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Optimization Method for Setting Waterproof Coal-Rock Pillar of Gently Inclined Coal Seam Under Cenozoic Loose Aquifer

Wang Hua[1, 2, 3]

[1]Institute of Mine Construction, Tiandi Science and Technology Co., Ltd., Beijing, China
[2]Beijing China Coal Mine Construction Engineering Company Co., Ltd., Beijing, China
[3]National Engineering Laboratory for Deep Shaft Construction Technology in Coal Mine, Beijing, China

Email address
wanghwa@sohu.com, 787577336@qq.com

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Abstract
Rationally setting waterproof coal-rock pillar of Cenozoic loose sedimentary aquifer is the presupposition to improve coal recovery and ensure mine safety. Firstly, we had rock mechanics test for overburden strata of 8 coal seam at the upper section in West No.1 Mining Area of Panji No.3 Mine in Huainan Panji-xieqiao Mining Area, and pumping test for the Lower Aquifer of Cenozoic loose sedimentary stratum and 8 coal seam roof sandstone water; Secondly, we used “Regulations of pillar leaving and coal mining under building, water, railway and main shaft and tunnel” (“Three Under Regulations” for short), “Water prevention regulation of coal mines” to analyze and calculate the safe waterproof coal pillar setting thickness between the Lower Aquifer of Cenozoic loose sedimentary stratum and 8 coal seam, and had optimization design of mining faces were carried out at this section; Thirdly, through similar simulation test, we studied the deformation evolution law of overburden strata along the inclined direction of 8 coal seam, and analyzed the relations between uphill caving angle, downhill caving angle and dip angle of coal seam, thereby the feasibility of reducing waterproof coal pillar between the Lower Aquifer of Cenozoic loose sedimentary stratum and 8 coal seam was calculated and analyzed, and the feasible research methodology for the reasonable design of waterproof coal and rock pillar for gently inclined coal seam under extremely thick unconsolidated strata were explored.

1. Introduction

China is not only the world's largest coal producing country, but also the world's largest coal consuming country[1]. In 1980, coal accounted for 72.15% of China’s total primary energy consumption. More than 20 years later, the proportion of coal in the primary energy consumption has remained steadily at around 70%[2]. As of the beginning of the 21st century, with the rapid and stable development of economy in China, the energy demand has been increasing enormously, and so has the coal production. In 2000, China’s coal production was 1 billion tons[3]; while in 2012, it reached 3.65 billion tons[4]. In the proved reserves of energy in China, coal accounted for 94%, oil accounted for 5.4%, natural gas accounted for 0.6%, due to this characteristic structure of energy resources, i.e., “*rich in coal,* but *poor in oil* and less in gas”, the coal-relied energy production and consumption patterns will be difficult to change for a long term in the future[5]. National

Energy Board of PRC predicted that China coal demand will reach 3.9 billion tons in 2015; thereafter yearly growth will be more than 4 billion tons. In addition, Chinese Academy of Engineering predicted that China's coal production will reach 4.012 billion tons in 2015, 4.503 billion tons in 2020, and 4.534 billion tons in 2030 [6].

Hydrogeological conditions in many coal fields are very complicated in China. Because of a variety of water threat in the process of mining coal, coal mine water prevention and control in production and scientific research is a technical difficulty. According to preliminary statistics, in China, about 47.5% of the national key coal mines are threatened by water, and the coal reserves with water hazard is up to 25 billion tons [7]. Many large coal fields in North China, East China, and Northeast China are concealed. There exists 130m~600m medium thick or thick Cenozoic loose sedimentary stratum on the strata of coal measures. At the bottom of the loose stratum often exists moderate aquifer, even strong aquifer; therefore, it is this zone that is prone to water and sand inrush accidents, threatening the safety of mine production. So, in coal mines, while making mining technical specifications, safety regulations and mining design, it is the conventional practice of setting 50-80m waterproof coal-rock pillars. According to the investigation data, for production safety, waterproof coal-rock pillars for loose sedimentary aquifer with a vertical height 60-80m were set in Yanzhou Mining Area, Shangdong Province in East China, the quantity of coal resources under these pillars is about 470 million tons, accounting for 12% of total reserves; in Linhuan and Suxian mining areas of Huaibei Coalfield, Anhui Province in East China, the design height of waterproof coal-rock pillars for loose sedimentary aquifer were all over 50m, of which the maximum height was 90m, and about 520 million tons of coal resources is under these pillars. In Panji-xieqiao Mining Area of Huainan Coalfield, Anhui Province, generally, vertical height of waterproof coal-rock pillars set for loose sedimentary aquifer were 60-80m in mining design, and the quantity of coal resources under these pillars is about 1.1 billion tons. Additionally, many coal mines in Heilongjiang Province, Jilin Province, Hebei Province, Shandong Province and Henan Province in China set very thick waterproof coal-rock pillars for loose sedimentary aquifer too. According to preliminary calculations, in China, there is about 5.0 billion tons of coal resources under waterproof coal-rock pillars for medium thick and thick loose sedimentary aquifer, wasting a large number of coal resources [8, 9].

