Data Driven Model of Gas Well Integrity and Its Application

Jiangling Hong1, Hongjie Zhang1, Jiaqi Wang2, Jinbo Liu1, Honglei Liu1, Chaodong Tan1*, Pengkun Hou1 and Wenrong Song3

1 No.1 gas production plant of Xinjiang Oilfield Branch of CNPC, Xinjiang, 834000, China
2 China University of Petroleum (Beijing), Beijing 102249
3 Beijing Yadan Petroleum Technology Development Co., Ltd., Beijing 102200, China

*Corresponding author email: tanchaodong@cup.edu.cn

Abstract. In view of the problems that there are many well control risk points and the situation is grim of Xinjiang No.1 gas production plant, this paper carries out the gas well integrity evaluation and risk assessment, and establishes the comprehensive fuzzy evaluation model (FCEM) of gas well integrity. This paper analysed the integrity status of gas wells in Xinjiang No.1 gas production plant, establishes the integrity evaluation index system with well barrier components, real-time dynamic index and management organization as the main influence factors, determines the membership function of each index, calculates the weight of each index by using analytic hierarchy process (AHP), and establishes the risk degree calculation model by using fuzzy comprehensive evaluation. Quantitative analysis of gas well integrity. In this paper, a case study of a well in Xinjiang No.1 gas production plant shows that the model can quantitatively calculate the risk of gas well integrity and provide a reference for early warning of gas well integrity failure.

Keyword: Gas well integrity; Well barrier; Evaluation index system; Analytic hierarchy process; Fuzzy evaluation method.

1. Introduction

Gas production plant No.1 of Xinjiang Oilfield has developed 4 gas fields and 18 gas reservoirs with a total of 190 gas wells. Among them, Kelameili gas field has been developed for 10 years, and PEN5 for 20 years. 84 wells have integrity problems, among which 15 cases of gas well barrier failure occurred from 2015 to 2018. Due to the lack of gas well integrity evaluation technology and supporting technical specifications, it is difficult to provide decision-making basis for gas well production and workover operation. Scholars have done lots of research on gas well integrity risk assessment. Dethlefs et al. [1] carried out risk assessment by establishing quantitative model of wellbore integrity risk level. Li Jun et al. [2] established risk score table based on AHP, and finally established the gas well integrity evaluation model. Sun Li et al. [3] completed the establishment of integrity evaluation system in view of the unclear concept of gas well integrity; Wang Tao et al. [4] studied the influence factors of integrity failure of oil and gas wells, and completed the quantitative analysis of integrity of oil and gas wells from the aspects of leakage analysis and risk level determination. Zhang Shaohui et al. [5] divided the wellbore integrity evaluation of CO2 flooding injection wells into wellhead, string and wellbore three units, established the wellbore integrity risk evaluation model by using the risk matrix method. He Yu et al. [6] divided the wellbore integrity risk factors into risk design factors and barrier factors, and established the wellbore design coefficient and wellbore barrier risk assessment model respectively. The above research has a
good effect on the risk assessment of gas well integrity, but there are still some problems such as strong subjectivity, complex calculation and incomplete risk factors. This paper establishes a reasonable evaluation index system and membership function of the influence factors, calculates the weight of the influence factors through AHP, changes the qualitative problems into quantitative problems, and carry out risk evaluation on all the influence factors, so as to achieve early warning and timely management.

2. Establishment of Gas Well Integrity Evaluation System in Xinjiang No.1 Gas Production Plant

2.1. Analysis of Well Integrity Status in Xinjiang No.1 Gas Production Plant

According to the dynamic and static data of 191 wells in No.1 gas production plant, the integrity failure of gas wells was found. The main types of well barrier failure were wellbore (47 wells) (corrosion perforation, damaged oil and casing, string falling off, casing deformation, safety valve failure, etc.), wellhead (13 wells) (leakage, wellhead freezing, wellhead device missing, leakage, etc.), well head subsidence, etc. and annulus pressure (42 wells).

