



Prevention of water and sand inrush during mining of extremely thick coal seams under unconsolidated Cenozoic alluvium

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Abstract

Mining extremely thick coal seams under layer of loose unconsolidated Cenozoic alluvium is common in north China. However, this may cause serious consequences including breaking down workface, submerging equipment, even serious flooding accident and casualties, because there is an alluvium aquifer composed of sand, clay, and gravels directly overlying above coal seams. Formulating preventive and control measures in advance is extremely important to a mine. In this paper, case study of water and sand inrush prevention is taken in Xiexin coal mine. A 15.5-m thick coal seam is threatened by unconsolidated Cenozoic alluvium water hazard during mining. By the research and exploitation of hydrological characteristics and strata lithology of unconsolidated Cenozoic alluvium, the lowermost layer in some areas is the layer of clay with good water resistance, and part of areas is permeable water-bearing sand mixed with gravel belonging to weak aquifer, which provide an advantageous condition to possibly set and optimally design sand-proof and caved-proof pillars. Considering its geological and hydrogeological characteristics, slice long-wall mining technology which extracts thick coal seams from top to bottom by dividing it into two slices is employed. Based on observations carried out in the field and physical model testing in the lab, strata failures induced by slice long-wall mining were investigated. The study indicated that the maximum height of the caved zone for upper slice was about 5.62 times of the upper slice mining height and the comprehensive height of the caved zone for two slices was about 4.71 times of the total mining height of two slices. The height of caved zone derived from physical model testing was consistent with the height obtained from field measurements. According to the hydrogeology of alluvium, overlying strata lithology, and mining conditions, the optimal design of sand-proof pillar at areas with weak water rich aquifer, and caved-proof pillar at areas with the lowermost layer of clay for workface 1702, workface 1704, and workface 1706 were given for safe production. The optimal design and technique measures, such as slice mining and reducing the thickness of extractions within the upper or lower slice, were successfully practiced. Overall, the conclusions are of engineering significance for coal mines suffering from water and sand inrush of unconsolidated Cenozoic alluvium.

Keywords Water and sand inrush · Unconsolidated Cenozoic alluvium · Extremely thick coal seams · Fractured zone · Caved zone · Slice long-wall mining

Introduction

In some mining areas of northeast and northwest of China, a layer of loose unconsolidated Cenozoic alluvium composed of

sand, clay, and gravels directly overlay the coal-bearing strata, which poses serious threats to safe mining extraction. If the coal-bearing strata are connected directly with the water-bearing alluvium aquifers by fracture and failures, water and sand inrush will cause serious consequences including breaking down working face, submerging equipment, even serious flooding accident and casualties.

There have been dozens of water and sand inrush accidents from unconsolidated Cenozoic alluvium aquifer in China. From September 24 to 25, 2001, the Qidong coal mine located in Huaibei coalfield, Anhui province, experienced water inrush at the first working face 3₂22, the maximum water output being 1520 m³/h, which eventually caused the coal mine soon

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drowned. In the north mining area of Qidong coal mine, most of working faces have been mined and at least 18 water inrush hazards happened (Chen et al. 2016a). On January 30, 2015, the Zhuxianzhuang coal mine located in Suzhou City, Anhui province, had a roof water inrush accident at the workface 866-1 with the instantaneous peak water inflow being 7200 m³/h, and the cumulative water output up to 800 m³, which left 7 miners dead. On July 28, 2010, a water and sand inrush disaster occurred at working face 22402 in Halagou coal mine, when the advancing distance reached 38 m from the starting cut with the mining height of 4.5 m. Accompanying with the accident, a sinkhole with diameter of 47 m and depth of 12 m was formed (Yan et al. 2018c). The statistics shows that about 285 coal mines (with estimated reserves exceeding 100 billion tons) out of 600 in China suffer from water inrush during extracting the coal seams covered by the unconsolidated Cenozoic formation (Chen et al. 2016a). Therefore, studying the water and sand inrush mechanisms, forecasting water and sand inrush, and formulating preventive and control measures in advance are extremely important to safe production and groundwater protection, especially for enhancing recovery in the shallow area.

Generally, the fractured zone and caved zone developed during mining under unconsolidated Cenozoic alluvium at shallow depth should be considered, because it provides access for water and sand inflow into mining workface (Liu 1981; Peng and Chiang 1984). To prevent water and sand inrush, it is of special interest for setting rock and coal pillar during coal mining. The height of rock and coal pillar is defined as the vertical distance between the aquifer and the working face. If the rock and coal pillar is small, fractured pathways within overlying strata will reach water bodies above the coal seam, rapid water influx, and quicksand or flooding accidents may occur, whereas it will lead to a loss of coal resource (Zhang and Shen 2004). Therefore, the optimal design for rock and coal pillar is of crucial importance for safety operation during mining under unconsolidated Cenozoic alluvium, and has been discussed in detail in some researches (Singh and Singh 1999; Gandhe et al. 2005; Singh et al. 2008; Xu et al. 2018).

Except for setting rock and coal pillars, many researches mitigating overburden failure and subsidence have been carried out to prevent water and sand inrush due to coal mining. Partial mining methods, such as strip coal pillar mining and room-and-pillar method is one of the effective technical measures to control overlying strata movement and surface subsidence around the world. Scott et al. (2010) introduced the room and pillar mining method in Australia and indicated that the method was much more flexible technique to implement than long-wall mining. Singh et al. (2008) reviewed and described the room and pillar mining method due to environmental impact in India, and indicated that it was a suitable mining method for underground coal extraction at

shallow depth. Backfilling mining is another special coal mining method, which can not only control the overlying strata deformation and movement, but also dispose the solid waste products, as a consequence have been used in recent years in China. Chen et al. (2016b) analyzed the method of strip mining combined with backfill mining, which employed cement paste backfill (CPB) body to replace strip coal pillar, and increased coal introduction. Liu et al. (2017) adopted an intermittent cut-and-fill mining method to maintain the roof stability under sand aquifers, which proved to be an effective way to reduce overburden failure and subsidence with coal mining under sand aquifers. Yan et al. (2018a, 2018b) used the solid backfill mining method to prevent the shaft deformation and failure caused by the movement of strata during the mining of ultra-contiguous coal seams. The properties of backfilling material, such as physical properties, mechanical properties, hydraulic properties, thermal properties, chemical properties, and microstructural properties are summarized by Fall et al. (2008), Orejarena and Fall (2008), Ghirian and Fall (2014, 2016), and Niroshan et al. (2018).

