



Risk assessment for oil leakage under the common threat of multiple natural hazards

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Abstract

Petroleum industry can create enormous wealth and employment opportunities, which is one of the pillars of the national economy. The transportation conditions of petroleum products are complex and changeable. The natural disaster-induced dangerous chemical leakage may damage the ecological environment, which leads to substantial economic losses. It significantly undermines the sustainable development agenda. Therefore, assessing the possibility of leakage and the potential environmental damages becomes a primary task to decision-makers to formulate maintenance plans. This paper evaluated the risk of an oil pipeline leakage under the regional geological disasters. Specifically, risk assessment indicators system was established considering the common threat of multiple natural hazards in the region. The sensitivities of the influence factors were determined using the combined GIS and the contribution rate model. The fuzzy analysis approach was used to process the expert's judgment to obtain a real-time disaster hazard. Meanwhile, in terms of the analysis of pipeline failure causes, the assessment system of disaster resistance ability was developed to determine the possibility of leakage. The leakage-induced environmental losses were quantified by monetary quantification. Finally, the level of environmental risk was determined using a 5×5 probability-currency matrix. Case results show that the risk level is medium, thereby appropriate maintenance measures need to be taken to reduce the risk. Overall, this study provides necessary help to prevent the leakage of petroleum products in transportation. Also, the environmental risk presented in the form of currency can promote non-environmental professional risk decision-makers better understand the degree of risk.

Keywords Oil leakage · Risk assessment · Natural hazard · Environmental risk

Introduction

With the development of the global economy, the demand for countries for petroleum energy is continuously increasing (Sharma and Maheshwari 2017). Long-distance transportation

is required due to the uneven distribution of petroleum resources. To be specific, transportation methods normally can be realized by vehicle, ship, and pipeline, in which pipeline transportation accounts for the vast majority of these methods. In the case of long-distance transit based on the pipeline, natural disasters will cause damage to facilities due to the external destructive power (Qureshi et al. 2019), which may lead to the leakage of hazardous chemicals. In consequence, this will generate environmental pollution and substantial economic losses, which cannot be ignored during the daily service. For example, in 2010, an oil pipeline broke down in Michigan, the USA, spilling about 4.5 million liters of oil to the Kalamazoo River. In 2013, an oil pipeline broke down in Arkansas, leading to require the evacuation of more than 20 houses (Cheng 2016). Given this, it is indispensable to ensure the safe service of the transportation facility through a series of preventive measures, especially for the long-distance metallic pipeline. Among them, risk assessment is an essential and vital link that can find local areas prone to leakage, which makes maintenance and repair targeted and timely.

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As the urgent requirements for sustainable energy supply and social development, risk assessment is the basis for preventing and mitigating environmental risks (Wang et al. 2014; He et al. 2018). Quantitative risk assessment work includes evaluating the occurrence likelihood and consequences of the hazard. The former in this work is to predict the occurrence possibility of hazards caused by natural disasters. Shan et al. (2018) established the historical failure model based on the database of the Pipeline and Hazardous Materials Safety Administration (PHMSA). The model proposed can reflect the objectivity of the evaluation. However, the accuracy of the assessment all depended on the applicability of the database. Not all pipelines were suitable for the published historical failure database due to the significant difference between the operating environment and the management level. Thus, scholars developed index scoring methods and fault tree methods (Muhlbauer 2004; Badida et al. 2019). The internal and external causes of pipeline failure were comprehensively analyzed to build the evaluation index system and basic event table for assessment. The fuzzy comprehensive evaluation method and expert judgment method used to quantify risk were suitable for the quantitative evaluation with insufficient historical fault data samples.