In China, science and technology workers have accumulated a lot of valuable experience and scientific data in the process of mining coal seams under a variety of water bodies. China's technology of coal mining under water bodies has been in a leading position in the world [10]. In terms of studying water-inrush mechanism of lower aquifer of great thick loose sedimentary stratum, development law of water flowing fractured zone in mining coal seam, rationally setting the waterproof coal-rock pillar, and so on, many advanced theories and research methods have been formed[11]. In 1981, Liu Tianquan, an academician of Chinese Academy of Engineering and a researcher of China Coal Research Institute, put forward the "upper three zone" theory[12], i.e. according to the movement and failure characteristics law of overlying strata after mining coal seam of longwall working face, overlying strata can be divided into the caving zone, water flowing fractured zone and bending sinking zone. And the key to prevention and control of roof water hazards is to mainly control the development heights of the caving zone and the water flowing fractured zone. The current "Three Under Regulations"[13], "Water Prevention Regulation of Coal Mines "[14] are mainly on the basis of this theory. In 1996, based on the "upper three zone" theory, Gao Yanfa[15] brought forward "Four zones" model of overlying strata movement, he thought that overlying strata structure has zonality, and after mining the structural mechanics model should be divided into four zones, namely, fracture zone, abscission zone, bending zone and loose alluvium zone, which further enrich and broaden the roof water-inrush theory. In 2003, Qian Minggao[16], an academician of Chinese Academy of Engineering and a professor of China University of Mining and Technology, put forward the concept of green mining of coal resources. The theory foundation of the green technique in coal mining is the distribution behaviour of joints, fractures and bed separations, the seepage flow behaviour of methane and water in broken rock strata caused by the key strata break after mining. In 2010, Zhan Yubao, et al.[17] analyzed the stability and anti-water-inrush ability of waterproof coal-rock pillar of a certain mine by using $FLAC^{3D}$ three-dimensional fluid-solid-interaction numerical simulation. Meng Zhaoping, Gao Yanfa, et al. drew reference from water inrush coefficient for coal mining over confined aquifer, brought forward the concept of "loose aquifer water inrush coefficient" to evaluate the water-inrush danger in mining coal seam under Cenozoic Quaternary loose sedimentary aquifer. And according to the water pressure of the loose aquifer, the need to increase thickness of protective layer has been calculated and determined by nonlinear equations, to set the waterproof coal pillar. The method was used in the mining design of 8 coal seam in Donghuantuo Minefield, Kailuan Mining Area, Hebei Province in North China, and achieved a good application effect[18,19]. In 2012, Jiao Yang, et al.[20] adopted theoretical analysis，numerical simulation and actual observation data contrast to show the development law of water flowing fractured zone in mining coal seam and its influence on the loose aquifer. However, because the fully-concealed coalfields under the Cenozoic Quaternary loose sedimentary stratum are widely distributed in China, the geological and hydrogeological conditions differ in thousands of ways, currently, for the reason, the roof water inrush accidents still occur frequently in the process of mining coal seam under thick loose stratum [21-24].

Therefore, the study of the deformation process of overlying strata in mining coal seam, and the reasonable determination of the height of waterproof coal-rock pillar for Cenozoic loose sedimentary stratum aquifer still have important theoretical and practical significances to ensure production safety and increase the recovery rate of coal resources in coal mines. In this paper, through rock mechanics tests, pumping tests, theoretical calculations, similar simulation test, we studied the development law of water flowing fractured zone in mining 8 coal seam of upper section in West No.1 Mining Area in Panji No.3 Coal Mine, and analyzed the mining feasibility of reducing the waterproof coal-rock pillar of Cenozoic loose sedimentary stratum aquifer.

2. Survey of the Panji No.3 Coal Mine

Panji No.3 Coal Mine is located in Panji-xieqiao Mining Area, Huainan City, Anhui Province in Eastern China. It is affiliated to Huainan Mining Group Co., Ltd. The east part of the mine field spreads along Prospecting Line IX, bordered with Panji No.1 Mine, and extends westward and joins Dingji Mine at XV, then stretches northward and joins Panji No.4 Mine at F_1 fault. Its southern border expands along the ground projection of 13-1 Coal Seam -900 m floor contour. The coalfield is 9.6 km long (W–E) and 5.8 km wide (N–S), with a total area of 56.3km^2. The mine field is fully covered by the Cenozoic loose stratum, therefore, categorized as the fully-concealed mine field. The Carboniferous and Permian are mainly coal-bearing formations. Among the strata, the Shanxi, Lower Shihezi and Upper Shihezi Formations of Permian are major coal-bearing strata, containing 12 mineable and locally-mineable coal seams from the bottom to the top, there exist the coal seams 1, 4-1, 4-2, 5-2, 6-1, 7-1, 8, 11-2, 13-1, 16-1, 6-2, and 17-1. The Cambrian and the Ordovician layers underlie the coal-bearing formations. The thickness of Cenozoic loose sedimentary strata is 186.54～483.55m, it is unconformity to the substrata, Carboniferous – Permian coal-bearing formations. It includes three aquifers (i.e. Upper Aquifer, Middle Aquifer and Lower Aquifer) and two aquifuges(i.e. Upper Aquifuge and Middle Aquifuge). The Lower Aquifer of Cenozoic loose sedimentary stratum (hereafter, Lower Aquifer for short) directly cover coal-bearing formations. It is abundant in moisture content as one of the main water-filled sources of the mine, so it is a greater threat to mine production. As designing the Panji No.3 Coal Mine, for each mineable coal seam the 80m waterproof coal pillar of vertical height has been set for Lower Aquifer water, where the quantity of coal under the waterproof coal pillars is nearly 30Mt [25].