These researches mentioned above have indicated that the partial mining and backfilling methods can effectively control the overburden strata failure and surface subsidence, and proved to be an effective way to prevent water and sand inrush. But these researches on water and sand inrush are mainly applied to thin and medium thick coal seam, and are difficult to apply to extremely thick coal seams distributed widely in China, especially in the provinces of eastern Inner Mongolia, Xinjiang, Gansu, Shannxi, and Ningxia. In the meanwhile, the partial mining technology, and setting outcrop rock and coal pillars for extremely thick coal seams have the disadvantage of low recovery and will lead to enormous coal losses, and backfilling method has the disadvantage of high filling costs and backfill material shortage. Given the limitations of current researches, this paper presents a case study of prevention of water and sand inrush in Xiexin coal mine with 15.5 m thick coal seams threatened by unconsolidated Cenozoic alluvium water hazard during mining.

Research background

Xiexin coal mine is located in the Duolun County in the eastern Inner Mongolia. The coalfield exists in a fault-depression synclinal basin stretching from north to south with a length of 6000 m and a width of 300 to 1400 m. The no. 7 coal seams with average thickness of 15.5 m are divided into two layers by an interburden with thickness of 1.0 m. The average thickness of the upper layer is 8.0 m, and the lower layer is 6.5 m. The overlying rock strata are sandstone and mudstone, which belongs to the sequence of Bayanhua Formation from the Upper Cretaceous Period. The sequence is overlain by a loose alluvium, and interbed with clay and gravels, which belong to

Neogene Period. The upper part is covered by loose alluvium belonging to Quaternary Period, as shown in Fig. 1.

According to the mining design, two-slice comprehensive mechanized long-wall mining method (as shown in Fig. 2) can be used during mining operation under the condition of the thickness of bedrock greater than 80 m. Therefore, only workface 1703, workface 1705, and workface 1707 in the south coalfield have the condition of two-slice comprehensive mechanized long-wall mining, and workface 1702, workface 1704, and workface 1706 in the north coalfield will need to adopt other mining methods, such as room-and-pillar method, small mining height method, according to the thickness of rock strata shown in Fig. 3. This will cause a large amount of coal resources stagnant and low mining production. In order to optimize mining methods, define reasonable upper limit, and achieve safe and efficient production, it is very important to further study the hydrogeological conditions of the unconsolidated Cenozoic alluvium, and the failure characteristics of overlying strata under the condition of two-slice comprehensive mechanized long-wall mining with full caving.

Geological and hydrogeological conditions

Lithology and hydrogeology

There are three types of rock and coal pillars in outcrop area, i.e., the water-proof pillar, the sand-proof pillar, and the caved-proof pillar. The pillars vary in their functions, sizes, and applicable conditions and response to hydrogeology (Zhang and Peng 2005). The water-proof pillar is used for preventing groundwater or surface water from flowing into mining workface through mining-induced fracture. Unit flow rate is generally used to define the water-bearing extent of the aquifer. Water flow (L/s) is tested when water drawdown is 10 m in a 91-mm diameter borehole, then the unit flow rate is the water flow (L/s) per meter length of drawdown. When the lowermost water-bearing layer belongs to a strong aquifer (unit flow rate $q > 1.0 L/(s.m)$), or medium strong aquifer (unit flow rate $q = 0.1-1.0 L/(s.m)$), the water-proof pillar is applied. The sand-proof pillar is designed for preventing sand in alluvium from flowing into mining workface through mining-induced caving. It allows fractured zone to penetrate partially into the

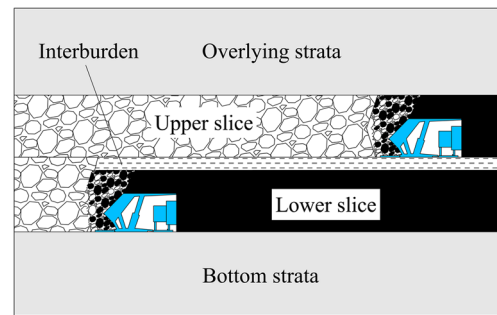
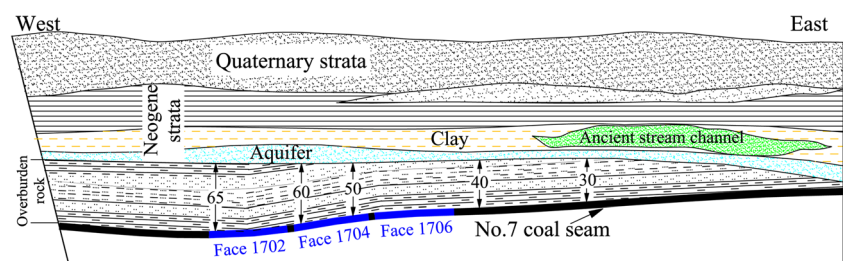


Fig. 2 Sketch map of two-slice comprehensive mechanized long-wall mining method

aquifer. When the lowermost water-bearing layer in alluvium belongs to a weak aquifer, the sand-proof pillar can be applied. When the lowermost layer in alluvium belongs to a thick layer of clay or a drainable weak aquifer, the caved-proof pillar can be applied (Peng and Zhang 2007).

Therefore, the design of the rock and coal pillars in the shallow mining are based primarily on the hydrological characteristics, strata lithology, and mining conditions. In order to obtain the lithology and hydrological features of Cenozoic alluvium, 55 boreholes composed of 24 previous and 31 later exploited were analyzed in detail to obtain a detailed strata lithology and hydrogeological conditions. Quaternary strata with a thickness of 16.5–83.2 m are composed of alluvial fine sand, and the largest thickness is mainly concentrated in the middle of the coal field. The Neogene alluvium with the average thickness of 83.90 m is comprised of mixed impermeable layer of clay with water-bearing sand and gravels. The lowermost layer in some part is the layer of clay with the thickness of 2.49–92.98 m, and part of areas is permeable water-bearing sands mixed with gravels, as shown in Fig. 4. Through pumping test, the unit flow rate of water-bearing sands with gravel is 0.01–0.05 $L/(s.m)$, the hydraulic conductivity is 0.22–0.64 m/d, and the water head pressure is 0.73–0.85 MPa, which indicates that it belongs to weak aquifer. Underlying the alluvium is the bedrock of coal beds with the thickness of 0–200 m, and the uniaxial compressive strength of sandstone and mudstone range from 1.4 to 11.6 MPa belonging to weak types. According to a composition statistics of overburden rock strata, mudstone accounts for 52%, indicating that the overburden rock strata have good water resistance.

