**INTRODUCTION**

As coal resources continue to be developed, more and more coal working faces are closed due to the end of coal mining. “Study on efficient recovery of coal resources and energy conservation strategy” shows that the number of abandoned mines in China will reach 12,000 around 2020 and reach 15,000 around 2030 and about 70% of the abandoned mines are high gas mines.1 Because of technical limitations, a large amount of coal resource remains underground containing nearly 500 billion m³ reserves of coalbed methane, which is considered as a clean energy source.1 Abandoned mines or gobs can cause various environmental and safety concerns. It is confirmed that the geological emissions of methane are an important source of greenhouse gases and the efficiency in trapping the heat of methane is more than 20 times that of the same quality carbon dioxide.2-5 A large part of methane geological emissions escape from...
abandoned mines or gobs through mining-induced fractures or geological faults to the atmosphere, which further exacerbates the global greenhouse effect and seriously threatens the lives and property of people on the ground.6-8 People may be poisoned, and even fires and explosions may occur on the ground when the surface methane concentration reaches a dangerous value.2 Therefore, the production of the gas resources in closed gob can directly benefit the environment and the safety of people on the ground, as well as alleviate the energy shortage problem to some extent in China.9

Comparing with surface wells in the in situ area, surface drilling and extraction for closed gob methane (CGM) is another coal seam gas development method.10 The gas remaining in the underground gob, the roadway, and the surrounding pressure relief coal and rock formations is extracted by negative pressure which is different from the development of coalbed methane in situ.11 At present, the United States, the United Kingdom, Germany, France, and other countries have achieved commercial gas resource in the closed gob.12 The development of coal seam gas in China is mainly from in situ or pressure relief coal seams.13,14 However, the development of coal seam gas in closed gob is still in the exploration stage.15 Several CGM wells have been drilled in the Tiefa and Jincheng mining areas with a success rate of less than 50% in recent years. The gas production of each well generally declines rapidly and is unstable as well as different due to the blindness of the sweet spots selection and well location. Up to now, the low success rate, small gas production rate, and poor stability are the main problems in CGM production.16 Only based on the coal mining experience to select CGM favorable areas would lead to a great risk. The lack of a reliable CGM potential assessment system is one of the main factors affecting CGM production in China or other countries around the world.7

The research on CGM focused on reservoir description, reserve evaluation, and well location optimization in recent years.17-20 There have been few studies on the comprehensive evaluation for CGM sweet spots selection. Qin et al.19 proposed that the adjacent gobs connected by mining-induced fractures can be regarded as a whole, and the closed gobs of Yangquan Coal Mine are divided into 28 regions for CGM reserves evaluation. Closed gob methane reserves are the basis for the development of gobs; however, it is not comprehensive to estimate the development potential of gobs simply by considering this single factor. A comprehensive evaluation for CGM sweet spots is a significant and valuable work because lots of gobs are not enriched in gas or lack development conditions. The evaluation index system has been widely used in the potential evaluation of in situ coalbed methane, and it can be used as a reference for CGM comprehensive evaluation.21-25 The development potential of the evaluation unit can be ranked and classified to select the sweet spots by the size of the evaluation value, which is a comprehensive reflection of the indicator conditions.21 Various mathematical methods on the comprehensive evaluation of in situ coalbed methane are available for CGM sweet spots selection including analytic hierarchy process, fuzzy matter element method, BP neural network method, and gray correlation method.8,22,23,26-28 However, each method has limited conditions and cannot be directly applied to CGM sweet spots selection.

Closed gob methane sweet spots selection is to optimize the favorable area with greater potential and avoid the blindness of well location and have a certain guiding role for CGM. Therefore, this paper follows the principle of combining subjective and objective, establishes a complete CGM selection evaluation system. This method is studied and discussed in the Tiefa mining area.

2 DESCRIPTION OF THE STUDY MINING AREA

Tiefa mining area is located in Tieling City, Liaoning Province, northeast China (Figure 1A). It is a continental sedimentary coalfield formed during Yanshan tectonic movement in the Mesozoic Early Cretaceous.29

As shown in Figure 1B, the research area is dominated by faulted structure with few folds and extensive magmatic activity.30 All faults are high-angle normal faults (dip angle of 50°-60°). Magmatic rocks develop near faults, which are formed by the invading magma along large faults.