There is gas well integrity problems in all blocks, and there are 58 wells in Kelameili gas field, accounting for 44%. Eight out of 10 wells in Mahe gas field have integrity problems, up to 80%. (As shown in Table 1)

Table 1. Statistics of integrity failure of each block in No.1 gas production plant.

| Block     | Total NO. of wells | NO. of wells with failure problems | Proportion of total investment (％) |
|-----------|--------------------|-----------------------------------|-----------------------------------|
| Ke75      | 30                 | 12                                | 40                                |
| Kelameili | 131                | 58                                | 44                                |
| Mahe      | 10                 | 8                                 | 80                                |
| Pen5      | 20                 | 7                                 | 35                                |
| Total     | 191                | 84                                |                                    |

According to the statistics and collation of the problems, the problems are mainly divided into three aspects: Well barrier components, real-time dynamic indicators and management organization.

2.1.1. Well barrier components. Barrier equipment is an important index affecting the integrity of gas wells. For No.1 gas production plant, the main components affecting the integrity are christmas tree and wellbore.

(1) Christmas tree
The problem of christmas tree in Xinjiang No.1 gas production plant accounts for 56% of the failed wells.

(2) Wellbore
The main failure of wellbore integrity in No.1 gas production plant is internal leakage of safety valve and casing leakage. Ten wells in the well barrier have the problem of safety valve failure, mainly in the form of internal leakage of safety valve. In well Ke77, DX1824 and PEN5, there are casing leakage problems. The main influence factors of casing leakage are internal pressure resistance and external collapse strength of casing. Therefore, the main consideration for the leakage problem is the thread connection ability of oil casing and cement sheath return height.

2.1.2. Real time dynamic data. When the gas well barrier is complete, the annulus and the tubing are independent. Once the safety barrier element fails and leakage occurs, the annulus and the tubing are connected, and the gas parameters in the annulus will change. Therefore, by monitoring the annulus pressure, gas composition and other parameters under the production state, the integrity state of the well can be identified.

(1) Annular pressure
The statistics of annular pressure in No.1 gas production plant are given in table 2.
Table 2. Annular pressure statistics of oil technology casing.

| Classification            | Annular pressure>0 | Annular pressure= 0 | No meter  | Unable to read | total |
|---------------------------|--------------------|---------------------|-----------|----------------|-------|
| NO. of wells              | 34                 | 80                  | 42        | 19             | 175   |
| Proportion (%)            | 19.4               | 45.7                | 24        | 10.9           | 100%  |

The problem of annular pressure is serious. When the annular pressure is too high, it will cause casing, tubing rupture and even blowout, which seriously threatens the safety of gas well.

(2) Gas composition
When CO₂ is dissolved in water, its corrosion to steel is more serious than hydrochloric acid at the same pH value. There are corrosion problems in well P5004, P5007 and well PEN5, and many parts of some devices have abnormal wall thickness.

2.1.3. Organization and management. For gas wells, organization and management mainly includes management system, construction specification and emergency measures. In No.1 gas production plant, some wells have carried out gas well integrity management research. However, most wells are shut in for maintenance only after the well barrier fails. Therefore, the establishment of a reasonable organization and management system is also important. According to the above analysis, for the gas well integrity evaluation index system, three aspects of well barrier components, real-time performance index and management organization should be established as the first level index, and reasonable second level index should be established for different failure problems. (As shown in Figure 1)

![Figure 1](image)

2.2. Establishment of Gas Well Integrity Evaluation Index System
Through the analysis of 2.1, the evaluation index system of gas well integrity is shown in figure 1.

3. Comprehensive Fuzzy Evaluation Model of Gas Well Integrity
The fuzzy comprehensive evaluation method establishes the gas well integrity evaluation index system according to the evaluation target and the actual field data, as shown in Figure 1; Then, the core idea of AHP[7] is used to determine the weight of each evaluation factor; The membership function of each index is constructed, and finally the evaluation matrix is generated, and the risk degree is calculated by the risk degree calculation model.
3.1. Determination of Membership Function

Membership function is a mathematical tool for representing fuzzy sets[8].

(1) Thread connection strength

The sealing performance is mainly reflected in the thread connection strength[9]. Controlling the pressure at the minimum thread connection strength can effectively prevent the sealing performance failure, and its membership function is as follows:

\[
R_1 = \begin{cases} 
\frac{P_f}{\mu P_j} & P_f < \mu P_j \\
1 & P_f > \mu P_j
\end{cases}
\]  

(1)

Where \(P_f\) is the tensile strength of the coupling, MPa; \(P_j\) is thread connection strength, MPa; \(\mu\) is the safety factor of casing strength, taken as 0.95.