Fig. 1 Typical cross-section of coalfield



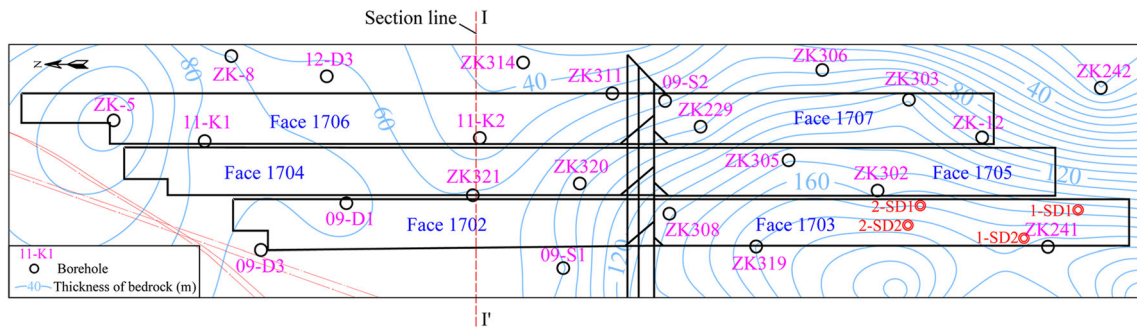


Fig. 3 Thickness contour plan map for bedrock

Water resistance of the lowermost layer of clay

The hydraulic properties of the lowermost layer of soils play an important role in preventing water and sand inrush from overlying strata, while water resistance is determined by its engineering properties. Generally, the water resistance was evaluated by liquid index and plastic index. Liquid index is used to determine the physical state of soil, and tells us if samples were likely to behave as plastic, solid, or even possibly a liquid. When the liquid index is less than 0, the clay is in a hard state. Plastic index is defined as the difference of the liquid limit and the plastic limit of soil, which is useful in engineering classification of fine-grained soils (Holtz and Kovacs 1983). The larger the plastic index, the finer the particle size and the larger specific surface area, the higher the content of clay or hydrophilic minerals in the soil. In order to acquire the engineering properties of the lowermost layer of soils, samples taken from borehole 1-SD1 and 1-SD2 at depth of 104.0 to 165.0 m were tested in laboratory according to the National Standard of People’s Republic of China (1999) (Standard for soil test method, GB/T50123-1999) (Fig. 5). The test results for physical parameters are shown in Table 1, and liquid limit and plastic limit are shown in Table 2.

The test results indicated that the lowermost of soils belongs to the layer of clay, and the average moisture content was 17.2%, and the average saturation was 91.6%, which showed that the clay has poor water absorption in natural state. The plastic index for all samples was greater than 17 except

the sample collected at the depth between 164 and 165 m, and the liquid index for all samples was less than 0, which indicated that the clay was in hard state, and as a consequence, has good water resistance and poor fluidity according to the National Standard of People’s Republic of China (2009) (Code for investigation of geotechnical engineering, GB50021-2001). To summarize, the layer of clay is very advantageous to prevent water and sand inrush during mining.

As mentioned above, the lowermost layer in some part of areas is weak aquifer for permeable water-bearing sands mixed with gravels. These areas can be provided with sand-proof pillar, and its minimum height (H_s) must not be less than the sum of the maximum height of the caved zone (H_c) and the height of a protective layer (H_p), as shown in Fig.6 a, i.e.,

$$H_s \geq H_c + H_p \tag{1}$$

The lowermost layer in some part of areas is the layer of clay and has good water resistance and poor fluidity, which provides a possibility for applying the caved-proof pillar. The height of caved-proof pillar should not be less than the maximum height of the caved zone, as shown in Fig.6 b, i.e.,

$$H_i \geq H_c \tag{2}$$

Therefore, whether it is a sand-proof pillar or a caved-proof pillar, the height of the caved zone is the most important parameter for their setting.

Fig. 4 Plan map of distribution for clay and sand with gravels in the lowermost layer at the north coalfield

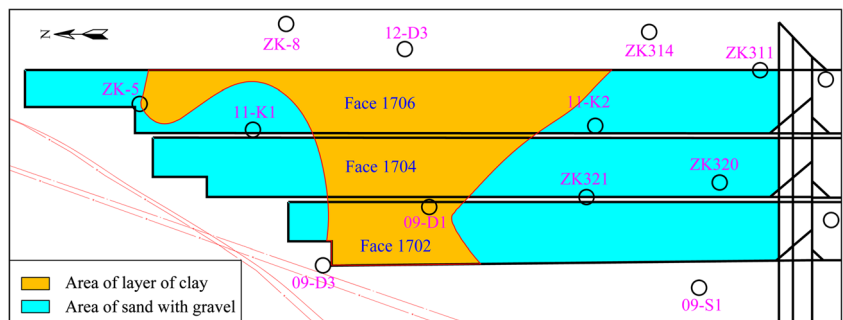




Fig. 5 The samples collected from boreholes. **a** Borehole 1-SD1. **b** Borehole 1-SD2

Failure characteristics of overburden strata for slice long-wall mining

In situ observation on the height of caved zone

The height of caved zone for upper slice

Considering its geological and hydrogeological characteristics, slice long-wall mining technology which extracts thick coal seams from top to bottom by dividing it into two slices was employed. In order to prevent water and sand inrush, and be able to mine safely under aquifer, it is very important to determine the height of the caved zone induced by slice long-wall mining in overburden strata. The caved zone for a single slice excavation with the mining thickness greater than 3 m is determined by in situ measurements in China currently, and the results could be used for predicting a maximum height of the caved zone for coal mines with similar geological conditions. For in situ measurements, drilling a borehole from the ground to rock strata and flushing the boreholes with water are generally used (Miao et al. 2011; Li et al. 2018). According to observations of water leakage in boreholes and borehole TV camera, the top interface of fractured zone and caved zone in overlying strata can be determined. The fractured zone shows overlying strata breakage and discontinuity, but rock retains stratified bedding usually. However, the caved zone shows serious strata deformation and changes irregularly, and as a consequence, voids occur.

