

# Water-Inrush Prediction of Coalbed Floor Based on the Limit Equilibrium Theory of Rockmass

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**Abstract**—Based on the limit equilibrium theory of rock mass, we analyzed the mechanism of water-inrush of seam floor and deduced the theoretical formulas of ultimate hydraulic pressure of seam floor through obtaining the facing length, the thickness and lithological association of floor rockmass into consideration. Water-inrush risks were predicted according to the geology condition.

**Keywords**—the limit equilibrium theory of rock mass; the mechanism of water-inrush of seam floor; ultimate water-inrush pressure; prediction of water-inrush

## I. INTRODUCTION

Coal-bearing strata in the North China Coalfield belong to the Carboniferous-Permian System. Ordovician limestone water-bearing thick stratum is the bedrock. As coal mining in deep-lying being developed, threaten from the Ordovician limestone aquifer is increasing [1].

Theories and methods for water-inrush risk evaluation include: Water Irruption Coefficient Method [2], Neural Network Method [3], Multi-source Information Fusion Method, Brittleness Number Method, etc. Water Irruption Coefficient Method is widely used for its simple operation. But this method just considers confined water head pressure and the floor aquiclude thickness. Thus, finding new method to evaluate the water-inrush risk is very important to the continual development of China Coal industry.

Baode Coalmine is located in the north of the Hedong coalfield of Shanxi Province, with simple and gently monoclinial structure. The attitude of stratum:direction is  $350^\circ$ , proneness  $260^\circ$ , and the dip is about  $5^\circ$ . Within the zone, there are wide and gentle sag and swell and scattered minor faults. The No.13 coal seam is the main mining coalbed of Baode Coal Mine, with the thickness of 1.11~13.28m, 6.67 meters on average. The No.13 coal seam can be mined stability through the whole mining area. Average distance between the seam floor and the Ordovician limestone aquifer is 73.45m. As the

aquiclude becoming thinner in the deeper, threaten from Ordovician system's limestone water increases.

## II. WATER-INRUSH PREDICTION BASED ON THE LIMIT EQUILIBRIUM THEORY OF ROCKMASS

Separating water ability of coal floor aquiclude determined water-inrush risks. That is the ultimate water pressure the coal floor aquiclude can bear. No.13 coal seam floor was considered as the horizontal strata for rocks bedding dip is only about  $5^\circ$ . The paper carried out dynamics analysis of the ultimate water pressure of the coal floor aquiclude. We built a mechanics model (shown in Figure 1) along the coal seam dip.  $M$  stands for the distance between the coal floor and the aquifer,  $L$  is the facing length.

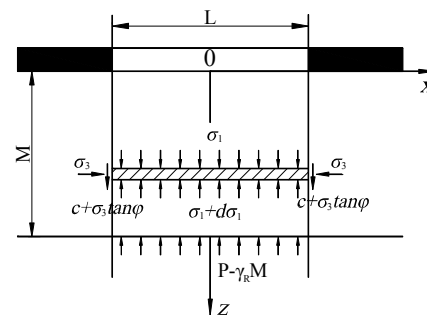


Figure 1. The mechanics analysis of the coal bed

Supposing coal floor aquiclude is approximately parallel to the coal wall, where occurred shear failure. Then the shear plane can be approximated to a vertical plane, and when the shear strength parameter of floor rockmass decreases to the critical value, that is, when skid resistance is equal to sliding power on the shear plane, floor rockmass will come close to the destabilizing state of limit equilibrium.

