

Mining Thick Coal Seams Under Thin Bedrock– Deformation and Failure of Overlying Strata and Alluvium

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Abstract In underground coal mines, the failure of overlying strata can have disastrous effects where the working face is overlain by thin bedrock covered with thick alluvium. Roof failure under these conditions can cause a massive water and sand inrush. This paper presents a case study for a design to prevent such disasters in the Baodian mine, China. First, the engineering geological and hydrogeological conditions of the overlying lithified strata and the alluvium were obtained from field and laboratory studies. Numerical models were then built with different bedrock thicknesses using distinct-element modelling software. The deformation, failure, and subsidence of the overlying strata during simulated coal mining were studied using these computer models. Finally, the results of the model studies were combined with the geological data to design a reasonable layout for the longwall panel to be mined in the Baodian mine. Initial results showed that the alluvium was somewhat impervious and water-poor. The models showed that the first caving and weighting intervals of the roof decreased with decreasing bedrock thickness, and decreasing bedrock thickness also increased

maximum subsidence of the alluvium. The maximum height of the caving zone and the minimum height of the sand-prevention coal and rock pillars were 34 m and 46 m, respectively. Knowing this allowed a somewhat shorter (204 m) but safe working face to be designed. This research provides a good background for the design of safe mines under similar conditions.

Keywords Thick alluvium · Thin bedrock · Caving zone · Failure features · UDEC4.0

1 Introduction

In northern and eastern China, many coalfields are concealed and overlain by 30–400 m of alluvium. In recent years, many coal mines in eastern China have exhausted their coal resources because they have been mined intensively for many years. To continue coal production in these areas, the shallow coal seams, previously ignored, must be exploited. However, these shallow coal seams are commonly overlain by thick water-bearing alluvium (Xu et al. 2012; Zhang and Peng 2005; Zhang et al. 2011). When mining under such conditions, the risk of water and sand in-rush disasters is significant.

Many studies on the safe exploitation of coal seams covered by thick alluvium but thin bedrock have been undertaken by engineers and technicians (Liu et al.

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2015; Fang et al. 2007; Zhang et al. 2015). For example, (Yin and Chang 2013) analysed the failure of overburden above fully-mechanized caving mining faces using similarity models. Wang et al. (2016), through mechanical analysis and numerical simulation, studied the stress in shallow working faces and the effect of both mining height and the thickness of the unconsolidated formations above the faces. Xu et al. (2012) studied the lithology of the alluvium and fracturing in the overburden and their effect on water and sand in-rush.

Although the studies mentioned above provided some underlying principles about mining under thick alluvium, the problem of overburden failure was not solved. Mining thick coal seams overlain by a relatively thin layer of bedrock covered by 100–400 m of alluvium still led to frequent overburden failures and water and sand in-rush disasters. Some investigators (Zhang et al. 2002; Yang et al. 2011, 2012) showed that the fundamental reason for these disasters was that the failure zone in the bedrock above the coal seam reached the bottom of the alluvial aquifer. Consequently, studying how the overlying strata deform and fail over mines with thin bedrock and thick alluvial cover is of great significance for the prevention of water and sand in-rush disasters.

Because the mining-induced failure of overlying strata is influenced by many factors including mining height, roof type, mining methods, and geological and hydrogeological conditions, deriving theoretical and analytical solutions is difficult. The UDEC software (v.4.0, Itasca Consulting Group, Minneapolis, USA), is two-dimensional numerical software for modelling discontinuous media that is effective for studying the mining-induced failure of overlying strata (Du and Bai 2012; Li et al. 2012).

For this research, the No. 3 coal seam in the Baodian mine, Shandong Province, China, was used as an example. The distribution and hydrogeological conditions of the overlying strata were obtained by field investigations and laboratory testing. Numerical models with different bedrock thicknesses were then built using the UDEC software to study the deformation, failure, and subsidence of the overlying strata. Finally, the heights of the caving zone and the coal and rock pillars were calculated and an appropriate layout for the No. 302 working face was proposed.

2 Engineering Background and Geological Conditions

2.1 Engineering Background

As shown in Fig. 1, an efflorescent oxygenised belt in the No. 3 coal seam (weathered coal) in the western part of the Baodian mine is regarded as the mine boundary. There, a thin layer of bedrock is overlain by 187–220 m of alluvium. In this area, the No. 3 coal seam averages 8.0 m in thickness and dips, on average, 5.6° . The coal mine is fully mechanised and uses the top coal caving method to advance the working face. Mining is moving gradually to the west and the No. 302 working face will be mined in the year 2017. Because the bedrock thickness decreases gradually from east to west and the lowest aquifers in the alluvium are in direct contact with the bedrock, the risk of water and sand in-rush at the No. 302 working face is relatively high. Therefore, determining the height of the overburden failure zone and prudent sizes for the coal and rock pillars is extremely important to ensure safety.

