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Evaluation Failure Possibility of Oil and Gas Pipelines Based on Uncertainty Measurement Theory

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This paper presents an uncertainty measurement theory approach to evaluate failure possibility from failure factors of buried pipelines. The approach considers five levels of failure possibility and selects twenty failure factors. Single index measurement functions for failure factors are used to calculate the measurement values to the failure levels. The measurement values form a single index measurement evaluation matrix, from which a weight vector is developed using information entropy theory. The multi-index uncertainty measurement is determined from the cross product of the single index measurement matrix and the weight vector. The level of failure possibility is judged by credible degree recognition criteria. The proposed approach is demonstrated to be applicable for evaluating failure possibility of pipelines and outperforms other methods.

1. Introduction

Underground pipelines have been widely accepted as the most economic, reliable and efficient means for oil and gas transportation. However, the failure of pipelines involving oil and gas release may result in enormous property damage and casualties to human beings (US DOT, 2015). Recently, the safety of pipelines has been increasingly concerned for frequent occurrence of accidents. Therefore, to evaluate failure possibility of pipelines is extremely important. If done in advance, we can save resources and guide targeted safeguard procedures (e.g. maintenance practices, periodic detection) for paying more attention to high risk segments, and the significant costs for replacement or failures can be avoided.

The failure possibility of pipelines is an important part of quantitative risk assessment. It has been studied for more than 30 years, and several methods have been proposed to predict the failure possibility. For example, fault tree analysis was used to estimate failure possibility (Dong & Yu, 2005). It spends a lot of manpower and material resources, so it is disadvantage to practical application. Kent scoring method (Muhlbauer, 1992) was applied to assess failure possibility from the expert scoring on failure factors. Several modified scoring methods including numerous factors are also available. The drawback of such methods is that they are subjective and disregard the relative importance of failure factors. Data mining methods (e.g. fuzzy based method, extension method, which are deemed to be more powerful and flexible to address multiple factors, have been presented by many authors (Markowsik & Mannan, 2009; Wang et al., 2015). However, the limitation of these methods can be summarized as follows: (1) they can't address a large amount of uncertainty/ qualitative failure factors and achieve the coexistence of qualitative and quantitative ones; (2) they often determine weight vector of failure factors too subjective; (3) the failure factors selected are often not comprehensive enough.

Uncertainty measurement theory is an effectual technique of solving uncertainty problems, and it has been widely employed in many areas (Liu et al., 1999). It's often used to quantify qualitative factors, and integrate them together with quantitative ones to make a comprehensive evaluation. In addition, the entropy weight method (cao et al., 2000) is often used to calculate weights of failure factors objectively.

In this study, the uncertainty measurement theory is applied to predict the failure possibility of pipelines. First of all, the uncertainty measurement of each failure factor is calculated, and the entropy weight method is used to determine weight vector of failure factors from single index measurement evaluation matrix. Finally, the level of failure possibility is determined by credible degree recognition criteria.

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2. Formal description of uncertainty measurement theory

In this section, we present some knowledge about the uncertainty measurement theory (Liu et al., 1999). Let an object space X be the collection of evaluation objects X_1, X_2, …, X_n, expressed as $X=\{X_1, X_2, …, X_n\}$. Consider an object X_i, having evaluation indexes I_1, I_2, …, I_m, so the index space is written as $I=\{I_1, I_2, …, I_m\}$. Suppose x_{ij} is the measured value of i-th evaluation object X_i with regard to j-th evaluation index I_j, so X_i can be denoted by m-dimension vector $X_i=(x_{i1}, x_{i2}, …, x_{in})$.

If measured value x_{ij} has evaluation ranks C_1, C_2, …, C_p, the rank space is denoted as $U=\{C_1, C_2, …, C_p\}$. Suppose the safety degree of rank k is higher than rank k+1(C_k>C_{k+1}), namely C_1>C_2>…>C_P, so $U=\{C_1, C_2, …, C_p\}$ is called an ordered partition sort of evaluation space U.