(2) Performance of christmas tree

\[
R_2 = \begin{cases} 
1 & \text{There is a problem with the Christmas tree} \\
0 & \text{christmas tree works normally}
\end{cases}
\]  

(2)

(3) Tubing collapse strength

When the external extrusion force of oil casing is greater than the carrying extrusion strength of oil casing, the casing will be damaged and damaged to a certain extent[10]. The membership function is as follows:

\[
R_3 = \begin{cases} 
\frac{\sigma_c}{\sigma_b} & \sigma_c < \sigma_b \\
1 & \sigma_c > \sigma_b
\end{cases}
\]  

(3)

Where \(\sigma_b\) is the carrying strength of oil casing; \(\sigma_c\) is the external extrusion forces on oil casing.

(4) Cement sheath return height

The return height of cement sheath has a great influence on the cementing quality of gas wells. The return height should be higher than the fixed sealing height, and it will damage the cementing quality and affect the wellbore integrity when it is lower than the fixed sealing height.

\[
R_4 = \frac{h_y - h_f}{h_y}
\]  

(4)

Where \(h_y\) is the height of solid sealing section, which is the height of cement sheath return height; \(h_f\) to the actual cement sheath height.

(5) Annular pressure

When the annular pressure is too high, it will lead to casing fracture or even blowout[11]. Its membership function is as follows:

\[
R_5 = \begin{cases} 
\frac{P_a}{P_w} & P_a < P_w \\
1 & P_a > P_w
\end{cases}
\]  

(5)

Where \(P_a\) is the real-time annulus pressure value; \(P_w\) is the maximum allowable annular pressure.

(6) CO\(_2\) partial pressure

Scholars believe CO\(_2\) partial pressure is one of the main factors to control corrosion[12].

\[
R_6 = \begin{cases} 
1 & \text{CO}_2\text{partial pressure} > 2.07 \times 10^{-1}\text{MPa} \\
\text{CO}_2\text{partial pressure} < 2.07 \times 10^{-1}\text{MPa} & \text{0MPa} < \text{CO}_2\text{partial pressure} < 2.07 \times 10^{-1}\text{MPa} \\
0\text{MPa} & \text{CO}_2\text{partial pressure} = 0\text{MPa}
\end{cases}
\]  

(6)

(7) Oil pressure

When oil pressure is high, the residual strength of oil casing string and other components decreases.

\[
R_7 = \begin{cases} 
\frac{P_o}{\mu P_f} & P_o < \mu P_{kf} \\
1 & P_o \geq \mu P_{kf}
\end{cases}
\]  

(7)
Where $P_o$ is the real-time oil pressure, $P_{kf}$ is the casing braking pressure, $\mu$ the fracture pressure coefficient of casing is 0.95.

Wellbore temperature

When the temperature is too high, it may cause tubing leakage. The membership function is as follows:

$$R_B = \begin{cases} 
1 - \sin\left(\frac{\pi}{40}(T - 60)\right) & T > 60 \degree C \\
0 & 0 \degree C < T < 60 \degree C \\
0 & T < 0 \degree C 
\end{cases}$$  \hspace{1cm} (8)

Management system

For the three secondary evaluation indexes of the management system, when the piecewise function is established, the value is 0 when the system is perfect, and 1 when the system is imperfect.

3.2. Determination of Gas Well Integrity Index Weight

In order to evaluate the integrity of gas well, it is necessary to transform the qualitative analysis of gas well into quantitative analysis, that is, to calculate the weight of each factor of the index according to AHP after establishing the index.

3.2.1. Establish judgment matrix

The hierarchical structure reflects the subordinate relationship, but the importance of the next level elements dominated by the same element is not the same, so the scaling method is used to compare the factors (Table 3).

| Rating degree | Meaning                          |
|---------------|----------------------------------|
| 1             | A is as important as B           |
| 3             | A is slightly more important than B |
| 5             | A is more important than B       |
| 7             | A is strong more important than B |
| 9             | A is Extremely more important than B |
| 2, 4, 6, 8    | The median value of the above values |
| Reciprocal    | Let $b_{ij}$ be the ratio of elements t, $b_{ij} = 1/t$ |

3.2.2. Hierarchical single criteria sorting

Single criteria ranking is divided into two parts: weight determination and consistency test.