2.2 Engineering Geology and Hydrogeological Conditions

The strata overlying the No. 3 coal seam in the Baodian mine can be divided into alluvium and bedrock. Lithology and structure are the main features that distinguish alluvium and bedrock. The alluvium is formed by the deposition of sand and clay. It is in most cases unconsolidated, has low strength and high porosity, and is not lithified. The bedrock, commonly many millions of years older than the Quaternary alluvium, is lithified by compaction from the overlying strata and other geological processes and is normally much stronger than the alluvium. The contact between the alluvium and bedrock is unconformable, the change in the lithology is obvious, and bedrock has been weathered.

To study the alluvium and bedrock above the No. 302 face, data from 18 boreholes in the study area (Fig. 1) were analysed. Borehole No. 25 (Fig. 1, in pink) was then drilled and cored, and a pumping test and soil tests were carried out.

Based on the borehole logs, a generalized stratigraphic column was constructed (Fig. 2). The logs were also used to create data files for the Surfer

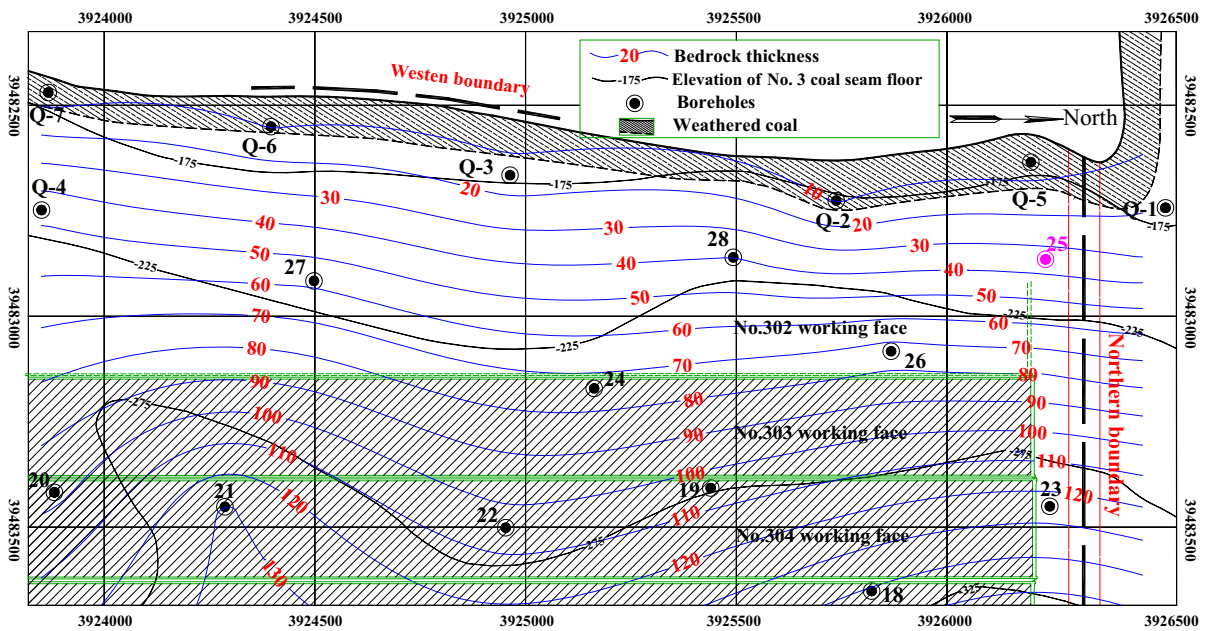


Fig. 1 Plan view of the -430 m level in the Baoian Mine, Shandong Province, China showing the shallow of the No. 3 coal seam

software package (v. 8.0, Golden Software LLC, Golden, CO, USA). Surfer was used to generate the thickness distribution map of the bedrock in the study area (the isopachs) shown in Fig. 1.

2.2.1 Distribution and Composition of the Alluvium

Figure 2 shows that the average thickness of the Quaternary alluvium is 204 m. The alluvium has been divided into three units from top to bottom: Upper Alluvial unit, Middle Alluvial unit and Lower Alluvial unit (abbreviated as Uau, Mau and Lau). These alluvial units are described below.

1. Upper Alluvial unit averages 80.2 m in thickness and is composed of loose gravel and clayey sand. Aquifer recharge is from precipitation and surface water. This unit has good permeability and the water is abundant with a specific yield of 0.894–16.039 L/(s·m).
2. Middle Alluvial unit averages 94.4 m in thickness and most of the unit is made up of grey–green clay and brown–yellow silty clay. There are five or six layers of dense clay in the Middle FM with a total thickness is 49.8 m. These clays effectively block any hydraulic connection between the upper and lower FMs.