2.1 Single index uncertainty measurement

Denote as u the degree of measured value x_{ij} belonging to k-th rank C_k, as expressed in Eq. (1). If u satisfies Eq. (2) ~ Eq. (4) simultaneously, it can be defined as uncertainty measurement.

$$u_{ijk} = u(x_{ij} \in C_k) \tag{1}$$

$$0 \le u(x_{ij} \in C_k) \le 1 \tag{2}$$

$$u(x_{ij} \in U) = 1 \tag{3}$$

$$u\left| x_{ij} \in \bigcup_{l=1}^{k} C_l \right| = \sum_{l=1}^{k} u(x_{ij} \in C) \tag{4}$$

where i=1, 2, …, n; j=1, 2, …, m; k=1, 2, …, p. Eq. (2) is “non-negativity and boundedness”. Eq. (3) is “normalized quality”. Eq. (4) is “additivity”.

The matrix $(u_{ijk})_{m\times p}$ shown in Eq. (5) is called single index measurement evaluation matrix

$$(u_{ijk})_{m\times p} = \begin{bmatrix} u_{i11} & u_{i12} & \cdots & u_{i1p} \\ u_{i21} & u_{i22} & \cdots & u_{i2p} \\ \vdots & \vdots & \vdots & \vdots \\ u_{im1} & u_{im2} & \cdots & u_{imp} \end{bmatrix} \tag{5}$$

When we establish single index measurement evaluation matrix, the single index measurement function should be constructed firstly, from which the measurement values of each index can be calculated. Presently, linear measurement function is commonly used in practice (Luan, et al., 2014).

2.2 Determine weight vector

The present approach requires information about the relative importance of failure factors, which is usually established by a set of preference weights w_i, as shown in Eq. (6).

$$w_i = \{w_{i1}, w_{i2}, \cdots, w_{im}\}\text{, where } 0 \le w_{ij} \le 1, \sum_{j=1}^{m} w_{ij} = 1 \tag{6}$$

Information entropy theory avoids the influence of subjective factors and reflects the difference of index weight in special conditions. It’s more objective than Analytic Hierarchy Process (AHP) or methods relying on expert judgment. Here, information entropy theory is used to calculate w_{ij} (Cao et al., 2000), as expressed in Eq. (7) and Eq. (8).

$$v_{ij} = 1 + \frac{1}{\lg p} \sum_{k=1}^{p} u_{ijk} \lg u_{ijk}, \lg 0 = 0 \tag{7}$$

$$w_{ij} = v_{ij} \Big/ \sum_{i=1}^{n} v_{ij} \tag{8}$$

Then, on the basis of Eq. (5), the weight vector w_i can be calculated by Eq. (7) and Eq. (8).

2.3 Multi-index comprehensive uncertainty measurement

If $u_{ik}=u(u_i \in C_k)$ is the degree of evaluation object X_i belonging to k-th rank C_k, u_{ik} is known as multi-index comprehensive measurement, as shown in Eq. (9).

$$u_{ik} = \sum_{j=1}^{m} w_{ij} u_{ijk} \text{ , where } 0 \le u_{ik} \le 1, \sum_{k=1}^{p} u_{ik} = 1 \quad (9)$$

The vector $u_{ik}=\{u_{i1}, u_{i2}, \dots, u_{ip}\}$ is multi-index comprehensive measurement evaluation vector of X_i.

2.4 Credible degree recognition criterion

In this study, the credible degree recognition criterion is introduced to determine the level of object X_i instead of maximum membership identification criteria to reduce misjudgements (Luan, et al., 2014).
Consider a credible degree λ (λ≥0.5), which generally takes 0.6 or 0.7. If evaluation space is ordered, namely $C_1>C_2>\dots>C_P$, the evaluation object belonging to K_0-th level can be denoted as C_{k0}, expressed as Eq. (10).

$$K_0 = \min \left| K : \sum_{k=1}^{K} u_{ik} > \lambda, K = 1,2,\cdots,p \right| \quad (10)$$

3. Procedure for evaluating failure possibility of pipelines

The procedure of the proposed approach to evaluate failure possibility of pipelines is as follows:
(1) Determine index system and classification standard for evaluating failure possibility of pipelines.
(2) Establish single index uncertainty measurement function of each evaluation index based on the classification standared.
(3) Construct single index measurement evaluation matrix based on the single index uncertainty measurement function and the measured data of evaluation objects.
(4) Calculate weight vector of failure factors using Eq. (5), Eq. (7) and Eq. (8).
(5) Calculate multi-index comprehensive uncertainty measurement using Eq. (9).
(6) Determine the level of failure possibility using Eq. (10).

