A Multi-hierarchy Fuzzy Comprehensive Evaluation Model for Shale Gas Surface Gathering System Schemes Optimization

You Zhang[1, a], Jianping Jiang[2, b]

[1]School of Civil Engineering and Architecture, Southwest Petroleum University,

Chengdu 610500, China;

[2]Sichuan Shengze Petroleum Engineering Technology Co,.LTD, Chengdu 610011, China.

[a]1009576125@qq.com, [b]840245918@qq.com

Abstract

Because the shale gas is different from the characteristics of conventional natural gas, the development mode and surface gathering system plan also cannot apply the method of conventional natural gas. The study of patterns suitable for China's shale gas field development mode and surface gathering system scheme of shale gas development is of great significance to our country. According to the characteristics of shale gas, the shale gas surface gathering and transportation optimization evaluation index system was established. Furthermore, the use of multi-hierarchy fuzzy comprehensive evaluation method on a comprehensive evaluation of the scheme was proposed. Finally, a domestic shale gas field as an example was to verify. The results showed that dispersed gas-gathering system station scheme is more suitable for shale gas development in the hilly area of our country. What’s more, the multi-level fuzzy comprehensive evaluation method has a good practice effect on shale gas surface gathering system optimization, which provides a theoretical basis for China’s shale gas surface gathering system transmission scheme optimization in the future.

Keywords

Shale gas, Rolling development, surface gathering system and transportation, analytic hierarchy process, scheme optimization.

1. Introduction

Unconventional characteristics of shale gas decide that its exploitation adopt the rolling development, and the surface gathering system schemes are not suitable for the conventional natural gas. Now China shale gas surface gathering system and transportation process is not yet mature, meanwhile, lots of hydraulic fracturing fluid and sewage will be produced during the exploitation process. How to deal with hydraulic fracturing fluid and sewage, how to output shale gas and oil after the separation of oil and gas are problems with large uncertainties, various possibilities and particularity[1,2]. The shale gas surface gathering system transmission process flow and data is not clear, especially, its development of surface engineering planning should be timely adjustment according to the actual situation in various stages of development[3]. Although, the over-ground and underground team also discuss, only relying on the experience and there is not a scientific and reasonable comprehensive evaluation method aiming at different ground engineering construction.

At present, there are many methods for scheme optimization. Sun[4]applied analytic hierarchy process (AHP) method to the oil field development‘s comprehensive evaluation and selection of scheme, as well as choosing a case to verify. Finally he obtained the conclusion that analytic hierarchy process which has characteristics of quick and convenient can determine the stand or fall of various schemes by the weighted average method. Lee [5] and others also used the improved analytic hierarchy process which mainly replaced 9 scale of the analytic hierarchy process by 3 degrees, so that the calculation would be more efficient and greatly simplifies the process of solving. The integration of the two methods can be described as an innovative approach, and is now widely used. Wang[6] integrated fuzzy comprehensive evaluation and grey correlation analysis which established the evaluation index system of three layers for optimizing enterprise's production and processing of parts design scheme. The combination of the two methods complemented each other, and case analysis also proved that integration of the two methods had a certain scientific and practical. Now there are many scientists in researching some new methods of comprehensive evaluation, like Fan[7] found incorrect negative weighting coefficient through the analysis of principal component analysis use conditions, considering to establish constraints to the weighted coefficient to of system. As a result, some improved models were obtained to be used in the oil and gas field development plan. In the use of principal component analysis, the situation that the weight coefficient is negative should be excluded.

Shale gas surface gathering system scheme optimization has not yet formed perfect evaluation system. With the shale gas's multi-level and multi-index problem, this paper used the analytic hierarchy process and fuzzy comprehensive evaluation method to solve scheme optimization. First of all, a evaluation index system was established, using Analytic Hierarchy Process to calculate the index weight. Furthermore, evaluation set was put forward using the multi-level fuzzy comprehensive evaluation, evaluating primary and secondary evaluation on various schemes. At the last, the solution which had the highest score is optimal. With a domestic shale gas field as an example, paper evaluated the shale gas surface gathering system scheme, to confirm theory and provide a certain of theoretical guidance for shale gas gathering system ground scheme optimization in the future.