Choose a unit from the floor aquiclude with the thickness  $d_z$ . In order to complete and prevent the floor aquiclude from being damaged, the retain balance condition should be:

$$\sigma_1 \cdot L + 2(c + \sigma_3 \tan \varphi) \cdot d_z - (\sigma_1 + d\sigma_1) \cdot L = 0 \quad (1)$$

$\sigma_1$  is the vertical principal stress of floor aquialude, MPa;  $\sigma_3$  is the horizontal principal stress of floor aquialude, MPa,  $L$  is the facing length, meter.

$$\frac{d\sigma_1}{d_z} - \frac{2 \tan \varphi}{L} \sigma_3 - \frac{2c}{L} = 0 \quad (2)$$

According to the Mohr-Coulomb criterion, when the floor rockmass is about to be damaged, the limit equilibrium condition is:

$$\frac{\sigma_1 + c \cdot \tan \varphi}{\sigma_3 + c \cdot \tan \varphi} = \frac{1 + \sin \varphi}{1 - \sin \varphi} \quad (3)$$

Let  $\frac{1 + \sin \varphi}{1 - \sin \varphi} = \lambda$ , then:

$$\sigma_3 = \frac{\sigma_1}{\lambda} + \left( \frac{1}{\lambda} - 1 \right) c \cdot \tan \varphi \quad (4)$$

Initial formula (4) into formula (2) and calculate,

$$\frac{d\sigma_1}{d_z} - \frac{2 \tan \varphi}{\lambda L} \sigma_1 = \frac{2c}{\lambda L} \quad (5)$$

Solve this first order non-homogenous linear equation and calculate:

$$\sigma_1 = A e^{2 \tan \varphi \cdot Z / \lambda L} - c \cdot \tan \varphi \quad (6)$$

When  $Z=0$ ,  $\sigma_1=0$ , initial it into formula (6) :

$$A = c \cdot \tan \varphi \quad (7)$$

$$\text{Then, } \sigma_1 = c \cdot \tan \varphi \cdot e^{2 \tan \varphi \cdot Z / \lambda L} - c \cdot \tan \varphi \quad (8)$$

When  $Z=0$ ,  $\sigma_1=P \cdot \gamma_R \cdot M$ , initial it into formula (8) , the ultimate water pressure of the coal floor aquialude is:

$$P_{\max} = c \cdot \tan \varphi \cdot e^{2 \tan \varphi \cdot Z / \lambda L} - c \cdot \tan \varphi + \gamma_R \cdot M \\ = (e^{2 \tan \varphi \cdot Z / \lambda L} - 1) c \cdot \tan \varphi + \gamma_R \cdot M \quad (9)$$

$\gamma_R$  is the unit weight of floor rockmass;  $M$  is the thickness of floor aquialude, other symbols ditto.

Formula above reflects that the ultimate water pressure of the coal floor aquialude is controlled by the thickness of floor aquialude, facing length and synthetical mechanical properties. Different synthetical mechanical property reflects different lithological association of floor rockmass in different sections. If floor aquialude thickness and the lithological association of floor rockmass are fixed, the longer facing length is, the smaller the ultimate water pressure will be, and the greater water inrush risk. If the facing length and the thickness of floor aquialude is fixed, the greater the synthetical rock strength of floor aquialude is, the smaller water inrush risk; the greater the thickness of floor aquialude, the smaller water inrush risk will.

Formula (9) is established under the state of limit equilibrium, and it is easy to get the criterion of water inrush.

Use PW to represent the Ordovician limestone pressure water, define the probability index of water inrush  $\xi = P_W / P_{\max}$ . Considering the transitional character of the water inrush, the criterion of water inrush can be expressed as:

$$\begin{cases} \xi > 1, & \text{the danger zone of water inrush from floor;} \\ 0.8 \leq \xi < 1, & \text{the transition zone of water inrush from floor;} \\ \xi < 0.8, & \text{the safety zone of water inrush from floor} \end{cases}$$

### III. PREDICTION OF WATER-INRUSH RISK IN THE 13TH COAL SEAM OF BAODE COAL MINE

#### A. Calculations of the ultimate water pressure

Working face length of the No.13 coalbed is about 200m. Using 15 bore holes' data in the coal field to calculate ultimate water pressure at the  $L=200m$  working face. First, determine the lithology and thickness of floor aquialude, and calculate proportions of every lithology in the floor aquialude; then, calculate the ultimate water pressure according to the formula when the floor aquialude consists of monotypic lithology; At last, based on monotypic lithology's ultimate water pressure and after the weighted average of its proportion, the paper determined the ultimate water pressure of floor aquialude with this thickness and lithology character.