3. As shown in Figs. 2 and 3, Lower Alluvial unit, which directly overlies the bedrock, is potentially the main source of water and sand that could invade the No. 302 workings. Its thickness ranges from 22.7 to 35.3 m, the average thickness being 28.7 m. It is a multi-layer composite aquifer made up of alternating layers of sand and clay. The sandy layers are mainly fine sand and silt (Fig. 3a, b), accounting for about 53 % of the lower FM. There are one or two layers of dense clay in the lower FM, mainly grey–green clay and brown–yellow clay (Fig. 3c, d). Soil tests show that the clay has low compressibility, high plasticity, and high expansivity (Table 1). The specific yield of the aquifers is 0.0332–0.0679 L/(s·m), implying relatively little groundwater is present. Based on pillar design regulations and coal mine water regulations published by Chinese National regulatory agencies, the design of sand-prevention coal and rock pillars for the No. 302 working face in the Baodian mine is feasible (NBCI 2000; SAPS 2009).

2.2.2 Bedrock and Weathered Bedrock

As shown in Figs. 1 and 2, the bedrock consists of mudstone and argillaceous sandstone and in general

Stratigraphic system		Rock core column	Lithology name	Strata thickness	Strata characters
Quaternary system	Upper Alluvial unit	Coreless		80.2 m	Alluvium
			Silty clay		
			Grit		
			Clay		
	Middle Alluvial unit		Medium sand	94.4 m	
			Silty clay		
			Clayey silt		
	Lower Alluvial unit		Clay	28.7 m	
			Silty clay		
			Medium sand		
		Clay			
		Silt			
		Silty clay			
Permian system	Shansi Formation		Mudstone	10.0 m	Weathered strata
			Siltstone	0–45.5 m	Main roof
			Medium sandstone		
			Mudstone		
			Packsand	2.8–7.3 m	Immediate roof
			Mudstone		
			Siltstone		
			Mudstone	8.0 m	Coal seam
	No. 3 coal seam				
			Packsand		Floor

◀ Fig. 2 Generalized stratigraphic column for the study area

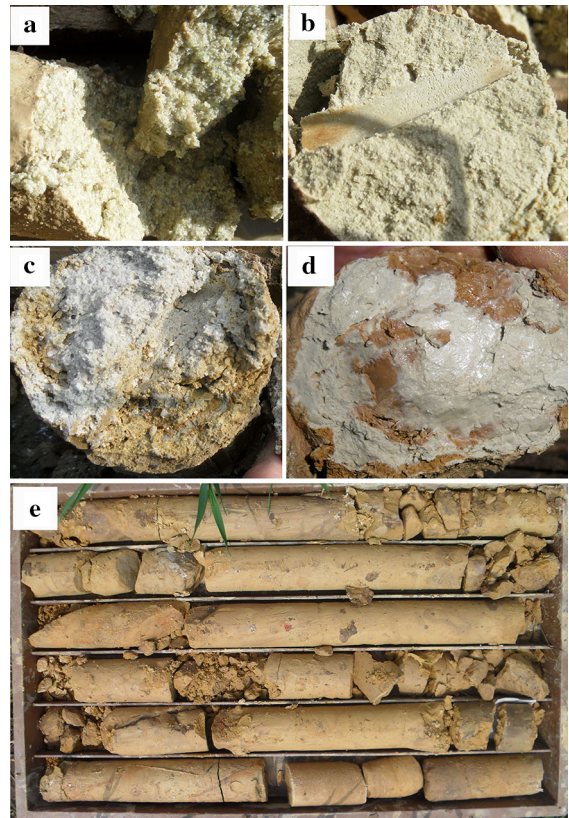


Fig. 3 Photographs of core samples: a Fine sand, b Slit, c Silty clay, d Clay, e Weathered rock

its thickness decreases from east to west. The immediate roof is mainly mudstone and sandy mudstone and the main roof is mainly medium and fine sandstone with a few thin mudstone interlayers. Compression tests show that the uniaxial compressive strength of the mudstone is 15.7–26.4 MPa, and that of the sandstone is 28.1–48.5 MPa. The top of the bedrock (the top ~10 m) has been weathered and up to 73 % of the rocks in this layer are mudstone and siltstone. This partially-weathered rock (Fig. 3f) has a good ability to prevent water-sand infiltration because it has low strength (the uniaxial compressive strength is 1.2–11.7 MPa), disintegrates rapidly, and softens when exposed to water. Thus it can readily seal fractures caused by mining (Xuan and Yang 2003).