2. Evaluation index system for Shale gas surface gathering system scheme

According to the characteristics of the shale gas field surface gathering system scheme, the following evaluation indexes are mainly put forward.

(1) Economic Benefits

Economic benefits indexes[8] can evaluate that the shale gas field surface gathering system schemes economic benefit is good or bad. It can be divided into the investment payoff period and investment utilization. Investment payoff period is the time that accumulative economic benefits are equal to the initial investment cost, as small as possible. Investment utilization is the ratio of additional business income which each yuan investment can bring.

(2) Cost Indexes

Cost index is consists of the pipeline investment costs, the station investment cost, operating cost and maintenance expense. Pipeline investment cost is related to unit weight of the pipeline, pipe diameter and pipe material, moreover, station investment costs mainly include all kinds of ground infrastructure investment and regional development costs. Operating costs are the amount of funds in the process of shale gas surface gathering system for facility operation. Additionally, maintenance expense is the cost of shale gas gathering system and transferring process for facilities or pipe maintenance.

(3) Operating Risk

Operating risk includes hydrate harm that refers to the risk of hydrate formation and gas supply diversification ability. The hydrate forming risk is bigger as a result of a long distance pipeline; hence, the risk of hydrate formation is a safety evaluation index of surface gathering system scheme. Gas supply diversification ability mainly investigates the conveying strain capacity of dangerous situations in the process of surface gathering system.

(4) Operability

Operability can be divided into the adaptability to the rolling development, gas recovery factor and gas quality. Different surface gathering system schemes' adaptability for the rolling development are different, and the more flexible the better[9]; Gas recovery factor can refers to the proportion of gas recovery contained the total gas reservoir, For the gas quality, the better the advantageous.

(5) External Environmental Indexes

HSE risk, floor area and interference on surrounding residents compose the external environmental indexes. From the health, safety and pollution to the environment, the scheme which has a minimal-impact on safety and the environment pollution is the best choice; Floor area is as small as possible, reducing the use of land resources; The interference on surrounding residents problem such as the use of water resources, the scheme with little affect is more suitable.

From the above mentioned, the index system has been established as figure 1.

