Risk assessment of the maintenance process for onshore oil and gas transmission pipelines under uncertainty

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ABSTRACT

Research on risk assessment of the maintenance process for onshore oil and gas transmission pipelines has been attracting ever more attention from the academic community. Due to the existence of uncertainties, risk propagation can hardly be precisely and/or robustly assessed. Therefore, in this paper, considering that decision-makers prefer uncertainty-informed risk information rather than unreliable "precise" risk values, a new insight is provided to deal with risk assessment of the onshore pipeline maintenance process under uncertainty. The risk assessment model is built on the framework of quantitative risk assessment based on AHP and expert knowledge. Meanwhile, to represent and quantify uncertainty, interval analysis is utilized to extend the whole model into an interval environment. As a result, an interval quantified risk assessment model is established for the onshore pipeline maintenance process. The study shows that interval analysis can effectively internalize, represent, quantify and propagate the uncertainty in the risk assessment model. In the specific case of emergency maintenance for the Gangqing dual pipeline, the interval scores to respectively characterize the occurrence likelihood and consequence severity are computed. As a result, the uncertainty-informed overall risk of the emergency maintenance process is determined and intuitively pinpointed in an interval risk matrix. The risk rating of the case is estimated as Level 2, indicating that operations with respect to emergency maintenance are well organized and the possibility of accident occurrence is low. Thus, maintenance can be carried out well under supervision. Even if a secondary accident would occur, the accident scope will be quite small and emergency measures are adequate enough to control the development of the accident and reduce accident losses. Moreover, the sensitivity sorting of sub-indexes of occurrence likelihood is obtained as $I_{11} > I_{23} > I_{13} > I_{22} > I_{34} > I_{12} > I_{33} > I_{21} > I_{31} > I_{32}$, indicating that improvement in the management capacity (I_{11}), normal operations (I_{13}) and completeness of protection (I_{22}) will effectively reduce the occurrence of accidents and improve operational safety. Furthermore, risk estimation under the condition of missing data is tackled by using Monte Carlo simulations and provides a reasonable option when crucial information is lacking.

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Key Words: Pipeline maintenance; Risk assessment; Uncertainty; Interval analysis; Interval analytic hierarchical process; Sensitivity analysis.

1. INTRODUCTION

In the context of safety management for onshore oil and gas transmission pipelines, most researchers and stakeholders focus much on leakage risk assessment[1-3], leak detection and monitoring[4,5] and inspection and maintenance strategies[6-7]. Yet, research on risks concerning secondary accidents possibly being triggered during the maintenance process for damaged or leaking pipelines should also be of concern, since a catastrophic explosion, being that type of accident, happened in Qingdao. The accident was triggered by mechanical sparks generated during the emergency maintenance procedure[8-10].

As a process involves frequent interactive activities among personnel, equipment and environment, numerous hazards inevitably exist in the maintenance procedure for onshore oil and gas transmission pipelines[11]. However, even if the hazards could be completely and correctly identified, the risks linked with the hazards are still difficult to be accurately and/or robustly assessed due to existing uncertainties. Rather than receiving an unreliable “precise” risk value without knowing the exact error, decision-makers prefer to propagate the uncertainty and to represent it in the analysis result in order to obtain uncertainty-informed risk information.

Uncertainty analysis in the context of risk assessment has therefore attracted a lot of attention in recent years[12-15]. Several methods were developed and elaborated to pursue appropriate characterization, interpretation, representation and quantification of uncertainty in relation to quantitative risk assessment and probabilistic risk assessment[13-15], including interval analysis[14,16], imprecise probability (interval probability)[17,18], probability bound analysis (probability analysis-interval analysis)[19], random sets (evidence theory)[20] and possibility theory[21].

In the risk analysis of any process or system, two kinds of uncertainty generally exist, i.e. aleatory and epistemic uncertainty[14,22]. The former is present due to intrinsic variability of the phenomenon and the latter is associated with systematic measurement error and lack of knowledge. Whereas epistemic uncertainty can be reduced by acquiring knowledge and information, aleatory uncertainty cannot, and that is why it is sometimes called irreducible uncertainty[13].

Usually, probability is the most widely accepted mathematical tool to characterize and represent uncertainty, but it can be challenged under the condition of limited or poor knowledge with respect to a high-consequence risk problem, for which the information available cannot provide a strong basis for a specific probability assignment[14,15]. However, if large epistemic uncertainty exists, it is advisable to limit the use of probabilities, as the numbers cannot be given a rigorous basis. To reflect the epistemic uncertainty, interval analysis and related approaches may for example be suggested (see for instance [14]). In terms of risk assessment for the onshore pipeline maintenance process, the information of interest is insufficient or inaccessible to elicit probabilities because of the suddenness and urgency of the unexpected activity. It is therefore questionable whether any probabilistic model is suitable for risk assessment of the onshore pipeline maintenance process under uncertainty.

Nevertheless, analytic hierarchical process (AHP), which characterizes the experts’ beliefs on phenomena by using scores, is believed to be an effective alternative method for quantitative risk assessment under uncertainty. Thus, a quantitative risk assessment framework based on AHP and expert knowledge is elaborated and employed in this paper to assess the process risk of onshore oil and gas transmission pipeline maintenance. In the process of quantitative assessment, the representation, quantification and propagation of uncertainty in risk factors is of great significance for uncertainty-informed risk information output. Multiple kinds of uncertainty like randomness, imprecision, vagueness, ignorance, and incompleteness coexist in different risk factors. Some factors contain a mixture of several kinds of uncertainty. To handle different uncertainties in the same framework at the same time, interval analysis is taken as a good choice. Besides, interval based assessment is more coherent with the human cognitive ability[23], being particularly suitable and user-friendly for expert knowledge based risk assessment under uncertainty[24]. As a result, interval analysis is utilized to transform the whole risk assessment model into an interval environment to internalize, represent and propagate uncertainty. It is worth noting that the uncertainties of concern in this paper are mainly epistemic, however aleatory uncertainties caused by stochastic, random error, and so on, are also included.

The rest of this paper is organized as follows: Section 2 explains the methods used in this paper, including the fishbone diagram for hazard identification, interval analysis and interval analytic hierarchical process (IAHP). In Section 3, the interval quantified risk assessment model for the onshore pipeline maintenance process is established. Subsequently, in Section 4, the interval quantified risk assessment model is applied to assess the process risk of a specific emergency maintenance mission for the Gangqing dual pipeline. In the case study, sensitivity analysis is performed as well as risk estimation under missing data. At the end, conclusions are drawn in Section 5.

2. METHODOLOGY

2.1 Fishbone diagram

The fishbone diagram was proposed by Professor Kaoru Ishikawa around 1960[25]. It was originally used for process quality management in the shipyard of the Kawasaki heavy industries and now it is widely applied in, amongst others, process safety analysis. As one of the important methods for causal analysis, the fishbone diagram is famous for its intuitive shape[26]. In the central place of the fishbone, a thick arrow (the main bone) points to an accident or some other undesired event. On both sides of the main bone, the various causes of the accident are identified layer by layer. A cause and effect diagram resembling a fishbone is eventually obtained as shown in Figure 1.

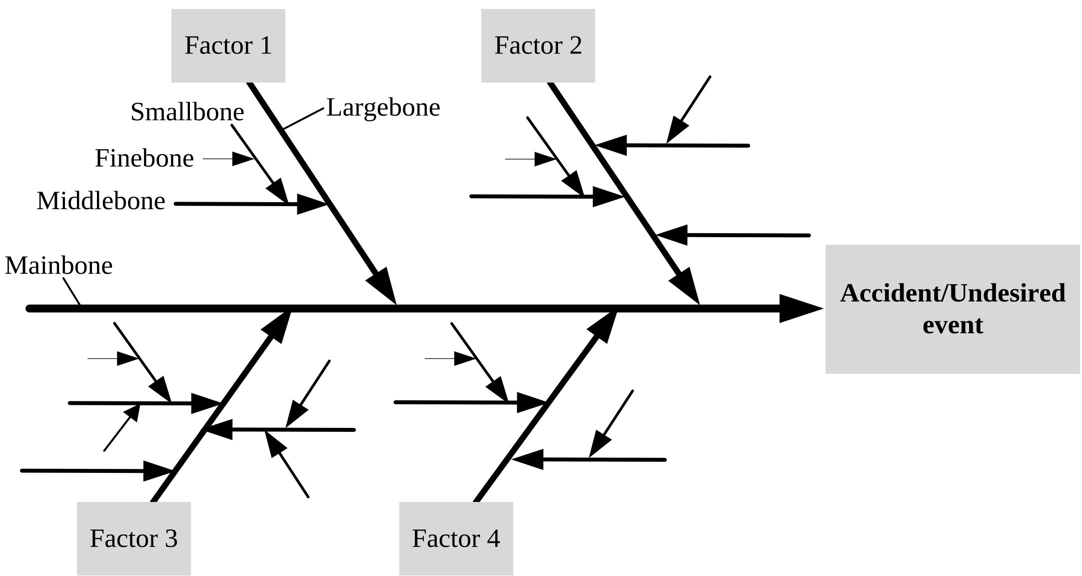

Fig. 1. Generic fishbone diagram

2.2 Interval analysis

Interval analysis[16,27] utilizes interval numbers to describe the nature and characteristics of parameters and phenomena. For those parameters and phenomena, of which the property values are uncertain, people cannot determine specific "point" (precise) values, but can only provide interval ranges, i.e., in the form of interval numbers.

Interval numbers and interval arithmetics are thus the basis of interval analysis. For any $a^-, a^+ \in \mathbb{R}$ ($\mathbb{R}$ is a real compact set), if there exists the order relation of $a^- \le a^+$, then $\left(a^-, a^+\right)$ can be defined as a standard open interval, notated as $\left[\bar{A}\right] = \left(a^-, a^+\right)$, where a^+ and a^- are respectively the upper and lower limits of the interval. In this paper, the term "interval" is always referred to "open interval". It is worth noting that $\left[\bar{A}\right]$ will be identified as the degenerate interval that coincides with the real number a when $a^- = a^+$, i.e., $a \equiv (a, a)$. This notion also permits us to regard the system of interval as an extension of the real number system.