Table 1 Soil test results for samples from the lowest Quaternary alluvial unit above the Baodian mine

Lithology	Sample depth (m)	Coefficient of compressibility (<i>a</i>)	Liquidity index (<i>I_l</i>)	Plasticity index (<i>I_p</i>)	Free swelling ratio (δ_{ef} , %)
Clay	178.2–179.6	0.05	0.02	20.9	68
Clay	185.4–187.0	0.07	0.04	22.4	73
Sandy clay	197.0–199.0	0.04	−0.02	17.5	47

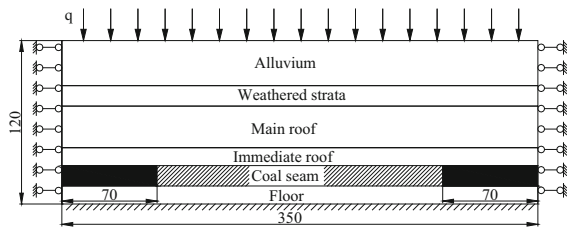


Fig. 4 Diagram showing the lithologic units considered in the numerical model and the dimensions of the model in metres. “*q*” represents the vertical stress imposed by the weight of the overlying alluvium

3 Model Building and Analysis

3.1 Model Structure and Size

Based on the lithology and structure of the sediments shown in Fig. 2, the geometric model shown in Fig. 4 was built. The model includes the alluvium, the weathered strata, the main roof, the immediate roof, the coal seam and the floor. In general, the immediate roof, composed of one or more layers of mudstone, shale, siltstone and other strata, directly overlies the coal seam. The sedimentary layers that make up the roof are generally thin, have little strength, and cave easily. The main roof, above the immediate roof, is composed of thick, strong, sandstones and limestones (Qian et al. 2010).

Four numerical models with bedrock thicknesses of 15, 30, 45, and 60 m were built. Based on analysis of the lithology, position, thickness, and strength of the strata, the main and immediate roof for each model can be determined.

As shown in Fig. 4, each model measured 350 m in width and 120 m in height. The 70 m wide coal pillars on the sides of the models were designated as fixed boundaries to eliminate boundary effects and the simulated mining height of the coal seam was 8.0 m. The study was directed at the 90 m of strata overlying the coal seam.

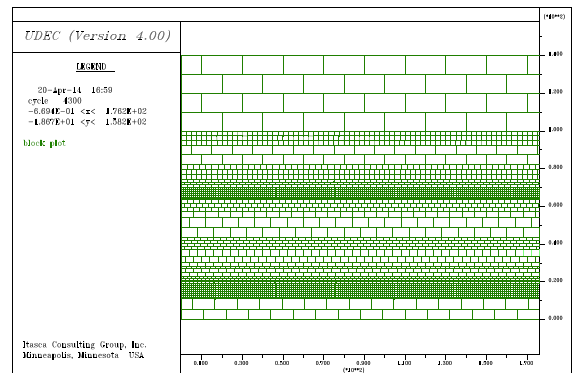


Fig. 5 Diagram showing the blocks in which each lithologic unit was divided for the numerical model. Blocks for physically weak units are small, blocks for strong units are large

3.2 Boundary Conditions

The displacement and velocity control method (Itasca Consulting Group, Inc. 2000) was used for the model boundaries. The y-direction displacement and velocity of the bottom boundary were both set to zero as were the x-direction displacements and velocities for both the left and right boundaries. The top was defined as a free surface with the vertical stress, *q*, represented by the weight of overlying alluvium (Fig. 4).

3.3 Block Sub-divisions

Considering the strength and joint distribution of each layer, blocks of each stratum were defined (Itasca Consulting Group, Inc. 2000). The blocks for the coal seam, immediate roof, and sand layers are small whereas the blocks for the floor and main roof are relatively large. All strata have horizontal and vertical joints, as shown in Fig. 5.

3.4 Material Parameters

There are nine types of material represented in the models. The physical and mechanical parameters of

Table 2 Physical–mechanical parameters of the Quaternary alluvium and the bedrock strata used in the numerical models

Lithology	Density (kg/m ³)	Elastic modulus (GPa)	Poisson's ratio	Tensile strength (MPa)	Cohesion (MPa)	Friction angle (°)
Clay	1900	0.6	0.32	0	0.14	31
Silty clay	1930	0.4	0.30	0	0.12	28
Fine sand	2000	1.2	0.23	0	0.03	18
Weathered rock	2300	3.7	0.29	0.30	4.4	30
Fine sandstone	2600	15.3	0.19	1.37	15.0	37
Medium sandstone	2650	10.2	0.19	0.70	9.3	40
Siltstone	2550	7.7	0.22	1.08	11.5	35
Mudstone	2490	6.5	0.25	0.82	7.8	34
No. 3 coal seam	1400	3.5	0.29	0.20	2.3	32

the coal, rocks, and soils used for the models are as listed in Table 2.

3.5 Loading and Initial Equilibrium

For the model to reach a state of equilibrium rapidly, the vertical and horizontal stresses were initialised to σ_v and σ_h , respectively, where σ_v and σ_h are obtained from Eqs. (1) and (2).

$$\sigma_v = \gamma h \quad (1)$$

$$\sigma_h = 0.5\gamma h \quad (2)$$

where σ_v is the vertical stress from gravitational loading on the overlying strata, Pa; σ_h is the horizontal stress, Pa; γ is the unit weight of the strata, N/m³; h is the buried depth of strata, m.

During the calculations, the maximum of the unbalanced forces are used to reflect the equilibrium state of the models (Itasca Consulting Group, Inc. 2000). A model can be considered to be in equilibrium when the maximum of the unbalanced force is small and stable (Fig. 6).