As shown in Figure 2, Cretaceous and Quaternary strata are the dominating research formations. The coal-bearing strata are the Lower Cretaceous Fuxin Group with a thickness of 700-950 m and an average of 850 m. The Fuxin Group is divided into four members from bottom to top: the bottom glutenite member (K1f1), the lower coal-bearing member (K1f2), the middle sand-mudstone member (K1f3), and the upper coal-bearing member (K1f4).31 The Fuxin Group contains 20 coal seams: Nos. 1-10 coal seams reside in K1f1 and Nos. 11-20 coal seams reside in K1f2. There are 12 mineable coal seams with an average total thickness of 35 m and a maximum thickness of 70 m. The Nos. 2, 4, 7, 9, 14, and 15 coal seams are the main mining coal seams.

The gas content in the research area is between 2.3 m³/t and 26.3 m³/t, on average 8 m³/t. The gas content increases gradually from north to south and from east to west. The gas content increases with the increase of the buried depth.

The Tiefa mining area consists of five producing mines, among which 4 mines are high gas mines and 1 mine is gas outburst mine. The Tiefa mining area has a mining history of more than 60 years, and the number of closed gob is large and widely distributed. More than 150 gobs have been
formed in the past 10 years in the five producing mines (Figure 1C).

3 METHODS AND RESULTS

3.1 CGM selection method

The target area for CGM ground development is not a single gob, but a gob group consisting of all gobs connected by mining-induced fractures (Figure 3). Gas in the gob group could flow and aggregate under pressure gradient or concentration difference while external conditions change. Therefore, dividing the gob group according to the connection of adjacent gobs is the first step in the CGM selection. In general, vertical connection and horizontal connection are two connection forms of adjacent gobs. While the spacing between the upper and lower gobs is smaller than the height of mining-induced fractures, the two achieve vertical communication, while the lateral spacing of the horizontally adjacent gobs is less than the width of the lateral fractures, the two achieve lateral communication. The height of the mining-induced fractures can be obtained according to the empirical formula or the measured data, and the width of the lateral fractures can be obtained by the mining pressure relief angle or numerical simulation.32

The use of a one-vote veto system to screen out a gob group with certain development potential is the second step of the CGM selection. Only when the gas resources in the gob group have certain development potential, the gob group can be regarded as an evaluation unit to participate in the comprehensive evaluation. Based on the potential of gas resources and the engineering feasibility of ground development, the following nine “one-vote veto” conditions are given to screen the CGM ground development evaluation unit:

1. A lower limit value of gas resource remains in the gob group should be set when economic benefits can be
realized considering the local natural gas market price and investment operation cost. The gob group with a gas resource below this value cannot be considered as an evaluation unit.

2. The longer the gob is closed, the more gas escapes. This paper mainly takes the gob with a closed time, which is within 10 years as the research units. The other gob groups are excluded.

3. The presence of accumulated water in the gob not only occupies the space of free gas but also inhibits gas desorption of the submerged coal. Therefore, if there is serious water accumulation in the gob, it is not considered to have resource potential.

4. If the mining fractures of the gob connects with the methane weathering zone, it is considered that the gas resource in the gob is seriously escaped, and the gob group has no resource potential.

5. If the surface ground of the gob group conditions is not conducive to drilling construction, the gob group is considered as having no engineering feasibility, for instance, the surface ground of the gob group is a water area or has dense buildings.

6. The gob group would be excluded while it is completely covered by other non-connected gobs, it is because drilling through the gob has greater engineering risks.

7. When there is a panel which will be mined above the target gob, the wellbore may be damaged due to the rock movement caused by coal mining. Therefore, this type of gob cannot be selected as an evaluation unit.

8. The gob group with the underground gas drainage system does not need to evaluate the development potential because the gas resources in such gob have been developed.

9. If the gob is not completely sealed, the gas would escape and it is likely to cause coal spontaneous combustion due to oxygen entering. This type of gob group should be excluded due to its high engineering risk.

Twenty evaluation units are selected from the five producing mines in the Tiefa mining area based on the connection of adjacent gobs and the nine one-vote veto conditions (Figure 4). These evaluation units are divided into three types according to the connection forms between the gobs: vertical connection, horizontal connection, and vertical-horizontal connection (both connections) (Table 1).

