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Life prediction method of fracturing manifold based on nonlinear dynamic risk assessment

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Abstract

Fracturing manifold is an indispensable equipment in acid fracturing operations in oil fields. As the depth of fracturing operations continues to increase, the manifold is prone to failure and damage, which reduces its service life and affects the safety of on-site operations. In view of the problem that the remaining life of the existing fracturing manifold is affected by uncertain factors and it is difficult to predict, a method of remaining life prediction based on risk assessment is proposed. Combine the analytic hierarchy process with the value function model to obtain the risk assessment value, and determine the relationship between the risk and the operating time of the manifold through the random fuzzy function of the risk index RI, and then establish the remaining life prediction model of the fracturing manifold based on the uncertainty theory , This model can more accurately assess the failure risk and remaining life of the fracturing manifold. The risk assessment of the monitoring data of the fracturing manifold after working for 150 hours shows that the overall risk of the manifold is at level II, and the remaining life expectancy is 448.18 hours. This research provides a reference basis for the risk assessment and life prediction of the fracturing manifold, and is of great significance for guiding the safety of the fracturing manifold on-site operation.

Keywords

Safety systematics；analytic hierarchy process; value function model; risk state evaluation;uncertainty theory;remaining life prediction.

1. Introduction

The extraction of unconventional oil and gas has attracted more and more attention in recent years as the demand for resources has increased. In order to produce unconventional oil and gas efficiently, large special equipment with complex structure and high cost is required in the fracturing process[1] The fracturing piping system has a significant role in ensuring that the high pressure is maintained. The fracture tubing sink system plays an important role in ensuring that high pressure fracturing fluid is pumped smoothly downhole to produce fractures. The system is subjected to high horsepower, large displacement and fluid-solid coupling impacts under the combined effect of the wellhead device and the transient output of all fracture pumps, leading to a number of serious failures, such as washout defects, stress corrosion and fatigue cracking[2] . Under the combined action of the internal high-pressure fluid and the external complex environment, these failures rapidly expand and extend to the outer surface, which can easily cause safety incidents such as tubing sink fractures and punctures, thus posing a threat to operators and equipment[3] This poses a threat to operators and equipment.

In order to ensure the safety of fracture manifold field operations, it is necessary to strengthen the evaluation of manifold failure risk and long-term remaining life prediction.[4] . At present, in terms of risk evaluation, 2018 years, Cai et al.[5] By dividing the spatial scale of the fracture piping sink system and using transfer entropy to find the causal relationship between risk

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variables, a risk scale inference model in the form of causal diagram is established to predict the risk propagation path of the piping sink. 2 019years, Zhang et al.[6] used historical failure data of fracture sink, specific parameters of condition indicators and expert judgment to build a hybrid Bayesian network model, thus reducing the uncertainty in risk assessment. Not surprisingly, the existing literature has limited research on the identification of risk-influencing factors and the interrelationships between various hazards affecting fracture manifold operations. In terms of remaining life prediction, today's research is mainly focused on aerospace and power coll[7-9] . In the field of oil pipeline equipment, less research has been conducted on the condition assessment and remaining life prediction of fracture manifolds.

Based on the failure mechanism and condition monitoring data of fracture manifold, this paper establishes a comprehensive evaluation method for risk state assessment and remaining life prediction of fracture manifold by using safety system theories such as hierarchical analysis, value function model, triangular fuzzy function and uncertainty theory. By evaluating the risk state of the fracture manifold system, a regular curve of the system risk state over time is formed, and the evaluation of equipment risk and remaining life prediction are completed.

2. Comprehensive assessment model for fracture sink life prediction

The safety performance of fracture sink operation is affected by several factors, and each factor has different degrees of influence on the remaining life of fracture sink. Under the constraints of technical conditions, environment and other factors, how to find out the evaluation factors and determine the degree of their influence on the risk performance of fracture manifold is the key to the prediction of remaining life of fracture manifold. By analyzing the failure mechanism of fracture sink to find out the typical failure failure, the failure type and real-time monitoring parameters are used as the evaluation index system, the hierarchical analysis method is introduced to determine the initial weights of the indexes, and a value function model is proposed to deal with the dynamic nonlinear index relationship between different levels, and the risk evaluation value is obtained by using the determined initial weights and value function; then the stochastic fuzzy function of the risk index RI is established to obtain The relationship between risk and piping sink operation time; finally, a prediction model of remaining life of fractured piping sink based on uncertainty theory is established. The flow of the integrated evaluation of the remaining life of fracture sink is shown in Figure 1 The flow of the integrated assessment of the remaining life of the fracture manifold is shown in the following table.