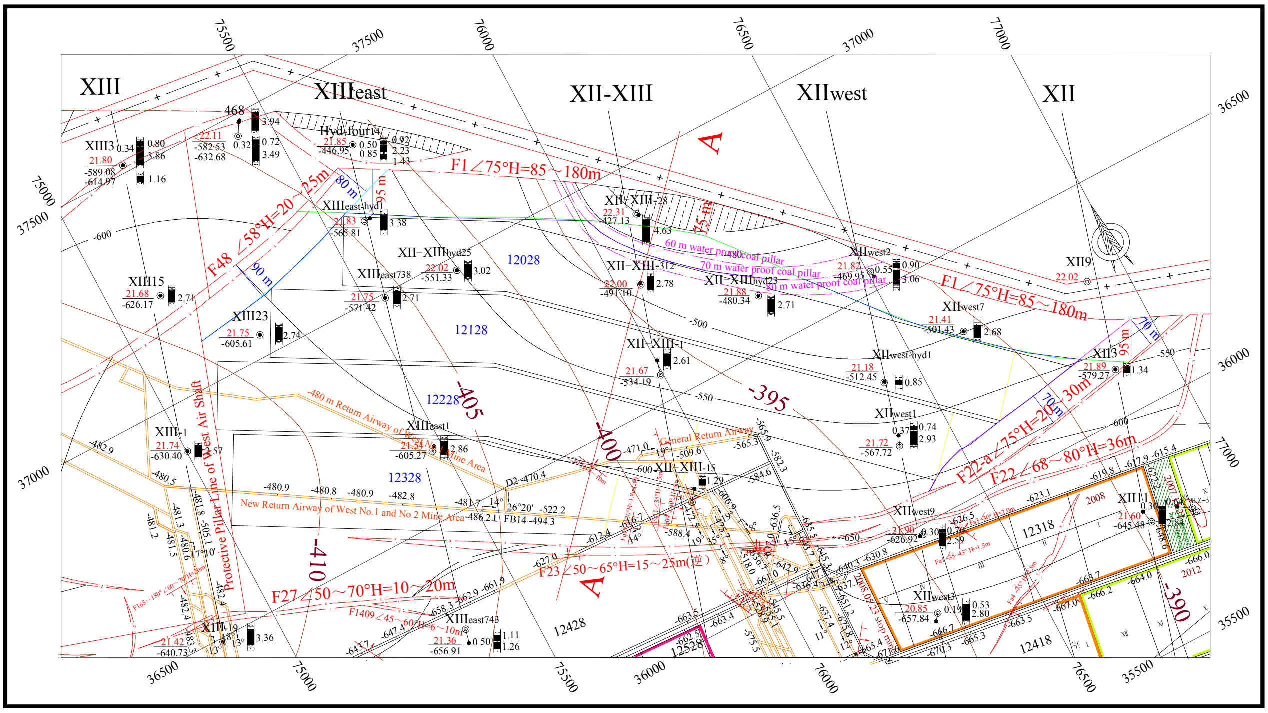

Fig. 1. The local excavation engineering chart of 8 coal seam in the upper section of West No.1 Mining Area in Panji No.3 Coal Mine.

The upper section of 8 coal seam in West No.1 Mining Area starts from F_1 fault in the north, extending south to F_{23} fault, bordering with F_{48} fault in the west and connecting with $F_{22\text{-}a}$ fault in the east (Fig.1). Within this section the major faults are as follows: F_1:∠75° H=85~180m (normal fault), $F_{22\text{-}a}$: ∠75° H=20~30m (normal fault), F_{23}:∠50~65° H=15~25m (inverse fault), F_{27}:∠50~70° H=10~22m (normal fault), F_{48}:∠58° H=20~25m (inverse fault). The thickness of 8 coal seam is 1.29~4.63m, with the average of 3.04m. Parts of the coal seam contain a layer of partings, of which the thickness is 0~0.55m, the dip angle is 8~26°, and the average angle is 18°. The 8 coal seam roof is composed of mudstone, sandy mudstone, siltstone, fine-grained sandstone and medium-grained sandstone(Fig.2). The thickness of the roof is 0.35~16.25m, with average of 4.23m. The seam floor comprises mudstone and sandy mudstone. The thickness of the seam floor is 1.26~5.88m, with average of 3.60 m. At present, the water level of the Lower Aquifer of Cenozoic loose sedimentary stratum is about -20m.

3. Rock Mechanics Test and Pumping Test

To further ascertain geological and hydrogeological condition of 8 coal seam in the upper section of West No.1 Mining Area, Jiangsu Bureau of Coal Geology Mine carried on the hydrogeological supplementary exploration in this area in 2012. Four boreholes were drilled, which were XII_{West7}, XII-XIII $_{hyd23}$, XII-XIII $_{hyd25}$ and $XIII_{23}$ (Fig.1), and the rock samples were collected from 8 coal seam roof to put to physical and mechanical tests. The rock samples were mainly medium-grained sandstone, fine-grained sandstone, siltstone and mudstone. The test results were shown in Table 1. The test results of water pressure tests on 8 coal seam roof sandstone aquifer, and pumping test on the Lower Aquifer of Cenozoic loose sedimentary stratum were shown in Table 2. Through hydrogeological supplementary exploration, we can see:

(1) The water level of the Lower Aquifer of Cenozoic loose sedimentary stratum was about -20m (the water level of XII-$XIII_{hyd25}$ was -19.61m, Table 2); unit outflow rate q=0.844 L/(s•m); permeability coefficient k = 2.073 m/d.