As for the interval arithmetic, let $\left[\bar{A}\right] = \left(a^-, a^+\right)$ and $\left[\bar{B}\right] = \left(b^-, b^+\right)$ be real intervals and $\ast$ stand for any of the binary operations of "addition", "subtraction", "multiplication" and "division", then the corresponding interval arithmetic can be defined as follows.

$$\left[\bar{A}\right] \ast \left[\bar{B}\right] = \left\{ a \ast b : a \in \left[\bar{A}\right], b \in \left[\bar{B}\right] \right\} \tag{1}$$

What is more significant is the fact that the binary operations can be expressed in the form of endpoint formulas, as shown in Formulas (2), (3), (4), (5) respectively.

$$\left[\bar{A}\right] + \left[\bar{B}\right] = \left(a^- + b^-, a^+ + b^+\right) \tag{2}$$

$$\left[\bar{A}\right] - \left[\bar{B}\right] = \left(a^- - b^+, a^+ - b^-\right) \tag{3}$$

$$\left[\bar{A}\right] \cdot \left[\bar{B}\right] = \left(\min\left(a^-b^-, a^-b^+, a^+b^-, a^+b^+\right), \max\left(a^-b^-, a^-b^+, a^+b^-, a^+b^+\right)\right) \tag{4}$$

$$\left[\bar{A}\right] / \left[\bar{B}\right] = \left[\bar{A}\right] \cdot \frac{1}{\left[\bar{B}\right]} = \left(a^-, a^+\right) \cdot \left(\frac{1}{b^+}, \frac{1}{b^-}\right) \text{ where } 0 \notin \left[\bar{B}\right] \tag{5}$$

In order to deal with multidimensional problems, interval analysis is also extended into matrix operations. The "addition", "subtraction", and "multiplication" operations of interval matrices are shown as follows.

$$\begin{aligned} \left[\bar{\mathbf{A}}\right] + \left[\bar{\mathbf{B}}\right] &= \left[\left[\bar{A}\right]_{ij}\right] + \left[\left[\bar{B}\right]_{ij}\right] = \left[\left[\bar{A}\right]_{ij} + \left[\bar{B}\right]_{ij}\right] \\ &= \begin{bmatrix} \left(a_{11}^- + b_{11}^-, a_{11}^+ + b_{11}^+\right) & \left(a_{12}^- + b_{12}^-, a_{12}^+ + b_{12}^+\right) & \cdots & \left(a_{1m}^- + b_{1m}^-, a_{1m}^+ + b_{1m}^+\right) \\ \left(a_{21}^- + b_{21}^-, a_{21}^+ + b_{21}^+\right) & \left(a_{22}^- + b_{22}^-, a_{22}^+ + b_{22}^+\right) & \cdots & \left(a_{2m}^- + b_{2m}^-, a_{2m}^+ + b_{2m}^+\right) \\ \vdots & \vdots & \vdots & \vdots \\ \left(a_{n1}^- + b_{n1}^-, a_{n1}^+ + b_{n1}^+\right) & \left(a_{n2}^- + b_{n2}^-, a_{n2}^+ + b_{n2}^+\right) & \cdots & \left(a_{nm}^- + b_{nm}^-, a_{nm}^+ + b_{nm}^+\right) \end{bmatrix} \end{aligned} \tag{6}$$

where $\left[\bar{\mathbf{A}}\right] = \left[\left[\bar{A}\right]_{ij}\right]$ and $\left[\bar{\mathbf{B}}\right] = \left[\left[\bar{B}\right]_{ij}\right]$ are matrixes that contain $n \times m$ interval entries, $i = 1, 2, \cdots, n;\ j = 1, 2, \cdots, m$.

$$\left[\bar{\mathbf{A}}\right]-\left[\bar{\mathbf{B}}\right]=\left[\left[\bar{A}\right]_{ij}\right]-\left[\left[\bar{B}\right]_{ij}\right]=\left[\left[\bar{A}\right]_{ij}-\left[\bar{B}\right]_{ij}\right]$$

$$=\begin{bmatrix} \left(a_{11}^{-}+b_{11}^{+},a_{11}^{+}+b_{11}^{-}\right) & \left(a_{12}^{-}+b_{12}^{+},a_{12}^{+}+b_{12}^{-}\right) & \cdots & \left(a_{1m}^{-}+b_{1m}^{+},a_{1m}^{+}+b_{1m}^{-}\right) \\ \left(a_{21}^{-}+b_{21}^{+},a_{21}^{+}+b_{21}^{-}\right) & \left(a_{22}^{-}+b_{22}^{+},a_{22}^{+}+b_{22}^{-}\right) & \cdots & \left(a_{2m}^{-}+b_{2m}^{+},a_{2m}^{+}+b_{2m}^{-}\right) \\ \vdots & \vdots & \vdots & \vdots \\ \left(a_{n1}^{-}+b_{n1}^{+},a_{n1}^{+}+b_{n1}^{-}\right) & \left(a_{n2}^{-}+b_{n2}^{+},a_{n2}^{+}+b_{n2}^{-}\right) & \cdots & \left(a_{nm}^{-}+b_{nm}^{+},a_{nm}^{+}+b_{nm}^{-}\right) \end{bmatrix} \tag{7}$$

$$\left[\bar{\mathbf{D}}\right]=\left[\bar{\mathbf{A}}\right]\cdot\left[\bar{\mathbf{C}}\right]=\left[\left[\bar{D}\right]_{ik}\right] \tag{8}$$

where $\left[\bar{\mathbf{C}}\right]=\left[\left[\bar{C}\right]_{jk}\right]$ is a matrix that contains $m\times p$ interval entries and $\left[\bar{\mathbf{D}}\right]=\left[\left[\bar{D}\right]_{ik}\right]$ is a matrix that contains $n\times p$ interval entries, $k=1,2,\cdots,p$.

$$\begin{aligned}\left[\bar{D}\right]_{ik} &= \sum_{j=1}^{m}\left(\left[\bar{A}\right]_{ij}\cdot\left[\bar{C}\right]_{jk}\right) \\ &= \left(\left(\min\left(a_{ij}^{-}c_{jk}^{-},a_{ij}^{-}c_{jk}^{+},a_{ij}^{+}c_{jk}^{-},a_{ij}^{+}c_{jk}^{+}\right),\max\left(a_{ij}^{-}c_{jk}^{-},a_{ij}^{-}c_{jk}^{+},a_{ij}^{+}c_{jk}^{-},a_{ij}^{+}c_{jk}^{+}\right)\right)\right)\end{aligned} \tag{9}$$

Besides, it is worth noting that the interval matrix $\left[\bar{\mathbf{A}}\right]$ is regarded to coincide with the matrix interval $\left[\mathbf{A}^{-},\mathbf{A}^{+}\right]$, where $\mathbf{A}^{+}$ is the upper limit matrix and $\mathbf{A}^{-}$ is the lower limit matrix.

2.3 Interval Analytic Hierarchy Process

AHP, which was developed by Saaty[28], is a multiple criteria decision-making tool that has been used in many applications related to decision-making[29]. However, the limitation of traditional AHP is that the data inputted and outputted are “point” (precise) data, possibly resulting in large errors in some flexible systems. That is, “precise” data tends to be inappropriate in some cases since imprecise information and knowledge may lead to uncertain expert judgments when making decisions[30].

Considering the aforementioned limitation, IAHP, which extends AHP into an interval environment, was proposed by Wu[31]. It utilizes interval numbers to express the quantitative comparison between indexes. As a result, the interval weights obtained through IAHP would be more flexible and the corresponding uncertainty can be reasonably represented and quantified under the condition of imprecise information and knowledge.

2.3.1 Interval judgment matrix

As mentioned, the comparative importance of indexes is expressed in interval format in IAHP. That is, for *n* indexes in the same type, the judgment matrix can be expressed as follows[32].

$$\left[\bar{\mathbf{A}}\right]=\begin{bmatrix} \left(a_{11}^{-},a_{11}^{+}\right) & \left(a_{12}^{-},a_{12}^{+}\right) & \cdots & \left(a_{1n}^{-},a_{1n}^{+}\right) \\ \left(a_{21}^{-},a_{21}^{+}\right) & \left(a_{22}^{-},a_{22}^{+}\right) & \cdots & \left(a_{2n}^{-},a_{2n}^{+}\right) \\ \vdots & \vdots & \vdots & \vdots \\ \left(a_{n1}^{-},a_{n1}^{+}\right) & \left(a_{n2}^{-},a_{n2}^{+}\right) & \cdots & \left(a_{nn}^{-},a_{nn}^{+}\right) \end{bmatrix} \tag{10}$$

where $\left[\bar{A}\right]_{ij}=\left(a_{ij}^{-},a_{ij}^{+}\right)$ represents the element in row *i* and column *j* of the interval judgment matrix. It means that the comparative importance of index i to j is in the range of $\left(a_{ij}^{-},a_{ij}^{+}\right)$.

Besides, the following conclusions can be made according to the reciprocity of the judgment matrix.

$$\left[\bar{A}\right]_{ii} = (1,1) \tag{11}$$

$$\left[\bar{A}\right]_{ji} = \frac{1}{\left[\bar{A}\right]_{ij}} = \left(\frac{1}{a_{ij}^{+}}, \frac{1}{a_{ij}^{-}}\right) \text{ where } 0 \notin \left[\bar{A}\right]_{ij} \tag{12}$$

2.3.2 Interval weight calculation

Currently, several methods exist to calculate interval weights, such as the iterative method, the interval eigenvalue method, the constructing complementary matrix method, etc[33]. In this paper, the interval eigenvalue method is adopted for its ability to accurately calculate the weights and reasonably represent uncertainty.

Given the interval judgment matrix $\left[\bar{\mathbf{A}}\right]$, the upper limit matrix $\mathbf{A}^{+}$ and lower limit matrix $\mathbf{A}^{-}$ can be obtained correspondingly[34].

$$\mathbf{A}^{+} = \begin{bmatrix} a_{11}^{+} & a_{12}^{+} & \cdots & a_{1n}^{+} \\ a_{12}^{+} & a_{22}^{+} & \cdots & a_{2n}^{+} \\ \vdots & \vdots & \vdots & \vdots \\ a_{n1}^{+} & a_{n2}^{+} & \cdots & a_{nn}^{+} \end{bmatrix}, \ \mathbf{A}^{-} = \begin{bmatrix} a_{11}^{-} & a_{12}^{-} & \cdots & a_{1n}^{-} \\ a_{12}^{-} & a_{22}^{-} & \cdots & a_{2n}^{-} \\ \vdots & \vdots & \vdots & \vdots \\ a_{n1}^{-} & a_{n2}^{-} & \cdots & a_{nn}^{-} \end{bmatrix} \tag{13}$$

Then, the maximum eigenvalues and their corresponding normalized eigenvectors of $\mathbf{A}^{+}$ and $\mathbf{A}^{-}$ can be calculated and denoted as λ^{+}, λ^{-} and $\mathbf{X}^{+}$, $\mathbf{X}^{-}$ [35].

$$\lambda^{+} = \sum_{i=1}^{n} \left(A^{+}X^{+}\right)_i \Big/ n X_i^{+}, \ \lambda^{-} = \sum_{i=1}^{n} \left(A^{-}X^{-}\right)_i \Big/ n X_i^{-} \tag{14}$$

Meanwhile, coefficients *k* and *m* should be calculated according to Formula (15).

$$k = \sqrt{\sum_{j=1}^{n} \frac{1}{\sum_{i=1}^{n} a_{ij}^{+}}}, \ m = \sqrt{\sum_{j=1}^{n} \frac{1}{\sum_{i=1}^{n} a_{ij}^{-}}} \tag{15}$$

Consequently, the interval weight vector $\left[\bar{\mathbf{W}}\right]$ corresponding to the interval judgment matrix $\left[\bar{\mathbf{A}}\right]$ can be obtained as $\left[\bar{\mathbf{W}}\right] = \left[k\mathbf{X}^{-}, m\mathbf{X}^{+}\right]$ while $\left[\bar{\mathbf{A}}\right]$ is normalized.