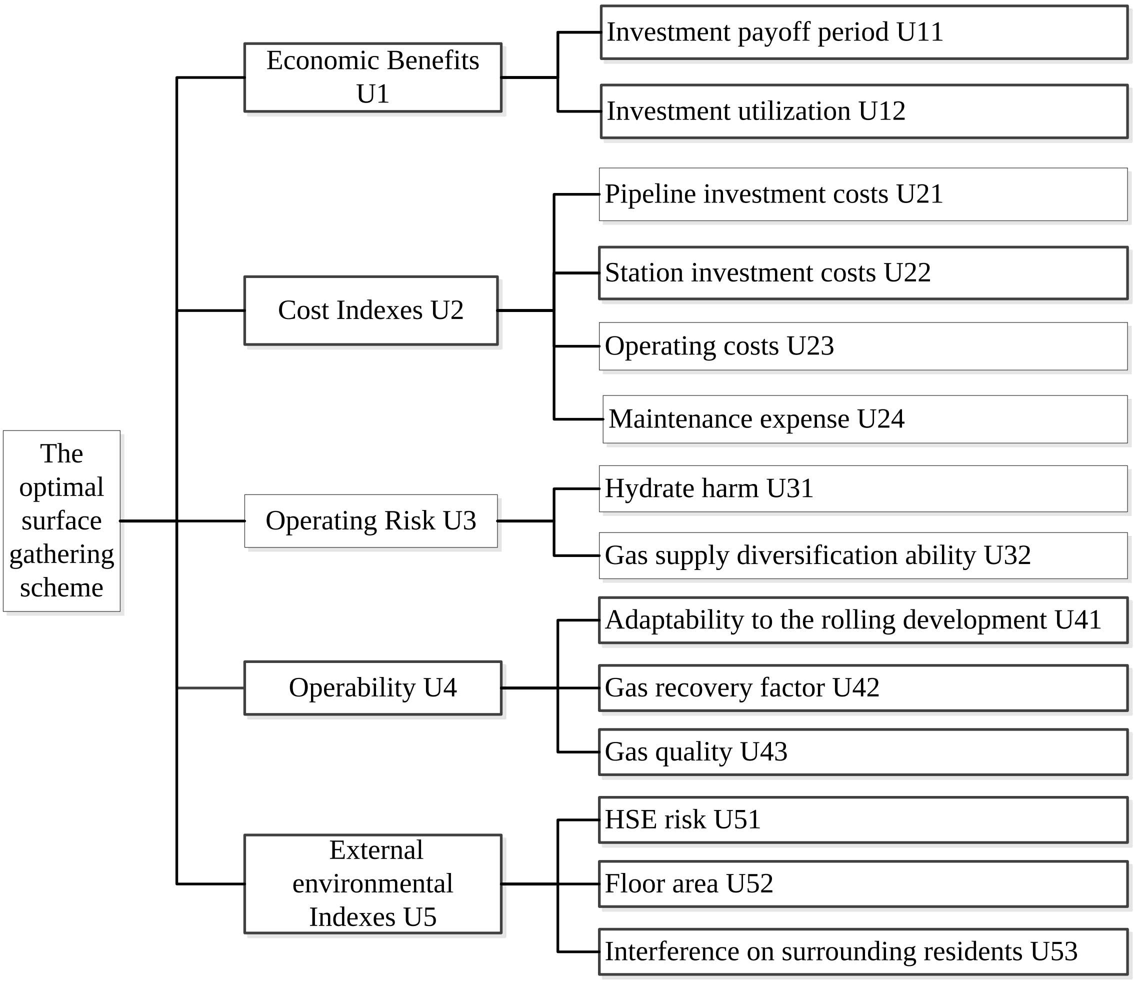

Fig.1 Multi-hierarchy evaluation index system

3. Multi-hierarchy fuzzy comprehensive evaluation model

Multi-hierarchy fuzzy comprehensive evaluation method refers to that established evaluation index system is divided into class hierarchy, then calculating weights with analytic hierarchy process. What's more, using hierarchical fuzzy comprehensive evaluation for each solution, finally the optimal solution is chosen according to the evaluate results. The specific steps of comprehensive evaluation [10] as follows:

(1)Establishment of evaluation factors set

Evaluation index mainly comes from the main criterion and sub-criterion layer, so that the main criterion layer set of each index is expressed as $U=\{U_1,U_2,\ldots,U_m\}$, which $U_i(i=1,2,\ldots,m)$ refers to the ith index of subset. Under each index subset U_i, there are j more detailed indicators, expressed as the $U_i=\{U_{i1}, U_{i2},\ldots, U_{ij}\}$.

(2)Weights Calculation

1) Construct judgment matrix

After building hierarchical analysis model, each layer of index are compared pairwise to construct judgment matrix. This paper generally chooses 1-9 scaling method for quantitating the comparison results, as shown in Table 1.

Table 1 The scale and definition of judgment matrix

Importance level	Value $C_{ij}= i/j$
Index i is of the same importance as j	1
Index i is slightly more important than j	3
Index i is significantly more important than j	5
Index i is much more important than j	7
Index i is extremely more important than j	9
Intermediate values of importance	2、4、6、8
C_{ij} is the ratio between i and j, Cij= 1/ Cji	Cut down

2) Calculate the product of elements in judgement matrix's each line Mi

$$M_i = \prod_{j=1}^{n} a_{ij}, (i = 1, 2, \cdots, n) \tag{1}$$

Where Mi denotes the product of matrix element of each line; a_{ij} is the elements of matrix in the ith line and the jth column; n refers to the order of matrix.