(2) The thickness of 8 coal seam roof sandstone aquifer is 38.10~44.56m, the average is 41.59m; water level is -162.93~-265.29m, the average is -213.52m; unit absorption is 3.953×10^{-6}~13.820×10^{-6}L/(min•Pa•m), the average is 7.379×10^{-6} L/(min•Pa•m); permeability coefficient k=1.960×10^{-6}~6.050×10^{-6}m/d, the average is 4.572×10^{-6}m/d .

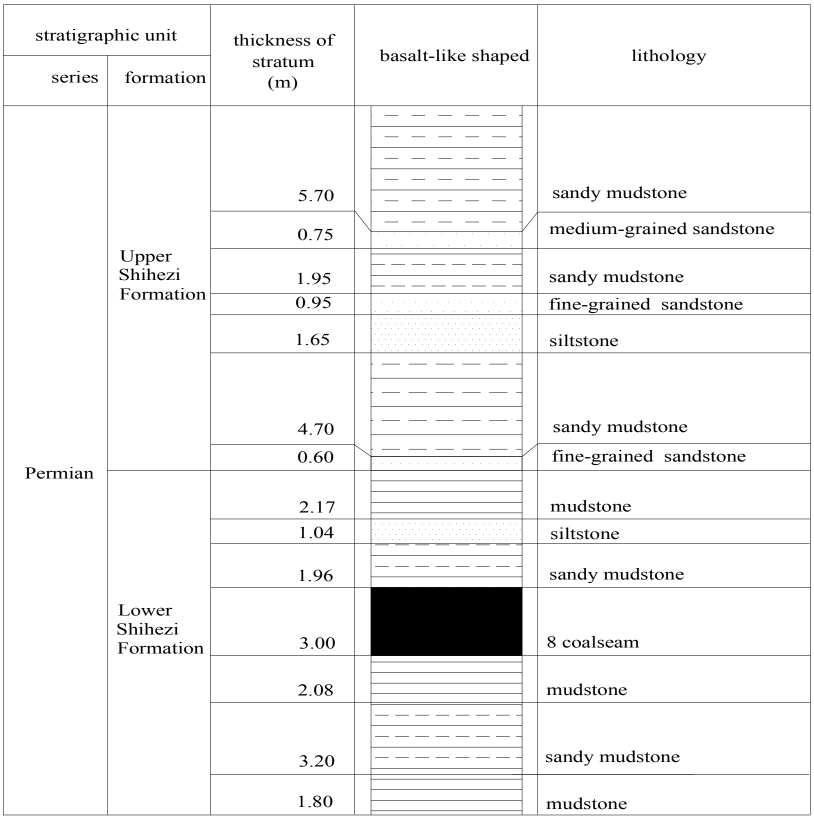

Fig. 2. Local geological column of XII~XIII$_1$ borehole.

4. Optimization Design on Working Faces of 8 Coal Seam in the Upper Section of West No.1 Mining Area

4.1. Calculating the Waterproof Coal (Rock) Pillar Between Working Face and the Lower Aquifer of Cenozoic Loose Sedimentary Stratum

According to reference [14], while outcrop of coal seam contacting water-rich stratum in loose aquifer, the height of waterproof coal (rock) pillar should be (Fig.3):

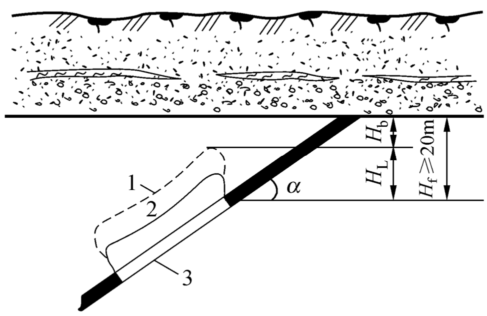

Fig. 3. The sketch of setting waterproof coal (rock) pillar while outcrop of coal seam contacting with strong watery stratum in loose stratum.

$$H_f = H_L + H_b \tag{1}$$

Where,

H_f——height of waterproof coal (rock) pillar, m;

H_L——height of water flowing fractured zone, m;

H_b——thickness of protective layer, m;

α——dip angle of coal seam, (°)。

In this section, the main rocks on 8 coal seam are sandstones, sandy mudstones, and the small amount of mudstones. Generally, the roof rock of 8 coal seam is medium-hard rock. According to reference [13], the maximal heights of caving zone and water flowing fractured zone, the thickness of the protective layer are respectively calculated as follows:

$$H_m = \frac{100\sum M}{4.7\sum M + 19} \pm 2.2 \tag{2}$$

$$H_L = \frac{100\sum M}{1.6\sum M + 3.6} \pm 5.6 \tag{3}$$

or

$$H_L = 20\sqrt{\sum M} \pm 10 \tag{4}$$

$$H_b = 6A \tag{5}$$

Where,

$\sum M$ ——total mining thickness, m;

$A = \frac{\sum M}{n}$;

n——the slice number of slicing mining (one mining of full coal seam of working face, n=1).