(1) Weight determination.

a. Product. The index scores of each row in the matrix are multiplied.

$$M_i = \sum_{j=1}^{n} a_{ij} \hspace{1cm} i = 1, 2, ..., n$$  \hspace{1cm} (9)

b. Square root. Calculate the n-th root of $M_i$.

$$\overline{M_i} = \sqrt[n]{M_i} \hspace{1cm} i = 1, 2, ..., n$$  \hspace{1cm} (10)

c. Normalization. Vector $\overline{M}_i = (\overline{M}_1, \overline{M}_2, ..., \overline{M}_n)$ Normalization.

$$W_i = \frac{\overline{M}_i}{\sum_{i=1}^{n} \overline{M}_i}$$  \hspace{1cm} (11)

(2) Consistency test

Because of the error, in order to judge whether the constructed judgment matrix and weight are reasonable, consistency test is needed. The test formula is as follows.

a. Maximum eigenvalue $\lambda_{\text{max}}$

$$\lambda_{\text{max}} = \frac{1}{n} \sum_{i=1}^{n} \frac{(AW)_i}{W_i}$$  \hspace{1cm} (12)

b. Consistency index C.I.
\[ C.I. = \frac{1}{n-1}(\lambda_{max} - n) \]  
\[ (13) \]

c. Consistency ratio C.R.
\[ C.R. = \frac{C.I.}{R.I.} \]  
\[ (14) \]

The R.I. values (table 4) are as follows:

| Order | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|-------|---|---|---|---|---|---|---|---|---|
| R.I.  | 0.00 | 0.00 | 0.52 | 0.89 | 1.12 | 1.26 | 1.36 | 1.41 | 1.46 |

When C.R.<0.1, the judgment matrix meets the consistency, and the weight of each index is the calculation result; When C.R. ≥ 0.1, the judgment matrix needs to be adjusted to recalculate.

3.2.3. Weight calculation results
(1) First order judgment matrix
Combined with the actual production and expert scoring method, the importance matrix and weight (table 5) are calculated.

| Gas well barrier components | Dynamic data | Organization management |
|-----------------------------|--------------|-------------------------|
| Gas well barrier components | 1            | 1/2                     | 2                        | 0.30 |
| Dynamic data                | 2            | 1                       | 3                        | 0.54 |
| Organization management     | 1/2          | 1/3                     | 1                        | 0.16 |

\[ \lambda_{max} = 3.01, CI = 0.003, RI = 0.58, CR = 0.005 < 0.1 \]

(2) Three level index judgment matrix
A. Judgment matrix of various factors of gas well barrier components (table 6).

| Performance of christmas tree | Thread connection strength | Casing collapse strength | Cement sheath return height | W     |
|-------------------------------|---------------------------|-------------------------|-----------------------------|-------|
| Performance of christmas tree | 1                          | 2                       | 1/3                         | 1/4   | 0.12 |
| Thread connection strength    | 1/2                        | 1                       | 1/5                         | 1/8   | 0.062|
| Casing collapse strength      | 3                          | 5                       | 1                           | 1     | 0.37 |
| Cement sheath return height   | 4                          | 8                       | 1                           | 1     | 0.448|

\[ \lambda_{max} = 4.02, CI = 0.006, RI = 0.89, CR = 0.067 < 0.1 \]

B. Judgment matrix of factors in real time dynamic data (table 7)

| Temperature | CO2 partial pressure | Annular pressure | Oil pressure | W     |
|-------------|----------------------|------------------|--------------|-------|
| Temperature | 1                    | 1/2              | 1/3          | 1     | 0.1398|
| CO2 partial pressure | 2             | 1                | 1/2          | 3     | 0.2974|
| Annular pressure  | 3             | 2                | 1             | 2     | 0.4161|
| Oil pressure     | 1                   | 1/3              | 1/2           | 1     | 0.1467|

\[ \lambda_{max} = 4.1036, CI = 0.0345, RI = 0.89, CR = 0.039 < 0.1 \]