According to the geological and mining conditions, two observation boreholes, named 1-SD1 and 1-SD2, were drilled above the workface 1703 after mining 1 month, as shown in Fig. 3. For borehole 1-SD1, the distance to the return airway was 20 m, and to the starting cut was 135 m. For borehole 1-SD2, the distance to the transport roadway was 20 m, and to the starting cut was 280 m. Figure 7 shows the water consumption quantity and the water level changed in two boreholes. According to observations of water leakage and change of water level, the water consumption quantity of borehole 1-SD1 was stable and fluctuated from 0.4 L/min to 7.2 L/min before the depth of 190 m. Water leakage increased subsequently and circulating fluid was suspended at the depth of 195 m (Fig. 7a). Up to the depth of 248 m, the water level descended significantly (Fig. 7b), and the core sample was cracked and strata became severely fractured, which indicated that the upper limit of the caved zone developed at the depth of 248 m for borehole 1-SD1. The mining depth in borehole 1-SD1 was 311.6 m, and the mining height was 9.6 m, then the height of fractured zone and caved zone was 112m and 54.0m, and was 11.67 and 5.62 times of the mining height, respectively. For borehole 1-SD2, the water consumption quantity increased abruptly and was suspended at the depth of 201 m (Figs. 7a, 8a). At the depth of 261 m, the drill string dropped and the rods became stuck due to the severe fractured strata, which indicated that the upper limit of the caved zone developed at the depth of 261 m for borehole 1-SD2 (Fig. 7b). The overlying strata showed breakage and discontinuity in

Table 1 The results of laboratory tests for physical parameters

Depth/m	Moisture content (%)	Wet density (g/cm ³)	Dry density (g/cm ³)	Void ratio	Saturation (%)
104.0–105.0	19.5	2.05	1.72	0.578	91.5
135.0–136.0	15.8	2.10	1.81	0.502	85.8
140.0–140.5	17.0	2.17	1.86	0.487	96.5
164.0–165.0	16.5	2.07	1.77	0.461	92.6
Average	17.2	2.10	1.79	0.507	91.6

Table 2 The results of laboratory tests for liquid and plastic limit

Depth/m	Liquid limit (%)	Plastic limit (%)	Plastic index	Liquid index	Soil classification	State of soil
104.0–105.0	51.7	28.3	23.4	−0.38	Clay	Hard
135.0–136.0	51.5	24.8	26.7	−0.34	Clay	Hard
140.0–140.5	43.8	24.8	19.0	−0.46	Clay	Hard
164.0–165.0	42.0	26.8	15.2	−0.68	Silty clay	Hard

fractured zone, and seriously deformed and changed irregularly in caved zone (Fig. 8b). The mining depth in borehole 1-SD2 was 321.1 m, and the mining height was 9.1 m, then the height of fractured zone and caved zone was 111 m and 51.0 m, and was 12.20 and 5.60 times of the mining height, respectively. Therefore, the observations demonstrated that the cave zone was about 5.60–5.62 times of the mining height.

The height of caved zone for lower slice

In order to acquire the caved zone of upper slice and lower slice long-wall mining excavation for extremely thick coal seams, two observation boreholes, named 2-SD1 and 2-SD2, were also drilled above the face 1703 after the lower slice had been mined, as shown in Fig. 3. For borehole 2-SD1, the distance to the air roadway was 40 m, and to the stopping line was 420 m. For borehole 2-SD2, the distance to the transport roadway was 20 m, and to the stopping line was 387 m. The observation method was same as the upper slice as mentioned above. Figure 9 shows the water consumption quantity and the water level changed in two boreholes. The upper limit of fractured zone and caved zone for borehole 2-SD1 was developed at the depth of 168.5 m and 222.7 m. The mining depth in borehole 2-SD1 was 310.4 m, and the cumulative mining height was 15.7 m, then the height of fractured zone and caved zone was 126.2 m and 72.0 m, and was 8.04 and 4.59 times of the mining height, respectively. Similarly, the upper limit of fractured zone and caved zone for borehole 2-SD2 was developed at the depth of 175.9 m and 234.3 m. The overlying strata showed breakage and discontinuity in fractured zone,

and seriously deformed and changed irregularly in caved zone (Fig. 10). The mining depth in borehole 2-SD2 was 320.5 m, and the cumulative mining height was 15.1 m, then the height of fractured zone and caved zone was 129.5 m and 71.1 m, and was 8.58 and 4.71 times of the mining height, respectively. Therefore, the observations demonstrated that the cave zone of lower slice long-wall mining excavation was about 4.59–4.71 times of the mining height.

Physical model testing for slice long-wall mining

Physical model set up and similarity coefficient

In order to acquire the characteristics of overburden rock strata deformation and failure for extremely thick coal seams, physical model testing was carried out to investigate the evolution rule of fractured zone and caved zone. Physical model testing is a simulation method that the strata are reduced to a certain proportion based on the principle of similarity, including geometric similarity, strength similarity, and time similarity. Physical model testing is one of the most effective methods to study the overlying strata movement induced by coal extraction, and has some advantages over field measurement, such as short experimental period, low cost, and visual evaluation process. Therefore, many researchers have used physical model testing to simulate the movement process of overlying strata (Dai et al. 2010; Wang et al. 2017; Zhu et al. 2018). Based on the geological conditions, the physical 2-D model of