2.3.3 Test of selected method

In order to verify the selected method's ability to accurately calculate the weights and represent the corresponding uncertainty, an example test is given and explained in this paper.

We assume that a traditional "point" value judgment matrix is obtained according to expert knowledge as follows. It is expressed in the form of interval matrix so as to unify the data format in the subsequent calculation.

$$\left[\bar{\mathbf{R}}\right] = \begin{bmatrix} (1,1) & (1/7,1/7) & (1/8,1/8) \\ (7,7) & (1,1) & (7/8,7/8) \\ (8,8) & (8/7,8/7) & (1,1) \end{bmatrix}$$

On the other side, taking the epistemic uncertainty of expert judgment into consideration, the judgment matrix is adjusted according to the degree of uncertainty as follows.

$$[\bar{\mathbf{A}}]=\begin{bmatrix}(1,1) & (1/9,1/6) & (1/9,1/6)\\ (6,9) & (1,1) & (1/2,1)\\ (6,9) & (1,2) & (1,1)\end{bmatrix}$$

Next, the iterative method[33] and the constructing complementary matrix method[33] are taken to quantitatively compare them with the selected method. Therefore, a criterion called “interval weight error” is defined as follows to judge the effects of the methods:

$$e=D\left([\bar{\mathbf{A}}]_W,[\bar{\mathbf{A}}]\right)=\left\|[\bar{\mathbf{A}}]_W-[\bar{\mathbf{A}}]\right\|_2=\left(\sum_{i=1}^{n}\sum_{j=1}^{n}\left([\bar{\mathbf{A}}]_{Wij}-[\bar{\mathbf{A}}]_{ij}\right)^2\right)^{\frac{1}{2}} \tag{16}$$

where $[\bar{\mathbf{A}}]_W$ is the new interval judgment matrix obtained according to the comparative importance of the interval weight vector $[\bar{\mathbf{W}}]$.

The weight results obtained from traditional and interval judgment matrices with different methods are respectively shown in Table 1 and Table 2. To compare the effects of the methods, weight results of each index from both traditional and interval judgment matrices are respectively drawn in Figures 2, 3 and 4.

Table 1. Weight results from traditional judgment matrix with different methods

Algorithm	Weight			Interval weight error
	Index 1	Index 2	Index 3	
Iterative method (M1)	(0.0625, 0.0625)	(0.4375, 0.4375)	(0.5000, 0.5000)	0
Interval eigenvalue method (M2)	(0.0625, 0.0625)	(0.4375, 0.4375)	(0.5000, 0.5000)	7.97e-15
Constructing complementary matrix method (M3)	(0.0625, 0.0625)	(0.4375, 0.4375)	(0.5000, 0.5000)	0

Table 2. Weight results from interval judgment matrix with different methods

Algorithm	Weight			Interval weight error
	Index 1	Index 2	Index 3	
Iterative method (M1)	(0.0358, 0.0882)	(0.2263, 0.6021)	(0.2802, 0.7674)	19.1300
Interval eigenvalue method (M2)	(0.0602, 0.0653)	(0.3796, 0.4464)	(0.4712, 0.5706)	2.5233
Constructing complementary matrix method (M3)	(0.0668, 0.0951)	(0.3969, 0.4666)	(0.4526, 0.5222)	4.6886

It is easy to conclude from the results of interval weight errors that all three methods are suitable to calculate the weights of a traditional judgment matrix. However, for the interval judgment matrix, the interval eigenvalue method (M2) is most appropriate, since it receives a more reasonable result with the smallest interval weight error. On the contrary, overestimation of uncertainty occurs in the weight result of M1, as can be seen from Figures 2-4. Besides, as shown in Figure 2, the interval weight obtained by using M3 possibly cannot cover the precise value.

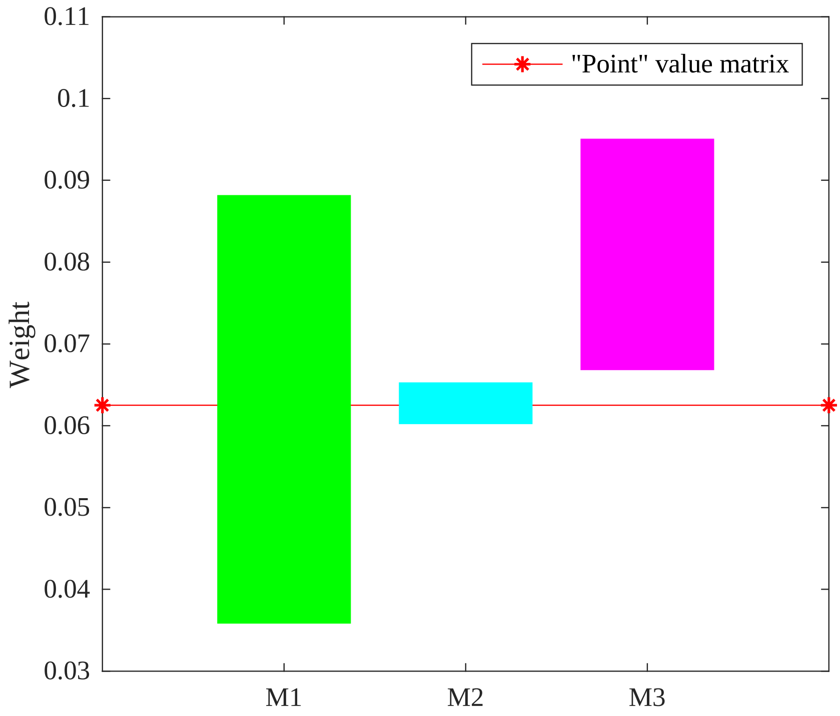

Fig. 2. Weights results of Index 1 with different methods

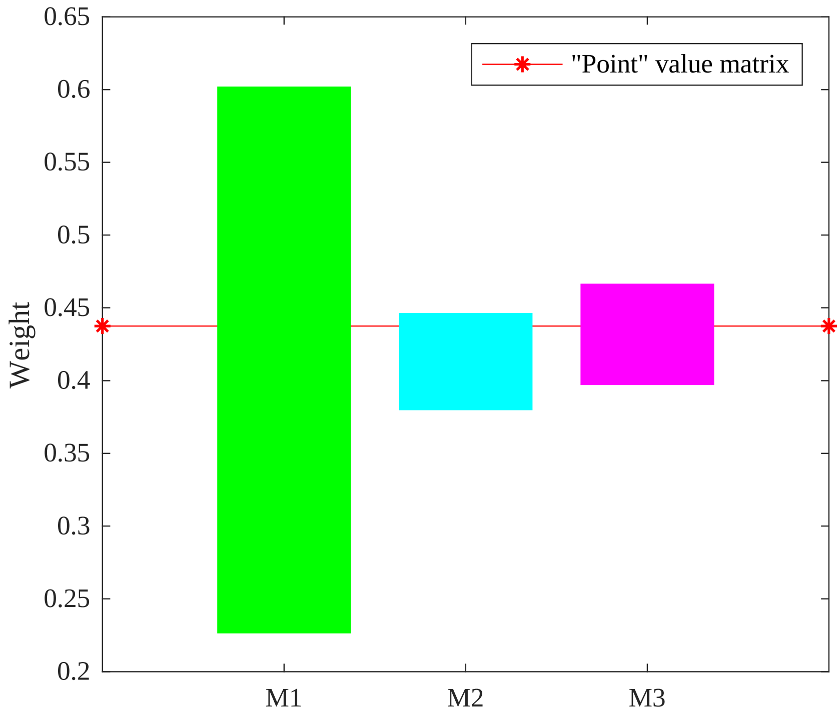

Fig. 3. Weight results of Index 2 with different methods

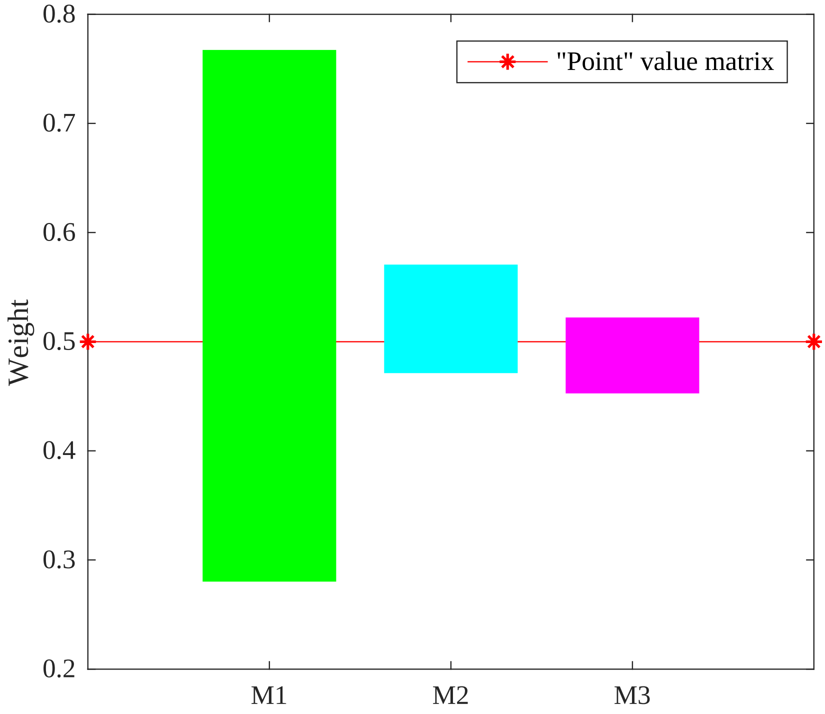

Fig. 4. Weight results of Index 3 with different methods

3. MODELING

Due to the interaction of multiple risk factors such as personnel, equipment and environment, numerous hazards are involved in the maintenance process for onshore oil and gas transmission pipelines. In addition, the propagation path of risk during the maintenance process is quite complex. Also, taking the existence of various uncertainties in risk factors into account, specific modeling for the risk assessment of the maintenance process is desirable in the context of safety management for onshore oil and gas transmission pipelines. By merging interval analysis to an AHP-based risk assessment framework, an interval quantified risk assessment model is established in this paper, realizing the internalization, representation and quantification of uncertainty while assessing the risk of the onshore pipeline maintenance process.

3.1 Generic onshore pipeline maintenance procedure

However, before undertaking the risk assessment, it is necessary to study the maintenance procedure. The specific maintenance procedure for onshore oil and gas transmission pipelines varies from damage modes, degrees and maintenance schemes. Nevertheless, according to practical experiences, the generic procedure is similar and can be summarized as shown in Figure 5.