3.2 Comprehensive evaluation system

The process of CGM comprehensive evaluation includes constructing a comprehensive evaluation index system, standardizing the actual parameters of each evaluation unit, determining the weight of each indicator, and calculating a comprehensive evaluation result. The greater the comprehensive evaluation value, the greater its development potential. The comprehensive evaluation system established in this paper was aimed at the Tiefa mining area, whether it is applicable in other mining areas requires further research.

3.2.1 Comprehensive evaluation index system

Resource potential and engineering risk are directly related to the economic benefits and are the factors to be considered in CGM ground development. The evaluation indicators must be able to fully characterize the resource potential and the engineering risks of each evaluation unit. Three categories of evaluation indicators (Figure 5), including resource conditions, storage conditions, and engineering conditions, are classified. Among them, six secondary indicators under
resource conditions and storage conditions are selected to characterize resource potential and three secondary indicators under engineering conditions are selected to characterize the engineering risks.

The CGM resource, CGM resource abundance, and drainage methane (DM) and ventilation air methane (VAM) ratio are classified as the secondary indicators for measuring CGM resource conditions. Closed gob methane resource refers to the remaining gas resource within the mining influence area of the gob group. In this paper, CGM resource is calculated by the material balance method which means that the CGM resource of the evaluation unit is the in situ gas resource stored in the mining influence area of the gob group minus the gas resource lost during and after the production. The details of the CGM calculation range and method have been discussed in detail in the previous literature.\textsuperscript{10,36} CGM resource abundance represents CGM resource per unit area and is an important indicator to evaluate the degree of CGM resource enrichment in the evaluation unit. DM and VAM ratio refers to the ratio of drainage methane (DM) and ventilation air methane (VAM) to in situ gas resource. The larger the ratio, the more serious the gas resource loss.

The average closed time, effective cap rock thickness, and extensional fault development are the secondary indicators for measuring the CGM storage conditions. The longer the gob is closed, the more the methane escape and the water filling, and the lower the resource potential. This paper uses the average closed time as an indicator to measure the CGM storage conditions because the closed time of each gob in the evaluation unit is different. The effective cap rock thickness refers to the bedrock thickness above the fracture zone of the evaluation unit. The greater the effective cap rock thickness, the more conducive to CGM storage. The extensional fault density can be used to quantitatively characterize the extensional fault development because the faults in the study area are all extensional and similar in scale. The extensional fault density is the ratio of the number of extensional faults to the area of the evaluation unit. The greater the extensional fault density, the more unfavorable for CGM storage.

The coal seam spontaneous combustion tendency, the burial depth of gob, and water filling degree are the secondary indicators for measuring the CGM engineering conditions. The spontaneous combustion of the coal seam is a
major safety hazard in CGM extraction. The spontaneous combustion tendency level of the coal seam is divided by measuring the coal oxygen absorption. Therefore, the coal oxygen absorption can be used to quantitatively characterize the spontaneous combustion tendency of the coal seam. The higher the oxygen absorption, the higher the risk of spontaneous combustion of the coal seam in the evaluation unit. The burial depth of gob is related to the difficulty and cost of engineering construction. The greater the burial depth of gob, the higher the possibility of drilling accidents and the construction investment cost. The water filling degree can be quantitatively characterized by the ratio of the volume of the water to the volume of all the gobs in the evaluation unit. The gob water will seriously inhibit gas desorption of residual coal and occupy the space of free gas. Residual coal exposed by drainage will greatly increase the development cost and engineering risk. The higher the water filling degree of the evaluation unit, the worse the engineering conditions.

The indicator parameters of these 20 evaluation units are shown in Table 2 through data collection and calculation.

### 3.2.2 Indicator processing method

To eliminate the differences in the dimension of different indicators, it is necessary to standardize the indicators in the evaluation of multi-indicator objects, that is, to convert them into dimensionless standard values. This paper uses the highly effective range transform method to standardize the evaluation indicators to ensure the accuracy of the comprehensive evaluation results. Equations (1) and (2) are the transform methods of positive and negative indicators, respectively. The standard values of each evaluation unit are shown in Table 3.