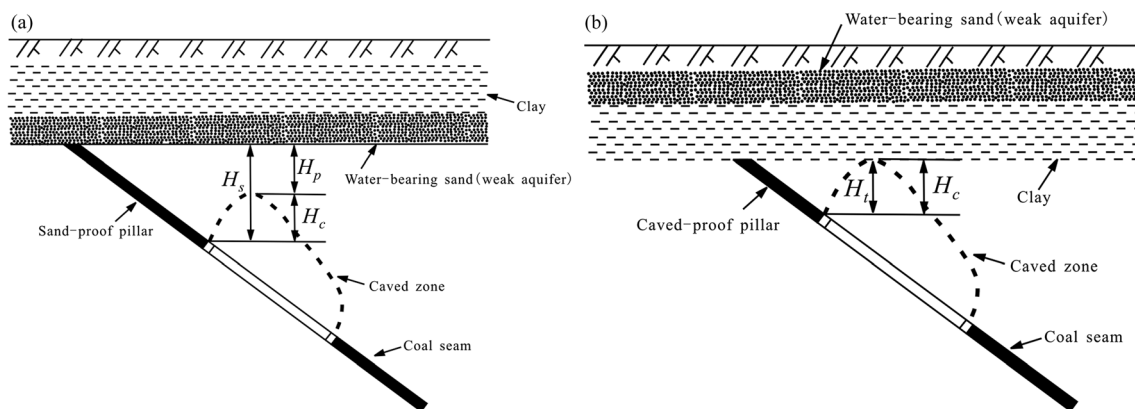
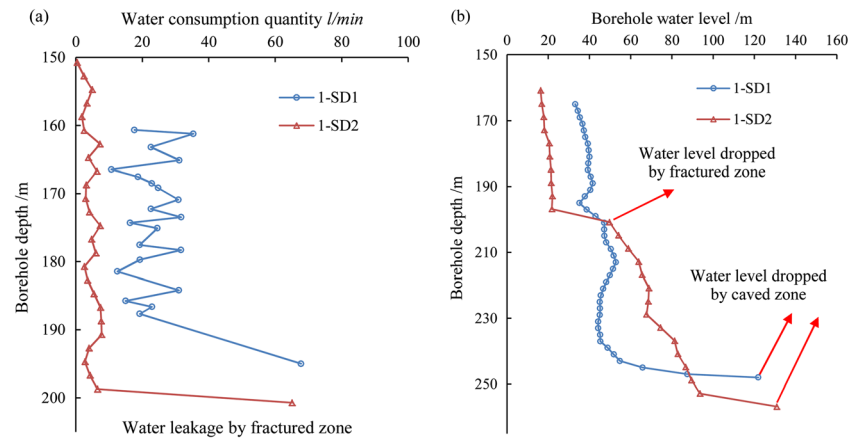


Fig. 6 The rock and coal pillar design. **a** Sand-proof pillar. **b** Caved-proof pillar (Zhang and Peng 2005)

Fig. 7 The water consumption quantity and water level changed in boreholes for upper slice. **a** Water consumption quantity. **b** Water level changes



the face 1703 was made of similar materials with size of 3200 mm × 250 mm × 1100 mm (length, width, and height). The coal seam with upper slice thickness of 8.0 m and lower slice thickness of 6.5 m was divided by coal interburden with thickness of 1.0 m. Due to the importance of the caved zone and fractured zone for mining under water bodies and the limit height of testing equipment, the top strata of Cenozoic alluvium was not established in the model, and vertical stress is applied to the top surface according to the weight of the overlying alluvium. The mining depth of the model was 900 mm, and the mining thickness was 77.5 mm.

Considering the experimental device and the length of simulation advance, the constant of geometric similarity (α_l) was taken as follows:

$$\alpha_l = l_m/l_s = 1/200 \quad (3)$$

where l_m is the length of model, m; l_s is the length of in situ area, m.

According to the properties of the similar materials and the ratio of the materials, the constant of bulk density similarity (α_γ) was taken as follows:

$$\alpha_\gamma = \gamma_m/\gamma_s = 1/1.6 \quad (4)$$

where γ_m is the bulk density of model material, kg/m^3 ; γ_s is the bulk density of in situ area, kg/m^3 . According to similarity principle and dimensional analysis, the constant of stress similarity (α_σ) should be satisfied as follows:

$$\alpha_\sigma = \alpha_l \alpha_\gamma \quad (5)$$

Then, the constant of stress similarity α_σ was 1/320.

Physical model testing results

Two-slice coal extractions can be used in the scale model test. The upper slice was mined firstly, and the lower slice was extracted latterly after the surrounding strata reached a stable state. The boundary of model was set to 100 m in length for the sake of reducing the boundary effect. Figure 10 shows the process of deformation and failure for overlying strata during mining. For the upper slice extraction, the immediate roof collapsed when the mining advanced to 20 m, and the fractures propagated upward (Fig. 11a). As the working face

Fig. 8 Photos of borehole 1-SD2 showing vertical fractures developed in fractured zone (a) and cracked strata developed in caved zone (b)

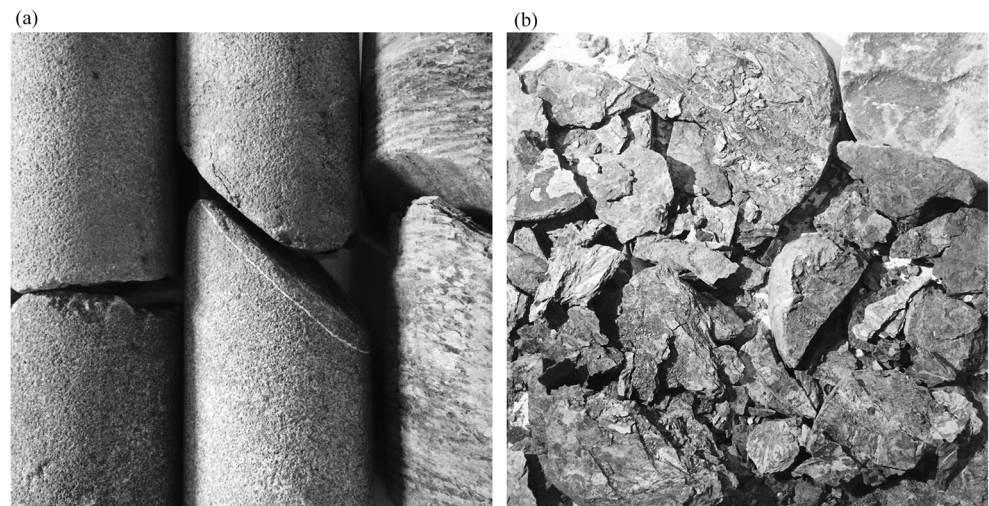
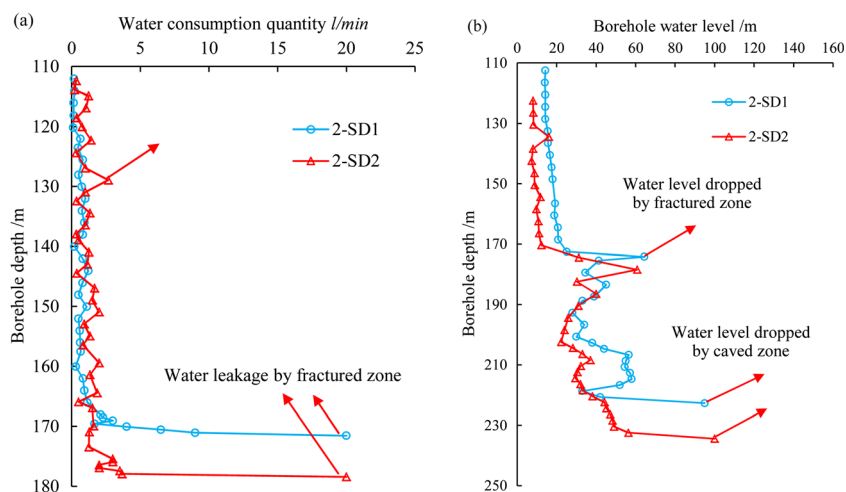