For $\sum M = 3.00$, $n = 1$ were substituted into the formula (2), (3), (4), (5), we got:

$$H_m = \frac{100\sum M}{4.7\sum M + 19} + 2.2 = \frac{100 \times 3.00}{4.7 \times 3.00 + 19} + 2.2 = 11.26\text{(m)}$$

$$H_L = \frac{100\sum M}{1.6\sum M + 3.6} + 5.6 = \frac{100 \times 3.00}{1.6 \times 3.00 + 3.6} + 5.6 = 41.31\text{(m)}$$

$$H_L = 20\sqrt{\sum M} + 10 = 20\sqrt{3.00} + 10 = 44.64\text{(m)}$$

$$H_b = 6A = 6 \times \frac{\sum M}{n} = 6 \times \frac{3.00}{1} = 18.00\ \text{(m)}$$

Note: Given safety, we took "+" value from formula (2), (3), (4) and the bigger one of two H_L values were calculated in formula (3), (4).

So, the minimum height of waterproof coal (rock) pillar in this section should be:

$$H_f = H_L + H_b = 44.64 + 18 = 62.64\text{(m)}$$

It's all too apparent that under setting waterproof coal and rock pillar of vertical height 70m between 8 coal seam and the Lower Aquifer of Cenozoic loose sedimentary stratum, the mining of 8 coal seam working faces would be safe.

Table 1. *Rock mechanics test results table for overburden strata of 8 coal seam in West No.1 Mining Area of Panji No.3 Coal Mine.*

Lithology	Unit weight (kg·m^{-3})	Compression strength (MPa)	Tension strength (MPa)	Shear strength (MPa)	Elastic modulus (GPa)	Poisson's ratio	Cohesion c (MPa)	Internal friction angle φ(°)
medium-grained sandstone	2514	57.9	11.80	19.03	15.10	0.229	12.07	49.83
fine-grained sandstone	2590	59.4	10.20	6.70	32.20	0.086	14.917	31.79
siltstone	2521	33.7	5.49	6.62	6.01	0.074	3.866	55.48
mudstone	2485	15.6	2.66	6.09	2.86	0.183	4.85	28.8

Table 2. *Well pumping and pressing test results table of additional prospection in West No.1 Mining Area of Panji No.3 Coal Mine.*

Hole	Surface elevation (m)	Watery stratum				Specific water absorption (L/min·Pa·m)	Specific yield (L/(s·m))	Permeability coefficient (m/d)	Remark
		Horizon	Start and end depth(m)	Thickness (m)	Static level(m)				
XII$_{west7}$	21.41	roof sandstone of 8 coal seam	475.60~520.16	44.56	-265.29	3.953×10^{-6}		5.705×10^{-6}	water pressure test
XII-XIII$_{hyd23}$	21.88	roof sandstone of 8 coal seam	460.00~498.10	38.10	-212.36	4.364×10^{-6}		6.050×10^{-6}	water pressure test
XIII$_{hyd\ 23}$	21.75	roof sandstone of 8 coal seam	582.50~624.62	42.12	-162.93	13.820×10^{-6}		1.960×10^{-6}	water pressure test
XII-XIII$_{hydr25}$	22.02	lower watery stratum of Quaternary	344.00~415.45	70.45	-19.61		0.844	2.073	pump test

4.2. Setting Waterproof Coal (Rock) Pillar Between Working Face and Fault

In this section, the main that influences setting working faces are four faults, which are F_1, $F_{22\text{-}a}$, F_{23}, F_{48}.

1212 (3) working face of 13-1 coal seam is just above the study section(the thickness of stratum between 8 coal seam and 13-1coal seam is about 170m), and the minimum distance between F_{23} fault and mining boundary of 1212 (3) working face is only 36m, it didn't break through of water during the course of driving roadways and mining the coal seam. These show that F_{23} fault water abundance and hydraulic conductivity are all weak; the fault brings no water inrush risk to mining the 8 coal seam.

Hua Wang, et al. [25] systematically studied respectively the reasonable waterproof coal and rock pillars of F_1, $F_{22\text{-}a}$, F_{48} to 8 coal seam, revealing that they were 70~95, 70~75, 80~90m (of which the shallow part is narrow, and the deep part is wide).

4.3. The Stope Layout and Working Faces Design

Through calculating vertical height of waterproof coal and rock pillar between 8 coal seam and the Lower Aquifer of Cenozoic loose sedimentary stratum, waterproof coal and rock pillars of each main fault to 8 coal seam working faces in upper section of 8 coal seam in West No.1 Mining Area, and by reference to the experience of setting waterproofing coal and rock pillar between two working faces of 8 coal seam in West No.1 Mining Area(i.e. the widths of 12318 to 12418 working face, and the widths of 12428 to 12528 were all set 9m), based on setting waterproof coal and rock pillar of vertical height 70m between 8 coal seam and the Lower Aquifer of Cenozoic loose sedimentary stratum, we designed four working faces, they were 12028, 12128, 12228, 12328(Fig.1). Their main parameters were shown in Table 3.

Table 3. *Main parameters of 8 coal seam design working faces at the upper section in West No.1 Mining Area.*

Working face	Mineable length(m)		Width (m)	Mineable area (m^2)	Average elevation of 8 coal seam floor(m)	Average thickness of 8 coal seam (m)
	Upper roadway	Lower roadway				
12028	1510	1470	150	223500	-500	3.0
12128	1525	1485	150	225750	-550	3.0
12228	1070	1030	150	157500	-600	3.0
12328	855	815	200~135	131250	-620	3.0

5. Similar Simulation Test

5.1. Selecting Profile and Parameters of Similar Simulation

We selected the two-dimensional simulation test bench in similar simulation test, of which the dimensions are as follows: length × width × height = 4.20m × 0.25m × 2.00m, and we selected the region between F_1 fault and F_{23} fault on 8 coal-floor contour map in West No.1 Mining Area as the simulating target. Through the XII-XIII$_{312}$ borehole and along the inclination of 12028 work face, we drew a profile line, A-A line(Fig.1). In the line, the distance between F_1 and F_{23} is 840m, including four working faces(12028、12128、12228、12328), where the simulating height is 300m(from elevation -350 ~ -650m). According to bore logs of XII-XIII$_{28}$、XII-XIII$_{312}$、XII-XIII$_1$、XIII$_{east743}$ boreholes close to the A-A profile line , we drew the composite columnar section of study area, and merged the stratum to adjacent stratum while its thickness was less than 1 m. Then combined with the 8 coal-floor contour map, the geological profile of A-A line was drawn.