Given the threat of geological disasters, scholars have developed the methods for single disasters such as earthquakes (Li et al. 2020), floods (Seejata et al. 2018), landslides (Ambrosi et al. 2018), and debris flows (Ouyang et al. 2019). Remote sensing, geographic information system (GIS), and InSAR technologies can be used to analyze disaster risk in combination with historical data on natural disasters. In practice, some pipeline sections are threatened by more than one type of geological hazard when passing a complex geological environment. The single hazard risk assessment method is no longer applicable. For this reason, scholars also developed regional geological disaster risk assessment methods, which were more suitable for real geological environments (Chen et al. 2019a, Johnson et al. 2016). Nevertheless, such methods have not been discussed in pipeline engineering. Note further, the pipe steel is disaster-resistant, which directly affects the possibility of leakage. The obtained leakage probability is conservative if ignoring that, which will make the assessment result greater than the actual risk and lead a waste of resources. For the assessment of the generalized consequences, there are many assessment projects involved, such as human health, property losses, and ecological environment pollution. Owing to the results are not the same dimension, it is hard to control the overall risk situation comprehensively. Furthermore, the evaluation involves environmental expertise. Consequently, it is challenging for non-environmental professional risk decision-makers to understand and communicate the analysis results.

Set against the above background, this study developed an environmental risk assessment approach to assess the leakage

risk of Lan-Cheng crude oil pipeline considering the common threat of multiple natural disasters. Specifically, this work (i) ① established a hazard assessment index system based on GIS, and ② developed an improved expert judgment method based on fuzzy set theory for hazard assessment of influence factors; and (ii) built a pipeline vulnerability assessment system to assess the resistance of the pipeline structure to natural disasters; next, (iii) unified the generalized environmental losses into monetary units for comprehensive analysis from the perspective of the operator. In short, this paper proposes a more comprehensive model of oil leakage-induced environmental risk assessment, which can help decision-makers understand the risk status intuitively and further help to develop more effective maintenance plans.

Site description

The study area locates in Lizhou District, Guangyuan City, China (Fig. 1). The average annual rainfall and temperature are 972.6 mm and 14.5 °C, respectively. More than 85% of the yearly rain is concentrated between May and October, leading to a climate phenomenon of dry winter, dry spring, summer flood, and waterlogging in autumn. This site is an area prone to natural disasters, and various natural disasters have occurred there according to historical records. Through geological exploration, there are groundwater outcrops and surface ponding in the front scarps and depressions of the slope. Furthermore, the front edge is a reservoir, the pipeline is buried in the backside, and there are residential buildings and crops.

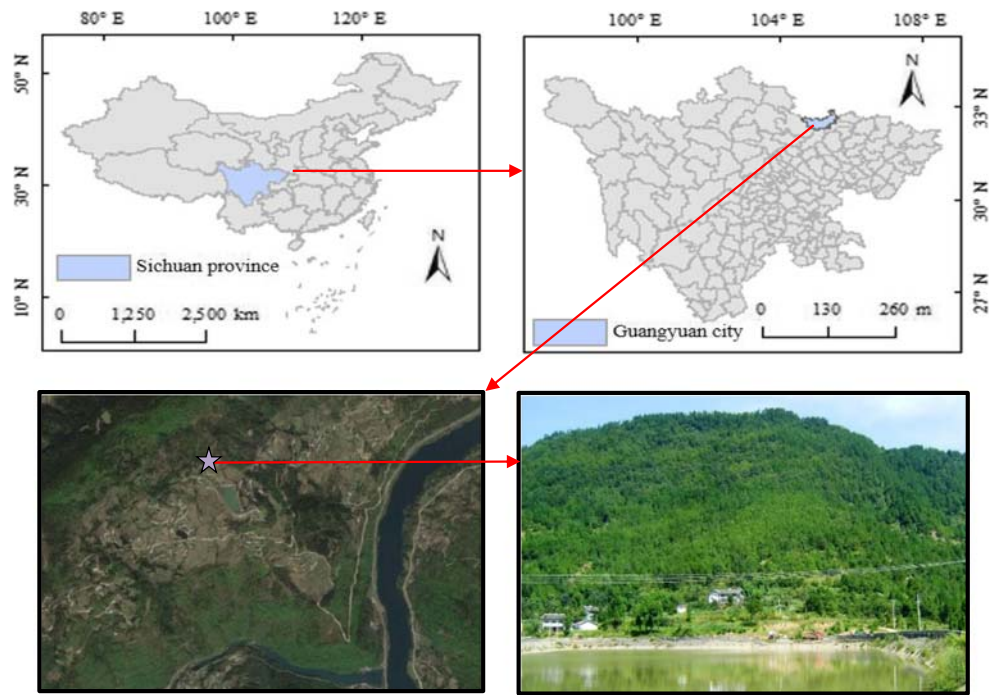
The Lan-Cheng crude oil pipeline through the study area began serving from 2014, with a total length of 882 km. It is made of X65 pipe steel with a diameter of 610 mm, a wall thickness of 9.5 mm, a designed pressure of 8–13.4 MPa, and an average velocity of 1.2 m/s².