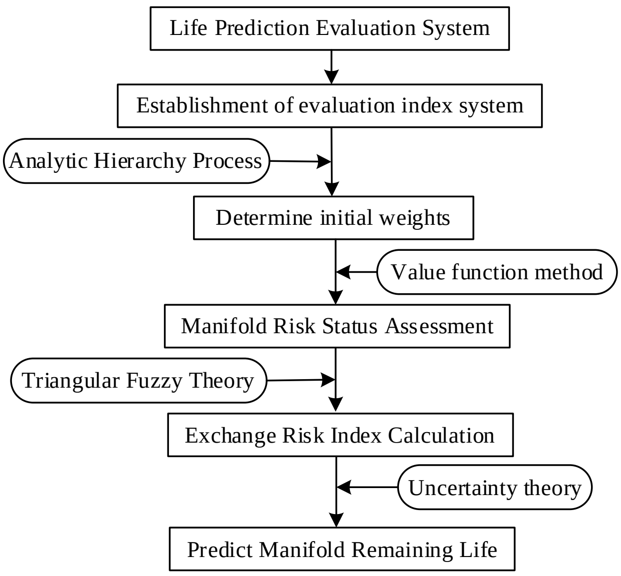

Figure1 Comprehensive evaluation process for remaining life of fracture manifold

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3. Fracture sink risk evaluation model

3.1. Frac sink evaluation index system

In order to fully reflect the operational risk status of fracture manifold, the analysis of fracture manifold failure mechanism based on condition data shows that vibration, cracking, erosion and corrosion are the key factors affecting the life of fracture manifold. Several studies have analyzed and demonstrated the inherent frequency of the sink[10] , erosion wear loss[11, 12] and corrosion fatigue limits[13] and corrosion fatigue limits as a function of real-time monitoring parameters pressure, displacement and sand content. The results of the appeal show that in most cases there is a non-linear relationship between the typical failure of the sink and the pressure, discharge, and sand content. However, the failure mechanism itself is not sufficient to reliably assess the overall safety of the fractured manifold, so a three-level indicator system is introduced, which is widely used in oil and gas extraction and transportation and can provide technical support for safety management[14] The three-level index system is widely used in the field of oil and gas extraction and transportation, and can provide technical support for safety management. Vibration, cracking, erosion and corrosion are used as primary indicators, and real-time monitoring parameters are used as secondary indicators. The evaluation indexes of vibration are pressure and discharge volume; the evaluation indexes of crack are pressure, discharge volume and service time; the evaluation indexes of erosion are pressure, sand content, erosion location and erosion size; and the evaluation indexes of corrosion are pressure, medium PH value, erosion location and erosion size. The evaluation index system of fracture pipe sink is shown in Table 1

.Table1 Fracture pipe sink evaluation index system

	Tier 1 Indicators	*Secondary indicators*
Fracturing Pipeline Sink Risk Assessment U	Vibration A_1	Pressure B_1
		Displacement B_2
	Crack A_2	Pressure B_3
		Displacement B_4
		Service Time B_5
	Erosion A_3	Pressure B_6
		Sand content B_7
		Erosion position B_8
		Erosion size B_9
	Corrosion A_4	Pressure B_{10}
		Medium PH value B_{11}
		Corrosion location B_{12}
		Corrosion size B_{13}

3.2. Calculate the initial weights of indicators

The initial weights of each indicator are determined by using hierarchical analysis W_i. Hierarchical analysis (*AHP*) quantifies the importance of each indicator based on experts' experience, and has the advantage that experts can find out the weights of each indicator for different criteria of the total objective U in a more reasonable way according to the actual situation[15] . Based on the real-time monitoring data of fracture pipe sink and experts' experience, the traditional 1-9 scaling method is used to establish a two-by-two comparison matrix of evaluation indicators, so as to quantitatively evaluate the state of fracture pipe sink, and then use the geometric mean method to solve the eigenvector corresponding to the maximum eigenvalue of the matrix, and the eigenvector is the initial weight of the indicators

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after the consistency test[16] After the consistency test, the eigenvectors are the initial weights of the indicators. The traditional 1 to 9 scaling method is shown in Table2. In order to verify whether the above matrix is reasonable, when the consistency ratio *C.R.* = *C.I./R.I.* < 0.1, the matrix is considered to pass the consistency test and is constructed reasonably. Where *C.I.* = (λ-n_{max})/(n-1) is the consistency index, λ_{max} is the maximum eigenvalue of the matrix and *n* is the number of elements, and *R.I.* is the random consistency index, whose value is shown in Table3 .

