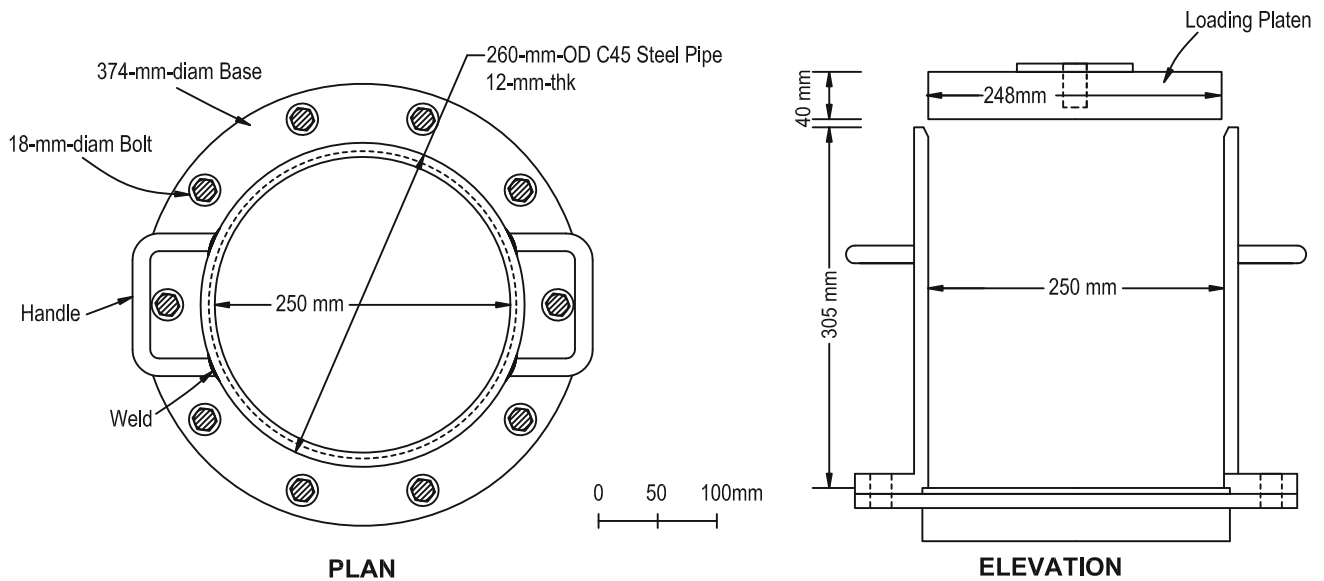


Fig. 7 Plan and elevation views of laboratory test chamber

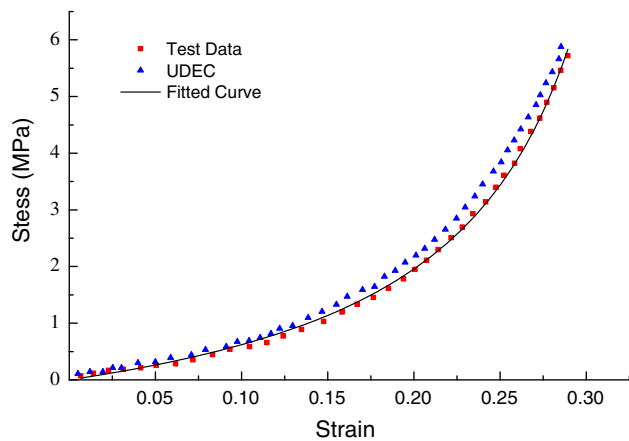


Fig. 8 Relationship between stress and strain in backfill material

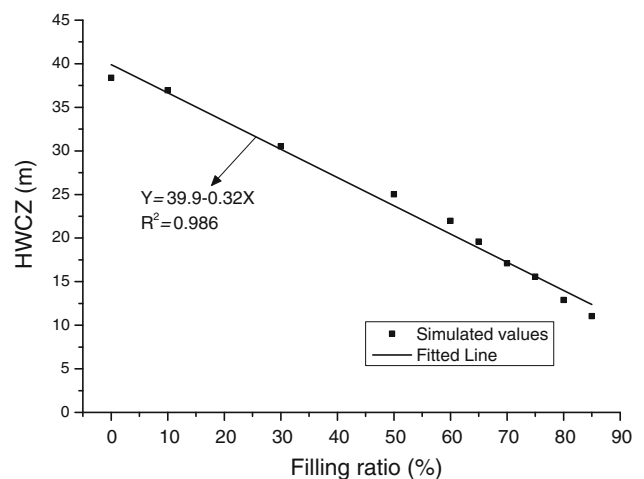


Fig. 9 Variation of HWCZ with filling ratio (at a fixed mining height of 3.5 m)