\[
 r_{ij} = \frac{x_{ij} - \min (x_i)}{\max (x_i) - \min (x_i)} \quad (1)
\]

\[
 r_{ij} = \frac{\max (x_i) - x_{ij}}{\max (x_i) - \min (x_i)} \quad (2)
\]

where \( r_{ij} \) is the standard value of the \( i \)-th secondary indicator of the \( j \)-th evaluation unit; \( x_{ij} \) is the actual parameter of the \( i \)-th secondary indicator of the \( j \)-th evaluation unit; \( i = 1, 2, \cdots, m; \ j = 1, 2, \cdots, n; \ m \) is the number of secondary

| Evaluation units | Connection type | Evaluation units | Connection type |
|------------------|-----------------|------------------|-----------------|
| DX-I             | Vertical-horizontal | DL-I           | Vertical-horizontal |
| DX-II            | Vertical-horizontal | DL-II          | Vertical-horizontal |
| DX-III           | Vertical         | DL-III          | Vertical-horizontal |
| XN-I             | Vertical-horizontal | DL-IV          | Horizontal      |
| XN-II            | Vertical-horizontal | XQ-I           | Horizontal      |
| XN-III           | Vertical-horizontal | XQ-II          | Vertical-horizontal |
| XN-IV            | Horizontal      | XQ-III          | Vertical-horizontal |
| XN-V             | Horizontal      | XM-I           | Vertical-horizontal |
| XN-VI            | Vertical-horizontal | XM-II          | Vertical-horizontal |
| XN-VII           | Vertical-horizontal | XM-III         | Vertical         |
evaluation indicators; and \( n \) is the number of evaluation units.

### 3.2.3 Indicator weight calculation

Analytic Hierarchy Process (AHP) is the most commonly used method to determine weights, but the main problem of this method is that the subjective factors of the evaluator are too strong, and the weight distribution lacks objectivity. The entropy is a method to determine the weight based on the sample data. It does not include the subjective opinion of the evaluator. The limitation is that the weight is too objective and may deviate from the actual importance of the indicator. In this paper, the two methods are combined, and the objective weights determined by entropy are used to correct the subjective weights obtained by the analytic hierarchy process, thus enhancing the rationality of the evaluation.

The determination of the AHP weight mainly includes three steps: the establishment of the judgment matrix, the calculation of the weight vector, and the consistency check.\(^{35}\) The details of calculation steps have been discussed in the previous literature.\(^{21}\) The AHP weight of the \( i \)-th secondary indicator is denoted as \( W_{Ai} \). The calculated values of AHP weights for the secondary indicators are shown in Table 4.
The entropy weight of the \(i\)-th secondary indicator is denoted as \(W_{Ei}\). Equations (3)-(5) provide the calculation steps for the entropy weights of secondary indicators. The calculated values of entropy weights for the secondary indicators are shown in Table 4.

\[
P_i = -\frac{1}{\ln(n)} \sum_{j=1}^{n} h_{ij} \ln(h_{ij})
\]

\[
H_i = 1 - P_i
\]

\[
W_{Ei} = \frac{H_i}{\sum_{i=1}^{m} H_i}
\]