3) Calculate n root mean square of Mi

$$\overline{W_i} = \sqrt[n]{M_i} \tag{2}$$

4) Normalization processing

$$W_i = \frac{\overline{W_i}}{\sum_{j=1}^{n} \overline{W_j}} \tag{3}$$

Then the desired feature vector is W=[W1,W2,…,Wn]T.

5) The consistency check of judgment matrix

Introduce the random consistency ratio CR as the consistency inspection standard.

$$CR=CI/RI \tag{4}$$

Where CI is the negative average value of remaining characteristic root; RI is the mean random consistency index. When CR is less than 0.10, paper regards that the judgment matrix is satisfied with consistency. Otherwise judgment matrix will be adjust to make it has satisfactory consistency.

(4) First-hierarchy evaluation

1) Establish evaluation set

Evaluation set is expressed as V={V1,V2,…,Vp}, and Vs(s=1,2,…,p) shows the sth possible corresponding evaluation scores. In a word, evaluation set V is the evaluation of factor set U.

2) Build weight index set

The calculated weights using the analytic hierarchy process (ahp) are summed up a set, expressed by Wi=(wi1, wi2,…, wij).

3) Establish single factor fuzzy evaluation matrixes

The sub-criterion layers are judged according to the evaluation index set, and it is concluded that each evaluation index's membership degree rijk of each evaluation index Uij For comprehensive evaluation [11,12]. As a result, the first-hierarchy fuzzy evaluation matrix Ri can be determined.

$$R_i = \left\{ \begin{matrix} r_{i11} & \cdots & r_{i1p} \\ \vdots & & \vdots \\ r_{in1} & \cdots & r_{inp} \end{matrix} \right\} \tag{5}$$

Where rijp is the membership degree of the ith line and the jth column element relative to the pth element of evaluation set.

4) Comprehensive evaluation vector Bi is achieve by using the synthesis of the fuzzy matrix operation.

$$B_i = W_i \circ R_i = (b_{i1}, b_{i2}, \cdots, b_{in}) \tag{6}$$

(5) Second-hierarchy evaluation

As the first-hierarchy single factor evaluation, Bi is became a row vector, to build the fuzzy evaluation membership degree between evaluation set V and factor set U. That is the secondary fuzzy evaluation matrix R.

$$R = \begin{pmatrix} \underset{\sim}{B}_1 \\ \underset{\sim}{B}_2 \\ \vdots \\ \underset{\sim}{B}_m \end{pmatrix} = \begin{pmatrix} W_1 \circ R_1 \\ W_2 \circ R_2 \\ \vdots \\ W_m \circ R_m \end{pmatrix} \tag{7}$$

Where Bm indicates the mth first-hierarchy comprehensive evaluation vector; Wm denotes the mth weight vector; Rm is the mth first-hierarchy fuzzy evaluation matrix.

Hence, secondary-hierarchy comprehensive evaluation vector is received.

$$B = W \circ R = (b_1, b_2, \cdots, b_n) \tag{8}$$

Where *W* is the weight vector of criterion layer.

(6) The final comprehensive evaluation results

Finally, according to the grades of each evaluation grade and fuzzy comprehensive evaluation results, comprehensive evaluation score of each scheme is achieved.

$$Z = \sum B_s \cdot V_s \tag{9}$$

Where Bs indicates the sth element of secondary-hierarchy comprehensive evaluation vector; Vs is the score of the sth comment in evaluation set. The scheme whose score is the highest is the optimal solution.

4. Case study

4.1 Case description

The shale gas field located in Sichuan province, covers an area of about 4000 km^2, mostly mountainous hilly and valley topography, and the distribution of the hills is the most. The output gas of the shale gas field contains about 89% CH_4, 0.40% CO_2 and a small amount of water and gas condensate, excluding H_2S. Bottom hole pressure is commonly 75 M pa and temperature is 110 ℃; Its largest gas production can reach 170000 Sm^3/d, the smallest gas production is 10000 Sm^3/d.