The stratigraphy of A-A geological profile was looked upon as prototype simulation. As geometric similarity ratio C_L = 200: 1, unit weight similarity ratio C_r = 1.6: 1, we got stress similarity ratio $C_\sigma = C_L \cdot C_r$=320:1. Due to similarity criteria, we could derive the converted relationship of strength parameters between the prototype and the model, i.e.:

$$[\sigma_c]_M = \frac{L_M}{L_P} \cdot \frac{\gamma_M}{\gamma_P} [\sigma_c]_P = \frac{[\sigma_c]_P}{C_L \cdot C_r} = \frac{[\sigma_c]_P}{C_\sigma} \tag{6}$$

Where,

$[\sigma_c]_M$ ——the uniaxial compressive strength of model, MPa;

$[\sigma_c]_P$ ——the uniaxial compressive strength of prototype, MPa;

L_M —— linear dimension of model, m;

L_P —— linear dimension of prototype, m;

γ_M ——unit weight of model, kN/ m^3;

γ_P ——unit weight of model of prototype, kN /m^3.

Because of many samples were damaged in drilling and machining, some rock samples were missing or insufficient (e.g. coal seams 8, 11-2, 13-1 and sandy mudstone, etc.), the rock mechanics parameters of them were selected according to references [26], [27] (table 4).

Table 4. *Composite columnar section of A-A profile and physical mechanic parameters of rocks.*

Stratum No.	Lithology	thickness of stratum(m)	Grand total thickness (m)	Density (kg·m^{-3})	Compression strength (MPa)
23	sandy gravel	30	300	2464	3.20
22	sandy mudstone	7	270	2570	10.71
21	silty fine sandstone	13	263	2590	59.40
20	sandy mudstone	21	250	2570	10.71
19	silty fine sandstone	19	229	2590	59.4
18	mudstone	16	210	2485	15.60
17	sandy mudstone	20	194	2570	10.71
16	13-1coal	4	174	1370	5.44
15	mudstone	16	170	2485	15.60
14	fine-grained sandstone	24	154	2590	59.40
13	mudstone	13	130	2485	15.60
12	silty fine sandstone	10	117	2590	59.40
11	mudstone	7	107	2485	15.60
10	11-2 coal seam	2	100	1370	5.44
9	fine-grained sandstone	5	98	2590	59.4
8	sandy mudstone	19	93	2570	10.71
7	mudstone	26	74	2485	15.60
6	fine-grained sandstone	21	48	2590	59.40
5	sandy mudstone	8	27	2570	10.71
4	silty fine sand	3	19	2590	59.40
3	sandy mudstone	10	16	2570	10.71
2	8coal seam	3	6	1370	5.44
1	mudstone	3	3	2485	15.6

5.2. Similar Materials Preparation and Model Creation

Similar material mainly consists of two ingredients, which are aggregate and binder. In the test, fine sand and Magnesium powder were aggregates, lime and gypsum were binders. Different binders mixed with aggregate will form different types of similar materials, which have different mechanical properties. According to the calculated mechanical parameters of the model, we selected aggregates and binders to have mixing proportion tests. In order to accurately select the mix proportion that it's well consistent with the calculated parameters, we had a number of mixing proportion tests, and made various tables. Finally, we chose the kind of table that met the similarity simulation test requirements.

According to A-A geological profile, we paved each stratum on the similar simulation test bench on the basis of geometric similarity ratio. In order to simulate the transmission of load from Lower Aquifer of Cenozoic loose sedimentary stratum to coal measures strata, we set several lifting jacks on top of the model. And for the purpose of conveniently observing and measuring the development of caving zone and water flowing fractured zone, we set measuring points on the model flank, of which the grid-density is 15cm × 15cm. In addition, in order to accurately and exhaustively grasp the changes of the direct roof of 8 coal seam, we encrypted the measuring points above the roof, based on the original vertical measuring points (Fig. 4).

At the upper roadway of 12028 working face the waterproof coal and rock pillar of the Lower Aquifer of Cenozoic loose sedimentary stratum was set vertical height 70m(the actual height was 35cm on the model flank), and the distance between the roadway and the right pillar of simulation test bench was 57cm. The others were set successively from right to left, where the distance between the lower roadway of 12328 working face and the left pillar of simulation test bench was 47cm (Fig.4).