C. Judgment matrix of organization and management factors (table 8)

| Management system | Construction specification | Emergency measure | W   |
|-------------------|----------------------------|-------------------|-----|
| Management system | 1                          | 1                 | 1/2 | 0.25 |
| Construction specification | 1                   | 1                 | 1/2 | 0.25 |
| Emergency measure | 2                          | 2                 | 1   | 0.5  |

\[ \lambda_{max} = 3, CI = 0, RI = 0.52, CR = 0 < 0.1 \]
(3) Weight of each factor

Through the calculation of (1) and (2), the calculation results of each factor judgment matrix are summarized, and the weight distribution table of each factor is obtained. (Table 9)

**Table 9.** Weight distribution of each factor.

| Factor                          | Weight Distribution |
|---------------------------------|---------------------|
| Gas well barrier components     | 0.30                |
| Performance of christmas tree   | 0.12                |
| Thread connection strength      | 0.062               |
| Casing collapse strength        | 0.37                |
| Cement sheath return height     | 0.448               |
| Dynamic data                    | 0.54                |
| Temperature                     | 0.1398              |
| CO₂ partial pressure            | 0.2974              |
| Annular pressure                | 0.4161              |
| Oil pressure                    | 0.1467              |
| Organizational management       | 0.16                |
| Management system               | 0.25                |
| Construction specification      | 0.25                |
| Emergency measure               | 0.5                 |

3.3. Calculation Model of Risk Degree

Based on AHP, the weight value of the feature vector of the monitoring index is obtained.

\[ A = [a_1, a_2, ..., a_{12}] \]  

(15)

Based on the membership function of each influence factor, the membership matrix is obtained as follows:

\[ R = \begin{bmatrix} R_{1,1} & R_{1,2} & \cdots & R_{1,n} \\ R_{2,1} & R_{2,2} & \cdots & R_{2,n} \\ \vdots & \vdots & \ddots & \vdots \\ R_{n,1} & R_{n,2} & \cdots & R_{n,n} \end{bmatrix} \]  

(16)

By multiplying the membership matrix R and the judgment matrix A, the warning index B of the objective function is obtained.

\[ V = A \cdot R = [a_1, a_2, ..., a_{12}] \cdot \begin{bmatrix} R_{1,1} & R_{1,2} & \cdots & R_{1,n} \\ R_{2,1} & R_{2,2} & \cdots & R_{2,n} \\ \vdots & \vdots & \ddots & \vdots \\ R_{n,1} & R_{n,2} & \cdots & R_{n,n} \end{bmatrix} = [b_1, b_2, ..., b_n] \]  

(17)

Where V is risk degree, and the relationship between risk range and risk is shown in table 10.

**Table 10.** Risk classification.

| Risk evaluation | Corresponding range |
|-----------------|---------------------|
| Very high       | 0.9 ≤ 𝜈₁ < 1       |
| High            | 0.7 ≤ 𝜈₁ < 0.9     |
| Commonly        | 0.5 ≤ 𝜈₁ < 0.7     |
| Low             | 0.3 ≤ 𝜈₁ < 0.5     |
| Very low        | 0.1 ≤ 𝜈₁ < 0.3     |

4. Case Study

Select a well for function verification. The well was put into production in October 2008 and has been overhauled once due to integrity failure. The tubing steel grade is P105, tubing collapse strength is 96.6mpa, casing steel grade is J55 and P110, internal pressure strength is 59.9mpa and 76.4mpa respectively. According to the calculation, the maximum annular pressure value is 42MPa, thread connection strength is 70MPa, cementing quality is good, cement sheath returns to the ground, christmas tree performance is good up to now, management system is perfect, dynamic data of overhaul day is shown in table 11.