Fig. 9 The water consumption quantity and water level changed in boreholes for lower slice. **a** Water consumption quantity. **b** Water level changes



reached to 60 m, the main roof collapsed for the first time, which indicated that the first weighting step distance is 60 m (Fig. 11b). As the mining advanced to 80 m from the starting cut, the periodic cracking and caving occurred obviously, and the caving step was about 20 m (Fig. 11c). When the working face advanced up to 160 m, the bed separation developed in the overlying strata, and the caved zone was basically compacted with the maximum height of 43 m (Fig. 11d). With the working face advancing up to 230 m, the caved zone was no further increasing, and the fractured zone reached the height of 103 m (Fig. 11e). As the working face moved forward to 260 m, the fractured zone was no further increasing with the height of 103 m (Fig. 11f). Therefore, the maximum

height of the caved zone was 5.38 times of the mining height and the water conducting fractured zone was 12.88 times of the mining height. For the lower slice extraction, the immediate roof collapsed immediately due to disturbance by upper slice mining, and the caved zone was more broken and disorder (Fig. 12a). With the working face advancing up to 140 m, the caved zone still remained constant, and the height was 43 m (Fig. 12b). As the mining advanced to 180 m, the fractured zone quickly increased in height, and cracks in overlying strata developed severely, especially developed at the opening cut and stop line (Fig. 12c), and the height of caved zone and fractured zone reached 72 m and 150 m, respectively. As the workface continued to advance to 200 m, the height of caved

Fig. 10 Photos of borehole 2-SD2 showing vertical fractures developed in fractured zone (a) and cracked strata developed in caved zone (b)



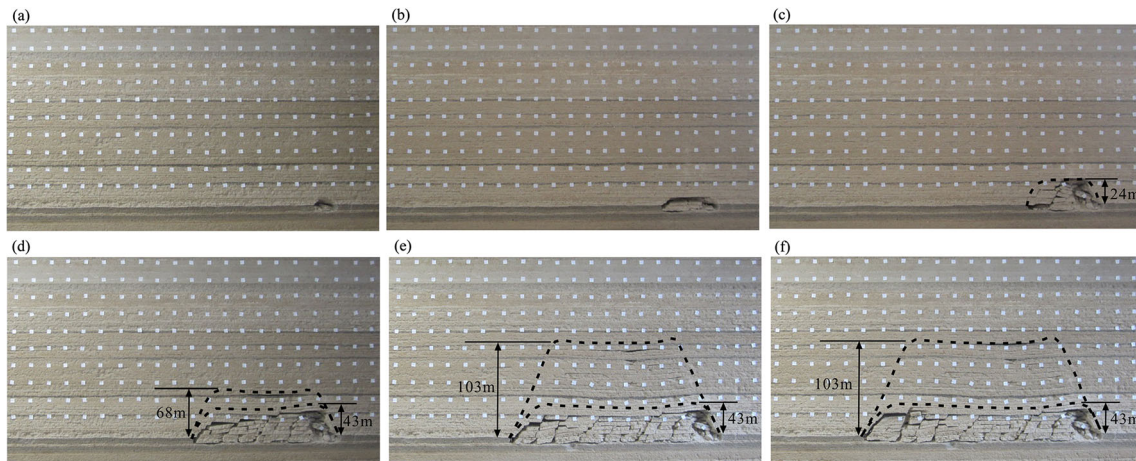


Fig. 11 Fracture evolution of overlying strata with upper slice long-wall caving mining. At advancing distance of 20 m (a), 60 m (b), 80 m (c), 160 m (d), 230 m (e), and 260 m (f)

zone and fractured zone remained constant, i.e., 72 m and 150 m in height (Fig. 12d). Therefore, the maximum height of the caved zone was 4.65 times of the mining height and the water conducting fractured zone was 9.68 times of the mining height.

According to the study of height of caved zone for slice long-wall mining, the maximum height of caved zone for the upper slice obtained by in situ investigation was about 5.60~5.62 times of the mining height, closed to that of 5.38 times of the mining height obtained by physical model testing. The caved zone of lower slice long-wall mining excavation was about 4.59~4.71 times of the mining height, very closed to that of 4.65 times of the mining height obtained by physical model testing.

Therefore, the height of caved zone derived from physical model testing was consistent with the height obtained by field observations.

Modifications and slice long-wall mining practices

Modifications to the mining design

From the detection and analysis of geological and hydrogeological conditions, along with the study on failure characteristics of overburden strata for slice long-wall mining, it provides a possibility to apply the sand-proof pillar at areas

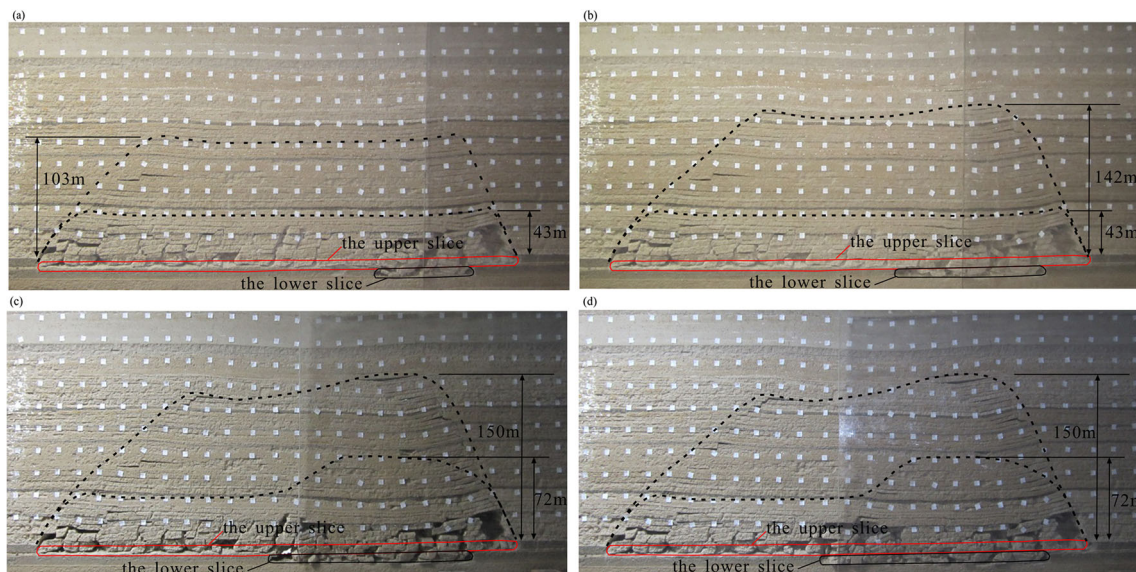


Fig. 12 Fracture evolution of overlying strata with lower slice long-wall caving mining. At advancing distance of 90 m (a), 140 m (b), 180 m (c), and 200 m (d)