3.6 Model Calculations

The procedure for the calculations is outlined below:

1. Calculate the initial equilibrium state of stress without mining.
2. Each model represents mining under different thicknesses of bedrock, but the mining methods and mining heights are identical for each model. The mining method is fully-mechanised top caving mining with a mining height of 8.0 m.

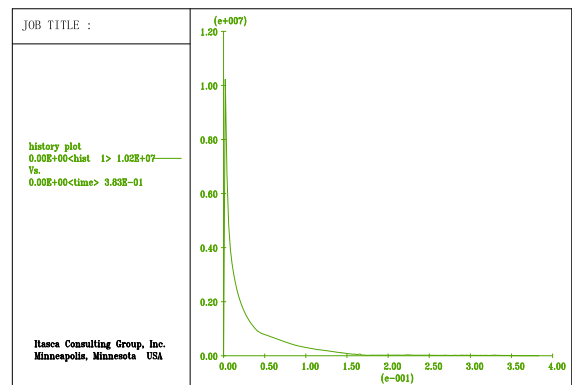


Fig. 6 Curve of the maximum unbalanced force in the model before mining

During modelled mining, each mining step was 2.5 m and the total distance mined was 210 m.

3. Running the model with a 45 m-thick layer of bedrock over the coal seam produces the caving zone shown in Fig. 7. The heights of the caving zone for the other three thicknesses of bedrock can also be calculated.

4 Results and Discussion

4.1 Effects of Bedrock Thickness on the Failure, Subsidence, and Deformation of the Overlying Strata

4.1.1 Effects of Bedrock Thickness on Failure

As shown in Fig. 8, when the thickness of the bedrock is 15 m, the immediate roof first collapses (that is, the

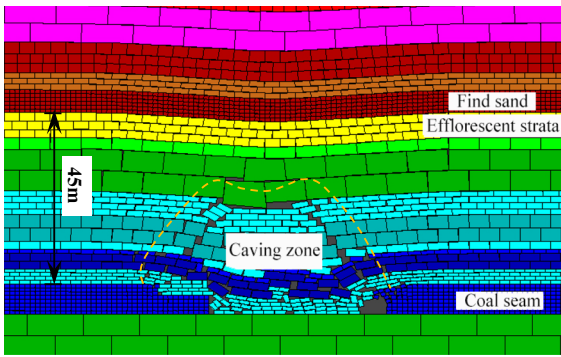


Fig. 7 UDEC model cross section showing deformation and failure of the overlying strata and the caving zone produced after mining under a 45 m-thick bedrock layer

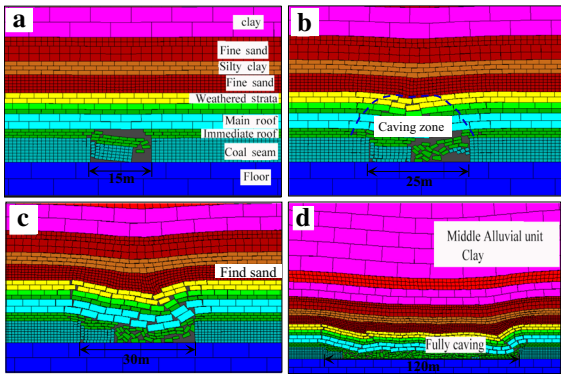


Fig. 8 UDEC model results showing deformation and failure of the overlying strata during mining as the working face advances with a bedrock thickness of 15 m. **a** The working face has advanced 15 m, **b** the face has advanced 25 m, **c** the face has advanced 30 m, **d** the face has advanced 120 m

first caving interval takes place) when the face has advanced 15 m. As the working face continues to advance, the immediate roof continues collapsing. The entire 15 m thickness of the bedrock initially caves at 25 m, causing widespread deformation and failure of both bedrock and the bottom of alluvium. That is, what will be called the first weighting interval of the main roof is at about 25 m. As the working face continues advancing, the whole bedrock section above the coal seam collapses and the caving zone reaches the bottom of the alluvium, resulting in large-scale deformation and failure.

As shown in Fig. 9, when the thickness of the bedrock is 30 m, the first caving interval of the immediate roof occurs when the face has advanced

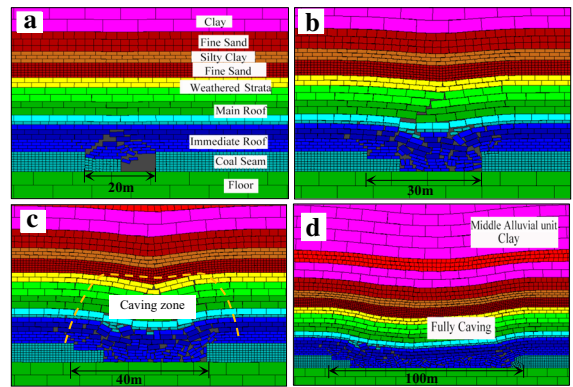


Fig. 9 UDEC model results showing deformation and failure of the overlying strata during mining as the working face advances with a bedrock thickness of 30 m. **a** The working face has advanced 20 m, **b** the face has advanced 30 m, **c** the face has advanced 40 m, **d** the face has advanced 100 m

20 m. At this stage, the main roof is still relatively stable. When the working face has advanced 30 m, however, the main roof breaks. Instantly the top of the bedrock and the bottom of alluvium become unstable. As the working face advances further, the main roof breaks periodically at intervals of about 10 m and, at the same time, the failure of the overlying strata gradually increases. The caving zone has reached the bottom of alluvium, so its height must be more than 30 m.