Table2 Scale "1 to 9" method

Difference in importance of two indicators	0～1	2 to 3	4～5	6～7	8～9
Comparative description of the importance of the two indicators	Equally important	Slightly more important	Obviously important	Strongly Important	Extremely important

Table3 Random consistency index

n	2	3	4	5	6	7	8	9	10
RI	0	0.515	0.893	1.119	1.249	1.345	1.42	1.462	1.487

3.3. System risk status assessment

In order to deal with the relationship of indicators between different levels and meet the needs of real-time monitoring and evaluation of fracture pipe sink, the value function model is used[17] The risk state assessment of the fracture piping sink system is performed to obtain the risk index *RI, which is* calculated as follows.

The value function is modeled and solved by the MIVES method, and the general expression of the value function v_i is

$$v_i = B_i \times \left[1 - e^{-K_i \times \left[\frac{|X - X_{\min}|}{C_i} \right]^{P_i}} \right] \tag{1}$$

where: *X* is the main variable, from $X_{\min}$to $X_{\max}$; P_i is the shape factor, containing linear, S-curve shaped, concave and convex shapes; $C_i$and K *are* $_i$approximated as the horizontal and vertical coordinates of the inflection point.Fig. 2 The range of values of $P_i$and K_i is shown. *B is the* factor that allows the function to remain in the range of values from 0 to 1. The factor is defined as

$$B_i = \left[1 - e^{-K_i \times \left[\frac{|X_{\max} - X_{\min}|}{C_i} \right]^{P_i}} \right]^{-1} \tag{2}$$

Due to the non-linear relationship between the primary and secondary indicators, linear weighting will produce large calculation errors and even lead to errors or mistakes in the results. Therefore, the value function is proposed to represent the nonlinear relationship, and the risk evaluation result RI_s of the secondary indicators is.

$$RI_s = \sum_{i=1}^{n} \omega_i^{II} \times v_i \tag{3}$$

Where: ω_i^{II} is the weight of secondary indicators and *n* is the number of corresponding secondary indicators under a certain primary indicator. The risk status assessment of the first-level indicators by the second-level indicator risk yields RI_v.

$$RI_v = \sum_{j=1}^{m} \omega_j^I \times RI_s \tag{4}$$

Where: ω_j^I is the weight of primary indicators, m is the number of primary indicators. The risk level criteria of fractured pipeline sink are classified according to the "Pipeline Risk Evaluation Technology".[18] The relationship between the risk status assessment level score and the risk status assessment level of fracture pipeline manifold system is shown in Table 4. The relationship between the risk status assessment score and the risk status assessment level of the fracture pipeline system is shown in .