Table 3 Initial mechanical parameters for modeling backfill material

K/MPa	G/MPa	$\gamma/(MN\ m^{-3})$	c/MPa	$\phi/^\circ$	σ_t/MPa
22,708	17,031	0.015	0.002	8	0

To measure HWCZ above the CT101 face, two boreholes (W1 and W2) were drilled above the face center 2 months after CT101 completion (Figs. 11, 12). Borehole diameters were 170 mm in the overburden (cased) and 91 mm in the bedrock (cased in the weathered zone only). When the boreholes reached unweathered bedrock, casing was not considered necessary, with drilling carried out using clean water. Fracture development in the strata above the gob was ascertained via observation of water leakage

variation in the boreholes. Borehole W1 was located near the starting cut since the covering strata in that area was thinnest above this panel, making this a key location to monitor. According to Liu (1981b), in general, the HWCZ should peak a certain distance from the starting cut, and so a second borehole, W2, was also drilled.

Measurement of HWCZ

Measured water leakage variations in boreholes W1 and W2 are presented in Fig. 13. Prior to reaching 255 m, water leakage was shown to increase gradually in W1, albeit with slight fluctuations; rock cores obtained from this

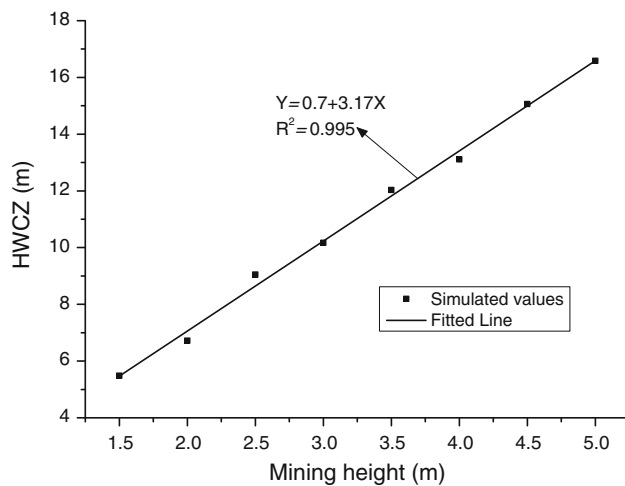


Fig. 10 Variation of HWCZ with mining height (at a fixed filling ratio of 85 %)