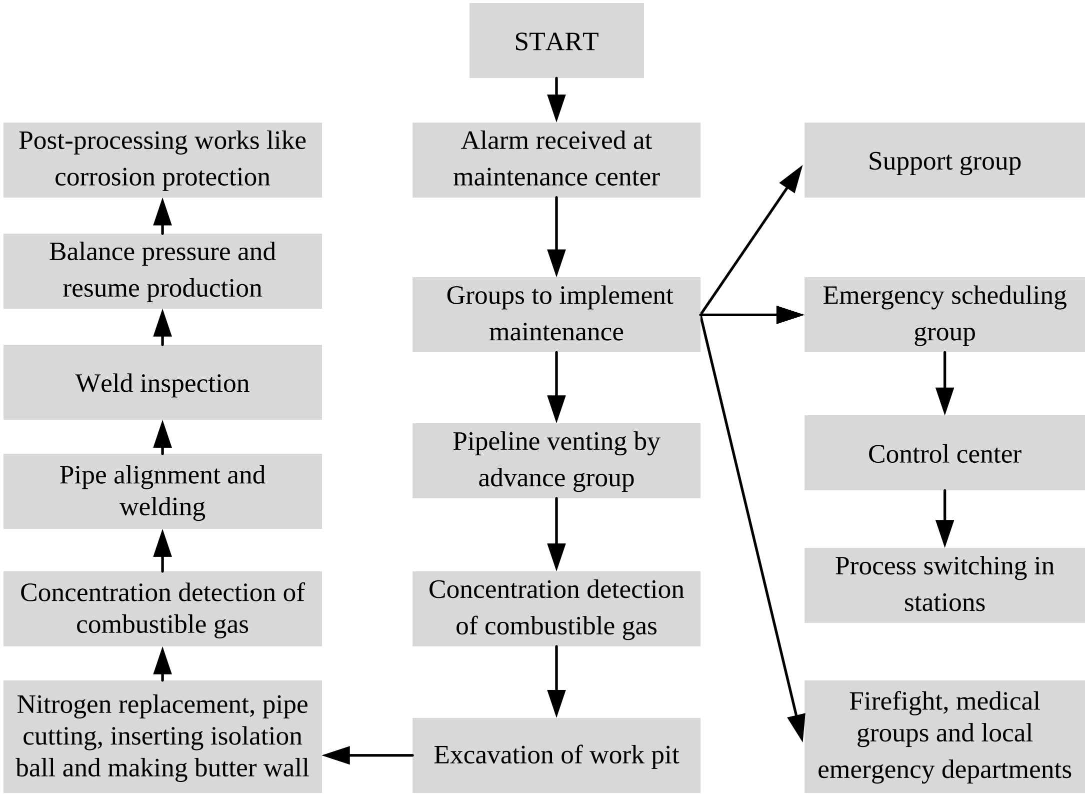

Fig. 5. Generic maintenance procedure for onshore oil and gas transmission pipelines

3.2 Hazard identification based on fishbone diagram

It is clear that the maintenance procedure involves complex works, multi-processes and continuous operations, and numerous hazards exist. Therefore, hazard identification is conducted with the help of the fishbone diagram. Using the theory of risk interface[11], fundamental causes of accidents occurring in the maintenance process are on account of the frequent interaction of personnel, equipment and environment at the interfaces. The hazards of the onshore pipeline maintenance procedure are related to 6 interaction-aspects, as shown in Figure 6.

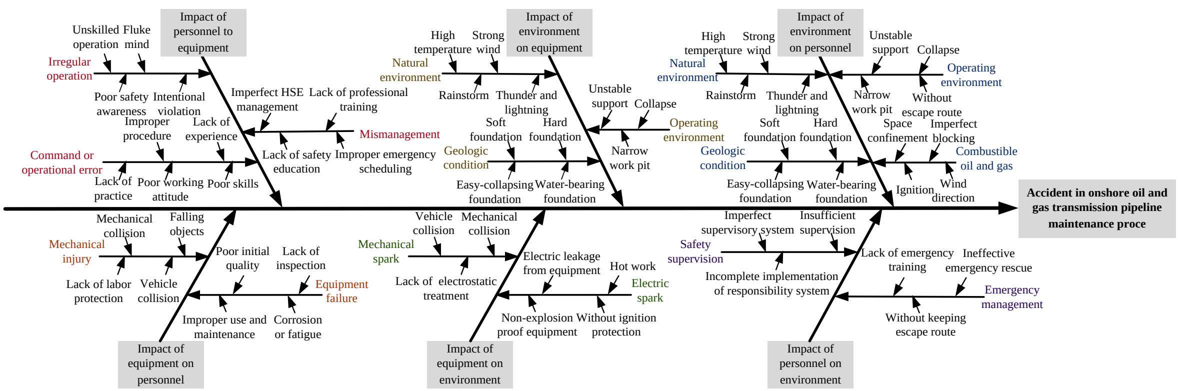

Fig. 6. Hazard identification for the onshore pipeline maintenance procedure

3.3 Index system for risk assessment of the maintenance process

The establishment of an index system has a decisive impact on the result of risk assessment. Focusing on the risk assessment of the oil and gas drilling process, Liu[36] classifies the indexes into two categories, namely the indexes to characterize the likelihood of accident occurrence and the indexes to characterize the severity of accident consequence.

Furthermore, occurrence likelihood indexes are divided into natural, technical, management and economic factors while consequence severity indexes are refined according to the frequency of accident, personnel distribution and loss, and disaster relief capability. Similarly, Zhao[37] analyzed the indexes for risk assessment of oil and gas drilling processes and divided them into risk generative indexes and consequence severity indexes. The former includes natural, technical, management and economic factors while the latter includes the occurrence probability of an accident, personnel distribution and loss, and disaster relief capability. At last, a total of 24 sub-indexes were established in this index system.

The indexes for the risk assessment of the onshore pipeline maintenance process are also established by two categories, namely occurrence likelihood indexes and consequence severity indexes. The occurrence likelihood indexes aim to provide a proxy of the proneness of a secondary accident occurring in the onshore pipeline maintenance process. The consequence severity indexes aim to evaluate the impact magnitude of possible accident consequences. Since the hazards of the onshore pipeline maintenance procedure have been identified, the reasons that may cause secondary accidents are also clarified. Therefore, 10 sub-indexes related to the aspects of personnel, equipment and environment can be identified to characterize the occurrence likelihood by using the result of hazard identification. Besides, according to the investigation of the characteristics of oil and gas accidents and considering the onshore pipeline maintenance procedure, 8 sub-indexes to reflect the consequence severity have been derived, taking into account aspects of accident severity, human distribution and rescue capacity.

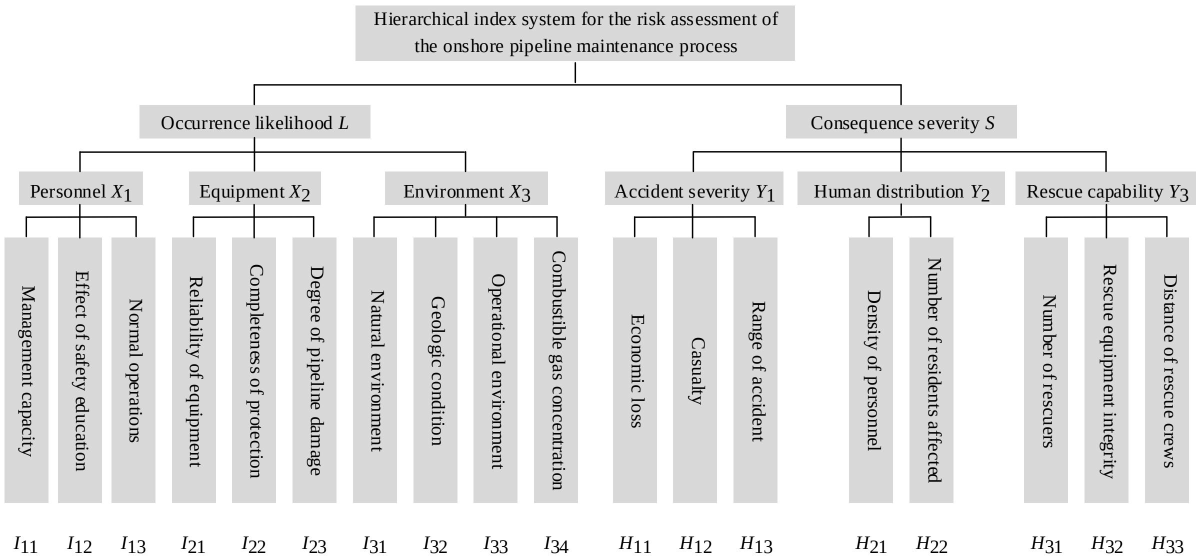

Fig. 7. Hierarchical index system for the risk assessment of the onshore pipeline maintenance process

As a result, a hierarchical index system is developed as shown in Figure 7. In the index system, the first layer indexes are respectively occurrence likelihood and consequence severity, denoted by L and S. The second layer indexes are denoted by X_i and Y_i while the corresponding sub-indexes are denoted by I_{ij} and H_{ij}. Taking the sub-indexes of personnel as an example, they are summarized from the fishbone diagram based hazard identification, reflecting the influence of management capacity (mismanagement, emergency management and safety supervision), effect of safety education and operational activities (irregular operation, command or operational error) on the likelihood of accident occurrence. Other sub-indexes of occurrence likelihood are obtained in a similar way. However, the sub-indexes of consequence severity are given according to the knowledge and experience of field experts.

3.4 Interval quantification criteria of indexes

The proposed index system is the foundation of an interval quantified risk assessment model for the onshore pipeline maintenance process. Since its hierarchical structure has been established, the risk value of the object can be obtained after the sub-indexes are scored and the corresponding weights are determined. Here, the sub-indexes can be categorized into qualitative and quantitative indexes. The qualitative indexes are scored by experts according to knowledge and experience while quantitative indexes are scored according to scientific measurements. However, both the lack of knowledge in qualitative indexes and the measurement errors in quantitative indexes would lead to uncertainties. As aforementioned, to internalize, represent and quantify uncertainty when assessing risk, interval analysis is utilized to transform the whole risk assessment model into an interval quantified one. Initially, interval quantification criteria for all sub-indexes need to be established, i.e. every index needs to be graded, and corresponding interval scores have to be assigned.

In this paper, every qualitative or quantitative index is classified into 5 levels. The difference is that the qualitative indexes are graded according to the linguistic descriptions of experts while the quantitative indexes are graded according to the quantitative criteria of corresponding standards, norms, papers, cases, and so on. For qualitative indexes, taking the management capacity as an example, from “excellent” to “extremely poor”, the linguistic descriptions to determine the 5 levels of the index are given as shown in Table 3. Meanwhile, the corresponding levels are respectively scored with interval numbers (0.8,1.0), (0.6,0.8), (0.4,0.6), (0.2,0.4) and (0.0,0.2). Taking the degree of pipeline damage as an example of quantitative indexes, the quantitative descriptions of damage degree are listed from general to more serious as shown in Table 4, with the corresponding interval scores gradually getting smaller from (0.8,1.0) to (0.0,0.2). Besides, the interval quantification criteria of other qualitative and quantitative indexes are respectively listed in Appendices A and B. It is worth noting that the smaller the interval score is, the greater the level is, meaning the larger the likelihood of accident occurrence or the higher the severity of accident consequence.