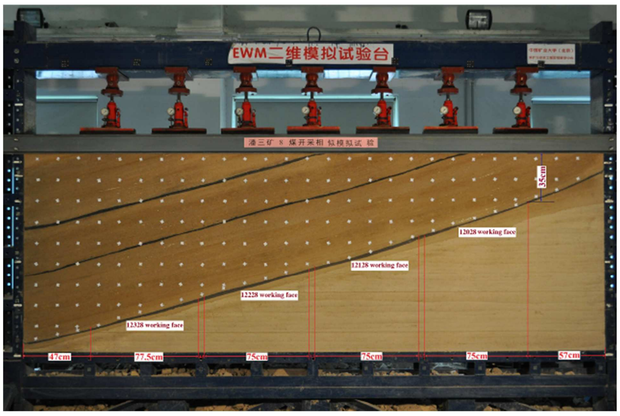

Fig. 4. *Similar simulation test bench being ready.*

5.3. Similar Simulation Process and Results Analysis

In order to avoid that the goaf water of the working face in the former phase threatens the working face in the latter phase in driving upper roadway and mining coal seam, and reduce the work of water exploration and drainage, to increase mine production efficiency, working surfaces were sequentially mined in the order of 12328→12228→12128→12028, from left to right. In order to fully grasp the whole process of overlying strata crack propagation and fracture in mining, we observed and measured changes of overlying strata at the same time. Once there was obvious change, we stopped mining and took photos. When a working face was finished, we had an interval of 12 to 24 hours, and then mined the next working surface. In the interval, we constantly observed, measured and photographed the model. After each working face finished, the crack propagation and fracture situation of 8 coal seam overlying strata appeared as in Fig.5~ Fig.9 and Table 5.

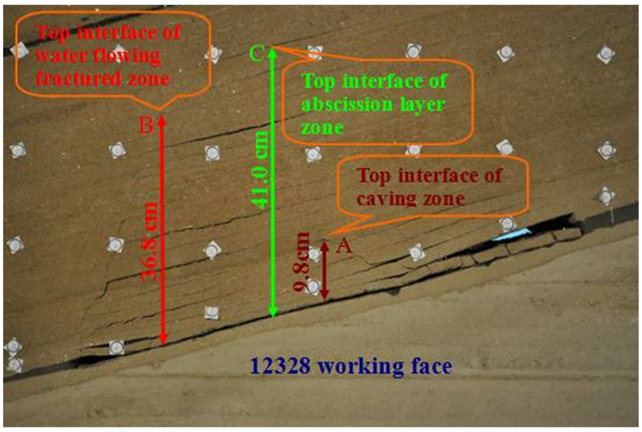

Fig. 5. Failure status of overlying rock mass after excavating the 12328 working face.

Test results (Table 5) showed that:

① In case of controlling mining height 3.0m of the upper section of 8 coal seam in West No.1 Mining Area, the height of caving zone is 16.6 ~ 25.4m, and the height of water flowing fractured zone is 40.0 ~ 70.6m;

② Uphill caving angles of rock strata are all 69º, and downhill caving angles are 31~44º. Generally, uphill caving angle is not affected by stratum dip angle; while stratum dip angle increases, downhill caving angles will decreases (Figure 10), basically corresponding with the following equation:

$$y = -1.5667x + 64.133 \tag{7}$$

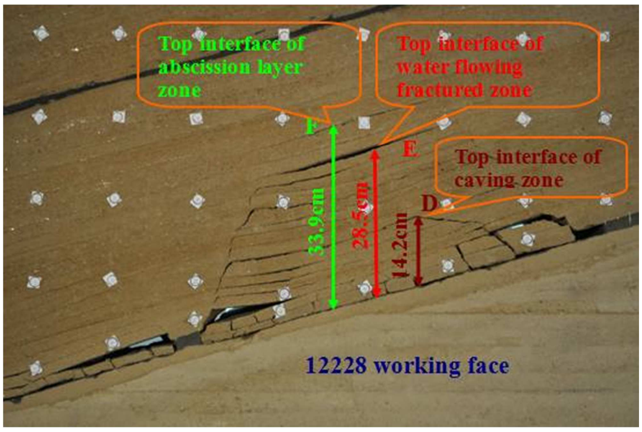

Fig. 6. Failure status of overlying rock mass after excavating the 12228 working face.

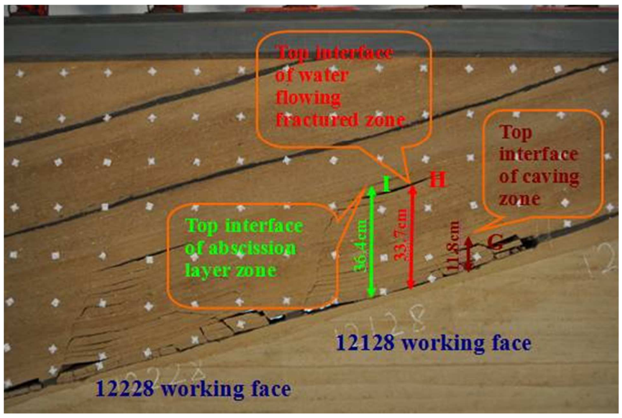

Fig. 7. Failure status of overlying rock mass after excavating the 12128 working face.

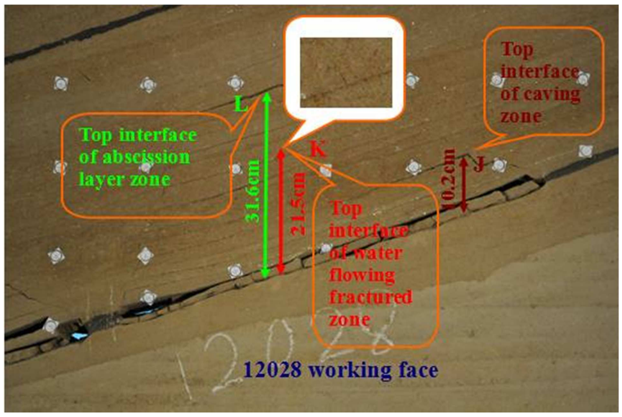

Fig. 8. Failure status of overlying rock mass after excavating the 12028 working face.