Table 3: Standard values of evaluation unit indicators

| Evaluation units | C11 | C12 | C13 | C21 | C22 | C23 | C31 | C32 | C33 |
|------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| DX-I             | 0.349 | 0.241 | 0.313 | 0.307 | 0.184 | 0.855 | 0.283 | 0.703 | 0.972 |
| DX-II            | 0.415 | 0.246 | 0.160 | 0.000 | 0.257 | 0.877 | 0.283 | 0.599 | 0.958 |
| DX-III           | 0.084 | 1.000 | 1.000 | 0.131 | 0.723 | 0.377 | 0.283 | 0.241 | 0.000 |
| XN-I             | 1.000 | 0.948 | 0.609 | 0.042 | 0.000 | 0.850 | 1.000 | 0.823 | 0.854 |
| XN-II            | 0.640 | 0.213 | 0.289 | 0.425 | 0.073 | 0.860 | 1.000 | 0.875 | 0.645 |
| XN-III           | 0.205 | 0.394 | 0.424 | 0.448 | 0.359 | 0.554 | 1.000 | 0.655 | 0.609 |
| XN-IV            | 0.083 | 0.420 | 0.498 | 0.940 | 0.359 | 0.501 | 1.000 | 0.940 | 1.000 |
| XN-V             | 0.137 | 0.292 | 0.780 | 0.739 | 1.000 | 0.702 | 0.528 | 0.328 | 1.000 |
| XN-VI            | 0.061 | 0.064 | 0.139 | 0.538 | 0.286 | 0.906 | 1.000 | 1.000 | 0.445 |
| XN-VII           | 0.000 | 0.009 | 0.000 | 0.922 | 0.398 | 0.776 | 0.528 | 0.000 | 1.000 |
| DL-I             | 0.604 | 0.181 | 0.369 | 0.589 | 0.218 | 0.885 | 0.189 | 0.797 | 0.992 |
| DL-II            | 0.939 | 0.368 | 0.353 | 0.364 | 0.335 | 0.870 | 0.189 | 0.509 | 1.000 |
| DL-III           | 0.177 | 0.791 | 0.600 | 0.801 | 0.252 | 0.648 | 0.189 | 0.720 | 1.000 |
| DL-IV            | 0.096 | 0.369 | 0.623 | 1.000 | 0.898 | 1.000 | 0.887 | 0.091 | 1.000 |
| XQ-I             | 0.013 | 0.000 | 0.090 | 0.798 | 0.917 | 0.897 | 0.774 | 0.622 | 0.928 |
| XQ-II            | 0.104 | 0.101 | 0.293 | 0.415 | 0.782 | 0.814 | 0.774 | 0.608 | 1.000 |
| XQ-III           | 0.154 | 0.294 | 0.701 | 0.353 | 0.850 | 0.863 | 0.774 | 0.526 | 0.861 |
| XM-I             | 0.260 | 0.260 | 0.624 | 0.321 | 0.352 | 0.813 | 0.000 | 0.935 | 1.000 |
| XM-II            | 0.011 | 0.072 | 0.061 | 0.869 | 0.097 | 1.000 | 0.000 | 0.897 | 0.935 |
| XM-III           | 0.010 | 0.247 | 0.400 | 0.327 | 0.311 | 0.000 | 0.000 | 0.974 | 0.649 |

Table 4: AHP, entropy and combined weights of evaluation indicators

| Primary indicator | Secondary indicator | \(W_{Ai} (\alpha = 1)\) | \(W_{Ei} (\alpha = 0)\) | \(W_i (\alpha = 0.5)\) |
|-------------------|---------------------|-------------------------|-------------------------|-------------------------|
| C1                | C11                 | 0.2998                  | 0.2560                  | 0.2779                  |
|                   | C12                 | 0.1128                  | 0.1590                  | 0.1359                  |
|                   | C13                 | 0.2124                  | 0.1011                  | 0.1568                  |
| C2                | C21                 | 0.1287                  | 0.0915                  | 0.1101                  |
|                   | C22                 | 0.0390                  | 0.1182                  | 0.0786                  |
|                   | C23                 | 0.0708                  | 0.0346                  | 0.0527                  |
| C3                | C31                 | 0.0624                  | 0.1444                  | 0.1034                  |
|                   | C32                 | 0.0200                  | 0.0622                  | 0.0411                  |
|                   | C33                 | 0.0540                  | 0.0330                  | 0.0435                  |

\(P_i\) is the entropy of the \(i\)-th secondary indicator; \(H_i\) is the difference coefficient of the \(i\)-th secondary indicator; \(h_{ij} = \frac{r_{ij}}{\sum_{j=1}^{m} r_{ij}}\), \(i = 1, 2, \ldots, m, j = 1, 2, \ldots, n; m\) is the number of secondary evaluation indicators; and \(n\) is the number of evaluation units. Assume that when \(h_{ij} = 0, h_{ij} \ln(h_{ij}) = 0\).

Set the combined weight model as a linear combination of AHP weight and entropy weight. The combined weight of the \(i\)-th secondary indicator is denoted as \(W_i\), that is:

\[
W_i = \alpha W_{Ai} + (1 - \alpha) W_{Ei}
\]
where $\alpha$ is the partition coefficient, in the range of 0-1. The size of $\alpha$ reflects the subjective and objective tendency of the combined weight. When $\alpha$ takes 0 and 1, the combined weights correspond to entropy and AHP weight, respectively; when $\alpha > 0.5$, it indicates that the combined weight is more subjective; and when $\alpha < 0.5$, the combined weight is more objective. The combined weight of each secondary indicator is calculated by taking $\alpha = 0.5$ as an example (Table 4).