Table 3. Interval quantification criterion of management capacity

Logic	Linguistic descriptions	Interval score	Level
Excellent	Evidently reasonable procedure and layout, evidently orderly operations and evidently effective HSE management	(0.8,1.0)	Level 1
Good	Reasonable procedure and layout, orderly operations and effective HSE management	(0.6,0.8)	Level 2
Moderate	Slightly reasonable procedure and layout, slightly orderly operations and slightly effective HSE management	(0.4,0.6)	Level 3
Poor	Unreasonable procedure and layout, disorderly operations and noneffective HSE management	(0.2,0.4)	Level 4
Extremely poor	Extremely unreasonable procedure and layout, extremely disorderly operations and extremely noneffective HSE management	(0.0,0.2)	Level 5

Table 4. Interval quantification criterion of degree of pipeline damage

Degree of pipeline damage	Interval score	Level
Corrosion pit with a diameter less than 5.0mm, corrosion crack with a length less than 50mm or corrosion crack with a width less than 1.0mm	(0.8,1.0)	Level 1
Corrosion pit with a diameter between 5.0-10.0mm, corrosion crack with a length between 50-200mm or corrosion crack with a width between 1.0-3.0mm	(0.6,0.8)	Level 2
Large area of dense corrosion pits with lengths greater than 2.0m	(0.4,0.6)	Level 3
Serious pipeline damage with oil and gas leakage occurring	(0.2,0.4)	Level 4
Extreme circumstances like huge leakage of oil and gas and pipeline fracture occur	(0.0,0.2)	Level 5

3.5 Determination of interval weights

As mentioned in Section 2.3, to handle the epistemic uncertainty of expert judgment in the weight calculation, IAHP is applied to construct interval judgment matrices and to calculate interval weights. However, to better represent and quantify the uncertainty in weight calculation, the principle to determine the interval judgment of comparative importance between indexes is preset as shown in Table 5. That is, the interval judgment $[\bar{A}]_{ij} = (a_{ij}^-, a_{ij}^+)$ is expressed in the form of $(r_{ij} - width, r_{ij})$ or $(r_{ij}, r_{ij} + width)$. Here, r_{ij} is determined according to the traditional reciprocal 1-9 scale table[38], as shown in Appendix C. "$width$" represents and quantifies the degree of uncertainty with a base width δ. In this paper, the base width is set as 1.

Table 5. Principle to determine the interval judgment of comparative importance between indexes

Degree of uncertainty	Unilateral judgment
Certain	(r_{ij}, r_{ij})
Basically certain	$(r_{ij} - \delta, r_{ij})$ or $(r_{ij}, r_{ij} + \delta)^*$
Possible	$(r_{ij} - 2\delta, r_{ij})$ or $(r_{ij}, r_{ij} + 2\delta)$

*Note: $(r_{ij} - \delta, r_{ij})$ represents that it is basically certain that the comparative importance of index *i* to *j* is smaller than r_{ij} while $(r_{ij}, r_{ij} + \delta)$ represents that it is basically certain that the comparative importance of index *i* to *j* is larger than r_{ij}.

Taking the second layer indexes of occurrence likelihood as an example, experts indicate that it is basically certain that the comparative importance of X_1 to X_2 is larger than 1 while that of X_1 to X_3 is larger than 3. Also, it is basically certain that the comparative importance of X_2 to X_3 is smaller than 3. Hence, the interval judgment matrix is determined as follows.

$$[\bar{\mathbf{A}}]_X = \begin{bmatrix} (1,1) & (1,2) & (3,4) \\ (1/2,1) & (1,1) & (2,3) \\ (1/4,1/3) & (1/3,1/2) & (1,1) \end{bmatrix}$$

Subsequently, according to the interval eigenvalue method, the maximum eigenvalues $\lambda_X^+ = 3.5324$ and $\lambda_X^- = 2.5949$ and their corresponding normalized eigenvectors $\mathbf{X}_X^+ = [0.5019, 0.3608, 0.1373]$ and $\mathbf{X}_X^- = [0.5019, 0.3469, 0.1527]$ are calculated.

At the same time, the coefficients *k* and *m* are calculated as follows.

$$k = \sqrt{\sum_{j=1}^{3} \frac{1}{\sum_{i=1}^{1} a_{ij}^+}} = 0.9161 \text{ , } m = \sqrt{\sum_{j=1}^{3} \frac{1}{\sum_{i=1}^{1} a_{ij}^-}} = 1.0801$$

As a result, the interval weight vector $[\bar{\mathbf{W}}]_X$ of the indexes is obtained as follows.

$$[\bar{\mathbf{W}}]_X = [k\mathbf{X}_X^-, m\mathbf{X}_X^+] = [(0.4598, 0.5421), (0.3178, 0.3897), (0.1385, 0.1483)]$$

Similarly, other interval judgment matrices of indexes are given according to expert knowledge and the corresponding interval weights are calculated as shown in Appendix D.

3.6 Interval quantification criteria for risk rating

Although there is still a doubt going on with respect to the understanding and the definition of risk, in this paper, for simplicity reasons, the risk is defined as a combination of the likelihood of accident occurrence and the severity of accident consequence. However, in non-interval risk assessment, the risk of the object will be quantified and visualized as a point in the risk matrix. In the interval quantified risk assessment model in this paper, a shaded rectangle of which the width equals the interval score $\left[\bar{L}\right]$ of occurrence likelihood and the length equals the interval score $\left[\bar{S}\right]$ of consequence severity, will be used to characterize the risk of the object. Equation (17) expresses this line of thought, and not only contains information about the risk of the object but also covers the uncertainty in the risk outcome.

$$R=\left(\left[\bar{L}\right],\left[\bar{S}\right]\right) \tag{17}$$

$\left[\bar{L}\right]$ can be computed through Formulas (18) and (19) while $\left[\bar{S}\right]$ can be obtained similarly.

$$\left[\bar{L}\right]=\sum_{i=1}^{n}\left[\bar{X}_i\right]\cdot\left[\bar{W}_i\right]_X \tag{18}$$

$$\left[\bar{X}_i\right]=\sum_{j=1}^{m}\left[\bar{I}_{ij}\right]\cdot\left[\bar{W}_j\right]_{I_i} \tag{19}$$

where $\left[\bar{I}_{ij}\right]$ and $\left[\bar{W}_j\right]_{I_i}$ are the interval scores and corresponding interval weights of sub-indexes of occurrence likelihood, $\left[\bar{X}_i\right]$ and $\left[\bar{W}_i\right]_X$ are the interval scores and corresponding interval weights of second layer indexes of occurrence likelihood.

However, to rate the risk of a specific object, corresponding quantification criteria should be established. In fact, the rating of overall risk is determined by the ratings of occurrence likelihood and consequence severity. Similar to the grading principle of sub-indexes, the grading of occurrence likelihood is defined as shown in Table 6 while that of consequence severity is shown in Appendix E. After the interval quantification criteria of occurrence likelihood and consequence severity are given, the interval risk matrix can be derived and the corresponding rating criterion for overall risk can be determined, as shown in Figure 8. It can be seen that the more red the color is, the higher the risk will be and the more green the color is, the lower the risk will be.

Table 6. Interval quantification criterion of occurrence likelihood

Level	Logic	Interval score	Linguistic descriptions
Level 1	Excellent	(0.8,1.0)	Operations at the pipeline maintenance site are perfectly organized; Risk factors and hazards that will affect operational safety are timely detected and eliminated; Personnel, equipment and environment are highly coordinated; The possibility of accident occurrence is extremely low; Maintenance can be carried out without restrictions.
Level 2	Good	(0.6,0.8)	Operations at the pipeline maintenance site are well organized; Risk factors and hazards that will affect operational safety may exist; Personnel, equipment and environment are well coordinated; The possibility of accident occurrence is low; Maintenance can be carried out well under supervision.
Level 3	Moderate	(0.4,0.6)	Operations at the pipeline maintenance site are more or less organized; There is a high possibility of existing risk factors and hazards that will affect operational safety; Personnel, equipment and environment are more or less coordinated; The possibility of accident occurrence is high; Maintenance can be carried out after rectification.
Level	Poor	(0.2,0.4)	Operations at the pipeline maintenance site are disorderly organized; Some

4			risk factors and hazards that will affect operational safety exist; Personnel, equipment and environment are poorly coordinated; The possibility of accident occurrence is extremely high; Not suitable for continuing maintenance.
Level 5	Extremely poor	(0.0,0.2)	Operations at the pipeline maintenance site are in chaos; Numerous risk factors and hazards that will affect operational safety exist; Personnel, equipment and environment are badly coordinated; An accident may occur at any time; Maintenance should be suspended immediately.

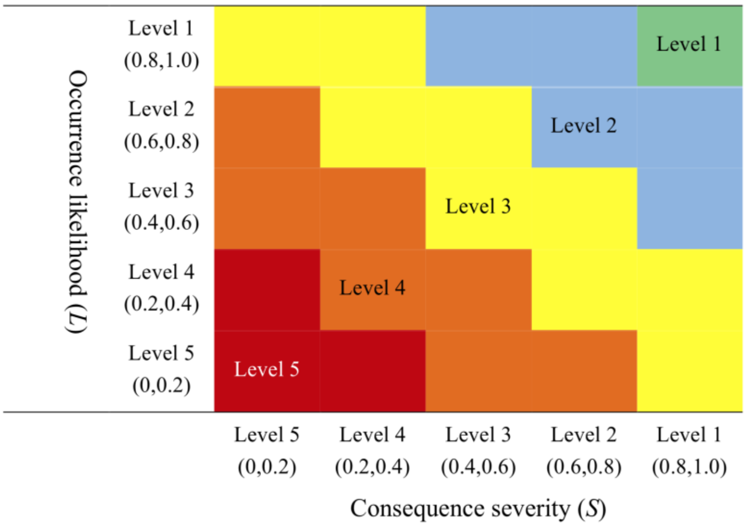

Fig. 8. Interval risk matrix

4. CASE STUDY

4.1 Brief introduction

The developed interval quantified risk assessment model for the onshore pipeline maintenance process is applied to the specific case of emergency maintenance for the Gangqing dual pipeline. The dual pipeline was initially designed and built as two buried gas pipelines. The design pressure and diameter are respectively 10 MPa and 711 mm. However, about 25% of the dual pipeline is now submerged under water because of the path change of a nearby river in 2012. Once some damage is caused on the pipelines, the current situation will definitely increase the difficulty and the risk of the emergency maintenance process.

From a practical viewpoint, emergency maintenance for the Gangqing dual pipeline is implemented according to the procedure as shown in Figure 5, once the alarm is received at the maintenance center. First of all, well-educated and trained maintenance groups rush to the scene with different missions. The gas transmission is shut down by the emergency scheduling group. The equipment and machinery are transported by the support group and are well arranged at the maintenance site as shown in Figure 10. Medical and firefighter groups are also on standby.