As shown in Fig. 10, when the thickness of the bedrock is 45 m, the immediate roof suffers its first cave-in when the face has advanced 20 m and the first caving distance of the No. 1 main roof is at 35 m of face advance. It can be inferred that the first weighting interval is about 35 m. As the working face advances, the main roof suffers periodic breaks at intervals of about 10–15 m. When the face has advanced 45 m, main roof No. 2 begins to bend and fracture. The height of the caving zone is 34 m, and the ratio of caving zone height to the 8.0 m mining height is 4.25.

As shown in Fig. 11, the first caving interval with a bedrock thickness of 60 m is similar to caving intervals for 30 m- and 45 m-thick bedrock, namely about 20 or 25 m. The first and the periodic weighting intervals are relatively large (40 m and 20–25 m, respectively). The height of the caving zone is 34 m, the same height as the 45 m-thick bedrock caving zone.

Table 3 shows that the first caving interval for the immediate roof, the first weighting interval for the

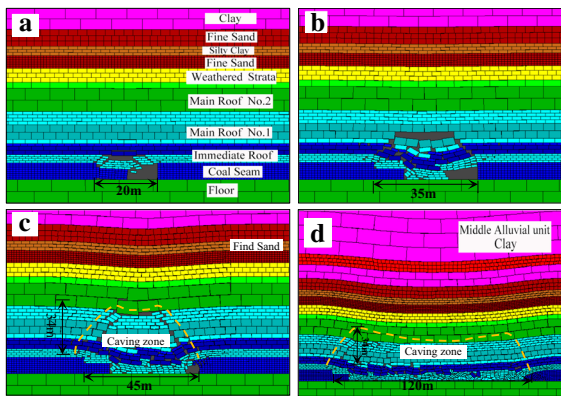


Fig. 10 UDEC model results showing deformation and failure of the overlying strata during mining as the working face advances with a bedrock thickness of 45 m. **a** The working face has advanced 20 m, **b** the face has advanced 35 m, **c** the face has advanced 45 m, **d** the face has advanced 120 m

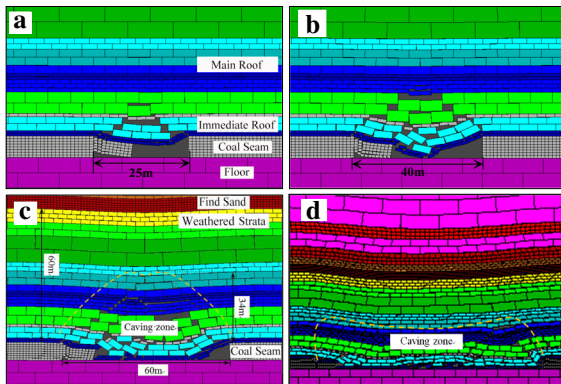


Fig. 11 UDEC model results showing deformation and failure of the overlying strata during mining as the working face advances with a bedrock thickness of 60 m. **a** The working face has advanced 25 m, **b** the face has advanced 40 m, **c** the face has advanced 60 m, **d** the face has advanced 120 m

main roof, and the periodic weighting intervals for the main roof all decrease with decreasing bedrock thickness. The maximum height of the caving zone is 34 m. The ratio of the caving zone height to the mining height is 4.25. Where the thickness of the bedrock is less than or close to the caving zone height, the entire thickness of the bedrock caves in and forms a cut-off that can connect the mine working to the aquifers in the alluvium. This could easily induce support crushing or a water and sand in-rush disaster. The numerical simulation can describe the real failure features of overlying strata within a reasonable margin of error.

4.1.2 Effects of Bedrock Thickness on Subsidence and Deformation

To analyse the effects of bedrock thickness on the subsidence and deformation of the overlying strata, 80 monitoring points in a horizontal line were defined at the bottom of the alluvium in each model. These points were used to monitor the vertical displacement of the alluvium during model-simulated mining.