4. Failure possibility evaluation index system

A large number of factors can contribute to the failure of oil and gas pipelines. In this section, we intend to establish a scientific and perfect index system to evaluate failure possibility of buried pipelines based on four aspects consideration: (1) the systematic analysis of accidents statistic data and accident cases; (2) the appendix B and C of the Guideline of pipeline risk assessment (Q/SY 1180.3, 2009); (3) the contribution rate of indexes to pipeline failures; (4) the opinions from related experts. The index system includes four second-grade indexes and twenty-three-grade index (denoted by I_1, I_2, …, I_{20}), as shown in table 1.

Table 1: Index system and classification standard for failure possibility evaluation of oil and gas pipelines

Second-grade index	Three-grade index	Level I (C_1)	Level II (C_2)	Level III (C_3)	Level IV (C_4)	Level V (C_5)
Third party damage	Minimum buried depth I_1/cm	>140	120~140	100~120	80~100	<80
	Ground activity degree I_2	1	2	3	4	5
	Road way signs serviceability I_3/%	>80	60~80	40~60	5~40	<5
	Publication education I_4	1	2	3	4	5
	Patrol frequency I_5 /(times/month)	>30	16~30	8~16	4~8	<4
Corrosion	Medium corrosivity I_6	1	2	3	4	5
	Internal protective layer measures I_7	1	2	3	4	5
	Soil resistivity I_8/Ω·m	>100	50~100	20~50	10~20	<10
	Design of cathodic protection I_9	1	2	3	4	5
	Detection period I_{10}	1	2	3	4	5
	Pipe coating material I_{11}	1	2	3	4	5
	Service life I_{12}/year	< 5	5~15	15~20	20~25	>25
Design	Steel pipe safety factor X I_{13}	>1.8	1.6~1.8	1.4~1.6	1.2~1.4	<1.2
	System safety factor Y I_{14}	>2.0	1.75~2.0	1.5~1.75	1.25~1.5	<1.25
	Fatigue factor Z I_{15}	<0.2	0.2~0.4	0.4~0.6	0.6~0.8	>0.8
	System pressure test H I_{16}	>1.6	1.4~1.6	1.25~1.4	1.1~1.25	<1.1
Misoperation	Design wrong operation I_{17}	1	2	3	4	5
	Construction wrong operation I_{18}	1	2	3	4	5
	Running wrong operation I_{19}	1	2	3	4	5
	Maintenance wrong operation I_{20}	1	2	3	4	5

Table 2: Classification standard of qualitative indexes for pipelines failure possibility evaluation

Indexes	Level I (C_1)	Level II (C_2)	Level III(C_3)	Level IV(C_4)	Level V(C_5)
values	1	2	3	4	5
I_2	No activity area, wilderness, desert	Level 1 area, low activity	Level 2area, medium activity	Level 3area, construction areas	Level 4 area, frequent construction areas
I_4	Extremely high	High	Medium	Low	Lower
I_6	No corrosion	Extremely low corrosion	Low corrosion	Medium corrosion	Strong corrosion
I_7	Excellent	Good	Medium	Inferior	No
I_9	Excellent	Good	Medium	Inferior	No
I_{10}	Less than 6 months	6 months to 1 year	1 year to 2 years	More than 2 years	No
I_{11}	Three layers composite	PE	FBE	Coal tar enamel, tape	No
I_{17}	Excellent	Good	Medium	Inferior	Very bad
I_{18}	Excellent	Good	Medium	Inferior	Very bad
I_{19}	Excellent	Good	Medium	Inferior	Very bad
I_{20}	Excellent	Good	Medium	Inferior	Very bad