After the preliminary preparation, eight engineers and some workers are then commanded to implement emergency maintenance operations. However, considering the special geological condition of the Gangqing dual pipeline, a cofferdam and drainage are employed to form a waterless work area. Before that, the natural gas which remained in the pipeline is evacuated while nitrogen (inert gas) is filled in to keep a positive pressure and to prevent ignition. Also, the concentration of natural gas around the maintenance site is continuously monitored. In this case, a work area of 14×10 m^2 is constructed around the damaged pipe section through an earthwork cofferdam. The work pit is then excavated in the waterless work area. After that, a series of maintenance operations such as nitrogen replacement, pipe cutting, isolation ball inserting, butter wall making, pipe welding, weld inspection, and so on, are completed one after the other, followed by post-processing works like corrosion protection and scene recovery.

Fig. 9. Gangqing dual pipeline before submerged and local scene of emergency maintenance operations

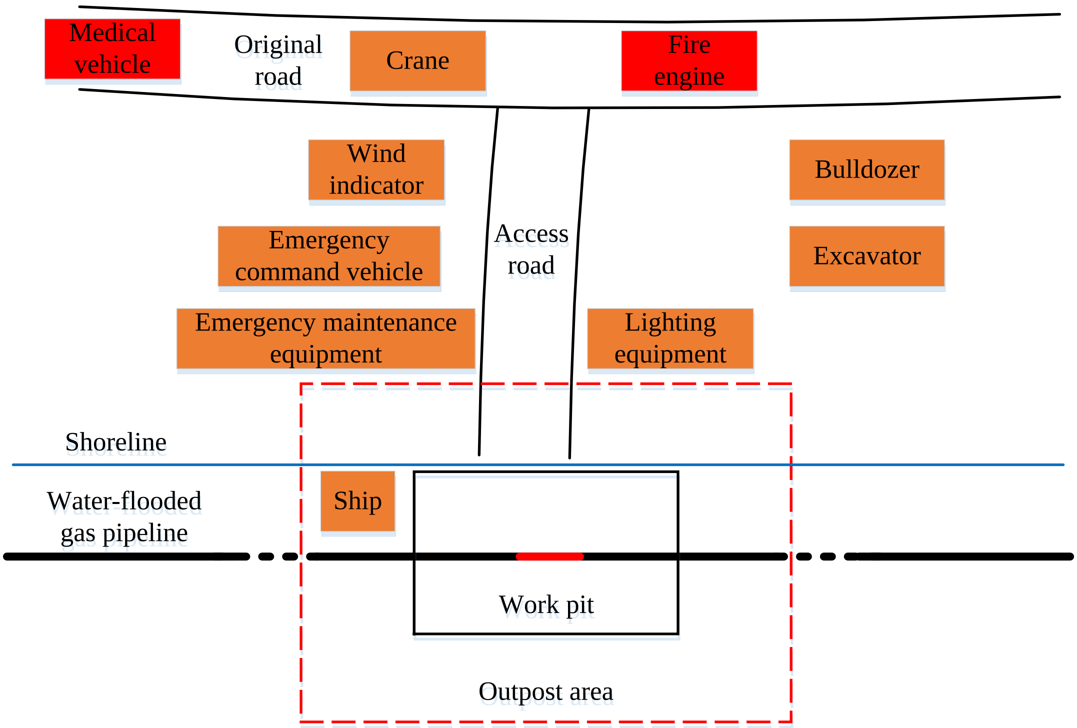

Fig. 10. Arrangement of emergency maintenance equipment and machinery at the maintenance site

4.2 Assessment of overall risk

Following the index system, the emergency maintenance process is assessed by experts. Experts indicate that safety management and normal operations at the scene still can be improved when the staff would be excellently educated and trained. But they are assumed to be "good enough". Meanwhile, the equipment only possesses moderate reliability because its explosion-proof performance has been reduced after long time being unused. Protection measures for staff at the scene are assumed to be "perfect". The damage is reported as a corrosion crack of about 120mm length. In terms of the environment, the natural environment is taken as perfect without high temperature, strong wind, and rain. The ground around the damaged pipe section is full of high water-bearing and low-intensity sludge after long time submergence. Thanks to appropriate processing after drainage, the geological condition is acceptable. The work pit is big enough with stable support but is not perfect because it is surrounded by water. Besides, the concentration of natural gas is always in the range of 25% to 50% of its lower explosion limit.

Moreover, the assessment of sub-indexes of consequence severity is also carried out by experts. The economic loss is predicted to be between 5 and 10 million RMB Yuan while no casualty is expected if a secondary accident occurs during emergency maintenance. The radius of accident range is estimated to be between 5 and 25 meters. The number of personnel at the maintenance site is around 25. The number of residents that can be affected is less than 15. The number of rescuers is between 11 and 20. They are on standby at 5 meters away with limited rescue equipment. As a result, the interval scores of all sub-indexes are listed in Table 7 according to the interval quantification criteria as aforementioned in Section 3.4.

Since the interval weights of the index system have been calculated in Section 3.5, the interval score of occurrence likelihood is then calculated as $\left[\bar{L}\right]=\left(0.60,0.83\right)$ through Formulas (18) and (19), and the interval score of consequence severity is also obtained through similar formulas as $\left[\bar{S}\right]=\left(0.68,0.85\right)$. Consequently, the shaded rectangle is generated in the interval risk matrix according to the interval scores of $\left[\bar{L}\right]$ and $\left[\bar{S}\right]$, to pinpoint the risk rating of the emergency maintenance for the Gangqing dual pipeline as shown in Figure 11. Since most part of the shaded rectangle falls in the blue area, the risk rating of this case is estimated as Level 2.

Table 7. Interval scores of sub-indexes for the specific emergency maintenance

Index	I_{11}	I_{12}	I_{13}	I_{21}	I_{22}	I_{23}
Interval	(0.6,0.8)	（0.8,1.0）	（0.6,0.8）	（0.4,0.6）	（0.8,1.0）	（0.6,0.8）
Index	I_{31}	I_{32}	I_{33}	I_{34}	H_{11}	H_{12}
Interval	（0.8,1.0）	（0.4,0.6）	（0.6,0.8）	（0.4,0.6）	（0.6,0.8）	（0.8,1.0）
Index	H_{13}	H_{21}	H_{22}	H_{31}	H_{32}	H_{33}
Interval	（0.6,0.8）	（0.4,0.6）	（0.6,0.8）	（0.2,0.4）	（0.4,0.6）	（0.4,0.6）

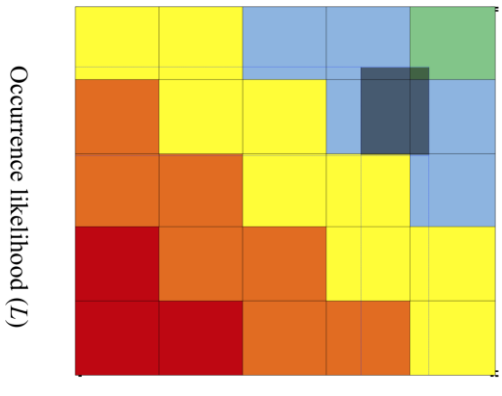

Fig. 11. Risk assessment result in interval risk matrix

4.3 Sensitivity analysis of occurrence likelihood indexes

Sensitivity analysis is hereafter implemented to figure out the impacts of different sub-indexes of occurrence likelihood on the overall risk. The derived sensitivity sorting of indexes will make a valuable contribution to the decision making on preventing the occurrence of accidents.

Given the interval weights of indexes, the sensitivity of a specific index is determined by the difference of the overall risk when gradually changing its level from Level 1 to Level 5.

Taking Index I_{23} (degree of pipeline damage) for example, the influence of upgrading its level from Level 1 (less damage) to Level 5 (more damage) on the overall risk, is calculated.

As shown in Table 8, a set of levels are randomly generated for the indexes as input information. Afterwards, Index I_{23} is considered as one of the 5 levels while randomly generating the interval scores of the other indexes in the range of their assigned levels. To ensure the stability of the result, 1000 simulations are made for every level of the specified index (I_{23}). The final results of $[\bar{L}]$ and $[\bar{S}]$ are constituted by the averages of the corresponding results of the 1000 simulations. As shown in Table 9 and Figures 12-14, the interval score of occurrence likelihood decreases as the level of Index I_{23} escalates from Level 1 to Level 5.

However, in order to quantify the sensitivities of the indexes, the sensitivity of index $S_e(I_{ij})$ is defined as shown in Formula (20):

$$S_e(I_{ij}) = m\left(d\left([\bar{L}]_{\text{Level 1}}^{I_{ij}}, [\bar{L}]_{\text{Level 5}}^{I_{ij}}\right)\right) \tag{20}$$

$$d\left([\bar{A}],[\bar{B}]\right) = \left(\min\left\{\left|b^- - a^-\right|,\left|b^+ - a^+\right|\right\}, \max\left\{\left|b^- - a^-\right|,\left|b^+ - a^+\right|\right\}\right) \tag{21}$$

$$m\left([\bar{A}]\right) = \left(a^- + a^+\right)/2 \tag{22}$$

where $S_e(I_{ij})$ denotes the sensitivity of Index I_{ij}, $d\left([\bar{A}],[\bar{B}]\right)$ denotes the distance between interval $[\bar{A}]$ and interval $[\bar{B}]$, and $m\left([\bar{A}]\right)$ denotes the midpoint of interval $[\bar{A}]$.

As a result, the sensitivity of Index I_{23} can be calculated as follows.

$$S_e(I_{23}) = m\left(d\left([\bar{L}]_{\text{Level 1}}^{I_{23}}, [\bar{L}]_{\text{Level 5}}^{I_{23}}\right)\right) = (0.15+0.21)/2 = 0.18$$

Similarly, the sensitivities of other sub-indexes of occurrence likelihood can be obtained accordingly as shown in Table 10. Consequently, the sensitivity sorting of sub-indexes of occurrence likelihood is as follows.

$$I_{11} > I_{23} > I_{13} > I_{22} > I_{34} > I_{12} > I_{33} > I_{21} > I_{31} > I_{32}$$

Table 8. Randomly inputted levels of sub-indexes of occurrence likelihood

Index	I_{11}	I_{12}	I_{13}	I_{21}	I_{22}	I_{23}
Level	Level 2	Level 3	Level 3	Level 4	Level 3	To be determined
Index	I_{31}	I_{32}	I_{33}	I_{34}	H_{11}	H_{12}
Level	Level 1	Level 3	Level 2	Level 3	Level 3	Level 3
Index	H_{13}	H_{21}	H_{22}	H_{31}	H_{32}	H_{33}
Level	Level 2	Level 1	Level 2	Level 4	Level 3	Level 3

Table 9. Influence of upgrading Index I_{23} from Level 1 to Level 5

Level of I_{23}	Level 1	Level 2	Level 3	Level 4	Level 5
$[\bar{L}]$	(0.63,0.89)	(0.59,0.83)	(0.56,0.78)	(0.52,0.73)	(0.48,0.68)
$[\bar{S}]$	(0.68,0.84)	(0.68,0.84)	(0.68,0.84)	(0.68,0.84)	(0.68,0.84)

Table 10. Sensitivities of sub-indexes of occurrence likelihood

Index	I_{11}	I_{12}	I_{13}	I_{21}	I_{22}	I_{23}	I_{31}	I_{32}	I_{33}	I_{34}
Sensitivity	0.268	0.0424	0.09	0.022	0.084	0.18	0.008	0.007	0.037	0.064