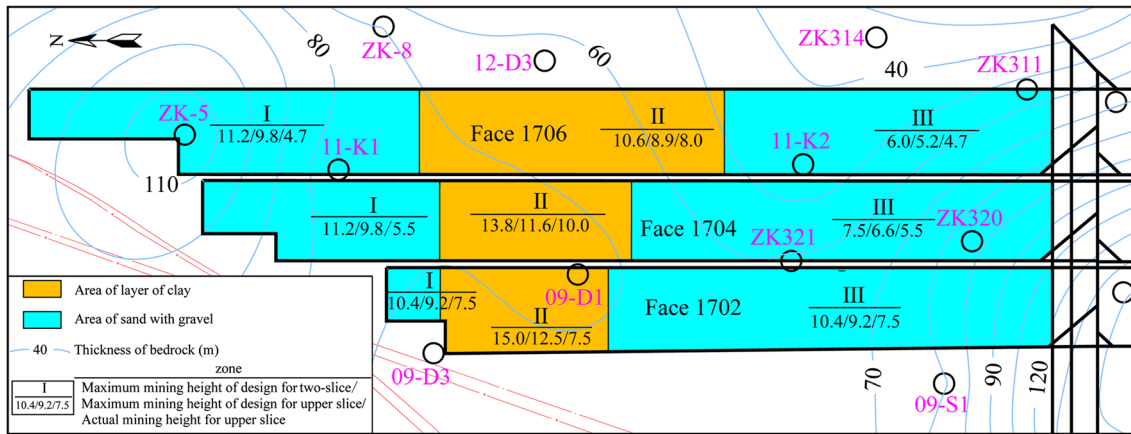


Fig. 13 The distribution of the lowermost layer of clay and mining height

with weak water rich aquifer, and caved-proof pillar at areas with the lowermost layer of clay for workface 1702, workface 1704, and workface 1706 in the north coalfield. Figure 13 is the thickness contour plan map for bedrock combining with the distribution of the lowermost layer of clay. To simplify the distribution and make it easier, workface 1702, workface 1704, and workface 1706 were divided into three zones, such as zone I, zone II, and zone III, according to the distribution of the lowermost layer of clay. The sand-proof pillar can be applied in zone I and zone III due to the overlying weak water rich aquifer, and the caved-proof pillar can be applied because of the overlying thick layer of clay.

As mentioned above, the maximum height of the caved zone for the upper slice was about 5.62 times of the mining height, and the comprehensive height of the caved zone for lower slice was about 4.71 times of the mining height, and the thickness of protective pillar (H_p) is usually determined to be $2M$ (the mining thickness) for weak strata based on experience (Zhang and Peng 2005). Therefore, the mining thickness can be obtained by backward calculation under the condition of given thickness of bedrock.

For workface 1702, the thickness of rock strata was 70 m in zone I, and ranged from 70 to 85 m in zone III within the mining area, the maximum mining height can be calculated as:

$$5.62M_1 + 2M_1 \leq 70 \quad (\text{for upper slice})$$

$$4.71\sum M + 2M_2 \leq 70 \quad (\text{for lower slice})$$

where M_1 is the maximum mining height of extracted upper slice and M_2 is the maximum mining height of extracted lower slice, m. Therefore, the maximum mining height for the upper slice was 9.2 m, and the actual first slice mining height of workface 1702 was 7.5 m for the sake of safe mining, which is less than the maximum mining height of design (Fig. 12). Thus, the maximum allowable mining height for the lower slice was 5.2 m. For zone II of workface 1702, the maximum mining height can be calculated as:

$$5.62M_1 \leq 70 \quad (\text{for upper slice})$$

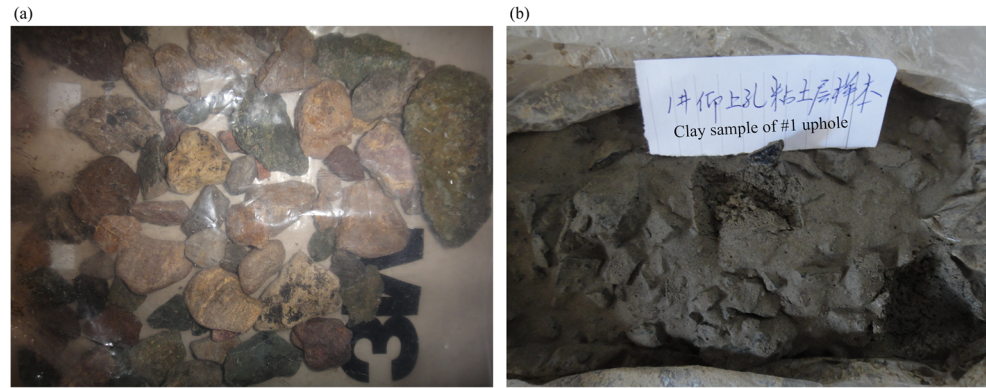
$$4.71M_2 \leq 70 \quad (\text{for lower slice})$$

Therefore, the maximum mining height for the upper slice was about 12.5 m, and the actual first slice mining height of

Table 3 The mining height of workface 1702, 1704, and 1706 for the upper slice and lower slice

Workface	Zone I			Zone II				Zone III				
	Thickness of overlying rock strata (m)	Maximum mining height for upper slice (m)	Actual mining height for upper slice (m)	Maximum mining height for lower slice (m)	Thickness of overlying rock strata (m)	Maximum mining height for upper slice (m)	Actual mining height for upper slice (m)	Maximum mining height for lower slice (m)	Thickness of overlying rock strata (m)	Maximum mining height for upper slice (m)	Actual mining height for upper slice (m)	Maximum mining height for lower slice (m)
1702	70	9.2	7.5	5.2	70	12.5	7.5	7.5	70–85	9.2	7.5	5.2
1704	75–105	9.8	5.5	7.3	65–75	11.6	10.0	3.8	50–65	6.6	5.5	3.6
1706	75–120	9.8	4.7	7.9	50–75	8.9	8.0	2.6	40–80	5.2	4.7	2.7

Fig. 14 Samples collected from underground upholes. **a** Water-bearing sand with gravel. **b** Lowermost layer of clay



workface 1702 was 7.5 m for the sake of safe mining. Similarly, the maximum allowable mining height for the lower slice was 7.5 m. Equally, the maximum mining height of workface 1704 and workface 1706 for the upper slice and lower slice can also be calculated, as shown in detail in Table 3.