**Table 11.** Dynamic data table.

| Tensile force (MPa) | External extrusion force (MPa) | CO₂ partial pressure(MPa) | Annular pressure(MPa) | Oil pressure(MPa) | Temperature (℃) |
|---------------------|-------------------------------|---------------------------|-----------------------|------------------|-----------------|
| 17.3                | 35                            | 6.7 × 10²                 | 37                    | 36.5             | 55              |
Using the membership function of each factor, the membership matrix $R$ is obtained:

$$R = \begin{bmatrix}
0 & 0.1757 & 0.4581 & 0.3237 & 0.2602 & 0.3623 & 0.22 & 0.7237 & 0.8286 & 0 & 0
\end{bmatrix}^T$$

According to 2.3 weight calculation results, the weight value of each factor is as follows:

$$W = \begin{bmatrix}
0.036 & 0.0186 & 0.111 & 0.1344 & 0.0755 & 0.1606 & 0.2247 & 0.0792 & 0.04 & 0.04 & 0.08
\end{bmatrix}$$

The final fuzzy evaluation value is obtained by calculation:

$$B = R \times W = 0.8962$$

The fuzzy evaluation value of the integrity of the gas well is 0.8962, which is near 0.9. According to table 10, the risk evaluation of the well is high, so in the actual production, there is a high probability that the well has integrity problems, and the well integrity may have failed. The results are consistent with the actual production results.

5. Conclusion

1. The gas well is divided into evaluation units for integrity evaluation, and the well barrier components, real-time dynamic indicators and organization management are determined as evaluation elements. The membership function is used to quantify each element, and AHP is introduced to determine the weight of each influence factor on integrity. Compared with the previous evaluation methods, the whole evaluation process is more comprehensive, more objective, and more operable, the influence of human factors on the evaluation results should be reduced as far as possible.

2. Combining AHP with FCER, the paper introduces the risk evaluation index and risk grade division of gas well integrity, establishes the gas well integrity risk evaluation method, and realizes the quantitative evaluation of gas well integrity risk. This method is helpful to reduce the risk of gas well integrity, and can provide the basis for formulating effective prevention and control technical countermeasures.

References

[1] Rocha-Valadez T, Hasan A R, Mannan S, et al. Assessing wellbore integrity in sustained-casing-pressure annulus[J]. SPE Drilling & Completion, 2014, 29(01): 131-138.

[2] Teasdale P, Keddie R, Fritsch J. Coiled Tubing Conveyed Expandable HP Patch-A Cost Effective Solution to Wellbore Integrity Problems[C]//SPE/IADC Middle East Drilling Technology Conference and Exhibition. Society of Petroleum Engineers, 2016.

[3] Sasser K N, Ford R T. A Three-Phase Approach to Mechanical Integrity[C]//ASSE Professional Development Conference and Exhibition. American Society of Safety Engineers, 1999

[4] Kang Y, Liu Z, Gonzales A, et al. Investigating the Influence of ESP on Wellbore Temperature, Pressure, Annular Pressure Buildup, and Wellbore Integrity[C]//SPE Deepwater Drilling and Completions Conference. Society of Petroleum Engineers, 2016.

[5] Zheng Youcheng, Zhang Guo, you Xiaobo, et al. Integrity and integrity management of oil and gas wells [J]. Drilling and production technology, 2008,31 (5): 6-9

[6] Sun Li, fan Jianchun, sun Yuting, et al. Preliminary study on the concept and evaluation index of gas well integrity [J]. China safety production science and technology, 2015,11 (10): 79-84

[7] Wang Tao, Luo Chunhong, Shi Chunxia. Quantitative risk analysis of oil and gas well integrity [J]. Safety and environmental protection technology of petrochemical industry, 2016,32 (2):45-47

[8] T.L. Saaty, The Analytic Hierarchy Process, McGraw-Hill, New York, NY, USA.1980.

[9] Yuan Y (1991). "Criteria for evaluating fuzzy ranking methods". Elsevier North-Holland, Inc.

[10] Liu Baojun, Qiao Lihua, Xu Fengping. Study on casing string strength design method considering the safety of gas well life cycle [J]. Drilling and production technology, 2018,41 (06): 9-12 + 5

[11] He Hanping. Discussion on calculation method of allowable pressure value in oil and gas well annulus [J]. Drilling and production technology, 2018,41 (04): 16-18 + 6

[12] Wu Baoyu, Song Zhenyun, Chen Ping. Gas well wellbore CO2 Experimental Study on corrosion and scaling monitoring [J]. Drilling and production technology, 2021,44 (01): 77-81