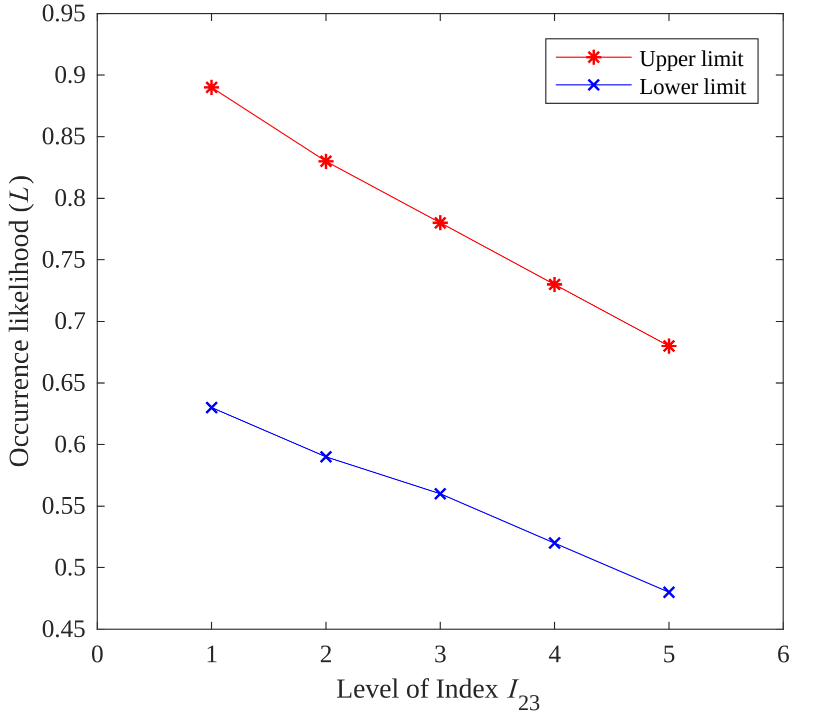

Fig. 12. Trend of occurrence likelihood while changing the level of Index I_{23}

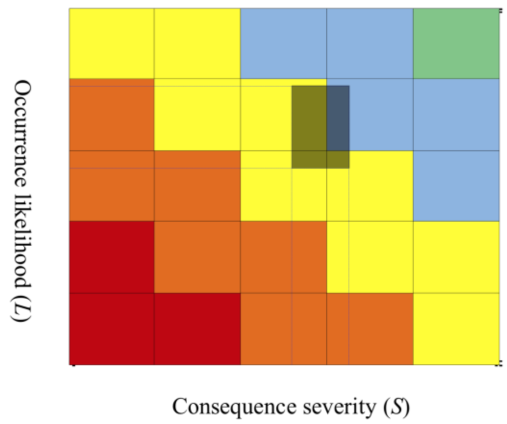

Fig. 13. Risk assessment result in interval risk matrix (I_{23}=Level 1)

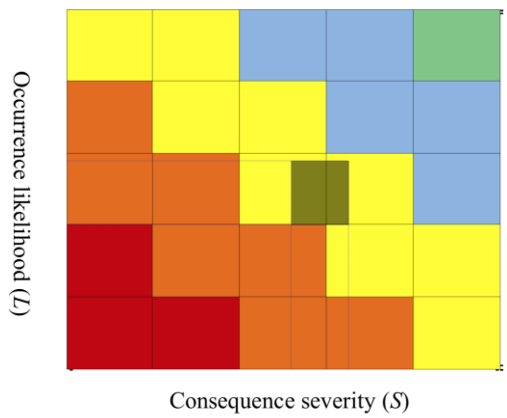

Fig. 14. Risk assessment result in interval risk matrix (I_{23}=Level 5)

4.4 Estimation of consequence severity under missing data

In the industrial practice of the onshore pipeline maintenance process, the data for risk assessment is always hard to acquire, and data collection is sometimes lagging far behind. Under this condition, estimating the overall risk under missing data makes sense.

In this paper, the estimation of consequence severity under missing data is studied as an example. Assuming that the state of a specific sub-index of consequence severity is known while the data of other sub-indexes are all missing, the probability distribution of the rating of consequence severity is calculated afterwards.

First of all, a representative sub-index of consequence severity is chosen according to the results as shown in Table 11. The results are obtained by using a MATLAB algorithm that is used to figure out the index configurations that will lead to the most serious consequence (Level 5 consequence severity) and to calculate the occurrence probabilities of the levels of all indexes.

As shown in Table 11, Level 5 with the highest occurrence probability in Index H_{12} is set as known data. Then, all the other indexes are simulated to upgrade from Level 1 to Level 5 to figure out the occurrence probabilities of the rating of consequence severity as shown in Table 12. The result shows that the consequence severity is most likely to be Level 4 when Index H_{12} is known as in Level 5.

Table 11. Occurrence probabilities of the levels of sub-indexes of consequence severity (S=Level 5)

		Sub-indexes of consequence severity							
		H_{11}	H_{12}	H_{13}	H_{21}	H_{22}	H_{31}	H_{32}	H_{33}
Level	Level 1	0.0480	0	0	0.1082	0	0.1793	0.1380	0.0732
	Level 2	0.0989	0	0	0.1471	0.0049	0.1896	0.1655	0.1196
	Level 3	0.1760	0	0.0023	0.1924	0.0692	0.1993	0.1970	0.1840
	Level 4	0.2768	0.0005	0.1546	0.2450	0.2768	0.2105	0.2306	0.2637
	Level 5	0.4003	0.9995	0.8431	0.3073	0.6491	0.2213	0.2688	0.3595

Table 12. Occurrence probabilities of the rating of consequence severity (H_{12}=Level 5)

Rating of consequence severity	Level 1	Level 2	Level 3	Level 4	Level 5
Times of occurrence	0	0	13041	60798	4287
Occurrence probability	0	0	0.1669	0.7782	0.0549

5. CONCLUSION

This paper expounds on providing a new insight to assess the risk related to the onshore oil and gas transmission pipeline maintenance process under uncertainty. The present research has illustrated that quantitative risk assessment based on AHP and expert knowledge is suitable for this purpose. Therefore, based on the hazard identification results, a hierarchical index system for the risk assessment of onshore pipeline maintenance process is established. However, to deal with uncertainties in the assessment, interval analysis is introduced to extend the risk assessment model into an interval environment. The method to calculate interval weights based on IAHP is therefore studied in this paper. Meanwhile, the interval quantification criteria for the index system are established correspondingly. As a result, the interval quantified risk assessment model for the onshore pipeline maintenance process is obtained. The study shows that interval analysis can effectively internalize and quantify uncertainty. Moreover, the interval risk matrix which is proposed in this paper can visually express the uncertainty-informed overall risk.

Furthermore, the proposed interval quantified risk assessment model is applied for the case of the emergency maintenance process for Gangqing dual pipeline. Since the interval weights for hierarchical indexes have been calculated and the interval scores of sub-indexes have been given by expert opinion, the interval scores $\left[\bar{L}\right]$ and $\left[\bar{S}\right]$ to respectively characterize the likelihood of accident occurrence and the severity of accident consequence are computed. As a result, the shaded rectangle determined by $\left[\bar{L}\right]$ and $\left[\bar{S}\right]$ can be pinpointed in the interval risk matrix to intuitively show the overall risk of the specific emergency maintenance process and the corresponding uncertainty in the risk outcome. Since most part of the shaded rectangle falls in the blue area, the risk rating is estimated as Level 2. According to the rating criteria of occurrence likelihood and consequence severity, operations of this emergency maintenance are well organized while risk factors and hazards may still exist. Personnel, equipment and environment are well coordinated. The possibility of accident occurrence is low. Thus, maintenance can be carried out well under supervision. Besides, even if a secondary accident would occur, the accident scope will be quite small and emergency measures are adequate enough to control the development of this secondary accident and reduce accident losses.

Further research on sensitivity analysis of sub-indexes of occurrence likelihood and risk estimation under missing data are treated. The result indicates that the sensitivity sorting of sub-indexes of occurrence likelihood is $I_{11} > I_{23} > I_{13} > I_{22} > I_{34} > I_{12} > I_{33} > I_{21} > I_{31} > I_{32}$. It is believed that promotion in the aspects of management capacity (I_{11}), normal operations (I_{13}) and completeness of protection (I_{22}) will effectively reduce the occurrence of accidents in the maintenance process and improve operational safety. Besides, when only the data of one or several indexes are known, the risk estimation method under missing data can be extremely useful to evaluate the overall risk. In the example of consequence severity estimation, under the condition of only knowing that the rating of Index H_{12} is Level 5, it can be estimated that the rating of consequence severity is most likely to be Level 4.

ACKNOWLEDGEMENTS

This paper is supported and funded by programs with Science Foundation of China University of Petroleum, Beijing (No. 2462015YQ0406), National Key R&D Program of China (Grant No. 2017YEC0805800), China Scholarship Council (No. [2016] 6188), Sino-Dutch Bilateral Exchange Scholarship programme (Grant CF No. 12273) and Fundamental Research Funds for the Central Public Welfare Research Institutes (Grant No. TKS170107).

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APPENDICES

A. **Interval quantification criteria of qualitative indexes**

Table A.1. Interval quantification criterion of effect of safety education

Logic	Linguistic descriptions of expert judgment	Interval score
Excellent	Personnel with excellent safety attitude and awareness, strong responsibility and excellent emergency skills	(0.8,1.0)
Good	Personnel with good safety attitude and awareness, evident responsibility and good emergency skills	(0.6,0.8)
Moderate	Personnel with moderate safety attitude and awareness, medium responsibility and moderate emergency skills	(0.4,0.6)
Poor	Personnel with slight safety attitude and awareness, inadequate responsibility and slight emergency skills	(0.2,0.4)
Extremely poor	Personnel with poor safety attitude and awareness, sparse responsibility and poor emergency skills	(0.0,0.2)

Table A.2. Interval quantification criterion of normal operations

Logic	Linguistic descriptions of expert judgment	Interval score
Excellent	Personnel extremely familiar with regulations and rules and with excellent professional skills and experience	(0.8,1.0)
Good	Personnel evidently familiar with regulations and rules and with good professional skills and experience	(0.6,0.8)
Moderate	Personnel slightly familiar with regulations and rules and with relatively professional skills and experience	(0.4,0.6)
Poor	Personnel unfamiliar with regulations and rules and with poor professional skills and experience	(0.2,0.4)
Extremely poor	Personnel extremely unfamiliar with regulations and rules and with extremely poor professional skills and experience	(0.0,0.2)

Table A.3. Interval quantification criterion of reliability of equipment

Logic	Linguistic descriptions of expert judgment	Interval score
Excellent	Equipment with excellent quality, perfect operational status and completely inspected	(0.8,1.0)
Good	Equipment with good quality, good operational status and recently inspected	(0.6,0.8)
Moderate	Equipment with acceptable quality, proper operational status and periodically inspected	(0.4,0.6)
Poor	Equipment with poor quality, poor operational status and hardly inspected	(0.2,0.4)
Extremely poor	Equipment with extremely poor quality, terrible operational status and never inspected	(0.0,0.2)