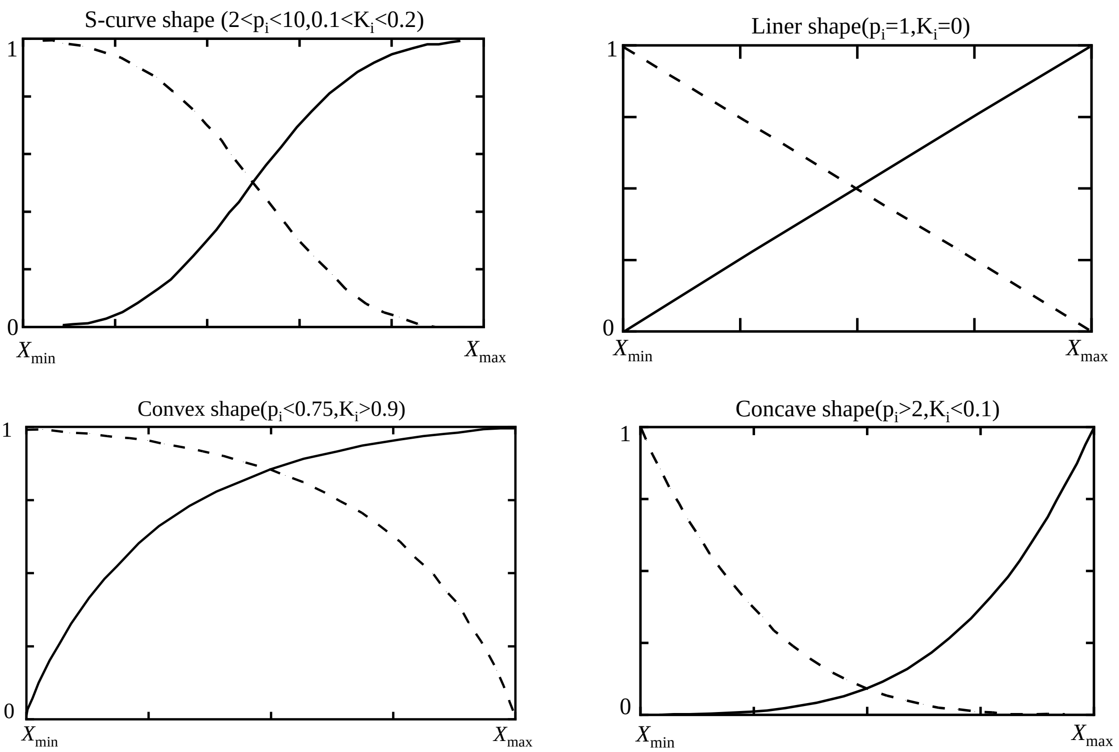


Fig. 2 Typical shapes and parameters of function values

Table 4 Risk assessment level against assessment level

Assignment interval	<0.2	0.2-0.4	0.4-0.5	0.5-1	>1
Risk Level	Level I	Level II	Level III	Level IV	Level V
Assessment Level	Low Risk	Minor risks	General Risk	Significant Risks	Very high risk

4. Fracturing sink remaining life prediction

4.1. Establish the stochastic fuzzy distribution function and graph of risk index RI

As the operating time of the fractured pipeline sink system increases, the level of degradation of the pipeline sink increases, which leads to a greater risk of failure of the pipeline sink. Since the risk distribution of pipelines generally adopts exponential distribution[19] Therefore, the exponential distribution function of fractured pipe sink risk based on the exponential distribution is established.

$$RI = a_0 + be^{-\lambda t} \tag{5}$$

where: a_0, b and λ are constants.

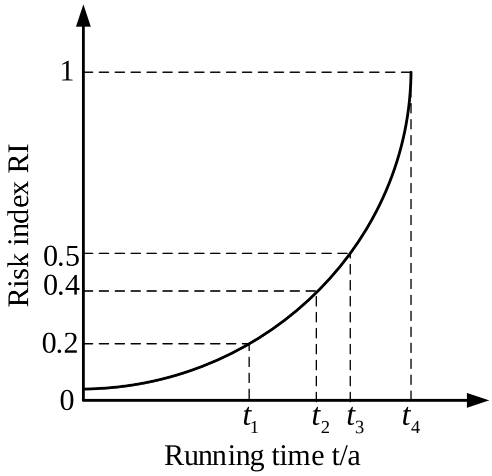


Figure 3 Fracture pipeline sink risk index curve

Based on the failure distribution curve and the distribution function of fracture sink risk index, the fracture sink risk index curve is established, asFigure 3 shown in Fig. The risk index of fracture manifold system increases exponentially with the operation time *t*. When RI<0.2, the risk of frac sink is low and normal operation; when 0.2≤ RI≤0.4, the risk of frac sink increases and the condition monitoring of frac sink should be strengthened; when 0.4≤ RI≤0.5, the sink should be monitored and the regular maintenance of frac sink should be paid attention to at the same time, when 0≤.5 RI≤1, the risk rate of frac sink increases exponentially with the increase of operation time, and the safety of frac sink operation site is reduced, and the equipment should be overhauled or replaced at this time. The equipment should be overhauled or replaced.

The parameter a_0 in the risk index distribution function of the fractured pipe sink is fuzzified using a triangular fuzzy function, and the stochastic fuzzy distribution function of its risk index *RI is* established as

$$RI(t) = a_n + be^{-\lambda t} \quad a_n = (a_0, a_1, a_2) \tag{6}$$

Where: t is the frac sink run time.