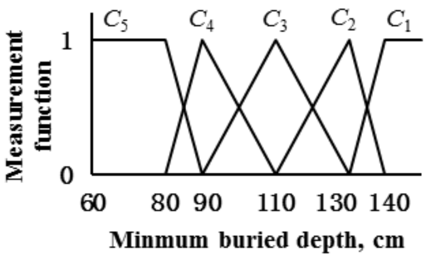

Figure 1: Uncertainty measurement function of minimum buried depth

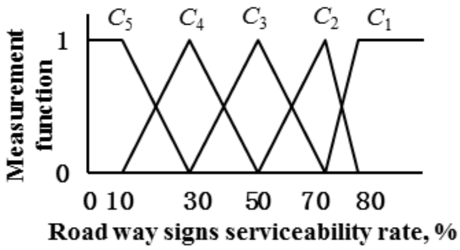

Figure 2: Uncertainty measurement function of road way signs serviceability rate

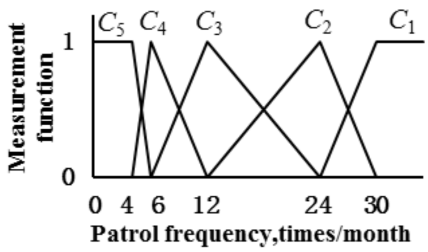

Figure 3: Uncertainty measurement function of patrol frequency

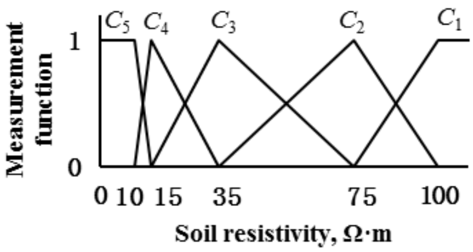

Figure 4: Uncertainty measurement function of soil resistivity

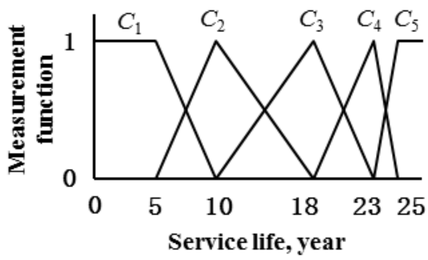

Figure 5: Uncertainty measurement function of service life

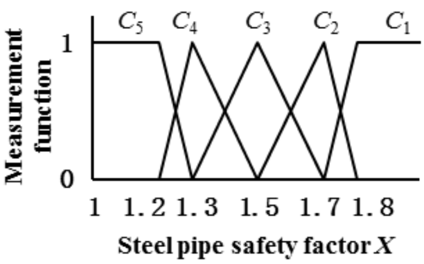

Figure 6: Uncertainty measurement function of steel pipe safety factor X

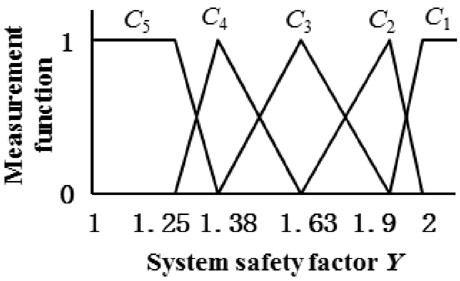

Figure 7: Uncertainty measurement function of system safety factor Y

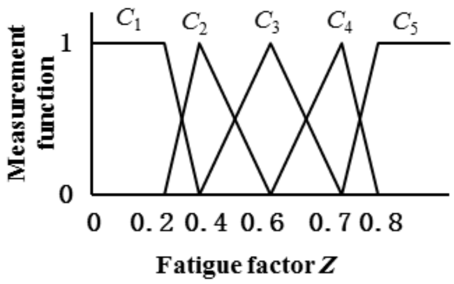

Figure 8: Uncertainty measurement function of fatigue factor Z

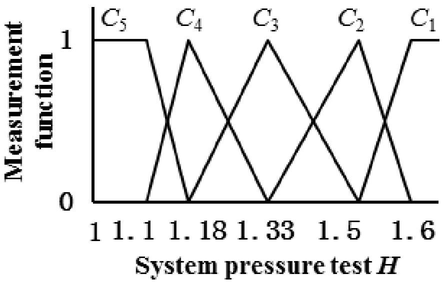

Figure 9: Uncertainty measurement function of system pressure test H

The failure possibility of pipelines is divided into five levels: I, II, III, IV and V, denoted the evaluation set as *(*C_1*,* C_2*,* C_3*,* C_4*,* C_5*)*, representing very low, low, medium, high, and very high respectively. The three-grade index system includes nine quantitative indexes and eleven qualitative indexes, the qualitative ones of which are translated into semiquantitative ones by a specific method from related technical regulations and empirical materials. The classification standard of the twenty indexes refers to pipeline risk assessment guideline (Q/SY 1180.3, 2009) and pipeline risk management manual (Muhlberger, 1992), as shown in table 1 and table 2.
The uncertainty measurement function of each index can be established according to the definition of single index measurement function in 2.1 and classification standard of indexes in table 1. In this study, the linear measurement function (Luan, et al., 2014) is used to establish single index measurement function. The measurement function of quantitative indexes sees Fig.1~Fig.9. The measurement values of quantitative indexes refer to table 2.

5. Case study

The data were collected from two underground natural gas pipelines located in China (Zhang, 2007; Lu & Zhang, 2008), as shown in table 3. The two segments are used as examples to examine the application of the present approach, and the results are compared with the extension method conducted in Wang et al. (2015).

Table 3: The evaluation indexes for two segments

Segment	I_1	I_2	I_3	I_4	I_5	I_6	I_7	I_8	I_9	I_{10}	I_{11}	I_{12}	I_{13}	I_{14}	I_{15}	I_{16}	I_{17}	I_{18}	I_{19}	I_{20}