### 3.2.4 Comprehensive evaluation value

The weighted summation method is used to obtain the comprehensive evaluation value (in the range of 0-1). The comprehensive evaluation value of the $j$-th evaluation unit is denoted as $F(j)$:

$$F(j) = \sum_{i=1}^{m} W_i \cdot r_{ij} \quad (7)$$

The comprehensive evaluation values of the 20 evaluation units are shown in Table 5 when using AHP weight, entropy weight, and combined weight ($\alpha = 0.5$), respectively. Each evaluation unit is ranked in descending order of the comprehensive evaluation value ranging from 0.228 to 0.726 while the comprehensive weight distribution coefficient is 0.5 (Table 5).

### 4 ANALYSIS AND DISCUSSION

#### 4.1 Development potential classification

The potential level can be classified by the size of the comprehensive evaluation value to provide reasonable suggestions for CGM development in the Tiefa mining area. Many scholars classify the level of development potential based on personal experience, which often has strong subjectivity.\textsuperscript{22,25} The optimal segmentation method is a more objective and accurate method to determine the intermediate nodes of the development potential level.\textsuperscript{23} The principles and calculation steps for this method have been discussed in detail in previous literature.\textsuperscript{40}

The 20 evaluation units are divided into 3 potential levels using the optimal segmentation method, including 1 level I evaluation units, 16 level II evaluation units, and 3 level III evaluation units (Table 5). The level I evaluation unit can be considered as a sweet spot for CGM extraction in the Tiefa mining area and can be developed preferentially. The comprehensive value for XN-I is 0.726, and XN-I is the only level

### Table 5 Evaluation results and ranking of the twenty evaluation units

| Evaluation units | CGM resource ($10^4 m^3$) | $\alpha = 1$ Evaluation value | $\alpha = 0$ Evaluation value | $\alpha = 0.5$ Evaluation value | Ranking | Development potential level |
|------------------|-----------------------------|-------------------------------|-------------------------------|-------------------------------|---------|-----------------------------|
| XN-I             | 3658.4                      | 0.727                         | 0.725                         | 0.726                         | 1       | I                           |
| DL-II            | 3448.8                      | 0.596                         | 0.529                         | 0.563                         | 2       | II                          |
| DL-IV            | 540.1                       | 0.549                         | 0.545                         | 0.547                         | 3       | II                          |
| XN-II            | 2415.6                      | 0.510                         | 0.524                         | 0.517                         | 4       | II                          |
| XN-V             | 679.0                       | 0.517                         | 0.500                         | 0.508                         | 5       | II                          |
| XN-II            | 493.7                       | 0.484                         | 0.520                         | 0.502                         | 6       | II                          |
| DL-III           | 817.5                       | 0.509                         | 0.462                         | 0.485                         | 7       | II                          |
| XQ-III           | 740.2                       | 0.473                         | 0.492                         | 0.483                         | 8       | II                          |
| DL-I             | 2293.2                      | 0.508                         | 0.441                         | 0.475                         | 9       | II                          |
| DX-III           | 499.1                       | 0.445                         | 0.448                         | 0.446                         | 10      | II                          |
| XN-III           | 916.6                       | 0.416                         | 0.466                         | 0.441                         | 11      | II                          |
| XM-I             | 1104.1                      | 0.425                         | 0.361                         | 0.393                         | 12      | II                          |
| XQ-II            | 568.0                       | 0.361                         | 0.413                         | 0.387                         | 13      | II                          |
| DX-I             | 1410.7                      | 0.390                         | 0.355                         | 0.373                         | 14      | II                          |
| XQ-I             | 253.1                       | 0.336                         | 0.406                         | 0.371                         | 15      | II                          |
| XN-VI            | 417.3                       | 0.306                         | 0.375                         | 0.341                         | 16      | II                          |
| DX-II            | 1639.6                      | 0.340                         | 0.332                         | 0.336                         | 17      | II                          |
| XN-VII           | 207.9                       | 0.277                         | 0.269                         | 0.273                         | 18      | III                         |
| XM-II            | 244.5                       | 0.279                         | 0.233                         | 0.256                         | 19      | III                         |
| XM-III           | 241.5                       | 0.224                         | 0.231                         | 0.228                         | 20      | III                         |
I evaluation unit among the 20 evaluation units. XN-I has the largest CGM resource of about $3658.4 \times 10^4$ m$^3$ and high resource abundance. They are conducive to get more gas production from XN-I. The development potential of level II is less than level I. Operators could develop selectively based on preferences. If operators are more inclined to the resource potential, the evaluation unit with a larger resource may be selected for development. If operators pay more attention to the feasibility of the project, the evaluation unit with a small spontaneous combustion tendency of the coal seam may be selected for development. Level III has the smallest development potential because the CGM resource is small and the coal seam has a high tendency to spontaneous combustion.