Take SK33 hole for example to introduce the solving process of the ultimate water pressure at the  $L=200m$  working face.

1) *Determination of the lithology and thickness of floor aquialude*: The lithology character and thickness of No.13 coal seam floor aquialude exposed by SK33 hole is shown in Table 2.

2) *Calculations of the ultimate water pressure of every rock stratum*

Analyze the table 2, in proportion to their content, the order of lithology in floor aquialude in SK33 hole from most to least is: Silt sandstone, Medium sandstone, Grit sandstone, Mudstone, Fine sandstone, Sandy mudstone and Coal seam. Suppose the floor aquialude only consists of a single lithology above. According to formula (9), calculate its ultimate water pressure with the fixed thickness of floor aquialude.

Suppose the floor aquialude only consists of Silt sandstone, then:  $M=71.3m$ ,  $\gamma_R=0.0266MPa \cdot m^{-1}$ ,  $c=25Mpa$ ,  $\lambda=3.537$ ,  $L=200m$ . Initial those parameters into formula (9), calculate ultimate water pressure of this Silt sandstone:

$$P_f = (e^{2 \tan 34 \times 71.3 / 3.537 \times 200} - 1) \times 25 \times \tan 34 + 0.0266 \times 71.3 = 3.886MPa$$

In a similar way, the relevant ultimate water pressure can be calculated when the floor aquialude only consists of Medium sandstone, Grit sandstone, Mudstone, Fine sandstone, Sandy mudstone or Coal seam:  $P_{zs}=2.865Mpa$ ,  $P_{cs}=2.307Mpa$ ,  $P_n=3.331Mpa$ ,  $P_{xs}=3.211Mpa$ ,  $P_{sn}=3.342Mpa$ ,  $P_m=1.152Mpa$ .

3) *Calculations of the ultimate water pressure of the floor aquialude*

The ultimate water pressure of single-lithology consist floor aquialude was calculated above. According to the table 2, considering every lithology proportion in floor aquialude, using

weighted average method to calculate the ultimate water pressure of the floor aquialude:

TABLE I. MECHANICAL PROPERTIES OF ROCKS IN 13TH COAL SEAM FLOOR

Lithology Mechanical properties	Mudstone	Sandy mudstone	Alumina mudstone	Silt sandstone	Fine sandstone	Medium sandstone	Grit sandstone	Coal seam	Mud limestone
Density /kg/m <sup>3</sup>	2670	2572	3280	2660	2654	2644	2460	1400	2480
Angle of internal friction /°	37.5	30.5	35	34	40	38.5	32.6	25	36.5
Cohesion (MPa)	16.9	20.5	15	25	15.2	11.4	7	2.4	4.2

TABLE II. THE CHARACTERS OF WATER-RESISTING LAYER ACCORDING TO DIFFERENT BORES

Bore No.	Floor aquiclude thickness /m	%								
		Mudstone	Sandy mudstone	Coal seam	Silt sandstone	Fine sandstone	Medium sandstone	Grit sandstone	Alumina mudstone	Mud limestone
CH1	62.02	1.610	39.12	/	13.5	15.65	3.70	12.86	6.82	6.74
CH2	59.68	4.49	72.35	/	2.01	3.99	/	/	6.20	10.96
CH3	64.21	35.51	27.67	2.49	1.98	10.59	2.44	5.76	6.54	7.02
CH4	80.63	3.84	47.72	/	/	15.33	22.06	4.55	2.16	4.34
CH5	88.54	7.33	23.96	/	8.40	19.84	/	40.47	/	/
G1	84.13	27.96	22.75	0.64	6.66	31.57	5.78	4.64	/	/
G2	60.49	35.12	22.73	3.79	11.12	4.52	/	14.84	7.88	/
G3	51.00	17.31	42.75	7.10	/	8.78	/	12.34	6.05	5.67
G5	56.04	15.70	48.07	/	15.35	6.07	/	14.81	/	/
CK2	98.63	30.27	24.34	1.20	/	33.16	/	/	11.03	/
T3	116.60	30.78	18.66	1.75	/	2.10	12.68	28.66	/	5.37
SK29	54.39	5.64	7.17	13.95	2.68	59.57	1.47	9.52	/	/
SK30	83.30	21.96	/	0.72	31.23	/	46.09	/	/	/
SK31	101.84	20.10	/	7.02	3.38	16.65	26.31	14.57	/	11.97
SK33	71.30	7.61	3.17	0.80	43.46	4.72	22.46	17.78	/	/

