Application of "direct method" in the evaluation of CBM resources in old goaf of Nanzhuang Coal Mine

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Abstract. With the cessation of mining in Nanzhuang Coal mine, the amount of gas extraction decreases, and the utilization rate of coalbed methane decreased significantly. Many coalbed methane resources exist in the old goaf after years of mining, which has a very high utilization value. Therefore, it is necessary to estimate the reserves of coalbed methane in goaf before mining. Based on the geology and production data of No.12 coal seam of Nanzhuang Coal Mine, the application of direct method in Nanzhuang coal mine is explored. The total amount of geological gas in No.12 coal seam was about 159,496,100 m³, among which, the total amount of free gas was about 20,637,100 m³.

1. Introduction
Nanzhuang Coal Mine was built in 1952, with an annual output of 2 million tons after renovation and expansion. The test mine belongs to coal seam group mining. After more than 60 years of mining, the No.12 coal seam in the middle and east of the mine area has been mined out in a large area. There are a lot of old goaf in the mining area, and a lot of coalbed methane is left and accumulated inside. On the one hand, this coalbed methane will escape to the surface through mining-induced cracks, causing air pollution; on the other hand, it may also flood into the working face with the mining of No.12 coal seam, increasing the difficulty in controlling underground gas and causing potential safety hazards.

Coalbed methane extraction from old gob (abandoned mine and stable mining area) is a new development mode of coalbed methane developed in the 1990s. This technology is mainly used to extract coalbed methane accumulated in the underground space of the mining area to the surface through negative pressure by using the original underground roadway or newly drilled surface well [1-2]. In recent years, this technology has made great progress in Germany, Belgium, Britain and other countries [3]. At present, the research on CBM extraction in old goaf in China has just started, with only sporadic experimental projects in Shanxi, Chongqing, Liaoning, Ningxia and other places [4], and many theoretical researches. Based on the three-belt theory and gas adsorption and desorption theory, Zhang Qun [5] determined the horizontal and vertical calculation ranges of gas resource quantity in goaf, but he did not further study the degree of pressure relief in each range. Qin Wei [6] established a relatively complete gas reserve prediction method for old goaf using the resource deduction method. Li Rifu [7] studied the description technology of gas reservoirs in mining stable areas, and constructed two relatively perfect and feasible gas assessment methods for mining stable areas.
2. Overview of No.12 Coal seam

2.1. No.12 Coal seam characteristics
No.12 coal seam is located in the middle of Taiyuan Formation, about 58.99m from No.6 coal seam, about 8.7m from K4 limestone, and about 5.87m from K3 limestone. The thickness of the coal seam is 0.18~1.70m, with an average of 1.22m. The coal layer is stable and has a simple structure. It contains 0–1 layer of gangue and the thickness of the gangue is 0.08~0.65m. In the well field, it can not be mined only near borehole No.128 in the south, which is a stable majority of the coal seam that can be mined. The roof of the coal seam is mudstone, sandy mudstone, and the floor is sandy mudstone, mudstone, medium and fine sandstone.

2.2. No.12 Coal seam reserve information
According to the annual report of Nanzhuang Coal Mine, as of December 31, 2019, the accumulative identified resource reserves of No.12 coal seam are 14865kT, 9298kT are utilized, and 5467kT are maintained.

2.3. No.12 Physical parameters of coal seam
(1) Physical characteristics of coal: the firming coefficient $F$ value of coal is 1.03, the initial gas emission velocity $\Delta P = 9$, the true density is $1.5t/m^3$, the apparent density is $1.56t/m^3$, and the porosity is 3.85%.
(2) Industrial analysis of coal samples: Moisture (Mad) yield was 2.28%, ash (Aad) yield was 13.83% and volatile (Vdaf) yield was 9.59%.
(3) Gas adsorption constant: Adsorption constant $A$ value is 41.2566, $b$ value is 1.3596.

3. Method selection of coal seam resource quantity evaluation

3.1. Evaluation method selection
The method of CBM resource assessment in old goaf can be divided into direct method and indirect method. On the basis of analyzing and obtaining the source and type of CBM in goaf, the direct method calculates the gas quantity of each source respectively, and finally adds the gas quantity of the whole goaf directly. This method is suitable for the target mining area where the production data is difficult to collect underground. Indirect method is based on the evaluation results of original CBM resource quantity, deducting all CBM quantities lost before and after underground production, and finally obtaining the evaluation results of goaf CBM quantity. This method is suitable for the target mining area where certain actual underground production data can be obtained.

According to the actual situation of No.12 coal seam, the direct method is used to calculate the amount of goaf resources.

3.2. Assess the suitability of the method
Since most of the lithology of the overburden of coal seam mining is mudstone, fine sandstone and limestone, the empirical formula of the height of the fracture zone of the roof of medium and hard lithology and the discriminant method of the height of key layers are used to calculate the effective relief height of the roof of each coal seam. The effective relief height of overburden of each coal seam calculated is shown in Table 1.

| Name of coal seam | Effective roof relief height /m |
|-------------------|-------------------------------|
| No.12 coal seam   | 15.1                          |
| No.15 coal seam   | 45.3                          |

Upper strata are mainly mudstone, limestone and sandstone, rock block adjustment coefficient $\Theta = 0.8$, No.12 coal seam mining height is 1.7 m, are:
Effective thickness of no. 12 coal seam cap: \(0.8 \times (135-15.1) = 95.92\) m
Minimum effective cover thickness: \(5 \times 1.7 = 8.5\) m
Since the effective thickness of the cap layer of no.12 coal seam is greater than the minimum effective cap thickness, it is considered that the target area of Nanzhuang coal mine meets the applicable conditions of the CBM resource evaluation model in the stable mining area.