4.2. Establishing an uncertainty theory-based remaining life prediction model

The remaining life of a frac sink system is predicted based on its risk index as described above, and the life of a frac sink is the maximum operating time of the sink system before it fails, i.e.

$$T = \max\{t | RI(t) \le RI_{\max}\} \tag{7}$$

Where: RI_{max} is the maximum risk index allowed for the frac sink system; T is the sink life.

CombiningFigure 3 and Eq. (6) with Eq. (7), it is deduced that the running time of the fracture sink satisfies

$$t \le \frac{1}{\lambda}\ln\left(\frac{RI_{\max} - a_n}{b}\right) \tag{8}$$

Based on uncertainty theory[20-22], the remaining life prediction model under the maximum risk index of the fracture pipe sink is developed.

$$\begin{cases} T = \max t \\ M_{ch}\left\{\frac{1}{\lambda}\ln\left(\frac{RI_{\max}-a_0}{b}\right)\geq t\right\}(\alpha)\geq\beta \\ T_r = T - t \end{cases} \tag{9}$$

Where: α and β are confidence levels; T_r is the remaining life of the frac sink.

5. Case Studies

With the help of the fracturing operating condition curves under the example study parameters of the fracturing manifold system of DPT-115 well in DaNudi gas field[23] The failure risk of the fracture manifold was evaluated using hierarchical analysis and value function model, and then the remaining life prediction model combined with the uncertainty theory of the fracture manifold was used to predict the remaining life of the high-pressure fracture manifold in this gas field.

5.1. Calculating the risk index for frac sinks

5.1.1. AHP method to calculate the initial weights

The initial weights of the fracture pipe sink system were calculated using the AHP method according to the above. The judgment matrix of *U-A is* established and its importance coefficients are calculated using the product square root method, as Table 5 .

Table 5 Judgment Matrix $U-A$

U	A_1	A_2	A_3	A_4	ω
A_1	1	1/3	1/5	1/3	0.078
A_2	3	1	1/3	1	0.201
A_3	5	3	1	3	0.52
A_4	3	1	1/3	1	0.201

Consistency test for all indicators, the maximum eigenvalue of the primary indicatorsλ_{max}=4.043， At this time n is 4, take the value of R.I. 0.893, get the consistency index C.I. U=0.0143, consistency ratio C.R. U=0.0159<0.1 。 Similarly, the initial weights of the secondary indicators corresponding to "vibration" are [0.25,0.75]; the initial weights of the secondary indicators for "cracking" are [0.659,0.185,0.156]; the initial weights of the secondary indicators for "erosion" are [0.293,0.207,0.207, 0.293]; the initial weights of the secondary indicators for "corrosion" are [0.167,0.5,0.166,0.167]. The parameters of the consistency test for the secondary indicators areTable 6 shown.

Table 6 Secondary index consistency test parameters

Judgment Matrix	Maximum eigenvalue λ_{max}	Consistency index *R.I.*	Consistency ratio *C.R.*
$A\text{-}B_1$	2	0	0
$A\text{-}B_2$	3.03	0.015	0.0291
$A\text{-}B_3$	4.121	0.0404	0.0452

A-B4	4.000	0	0

It can be seen that the consistency ratios of the appeal judgment matrix are all less than 0.1, which satisfies the consistency and its construction is reasonable.

5.1.2. Determine the risk index of the fracture sink

The fracturing operation curves of stages 1-5 after 1 50hour of work were obtained from the field research data (see Figure1 (a)), combined with the proposed integrated approach to assess the risk of high-pressure sink failure. This study focuses on pressure, discharge and sand content, and analyzes the risk of manifold failure for these monitoring parameters. In addition, the ranges, units and values of other monitoring parameters are shown inTable 7 are shown.