Slice long-wall mining practices

In order to further determine the thickness of bedrock and water-bearing characteristics in the mining area, upholes of workface are usually drilled before extraction. Because it is difficult to test the unit flow rate of upholes underground, average water inflow can be used to verify the pumping test results of aquifers. Four upholes were drilled in the area of workface 1702, and the samples were collected as shown in Fig. 14. Three boreholes were drilled into gravel aquifer and the average water inflow was $4.2 \text{ m}^3/\text{h}$ (Fig. 14a), which indicated that the lowermost water-bearing sand with gravel were weak aquifer. One borehole was drilled into the layer of clay (Fig. 14b), and the water inflow was $0.2 \text{ m}^3/\text{h}$.

Of course, to mine subsequent workface 1704 and 1706 safely, the actual upper slice mining height of workface 1704 and 1706 was also less than the maximum mining height of design (Fig. 12), as shown in Table 3. For workface 1704, the actual mining heights in zone I (zone III) and zone II were 5.5 m and 10.0 m, respectively. Five upholes were drilled into the lowermost water-bearing sand with gravel aquifer and the average water inflow was $2.6 \text{ m}^3/\text{h}$, which indicated that the lowermost water-bearing sand with gravel were weak aquifer. For workface 1706, the actual mining heights in zone I (zone III) and zone II were 4.7 m and 8.0 m, respectively. Five boreholes were all drilled into the layer of clay and the average water inflow was $0.2 \text{ m}^3/\text{h}$, which indicated that the lowermost layer of clay has better water resistance. The upper slice of workface 1702, 1704, and 1706 were all safely mined according to the optimal design of sand-proof and caved-proof pillars, and the maximum water inflow was 3.6, 3.6, and $4.3 \text{ m}^3/\text{h}$, respectively, during mining due to inherent weak water aquifer and previous drainage (Fig. 15).

The lower slice mining started from workface 1702, the maximum mining height for lower slice was 5.2 m and 7.5 m in zone I (zone III) and zone II after the upper slice completion. To be on safer ground, the actual mining height in zone I (zone III) and zone II for lower slice was set to 2.8 m and 7.0 m, respectively. The maximum water inflow was $20 \text{ m}^3/\text{h}$ during mining for the lower slice of workface 1702. Therefore, these mining practices indicated that optimal design of sand-proof and caved-proof pillar, or reducing the thickness of extractions according to hydrogeological conditions were of crucial importance for higher coal recovery and safe mining.

Conclusions

In order to solve water and sand inrush from unconsolidated Cenozoic alluvium during mining of extremely thick coal seams, this research took three workface of Xiexin coal mine with 15.5 m thick coal seams threatened by unconsolidated Cenozoic alluvium water hazard as an example, summarized the hydrogeological exploitations obtained from underground and surface boreholes, and studied the failure characteristics of overburden strata for slice long-wall mining through in situ borehole observations and physical model testing. The following conclusions were derived:

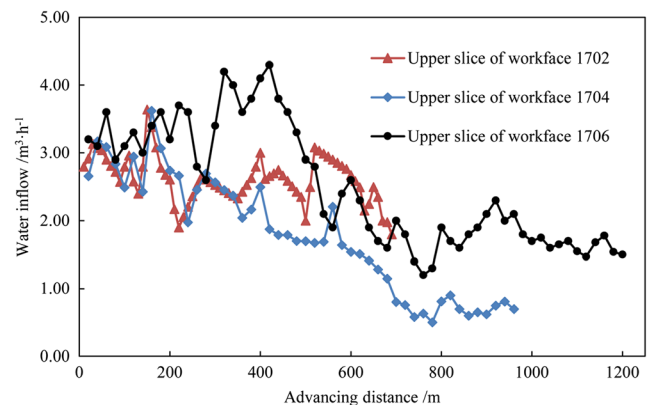


Fig. 15 Water inflow of workface 1702, 1704, and 1706 during upper slice mining

1. The hydrogeological characteristics and strata lithology of unconsolidated Cenozoic alluvium is of crucial importance to safe mining. The water-proof pillar, the sand-proof pillar, and the caved-proof pillar can be applied according to lithology and hydrogeology varies. The exploitation results of case study indicated that the lowermost layer in some areas is clay the layer with good water resistance, and part of areas is permeable water-bearing sand mixed with gravel belonging to weak aquifer, which made it possible to set and optimally design sand-proof and caved-proof pillars.
2. The height of the caved zone is the most important parameter for setting sand-proof and caved-proof pillars. In order to obtain failure characteristics of overburden strata for slice long-wall mining, and to define the maximum height of caved zone, two boreholes for upper slice and lower slice were drilled respectively, and physical model testing was carried out to investigate an evolution of fractured zone and caved zone. The height derived from physical model testing was consistent with the height obtained from field observations. The study indicated that the maximum height of the caved zone for the upper slice was about 5.62 times of the mining height and the comprehensive height of the caved zone for lower slice was about 4.71 times of the mining height.
3. The optimal design of sand-proof pillar at areas with weak water-bearing aquifer, and caved-proof pillar at areas with the lowermost layer of clay for workface 1702, workface 1704, and workface 1706 were determined according to the hydrogeology of alluvium, overlying strata lithology, and mining conditions. The optimal design and the technique measures, such as slice mining and reducing the thickness of extractions within the first or second slice, were successfully practiced. Therefore, the inherent favorable hydrogeology, lithology conditions of overlying alluvium and bedrock were of importance for the probability of optimal design, and slice mining was extremely beneficial in minimizing the height of the fractured zone and caved zone. The favorable external factors combining with external factors are crucially important to higher coal recovery and safe mining.

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