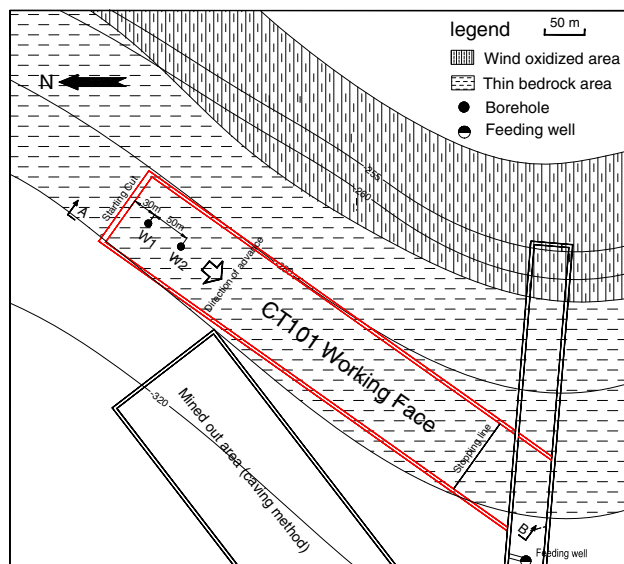


Fig. 11 Layout of the CT101 working face

section exhibited a high level of structural integrity. As drilling advanced, measured water leakage increased from 0.72 to 3.89 m³/h, due to pre-existing fissures. These were subsequently plugged, resulting in a return to low measured leakage, ranging from 0.24 to 1.98 m³/h. Rock cores from this section were also relatively intact. When W1 reached a depth of 278.35 m, water leakage increased rapidly from approximately 2.0 to 4.67 m³/h, with <50 % of rock core recovered due to induced fissuring. As drilling continued, water leakage exhibited small fluctuations while remaining high. Accordingly, it may be concluded that the water-conducting zone extended to a drilling depth of 278.35 m.

Since the elevations of borehole W1 and the immediate roof are +26.92 and −261.01 m, respectively, the HWCZ was calculated to be 9.78 m thick, considering surface subsidence.

Water leakage fluctuated in borehole W2 from 0.12 to 2.04 m³/h to a depth of 284.14 m, in parallel with a core recovery rate of >75 %, and an absence of obvious fissuring. As drilling proceeded from this depth, leakage rose rapidly from 2.03 to 4.21 m³/h in the presence of a highly fragmented core. Continued drilling from this depth was associated with sustained high leakage. Thus, we concluded that the peak point of the water-conducting zone was located at a drilled depth of 284.14 m, with the HWCZ in W2 calculated to be 10.89 m. Rock cores from W1 and W2 were sandstone, contained large amounts of argillaceous-like montmorillonite and kaolinite, and was characterized by water swelling and high plasticity; this may be causative in terms of the reduced degree of mining-induced fissure development observed during field trials.

Comparative Analysis on the Developed Height of the Water-Conducting Zone

The predicted and measured values of HWCZ for the CT101 working face, together with values for the adjacent working faces using the caving method are presented in Table 4.

The maximum HWCZ above the CT101 face is about 10.89 m (Table 3), which is slightly less than the predicted value of 13.84 m (the measured filling ratio was 80.2 %). The ratio of HWCZ to the mining height was 6.1–12.2 in adjacent working faces using the caving method, but it was only about 3.0 for SBM, indicating that SBM may be successfully used to reduce the magnitude of overlying strata failure caused by coal mining.

Conclusions

Accurate determination of the HWCZ associated with coal mines operating under aquifers is of critical importance in terms of both human safety and economic feasibility. Field measurements indicate that backfilling of the gob area with solid waste as part of SBM operations creates both fractured and bending zones in overlying strata. Moreover, the current study indicates that SBM should be the primary solution for mining under water-bearing geological formations.

Through analyses, mining height and filling ratio have been highlighted as the primary factors influencing HWCZ. Numerical simulation was utilized to acquire parametric relationships between HWCZ and these two factors, followed by the development of a predictive regression

Fig. 12 A–B section illustrating the aquifer location and boreholes at the field trial site