Table A.4. Interval quantification criterion of completeness of protection

Logic	Linguistic descriptions of expert judgment	Interval score
Excellent	Extremely comprehensive protection measures with perfect protection quality	(0.8,1.0)

Good	Fairly comprehensive protection measures with good protection quality	(0.6,0.8)
Moderate	Slightly comprehensive protection measures with moderate protection quality	(0.4,0.6)
Poor	Limited protection measures with poor protection quality	(0.2,0.4)
Extremely poor	Almost without protection measures with extremely poor quality	(0.0,0.2)

Table A.5. Interval quantification criterion of natural environment

Logic	Linguistic descriptions of expert judgment	Interval score
Excellent	Under excellent natural environment without the interference of high temperature, strong wind, rainstorm, etc.	(0.8,1.0)
Good	Under good natural environment with the slight interference of high temperature, strong wind, rainstorm, etc.	(0.6,0.8)
Moderate	Under acceptable natural environment with the interference of high temperature, strong wind, rainstorm, etc.	(0.4,0.6)
Poor	Under poor natural environment with the evident interference of high temperature, strong wind, rainstorm, etc.	(0.2,0.4)
Extremely poor	Under extremely poor natural environment with the severe interference of high temperature, strong wind, rainstorm, etc.	(0.0,0.2)

Table A.6. Interval quantification criterion of geologic condition

Logic	Linguistic descriptions of expert judgment	Interval score
Excellent	Extremely stable geologic condition, foundation with perfect hardness and water content	(0.8,1.0)
Good	Fairly stable geologic condition, foundation with appropriate hardness and water content	(0.6,0.8)
Moderate	Slightly stable geologic condition, foundation with acceptable hardness and water content	(0.4,0.6)
Poor	Unstable geologic condition, foundation with inappropriate hardness and water content	(0.2,0.4)
Extremely poor	Extremely unstable geologic condition, foundation may collapse at any time	(0.0,0.2)

Table A.7. Interval quantification criterion of operational environment

Logic	Linguistic descriptions of expert judgment	Interval score
Excellent	Excellent operational environment, extremely standardized work pit and support measures with reasonable escape route	(0.8,1.0)
Good	Good operational environment, evidently standardized work pit and support measures with escape route	(0.6,0.8)
Moderate	Moderate operational environment, slightly standardized work pit and support measures with poor escape route	(0.4,0.6)
Poor	Poor operational environment, fairly unstandardized work pit and support measures without reasonable escape route	(0.2,0.4)
Extremely poor	Extremely poor operational environment, poor work pit and support measures without escape route	(0.0,0.2)

Table A.8. Interval quantification criterion of rescue equipment integrity

Logic	Linguistic descriptions of expert judgment	Interval score
Excellent	High completeness and practicality of rescue equipment	(0.8,1.0)
Good	Slightly high completeness and practicality of rescue equipment	(0.6,0.8)
Moderate	Moderate completeness and practicality of rescue equipment	(0.4,0.6)
Poor	Poor completeness and practicality of rescue equipment	(0.2,0.4)
Extremely poor	Extremely poor completeness and practicality of rescue equipment	(0.0,0.2)

B. **Interval quantification criteria of quantitative indexes**

Table B.1. Interval quantification criterion of combustible gas concentration

Combustible gas concentration	Interval score
0-10%LEL	(0.8,1.0)
10-25%LEL	(0.6,0.8)
25-50%LEL	(0.4,0.6)
50-75%LEL	(0.2,0.4)
75-100%LEL	(0.0,0.2)

Table B.2. Interval quantification criterion of economic loss

Economic loss (Unit: 10,000 Yuan)	Interval score
<500	(0.8,1.0)
500-1000	(0.6,0.8)
1000-5000	(0.4,0.6)
5000-10000	(0.2,0.4)
>10000	(0.0,0.2)

Table B.3. Interval quantification criterion of casualty

Casualty (Unit: Person)	Interval score
None	(0.8,1.0)
1-3 deaths or 1-10 seriously injured	(0.6,0.8)
3-10 deaths or 10-50 seriously injured	(0.4,0.6)
10-30 deaths or 50-100 seriously injured	(0.2,0.4)
>30 deaths or >100 seriously injured	(0.0,0.2)

Table B.4. Interval quantification criterion of range of accident

Range of accident (*d* represents the radius from the accident center; Meter)	Interval score
0<*d*≤5	(0.8,1.0)
5<*d*≤25	(0.6,0.8)
25<*d*≤50	(0.4,0.6)
50<*d*≤100	(0.2,0.4)
d>100	(0.0,0.2)

Table B.5. Interval quantification criterion of density of personnel

Density of personnel (*n* represents the overall number of personnel in the operating zone; Person)	Interval score
0<*n*≤10	(0.8,1.0)
11<*n*≤20	(0.6,0.8)
21<*d*≤30	(0.4,0.6)
31<*d*≤40	(0.2,0.4)
d>40	(0.0,0.2)

Table B.6. Interval quantification criterion of number of residents affected

Number of residents affected (The number of residents within the scope of 2km along the pipeline and 200m from both sides the pipeline; Household)	Interval score
0	(0.8,1.0)
1-15	(0.6,0.8)
16-100	(0.4,0.6)
>100	(0.2,0.4)
Region concentrated with buildings of more than 4 stories, frequent traffic and underground facilities	(0.0,0.2)

Table B.7. Interval quantification criterion of number of rescuers

Number of rescuers (*M* represents the number of rescuers; Person)	Interval score
M>40	(0.8,1.0)

31<M≤40	(0.6,0.8)
21<M≤30	(0.4,0.6)
11<M≤20	(0.2,0.4)
0<M≤10	(0.0,0.2)

Table B.8. Interval quantification criterion of distance of rescue crews

Distance of rescue crews (L represents the distance of rescue crews; Km)	Interval score
0<L≤2	(0.8,1.0)
2<L≤4	(0.6,0.8)
4<L≤6	(0.4,0.6)
6<L≤8	(0.2,0.4)
L>10	(0.0,0.2)

Note: The interval quantification criteria of economic loss and casualty are established on the reference of "Regulations on the Reporting, Investigation and Disposition of Work Safety Accidents"; The interval quantification criterion of number of residents affected is established on the reference of "GB50251-2003 Code for design of gas transmission pipeline engineering"; The interval quantification criteria of range of accident, density of personnel, number of rescuers and distance of rescue crew are established according to Reference [37].

C. **Traditional reciprocal 1-9 scale table**

Table C.1. traditional reciprocal 1-9 scale table

Comparative importance	Definition	Description
1	Equally	Equally contribute to the target
3	Slightly	The former is slightly more important than the latter
5	Evidently	The former is evidently more important than the latter
7	Strongly	The former is strongly more important than the latter
9	Extremely	The former is extremely more important than the latter
2, 4, 6, 8	Intermediate judgment values	The intermediate values of adjacent judgments

D. **Interval judgment matrices and interval weights**

Table D.1 Interval judgment matrix and interval weights of indexes of personnel

	I_{11}	I_{12}	I_{13}
I_{11}	(1,1)	(5,6)	(3,4)
I_{12}	(1/6,1/5)	(1,1)	(1/3,1/2)
I_{13}	(1/4,1/3)	(2,3)	(1,1)
Interval weights	(0.6536,0.6843)	(0.1024,0.1090)	(0.2105,0.2371)

Table D.2 Interval judgment matrix and interval weights of indexes of equipment

	I_{21}	I_{22}	I_{23}
I_{21}	(1,1)	(1/5,1/4)	(1/8,1/6)
I_{22}	(4,5)	(1,1)	(1/3,1/2)
I_{23}	(6,8)	(2,3)	(1,1)
Interval weights	(0.0745,0.0790)	(0.2867,0.3068)	(0.5901,0.6579)

Table D.3 Interval judgment matrix and interval weights of indexes of environment

	I_{31}	I_{32}	I_{33}	I_{34}
I_{31}	(1,1)	(1,1)	(1/7,1/5)	(1/8,1/7)

I_{32}	(1,1)	(1,1)	(1/7,1/5)	(1/8,1/7)
I_{33}	(5,7)	(5,7)	(1,1)	(1/3,1/2)
I_{34}	(7,8)	(7,8)	(2,3)	(1,1)
Interval weights	(0.0624,0.0616)	(0.0624,0.0616)	(0.2930,0.3355)	(0.5334,0.5800)

Table D.4 Interval judgment matrix and interval weights of indexes of consequence impact

	Y_1	Y_2	Y_3
Y_1	(1,1)	(5,6)	(6,7)
Y_2	(1/6,1/5)	(1,1)	(2,3)
Y_3	(1/7,1/6)	(1/3,1/2)	(1,1)
Interval weights	(0.7292,0.7426)	(0.1618,0.1817)	(0.0867,0.0919)

Table D.5 Interval judgment matrix and interval weights of indexes of accident severity

	H_{11}	H_{12}	H_{13}
H_{11}	(1,1)	(1/7,1/5)	(1/4,1/3)
H_{12}	(5,7)	(1,1)	(2,3)
H_{13}	(3,4)	(1/3,1/2)	(1,1)
Interval weights	(0.0897,0.0961)	(0.5866,0.6537)	(0.2737,0.2972)

Table D.6 Interval judgment matrix and interval weights of indexes of human distribution

	H_{21}	H_{22}
H_{21}	(1,1)	(1/4,1/3)
H_{22}	(3,4)	(1,1)
Interval weights	(0.2183,0.2295)	(0.7563,0.7952)

Table D.7 Interval judgment matrix and interval weights of indexes of rescue capability

	H_{31}	H_{32}	H_{33}
H_{31}	(1,1)	(1/4,1/3)	(1/7,1/5)
H_{32}	(3,4)	(1,1)	(1/3,1/2)
H_{33}	(5,7)	(2,3)	(1,1)
Interval weights	(0.0879,0.0961)	(0.2737,0.2972)	(0.5866,0.6537)

E. **Interval quantification criterion of consequence severity**

Table E.1 Interval quantification criterion of consequence severity

Index level	Logic	Interval score	Linguistic description
Level 1	Excellent	(0.8,1.0)	The accident scope is very small and the consequence severity is very low; Emergency measures are complete and can perfectly control the development of accident and minimize accident losses.
Level 2	Good	(0.6,0.8)	The accident scope is small and the consequence severity is low; Emergency measures are relatively complete and can control the development of accident and reduce accident losses.
Level 3	Moderate	(0.4,0.6)	The accident scope is medium and the consequence severity is medium; Emergency measures are generally complete and can control the development of accident and reduce accident losses to a certain extent.
Level 4	Poor	(0.2,0.4)	The accident scope is large and the consequence severity is high; Emergency measures are not complete and can hardly control the development of accident.
Level 5	Extremely poor	(0.0,0.2)	The accident scope is very large and the consequence severity is very high; Emergency measures cannot control the development of accident.