A	120	3	65	3	9	3	4	45	1	1	4	2	1.05	1.6	0.05	1.25	2	3	4	3
B	100	5	75	2	5	2	4	25	2	2	3	12	1.2	1.6	0.48	1.38	3	2	3	3

The uncertainty measurement values of 9 quantitative indexes can be determined on the basis of the single index uncertainty measurement functions shown in Fig.1~Fig.9, from which the single index measurement evaluation matrixes of two segments are obtained by Eq. (5). The weight vectors of the two segments are determined using entropy weight method shown in Eq. (7) and Eq. (8). Using the single index measurement evaluation matrix and the weight vector obtained, the multi-index comprehensive uncertainty measurements of the two segments can be calculated by Eq. (9), as shown in table 4.
In this study, the evaluation set *{*C_1*,* C_2*, …,* C_5*}* is ordered, the safety degree of *k*-th level is higher than (*k*+1)-th level, denoted as $C_1>C_2>C_3>C_4>C_5$. The credible degree identification criterion is used to determine the level of failure possibility of pipelines. Take the credible degree λ=0.6, the level of failure possibility could be judged using table 4 and Eq. (10). Take segment A as an example, from level I to V, k_0=0.2249+0.1088+0.4030=0.7367>λ=0.6, the level of failure possibility is III. From level V to I,

k_0=0+0.0562+0.2070+0.4030=0.6662>λ=0.6, the level of failure possibility is III too. Thus, we determine the level of failure possibility of segment A as III. Similarly, segment B is determined as III. The failure possibility of the two segments is medium.

Table 4: Comparison of uncertainty measurement approach and extension method

Segment\	Comprehensive uncertainty measurement					Recognition results	Extension method
	C_1	C_2	C_3	C_4	C_5		
A	0.2249	0.1088	0.4030	0.2070	0.0562	III	III
B	0.0164	0.3669	0.3725	0.1124	0.1319	III	III

The comparison of the proposed approach and the extension method conducted in Wang et al. (2015) is shown in table 4. The results suggest that the present approach is well consistent with the extension method.

6. Conclusions

In conclusion, the approach addresses a great number of qualitative failure factors existing in evaluation and realizes the coexistence of qualitative and quantitative factors. It's more comprehensive and objective and improves the evaluation precision. It was demonstrated to be applicable and effective. It can yet tentatively serve as an alternative approach in engineering practice and guide targeted actions of pipeline operators to prevent future catastrophic failures.

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