4.2 Scenario Generation

Due to the different schemes of shale gas, oil, gas and water treatment and position are also different [13]. Through objective analysis and comparison, 5 set of alternatives options are proposed. The first is well site processing scheme, the second is scattered gas gathering system station processing scheme, the third is central treatment station scheme, the forth is well site-gas gathering system station processing scheme, the fifth is gas gathering system station-central treatment station scheme.

4.3 Evaluation Results

According to 1-9 scaling method, the judgment matrix U of criterion layer is showed as Table 2.

Table 2 Judgment matrix U of criterion layer

j *i*	Economic Benefits	Cost Indexes	Operating Risk	Operability	External environmental Indexes
Economic Benefits	1	1/3	3	5	7

Cost Indexes	3	1	5	7	9
Operating Risk	1/3	1/5	1	3	5
Operability	1/5	1/7	1/3	1	3
External environmental Indexes	1/7	1/9	1/5	1/3	1

The feature vector W=[0.2638,0.5101,0.1296,0.0636,0.0329]T, $\lambda_{\max}$ =5.2370, CR=0.0528<0.10. Similarly, Calculation result of the index layer can be obtained and showed as Table 3-7.

Table 3 Judgment matrix U1 of index layer

j *i*	Investment payoff period	Investment utilization
Investment payoff period	1	3
Investment utilization	1/3	1

The feature vector W1=[0.75,0.25]T, $\lambda_{\max}$ =2, CR=0<0.10.

Table 4 Judgment matrix U2 of index layer

j *i*	Pipeline investment costs	Station investment costs	Operating costs	Maintenance expense
Pipeline investment costs	1	1/3	5	3
Station investment costs	3	1	7	5
Operating costs	1/5	1/7	1	1/3
Maintenance expense	1/3	1/5	3	1

The feature vector W2=[0.2634,0.5638,0.0550,0.1178]T , $\lambda_{\max}$ =4.1170, CR=0.043<0.10.

Table 5 Judgment matrix U3 of index layer

j *i*	Hydrate harm	Gas supply diversification ability
Hydrate harm	1	7
Gas supply diversification ability	1/7	1

The feature vector W3=[0.8750,0.1250]T , $\lambda_{\max}$ =2, CR=0<0.10.

Table 6 Judgment matrix U4 of index layer

j *i*	Adaptability to the rolling development	Gas recovery factor	Gas quality
Adaptability to the rolling development	1	3	5
Gas recovery factor	1/3	1	3
Gas quality	1/5	1/3	1

The feature vector W4=[0.6370,0.2583,0.1047]T , $\lambda_{\max}$ =3.0385, CR=0.033<0.10.

Table 7 Judgment matrix U5 of index layer

j *i*	HSE risk	Floor area	Interference on surrounding residents
HSE risk	1	3	5
Floor area	1/3	1	3
Interference on surrounding residents	1/5	1/3	1

The feature vector W5=[0.6370,0.2583,0.1047]T , $\lambda_{\max}$ =3.0385, CR=0.033<0.10.

Then the total order of all indexes is showed in table 8.

Table 8 Total order of all indexes

Criterion layer		Index layer		Total order
Economic Benefits	0.2638	Investment payoff period	0.75	0.1978
		Investment utilization	0.25	0.066
Cost Indexes	0.5101	Pipeline investment costs	0.2634	0.1344
		Station investment costs	0.5638	0.2876
		Operating costs	0.0550	0.0280
		Maintenance expense	0.1178	0.0601
Operating Risk	0.1296	Hydrate harm	0.8750	0.1134
		Gas supply diversification ability	0.1250	0.0162
Operability	0.0636	Adaptability to the rolling development	0.6370	0.0405
		Gas recovery factor	0.2583	0.0164
		Gas quality	0.1047	0.0067
External environmental Indexes	0.0329	HSE risk	0.6370	0.0210
		Floor area	0.2583	0.0085
		Interference on surrounding residents	0.1047	0.0034