The results shown in Fig. 12 indicate that subsidence of the alluvium reached its maximum extent most quickly when the bedrock thickness was 15 m. When the mining face had advanced 55 m, the vertical displacement with a 15 m layer of bedrock was the first to reach its maximum, about 7.1 m. As the working face advanced further, alluvial subsidence remained stable at this maximum value. When the bedrock thickness was 30 m, maximum alluvial subsidence did not take place until the face had advanced 80 m and the maximum vertical displacement was somewhat less, about 6.5 m. The maximum amount of subsidence for 45 and 60 m layers of bedrock were both smaller than subsidence for 15 m and 30 m layers and it took a longer time and a greater distance to reach maximum subsidence.

These numerical models have shown that different thickness of the bedrock above the coal seam had a significant influence on both when the alluvium above the bedrock starts to subside and how far it subsides. When mining coal below a relatively thin layer of bedrock covered by thick alluvial deposits, the smaller the bedrock thickness is, the sooner the alluvium starts to subside and the larger the total subsidence. The time required to reach a steady state is also shorter for thinner layers of bedrock.

4.2 General Analysis

The reason the thin layer of bedrock described above collapse as described is because the strength and integrity of the strata were greatly weakened by weathering. This results in a lower carrying capacity than that of a thicker sequence of bedrock; thin bedrock is more likely to cave in at short intervals after mining. In addition, once the bedrock is unstable, loose fine sand with no bearing capacity can infiltrate rapidly which may cause crushing and water and sand in-rush disasters. Where the thickness of the bedrock is greater than the height of the caving zone, the upper

Table 3 Bedrock failure data from four different UDEC numerical simulation models

Bedrock thickness (m)	First caving interval of immediate roof (m)	First weighting interval of the main roof (m)	Periodic weighting interval of the main roof (m)	Maximum height of caving zone (m)
15	15	25	≤5	Bedrock fully caving
30	20	30	10	Bedrock fully caving
45	20	35	10–15	34
60	20–25	40	20–25	34

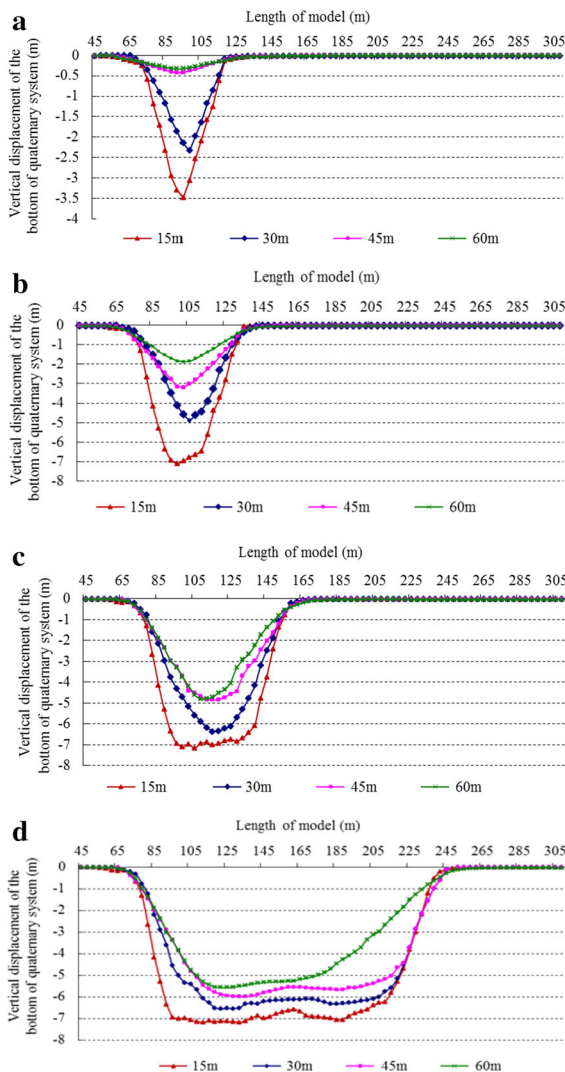


Fig. 12 Graphs showing the vertical displacement at the bottom of Quaternary section as the working face advances during mining. Mining under different thicknesses of bedrock layers is indicated by the coloured curves. **a** The face has advanced 35 m, **b** the face has advanced 55 m, **c** the face has advanced 80 m, **d** the face has advanced 160 m

somewhat deformed bedrock (the area where water flows into the fractured zone and the bending zone) will fracture and bend. With increasing bedrock thickness, the carrying capacity of the bedrock is greater and this may reduce or delay the subsidence of the upper strata.

Numerical simulations showed that the maximum height of the caving zone above the No. 302 working face would be 34 m. To ensure safety, the mining-induced caving zone should not reach the aquifer in the alluvium and there should be a specific thickness of relatively solid rock to serve as a protective layer between the aquifer and the caving zone. According to Chinese pillar design regulations (NBCI 2000) and ground control procedures described by Huang et al. (2007), the minimum thickness of the protective layer required can be obtained from Eq. (3), and the minimum height of the sand-prevention coal and rock pillars can be obtained from Eq. (4):

$$H_b \geq 1.5 \cdot A \tag{3}$$

where H_b is the height of caving zone, m; A is the mining height, and

$$H_s \geq H_m + H_b \tag{4}$$

where H_s is the height of the sand-prevention coal and rock pillars, m; H_m is the height of the caving zone, m; H_b is the thickness of the protective layer, m.