$$P_{max}=P_f\delta_f+P_{zs}\delta_{zs}+P_{cs}\delta_{cs}+P_n\delta_n+P_{xs}\delta_{xs}+P_{sn}\delta_{sn}+P_n\delta_n$$

$$=3.886\times0.435+2.865\times0.2246+2.307\times0.1778+3.331\times0.0761+$$

$$3.211\times0.0472+3.342\times0.0317+1.152\times0.008=3.23\text{Mpa}$$

In a similar way, ultimate water pressure of other 14 holes can be calculated.

TABLE III. ULTIMATE WATER PRESSURE OF DIFFERENT BORES

Bore No.	CK2	SK29	SK30	SK31	CH1	CH2	SK33	CH3
Ultimate pressure /mpa	4.05	2.44	3.84	4.38	2.79	3.38	3.23	2.78
Bore No.	CH4	CH5	G1	G2	G3	G5	T3	
Ultimate pressure /mpa	3.47	2.44	3.86	4.58	2.79	2.89	4.67	

#### B. Water-inrush prediction of the NO.13 coal seam floor

According to the Ordovician limestone water pressure, the paper constructed the contour map of partition of fatalness with water-inrush floor. It was shown in figure 2.

The danger zone is in the deep coal area. Combined with geologic data of Baode coal mine, the thickness of the No.13 coal seam floor aquialude becomes thinner as the depth increasing, and the proportion of the sandstone increases, made the separating water ability of coal floor aquialude reduced and Ordovician limestone water pressure increacing. Those three aspects cause water-inrush risks greater as the depth increasing.

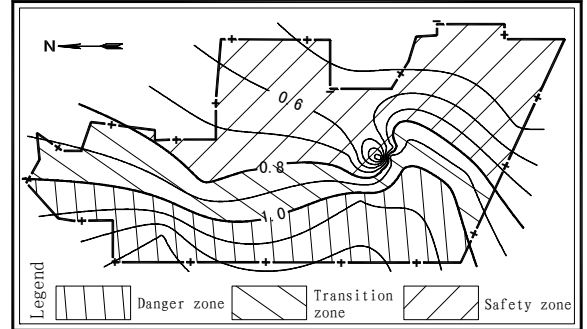


Figure 2. The map of partition of fatalness with water-inrush floor

#### IV. CONCLUSIONS

1) Based on the limit equilibrium theory of rock mass, we deduced the theoretical formulas of limit hydraulic pressure of seam floor according to the facing length, the thickness and lithological association of floor rock-mass. The paper provided a new method for water-inrush prediction.

2) Using ultimate water-inrush pressure formula, we calculated the ultimate water-inrush pressure of the No.13 coal seam floor. Predicted the water-risk when the facing length  $L=200\text{m}$ . It also divided the area into the safety zone, the transition zone, and the danger zone of water inrush. Come to the conclusion that the No.13 coal seam floor aquialude becomes thinner as the depth increasing, and the proportion of the sandstone increases, which leads to the reduction of separating Water

ability of coal floor aquialude. At the same time, Ordovician limestone water pressure is increasing.

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