4.2 Relationship between comprehensive evaluation value and CGM resource

The CGM development potential is not only related to the amount of gas resource in the block, and the block with large resources does not necessarily have large CGM development potential. It can be found in Figure 6 that the consistency between CGM resource and the comprehensive evaluation value is poor. Closed gob methane resource is the most important secondary indicator with a combined weight of 0.2779 while other indicators are all below 0.16 (Table 4). However, the development potential of a block cannot be estimated simply by the factor of CGM resource, because the development potential is a comprehensive reflection of resource conditions, storage conditions, and engineering conditions. For example, the development potential of DL-II is reduced by the high engineering risk due to the high coal seam spontaneous combustion tendency despite its abundant CGM resource. By contrast, although the CGM resource of DL-IV is much lower than that of DL-II, the development potential of DL-IV is close to that of DL-II due to the better storage conditions and engineering conditions. Therefore, the comprehensive evaluation value should be the main reference in CGM sweet spots selection.
4.3 The influence of the distribution coefficient \( \alpha \) on the evaluation results

The correlation analysis between the two sets of evaluation values obtained by AHP weight (when \( \alpha = 1 \)) and entropy weight (when \( \alpha = 0 \)) showed that the two groups of data are highly correlated, with a correlation coefficient of 0.936. It shows that the evaluation results obtained under the two weights can be mutually verified and have high consistency. Therefore, it is feasible and reasonable to take the linear combination of AHP weight and entropy weight as the combined weight model (Equation 6) to evaluate the CGM development potential in the Tiefa mining area. The AHP weights (when \( \alpha = 1 \)) of the three primary indicators of resource conditions (\( C_1 \)), storage conditions (\( C_2 \)), and engineering conditions (\( C_3 \)) are 0.625, 0.2385, and 0.1365, and the entropy weights (when \( \alpha = 0 \)) are 0.5161, 0.2443, and 0.2396, respectively (Table 4). It can be seen that the size of \( \alpha \) has a very small influence on the combined weight of storage conditions (\( C_2 \)), while a relatively large influence on the combined weights of resource conditions (\( C_1 \)) and engineering conditions (\( C_3 \)). The larger the value of \( \alpha \), the larger the combined weight of resource conditions (\( C_1 \)) and the smaller the combined weight of engineering conditions (\( C_3 \)). Therefore, for the evaluation units with better resource conditions than engineering conditions (\( C_3 \)), the larger the value of \( \alpha \), the larger the evaluation value. Conversely, for the evaluation units with better engineering conditions than resource conditions, the smaller the value of \( \alpha \), the larger the evaluation value. It can be seen from Figure 7 that the difference in the evaluation values of each evaluation unit obtained by the AHP weight (when \( \alpha = 1 \)) and the entropy weight (when \( \alpha = 0 \)) is small, within 0.1. This indicates that the size of the distribution coefficient \( \alpha \) has little effect on the comprehensive evaluation values and only affects the ranking of evaluation units in a small range.

5 CONCLUSIONS

1. A comprehensive evaluation system based on AHP—entropy combined weight model is constructed to select sweet spots for CGM extraction with surface wells. The evaluation units are selected based on the connection of adjacent gobs and nine one-vote veto conditions. The rationality of the evaluation results can be improved by the combined weight model.
2. Twenty evaluation units are evaluated to select sweet spots by the comprehensive evaluation index system in the Tiefa mining area. The development potential of the evaluation units is classified as three levels by the optimal segmentation method to make development decisions easily.
3. The development potential of a block cannot be estimated simply by the factor of CGM resource because the consistency between the comprehensive evaluation value and CGM resource is poor. The comprehensive evaluation value should be taken as the main reference in CGM sweet spots selection.
4. It is feasible and reasonable to take the linear combination of AHP weight and entropy weight as the combined weight model to evaluate the CGM development potential in the Tiefa mining area. The size of the distribution coefficient has little effect on the comprehensive evaluation values and only affects the ranking of evaluation units in a small range.

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