Table 7 Fracture pipe sink monitoring data

Monitoring parameters	Scope	Unit	Numerical value
Pressure	0-100	*MPa*	-
Displacement	0-20	m/min^3	-
Sand content	0-100	%	-
Service Hours	0-600	*h*	150
Erosion location	0-1	-	0.5
Erosion size	0-3	mm	1
Medium *PH*	0-7	*PH*	5
Corrosion location	0-1	-	0.5
Corrosion size	0-3	mm	1
Materials	40CrMo	-	-

In the figure4, the value function on pressure and discharge volume is expressed as Eqs. (10)-(11) under the vibration level indicator for the risk at 2 25minutes of the fracture pipe sink:

$$v_1 = B_1 \times \left[1 - e^{-K_1 \times \left[\frac{|X_1 - X_{\min}|}{C_1}\right]^{P_1}}\right] = \left[1 - e^{-K_1 \times \left[\frac{|100-0|}{C_1}\right]^{P_1}}\right]^{-1} \times \left[1 - e^{-K_1 \times \left[\frac{|37.69-0|}{C_1}\right]^{P_1}}\right] \tag{10}$$

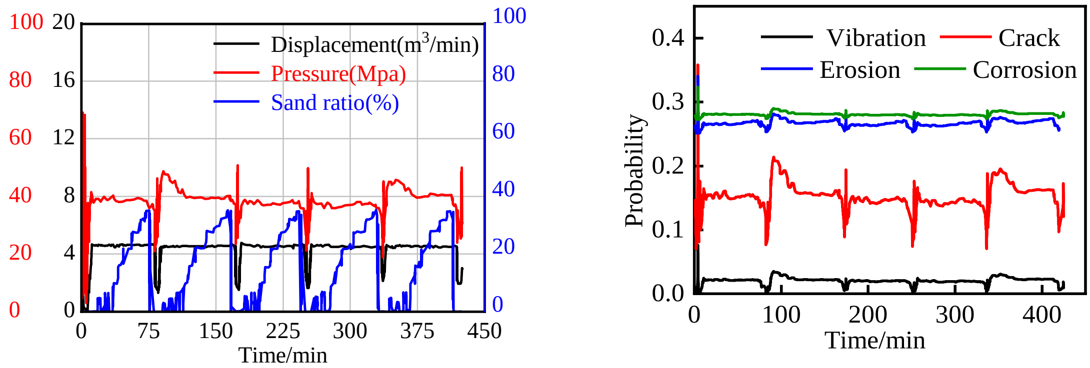
$$v_2 = B_2 \times \left[1 - e^{-K_2 \times \left[\frac{|X_1 - X_{\min}|}{C_2}\right]^{P_2}}\right] = \left[1 - e^{-K_2 \times \left[\frac{|20-0|}{C_2}\right]^{P_2}}\right]^{-1} \times \left[1 - e^{-K_2 \times \left[\frac{|4.50-0|}{C_2}\right]^{P_2}}\right] \tag{11}$$

It is known from the 3.1section that the fracture pipe sink risk is exponentially distributed, which corresponds to the concave function in the value function. After communicating with relevant experts, the pressure under vibration index P_i is set to 3.5, C_i, *K is* 60 and respectively$_i$0.1; the displacement index P_i is set to 3, C_i, K_i is 2 0and0.01 respectively. At this time, the secondary index v=0$_1$.0432,$_2$v=0.0119, and then combined with the index weights, according to the formula (3) to calculate as well as the probability of failure of the index vibration:

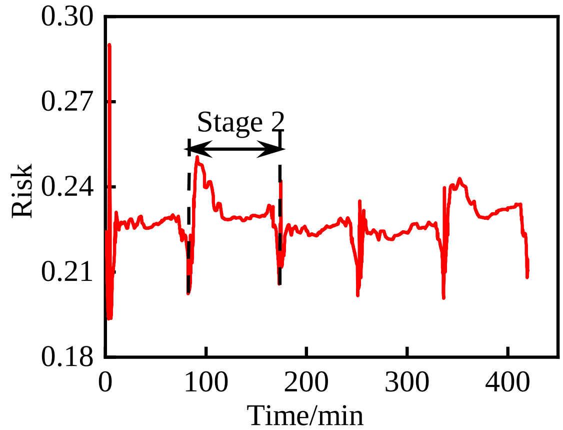
$$RI_s = \sum_{i=1}^{n} \omega_i^{II} \times v_i = 0.25 \times v_1 + 0.75 \times v_2 = 0.0197 \tag{12}$$

Similarly, the failure probabilities for cracking, erosion, and corrosion are 0.085, 0.2669, and 0.3614, respectively (see6 Figure (b)). The final failure risk RI_v is evaluated by Equation (13), as6 shown in Figure (c).