For scheme 1, selecting evaluation set $V=\{V_1,V_2,V_3,V_4\}$ = (excellent, good, medium, bad), which can be expressed as 95,85,75 and 65 with centesimal system, as 0.30,0.27,0.23,0.20 with normalized processing. Expert panel is composed of several experts, using the established index system to evaluate the scheme 1, then normalized processing and membership degree matrix is obtained as follows:

$$R_1=\begin{pmatrix}0.1 & 0.7 & 0.2 & 0\\ 0.2 & 0.6 & 0.2 & 0\end{pmatrix},\quad R_2=\begin{pmatrix}0.6 & 0.3 & 0.1 & 0\\ 0.1 & 0.8 & 0.1 & 0\\ 0 & 0.2 & 0.6 & 0.2\\ 0 & 0.1 & 0.8 & 0.1\end{pmatrix},\quad R_3=\begin{pmatrix}0 & 0 & 0.3 & 0.7\\ 0 & 0 & 0.2 & 0.8\end{pmatrix},$$

$$R_4 = \begin{pmatrix} 0.1 & 0.2 & 0.6 & 0.1 \\ 0.1 & 0.1 & 0.8 & 0 \\ 0 & 0.1 & 0.9 & 0 \end{pmatrix}, \quad R_5 = \begin{pmatrix} 0.1 & 0.6 & 0.3 & 0 \\ 0.2 & 0.7 & 0.1 & 0 \\ 0.1 & 0.3 & 0.6 & 0 \end{pmatrix}.$$

Similarly, through the first- hierarchy and secondary-hierarchy evaluation, comprehensive evaluation scores of five schemes are calculated in Table 9.

Table 9 Comprehensive evaluation scores of schemes

Scheme	Scheme 1	Scheme 2	Scheme 3	Scheme 4	Scheme 5
comprehensive evaluation score	0.257	0.279	0.253	0.264	0.270
Rank	4	1	5	3	2

In Table 9 are listed the evaluation results obtained. As can be seen, scheme 2 that the scattered gas gathering system station processing is the optimum scheme. The principle work flow is that the output gas from well site through the three-phase mixing transportation is processed in the scattered gas gathering system station. Through three-phase separator, the moisture will be saled from the pipeline after teg dehydration. Isolated water is transported by tank storage or pumping to the central treatment station. Condensate is dehydrated and stable processing firstly and stable condensate will produce a small amount of gas and water. Flash gas mixed with moisture is pumped to the pipeline sale after dehydration and stored.

5. Conclusion

(1) When carrying on the comprehensive evaluation to determine the evaluation index good or bad, it tends to produce a great impact on the final evaluation results. Thus establishing the indicators should possess these characteristics that is representativeness, diversity, feasibility, simple and independence. What’s more, indexes are needed to be chosen according to the characteristics of the research object, for guarantying the quality of indicators.

(2) Using the analytic hierarchy process to determine the weight of each indicator should be carried out step by step. Firstly, it should construct judgment matrix, after hierarchical single rank and testing the consistency of judgement matrix, finally hierarchy total rank is obtained. Multi-hierarchy fuzzy comprehensive evaluation is based on the analytic hierarchy process to calculate the weight, and then to carry out the scheme evaluation. Through first-hierarchy evaluation and secondary- hierarchy evaluation, it is concluded that which has the highest comprehensive evaluation score is the optimal solution.

(3) With a domestic shale gas field as an example, scheme 2 that the scattered gas gathering system station processing is selected to be the optimum scheme of shale gas surface gathering system eventually. Due to the mountainous hilly region and more dispersed well site location, using wellsite processing scheme will consume a large amount of money. Central treatment station scheme with the long distance pipeline wastes quantities of shale gas production capacity and enhances security risk. As a result, the scattered gas gathering system station processing is relatively suitable shale gas gathering system, which confirm the validity of the results by quantitative analysis.

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