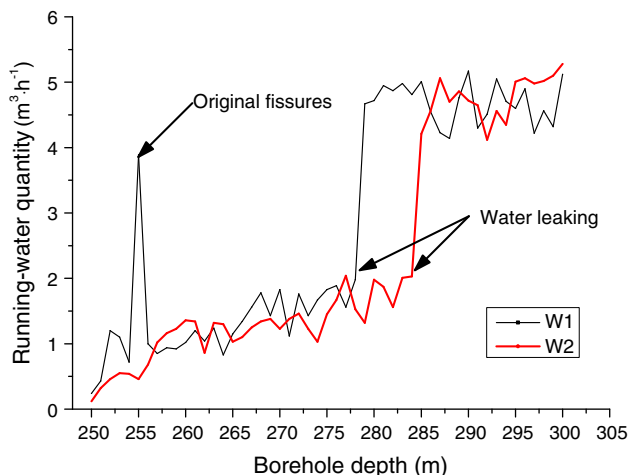
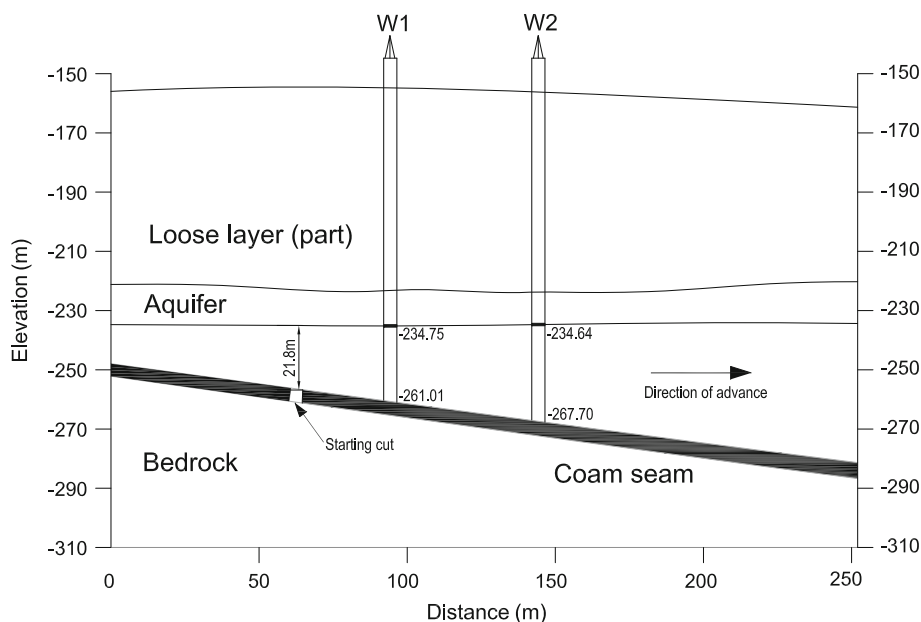


Fig. 13 Observed water leakage at boreholes W1 and W2

Table 4 Comparison of HWCZ values for SBM and the caving method

	CT101 (SBM)			Adjacent working faces (caving method)
	Borehole W1	Borehole W2	Predicted value from Eq. (3)	
HWCZ (m)	9.78	10.89	13.84	21.35–42.7
Ratio of HWCZ to mining height	2.79	3.11	3.95	6.1–12.2

equation pertaining to HWCZ in SBM. A field trial was undertaken in relevant hydrogeological conditions, with HWCZ characterized via measured water leakage. Field results were highly comparable with those garnered through use of the developed predictive equation, indicating a high level of validity. Measured HWCZ was significantly less than that associated with the ‘caving method’, thus indicating that SBM be appropriately employed to limit strata movement and deformation. Study results have general relevance for coal mining operations located beneath aquifers, both in China and abroad.

Acknowledgments The authors gratefully acknowledge financial support from the Fundamental Research Funds for the Central Universities (China University of Mining and Technology) under Grant 2014ZDPY02 and Qing Lan Project.

References

Bai M, Elsworth D (1990) Some aspects of mining under aquifers in China. *Min Sci Tech* 10:81–91
 Bai QS, Tu SH, Yuan Y, Wang FT (2013) Back analysis of mining induced responses on the basis of goaf compaction theory. *J China Univ Min Technol* 42(3):355–362
 Bian ZF, Miao XX, Lei SG, Chen SE (2012) The challenges of reusing mining and mineral-processing wastes. *Science* 373:701–703
 Chuen LT (1979) Practice and knowledge of coal mining under water bodies. In: *Proceedings 10th World Mining Congress Expo, Istanbul, Turkey, vol 3, pp 1–15*
 Dahl HD, Von Schonfeld HA (1976) Rock mechanics element of coal mine design. In: *Proceedings 17th US Symp. on Rock Mechanics, Univ of Utah, ISBN: 0-89520-046-5, pp 31–39*
 Du JP, Wang LH (2005) *Special coal mining methods*. China University of Mining and Technology Press, Xuzhou