$$RI_v = \sum_{j=1}^{m} \omega_j^I \times RI_s = 0.2301 \tag{13}$$



(a) Fracturing operation curve (b) Probability of failure of primary indicator



(c) Overall frac sink risk

Figure4 Fracture sink visual risk map

The risk of fracture pipe sink is shown inFigure4 (b-c) show that, based on the pressure, discharge volume and sand content rate as the main evaluation data, the probability of failure of the pipe sink is higher for erosion and corrosion, among which the probability of failure of erosion is the highest and is the main failure type. During the whole fracturing stage process, the failure risk of the pipe sink at the beginning, middle and end of each fracturing stage presents a sudden rise to fall, smooth fluctuation and sudden fall, respectively, with pressure being the most important parameter affecting the risk of the pipe sink. The risk is the highest in fracturing stage 2, but the average failure risk is within .20~0.4, and the risk status is at level *II*, which is a slight risk and can continue the fracturing operation. Using the same method, the risk index was calculated for the fracturing pipe sink within the recommended service life[24, 25] The risk index is calculated, and the risk index curve of fracturing pipe sink is fitted by Matlab (see Chart5), and the distribution function of the risk index is

$$RI(t) = 0.05994 + 0.09285e^{0.00387t} \tag{14}$$

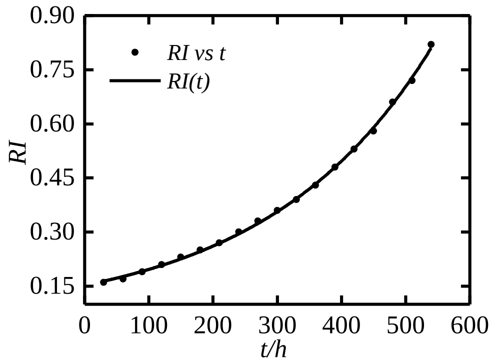


Chart5 Risk Index Curve

Fuzzifying the parameter a_n in the distribution function *RI(t) of the* fractured pipe sink, the fuzzy random distribution function of the fractured pipe sink risk index is

$$RI(t) = a_n + 0.09285e^{0.00387t} \tag{15}$$

5.2. Predicting the life and remaining life of fracture manifolds

Substituting the risk index into the remaining life prediction model, the remaining life is shown in Equation (16).

$$\begin{cases} T = \max t \\ M_{ch}\left\{\dfrac{1}{0.00387}\ln\left(\dfrac{RI_{\max} - a_n}{0.09285}\right) \geq t\right\}(\alpha) \geq \beta \\ T_r = T - t \end{cases} \tag{16}$$

At the highest risk index *RI* of 1, when$_{max}$ β=RI=1, take a=$_n$(0.05067,0.05994,0.06921), the life of fracture pipe sink is T=598.*18h* calculated by using stochastic simulation model, then its remaining life is $_r$T=598.18-150=448.*18h*.

6. Conclusion

Based on the relationship between fracture sink failure risk and remaining life, this paper proposes a method to predict the remaining life of fracture sink based on risk index and uncertainty theory. For the fracture sink failure risk, hierarchical analysis is proposed to calculate the initial weights, and the risk status is evaluated by the value function model. The main conclusions are as follows.

(1) Based on the calculation of index weights by hierarchical analysis method, a dynamic nonlinear model - value function model is proposed to deal with the relationship of indicators between different levels to meet the needs of real-time monitoring and evaluation of fractured pipe sinks and reflect the level of pipe sink failure risk more objectively.

(2) On the basis of hierarchical analysis and value function model, the risk evaluation model of fracture pipe sink is established, and the risk status of the fracture pipe sink which has been working for 1 50hour is evaluated, and the overall risk of the pipe sink is in level *II, and* erosion is the main failure type.

(3) An uncertainty theory-based model for predicting the remaining life of fracture sink is established based on the risk index. The model not only reflects the change law of fracture manifold risk state with time, but also predicts the manifold life and remaining life more accurately. When the risk index of the fracture manifold reaches the highest in the operating 150hours, its calculated life meets the requirements of the recommended life of the fracture manifold.

(4) The fracture sink life prediction model based on nonlinear dynamic risk evaluation can effectively grasp the real-time risk status of the sink and realize the priority maintenance of the sink as well as the safety of field operations.

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