Evaluating these equations for the No. 302 mining face means the protective layer must be 12 m thick and the sand-prevention coal and rock pillars must be 46 m high.

In other words, when the No. 302 working face is mined with a mining height of 8.0 m, the thickness of the bedrock above the seam should be more than 46 m to ensure safe mining. Therefore, the No. 302 working face was designed to be in an area where the bedrock thickness was greater than 46 m. To recover as much

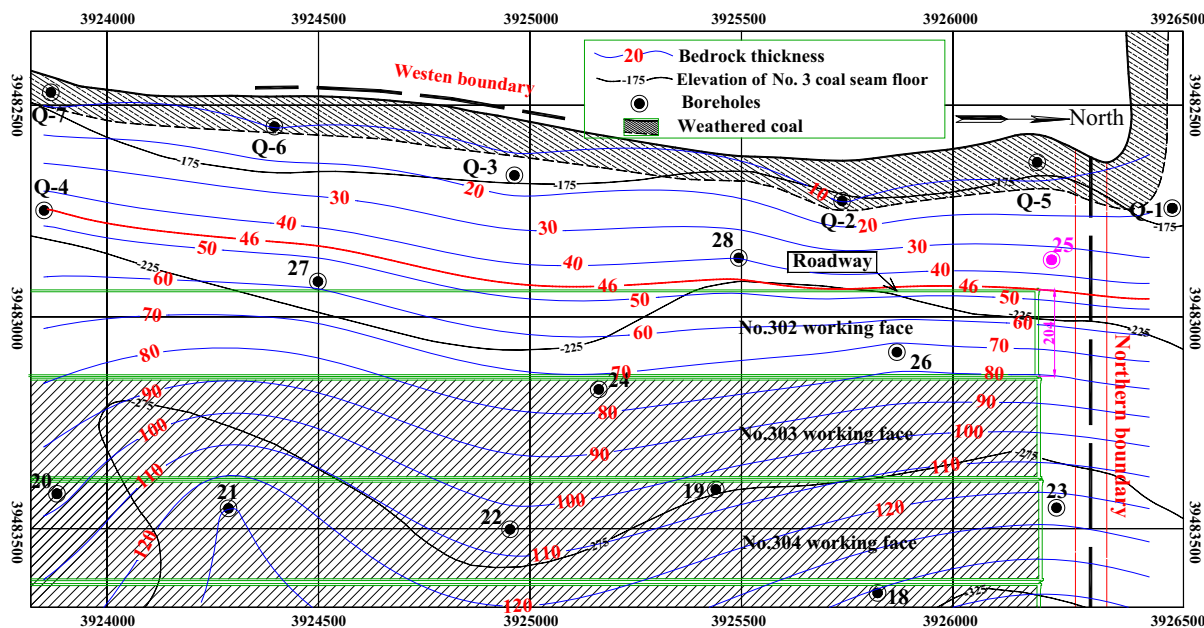


Fig. 13 Plan view of the -430 m level in the Baodian Mine, Shandong Province, China showing the shallow of the No. 3 coal seam. The red line is the 46 m bedrock thickness isopach,

the roadway has been aligned to be inside that line for safety reasons, and the width of the 302 working face is to be 204 m

coal as possible from this mining panel, the roadway for the No. 302 face was designed to be close to the 46 m isopleth of bedrock thickness, the line in bold red in Fig. 13. Putting the roadway at this location meant that the inclined length of the No. 302 working face would be 204 m. Of course, to mine subsequent faces safely, the mining height will have to be reduced appropriately or some other mining method, perhaps slicing mining or filling mining, will have to be used.

5 Conclusions

1. Analysis of the geological conditions shows that the lower formation of the alluvium above the No. 302 working face in the Baodian mine, China, is a composite aquifer formed from interlayered sand and clay. Because the lower formation has a high clay content, low permeability, low recharge, and does not hold a large amount of water, effective sand-prevention coal and rock pillars can be designed.
2. Numerical simulations show that the thickness of bedrock has a great influence on the deformation

and failure of the strata overlying the working face. The first weighting interval and periodic weighting intervals of the roof decrease with decreasing bedrock thickness, and the maximum subsidence and damage at the bottom of the alluvium increase significantly where the overlying bedrock is thin.

3. The maximum height of the caving zone above the No. 302 working face at the Baodian mine when using fully-mechanised top caving mining on an 8.0 m coal seam is 34 m. Under these conditions, the minimum height for sand-prevention coal and rock pillars is 46 m. Combining this conclusion with the distribution of the bedrock and the position and orientation of the No. 302 working face in the mine, it was determined that the inclined length of the No. 302 face could be no more than 204 m.

This research provides a reference for designing mine layouts for coal seams under similar conditions.

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