- Fawcett RJ, Hibberd S, Singh RN (1986) Analytic calculations of hydraulic conductivities above longwall coal faces. *Int J Mine Water* 5(1):45–60
- Hasenfus GJ, Johnson KL, Su DWH (1998) A hydro geo-mechanical study of overburden aquifer response to longwall mining. In: *Proceedings of 7th International Conf on Ground Control in Mining*, West Virginia Univ, Morgantown, WV, USA, pp 149–162
- Hu XJ, Li WP, Cao DT, Liu MC (2012) Index of multiple factors and expected height of fully mechanized water flowing fractured zone. *J China Coal Soc* 37(4):613–620
- Huang YL, Zhang JX, An BF (2011a) Overlying strata movement law in fully mechanized coal mining and backfilling longwall face by similar physical simulation. *J Min Sci* 47(5):618–627
- Huang YL, Zhang JX, Zhang Q (2011b) Backfilling technology of substituting waste and fly ash for coal underground in China coal mining area. *Environ Eng Manag J* 10(6):769–775
- Islam RM, Hayashi D, Kamruzzaman ABM (2009) Finite element modeling of stress distributions and problems for multi-slice longwall mining in Bangladesh, with special reference to the Barapukuria coal mine. *Int J Coal Geol* 78(2):91–109
- Itasca (2004) UDEC version 4.0, user's manual. Itasca Consulting Group Inc, Minneapolis
- Li J, Zhang JX, Huang YL, Zhang Q, Xu JM (2012) An investigation of surface deformation after fully mechanized solid back fill mining. *Int J Min Sci Technol* 22(4):453–457
- Liu T (1981a) Coal mine ground movement and strata failure. *Coal Industry Publ House*, Beijing
- Liu TQ (1981b) Surface movements, overburden failure and its application. *Coal Industry Press*, Beijing
- Miao XX, Zhang JX, Guo GL (2010a) Method and technology of fully-mechanized coal mining with solid waste filling. *China University of Mining and Technology Press*, Xuzhou
- Miao XX, Zhang JX, Guo GL (2010b) Study on waste-filling method and technology in fully-mechanized coal mining. *J China Coal Soc* 35:1–6
- Miao XX, Cui XM, Wang JN, Xu JL (2011) The height of fractured water-conducting zone in undermined rock strata. *Eng Geol* 120:32–39
- Min KB, Rutqvist J, Tsang CF, Jing L (2004) Stress-dependent permeability of fractured rock masses: a numerical study. *Int J Rock Mech Min Sci* 41:1191–1210
- Pappas DM, Mark C (1993) Behavior of simulated longwall gob material. *US Bureau of Mines*, Washington
- Peng SS (1992) Surface subsidence engineering. *SME*, Littleton
- Peng SS, Chiang HS (1984) Longwall mining. *Wiley*, New York City
- SPSS (2004) SPSS software version 13.0. *SPSS Inc*, Chicago
- Styler N (1984) Prediction of inter-strata movements above longwall faces. In: *Proceedings of 25th US Symposium on Rock Mechanics*, Paper No. 84-0651, Evanston, IL
- Tao QF, Ghassemi A, Ehlig-Economides CA (2011) A fully coupled method to model fracture permeability change in naturally fractured reservoirs. *Int J Rock Mech Min Sci* 48:259–268
- Wang YN (1982) Prediction of the height of water conducting fissured zone by amazing the stress distribution in overlying strata. *J China Coal Soc* 1:92–99
- Zhang YJ, Li FM (2011) Monitoring analysis of fissure development evolution and height of overburden failure of high tension fully-mechanized caving mining. *Chin J Rock Mech Eng* 30(S1):2994–3001
- Zhang JC, Shen BH (2004) Coal mining under aquifers in China: a case study. *Int J Rock Mech Min Sci* 41:629–639
- Zhang J, Zhang Y, Liu T (1997) Rock mass permeability and coal mine water inrush. *Geological Publ House*, Beijing
- Zhang JX, Miao XX, Guo GL (2009) Development status of backfilling technology using raw waste in coal mining. *J Min Saf Eng* 26(4):395–401
- Zhang JX, Wu Q, Huang YL (2010) Strata pressure behavior by raw waste backfilling with fully-mechanized coal mining technology. *J China Coal Soc* 35(8):1–4
- Zhou Y (1991) Evaluating the impact of multi-seam mining on recoverable coal reserves in an adjacent seam. *Virginia Division of Mineral Resources*, Virginia Department of Mines, Minerals and Energy, Publ. 104
- Zhou YJ, Chen Y, Zhang JX, He Q (2012) Control principle and technology of final compression ratio of backfilling material. *J Min Saf Eng* 3:351–356