③ The water flowing fractured zone height (H_L) of 12021 working face is 60.2m; coal dip angle(α) is 21º; and downhill caving angle(β_X) is 31º(Table 5). In ΔMNO (Fig.9),

$$\frac{\overline{MN}}{\sin\angle NOM} = \frac{\overline{NO}}{\sin\angle NMO} \tag{8}$$

Thereby,

$$\overline{MN} = \frac{\overline{NO}}{\sin\angle NMO}\cdot\sin\angle NOM = \frac{40.0}{\sin(\beta_X+\alpha)}\cdot\sin(90^\circ-\alpha)$$

$$= \frac{40.0}{\sin(31^\circ+21^\circ)}\cdot\sin(90^\circ-21) = 47.39(\text{m})$$

In $Rt\Delta MNP$,

$$\overline{NP} = \overline{MN}\cdot\sin\angle NMP = 47.39\times\sin\beta_X = 24.41(\text{m})$$

The distance between point M and bedrock surface is:

$$h = 70 - \overline{NP} = 45.59 \text{ m} > H_b = 6A = 18.0\text{m}$$

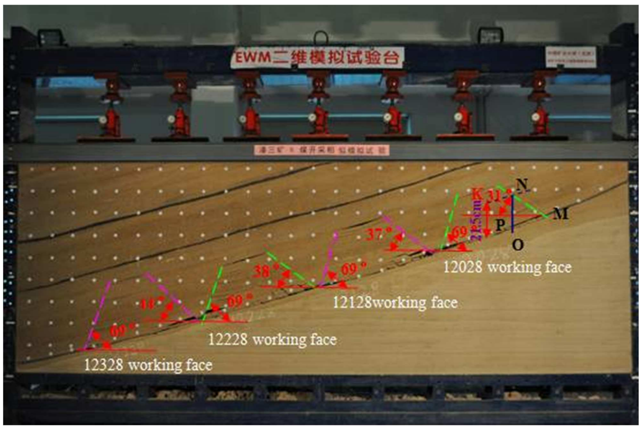

Fig. 9. *Failure status of overlying rock mass after excavating all working faces in the section.*

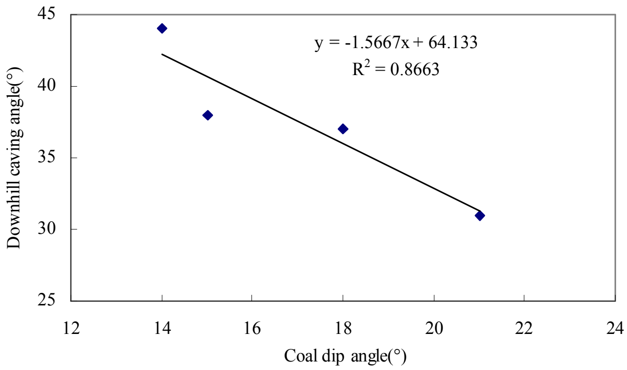

Fig. 10. *Relation curve between downhill caving angle and dip angle of coal seam.*

Table 5. *Results of similar simulation test.*

Working face No.	Width (m)	Coal dip angle (°)		height of caving zone (m)	height of water flowing fractured zone (m)	caving angle(°)	
		Lower road-way	Upper road-way			Up-hill	Down-hill
12328	155	14	14	16.6	70.6	69	44
12228	150	14	15	25.4	54.0	69	38
12128	150	15	18	20.6	64.4	69	37
12028	150	18	21	17.4	40.0	69	31

Thence, under setting waterproof coal-rock pillar of vertical height 70m between 12021 working face and the Lower Aquifer of Cenozoic loose sedimentary stratum, the mining is safe.

6. Conclusions

Theoretical analysis and similar simulation test were carried out in order to study the deformation and fracture characteristics of the overlying rocks of 8coal seam in the upper section of West No.1 Mining Area in Panji No.3 Mine, the coal seam is gently inclined and under thick Cenozoic loose sedimentary stratum. The following conclusions could be drawn:

(1) In case of controlling mining height 3.0m 8 coal seam, according to “Three Under Regulations” , the caving zone height is 11.26m and water flowing fractured zone height is 44.64m; similar simulation test results: caving zone height is 16.6 ~ 25.4m and water flowing fractured zone height is 54.0 ~ 70.6m. On the whole, the similar simulation test results are all bigger than the calculated value by “Three Under Regulations” and empirical formula(in Huainan Coalfield, caving zone height is generally 4-6 times of coal seam mining height and water flowing fractured zone height is generally 14 - 16 times of it.)

(2)Uphill caving angle is not affected by stratum dip angle; while stratum dip angle increases; downhill caving angles will decrease; basically corresponding with the linear equation: $y = -1.5667x + 64.133$.

(3) Theoretical analysis and similarity simulation test show that under setting the waterproof coal and rock of vertical height 70m pillar between 8 coal seam and the Lower Aquifer of Cenozoic loose sedimentary stratum, mining 8 coal seam is safe.

(4) After mining 8coal seam, the roof "Four zones" (i.e. fracture zone, abscission zone, bending zone and loose alluvium zone) will remarkably develop in Panji No.3 Coal Mine.

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