4. Calculation of resources in No.12 coal seam goaf

According to the coal seam outburst risk report of Nanzhuang Mine, it is learned that the surrounding rocks of the roof and floor of No.12 coal seam are mostly mudstone, sandy mudstone, sandy mudstone, medium and fine sandstone, and it is judged as medium and hard enclosed rock according to its hardness.

The calculation formula for the height of the riser zone in the middle hard roof strata near the horizontal coal seam is as follows:

\[
H_s = \frac{100 \sum M}{1.6 \sum M + 3.6} \pm 5.6
\]

Where, \(\sum M\) — Accumulated mining thickness.

Applicable scope of the formula: single layer mining thickness 1~3m, accumulated mining thickness does not exceed 15m.

Maximum failure depth \(h_i\) of rock mass in mining coal floor is calculated by the following formula:

\[
h_i = \frac{x_a \cos \phi}{2 \cos \left(\frac{\pi + \phi}{4}\right)} e^{\frac{(\pi + \phi) g \phi}{4}}
\]

Where, \(x_a\) — Length of coal pillar yield zone; \(\phi\) — Internal friction Angle of floor rock mass.

When the maximum concentrated stress value in the coal seam is \(\sigma_z = n \gamma \cdot H\), the yield zone length of the coal seam is calculated as follows:

\[
x_a = \frac{m}{2 K_m g \phi} \ln \frac{n \gamma \cdot H + C_m \cos \phi}{K_m C_m \cos \phi}
\]

Where, \(\phi\) — Angle of internal friction of coal seam; \(C_m\) — The cohesion of coal seams; \(m\) — Coal seam mining height are broken; \(H\) — Seam burial depth; \(\gamma\) — The bulk density of floor rock mass;

\(K_m = \frac{1 + \sin \phi}{1 - \sin \phi}\).

According to Equation (1), it can be calculated that the height of the riser belt of No.3 coal seam roof is 19.37~27.57m; According to Equations (2) and (3), it can be calculated that the maximum failure depth of no.3 coal seam floor is 6.05m.

The effective adjacent layers of No.3 coal seam mining stability zone are only No.5 and No.6 coal seam, and the gas emission rate of coal seam is about 51.41% and 31.4%, respectively; However, the effective relief height of surrounding rock in No. 3 coal seam mining stability zone ranges from 41.6 m to 52.8m for the roof and 31.87m for the floor.

According to the backstopping data of No.12 coal seam and the rock lithology analysis data of surrounding rocks, it can be calculated that the surrounding rock gap in the effective pressure relief area is 36,646,500 m³.

Maple software is used to calculate the subsidence volume of each working face of No.12 coal seam.
It is calculated that the total volume of No.12 coal seam sinking is 589,800 m$^3$.

The gas content in the fracture space in the mining-stabilized zone of Nanzhuang Mine is about 20%. Then the total amount of free gas in the pressure-relief surrounding rock void in the mining-stabilized zone can be calculated by using the following formula:

$$Q_1 = nV = n(V_1 + V_2 - V_3)$$  \hspace{1cm} (4)

Where, $V$—Total pore volume in the stable area, m$^3$; $V_1$—Produced coal volume, m$^3$; $V_2$—The original pore volume of surrounding rock in the mining stability area, m$^3$; $V_3$—Surface subsidence basin volume, m$^3$.

It can be obtained that the total amount of gas in the void space of the pressure-relief surrounding rock in the mining stable area is about $Q_1 = 20,637,100$ m$^3$.

The total amount of coal left in the goaf of No.12 coal seam is about 56.74 million t, and the residual gas content of coal left is 1.74 m$^3$/t, so the total amount of residual gas left in coal seam is about $Q_2 = 987.28$ million m$^3$. The total amount of residual gas in coal within the pressure relief range is about $Q_3 = 40,131,000$ m$^3$.

Then the total amount of residual geological gas in the mining stability zone of No.12 coal seam can be calculated using the following formula:

$$Q = Q_1 + Q_2 + Q_3$$  \hspace{1cm} (5)

Where, $Q_1$—The total amount of free gas in the voidage of surrounding rock in mining-stabilized zone; $Q_2$—The total amount of coal residual gas in goaf; $Q_3$—The total amount of coal residual gas in the pressure relief range near the coal seam.

By putting the calculated values into Formula (5), it can be calculated that the total amount of residual geological gas in the mining stability area of No.12 coal seam is about 159,496,100 m$^3$, among which the total amount of free gas is about 20,637,100 m$^3$.  

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**Figure 1** Main section of surface subsidence in inclined direction of working

**Figure 2** Overlooking contour map of surface subsidence basin of working face
5. Conclusion
(1) The methods of CBM resource assessment in old goaf can be divided into direct method and indirect method.
(2) The test mine is a resource-exhausted mine, and the goaf has a long history and some data are lost. Therefore, it is appropriate to use the direct method to estimate the resource amount of coalbed methane in the old goaf.
(3) The total amount of geological gas in No.12 coal seam was about 159,496,100 m³, among which, the total amount of free gas was about 20,637,100 m³.

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