Method

Hazard assessment

Through geological hazard investigation, remote sensing images, and existing literature and records, the index system for single disaster risk assessment can be built in the region. Hazards of natural disasters can be obtained by quantifying the impact of each index on the occurrence of geological hazards, while this method will no longer be applicable if multiple geological disasters occur in the same area. Hence, this study will propose an approach for risk assessment under the common threat of multiple geological hazards. Specifically, it includes the following steps: (i) identifying the type of natural disaster in the study area; (ii) developing an index system for regional hazard risk evaluation; (iii) assessing the sensitivity

Fig. 1 Location of the study area



of the impact factors; and finally, (iv) quantifying the hazard of each factor.

Developing risk assessment index system

Topography and geomorphology, characteristics of geotechnical bodies, the intensity of human engineering activities, and precipitation are critical influencing factors affecting the risk assessment of geological disasters (Sarmiento 2009; Johansson 2015; Vezzoli et al. 2017). Nonetheless, various factors have different degrees of influence on specific disasters. Consequently, it is necessary to comprehensively integrate the existing data to identify the main types of disasters in the region and discuss the factors affecting the catastrophes occurring. Thereby the index system of geological hazard risk assessment is developed, and the primary and secondary factors are selected. Finally, the common factors of different types of geological disasters in the region are selected from the main factors to establish an evaluation index system.

Determination of impact factor sensitivity

Identifying influencing factors and sensitivity assessment are the basics of hazard assessment. The sensitivity reflects the weight of each influencing factor, and it will affect the accuracy of the evaluation results directly. Currently, there are two types of methods for determining sensitivity, including subjective and objective approaches. The subjective one adopts the expert consultation method. It depends on the experience of experts to give approximate impact factor weights in the case of insufficient data (Chen et al. 2016). This method has

high operability and is suitable for semi-quantitative and qualitative risk analysis.

The objective methods include such as the entropy weight method (Liang et al. 2019) and the contribution rate analysis method (Wang et al. 2016). The entropy weight method is to determine the objective weight according to the difference of the index. The weight becomes smaller as the entropy value gets larger. The calculation steps of weight are standardizing data, calculating entropy, and determining entropy weight.

Normalizing the raw data:

$$L_{mn} = (I_{ij})_{mn} \tag{1}$$

where $I_{ij} \in L_{mn}$. The original data has m indicators and n evaluation units; L_{mn} represents normalized data.

Calculating entropy, the entropy of the i th evaluation index e_i is:

$$e_i = \frac{\sum_{j=1}^n p(x_{ij}) \ln p(x_{ij})}{\ln n} \tag{2}$$

where $p(x_{ij}) = \frac{I_{ij}}{\sum_{j=1}^n I_{ij}}$.

Determining entropy weight, the entropy weight of the i th evaluation index w_i is:

$$w_i = \frac{1-e_i}{\sum_{i=1}^n (1-e_i)} (0 \leq w_i \leq 1) \tag{3}$$

where $\sum_{i=1}^m w_i = 1$.

The sensitivity of the influence factor is the contribution of each factor to the development of geological hazards. Consequently, the contribution rate analysis method for economic benefit analysis is introduced to assessing the natural disaster hazard, thereby proposing the contribution rate model. The advantages of this model are simple and not limited by region. It can objectively reflect the sensitivity of each evaluation factor (Chen et al. 2019c).

$$t_m = \sum_{n=1}^N t_{mn} \tag{4}$$

$$S_m = \frac{t_m}{\sum_{m=1}^M t_m} \tag{5}$$

where t_{mn} is the score of the m th evaluation index in the n th disaster sample; N is the number of geological disaster samples; t_m is the total contribution value of the m th evaluation index; M is the number of evaluation indicators; S_m is the weight of the m th evaluation index.

Hazard assessment of the indexes

After determining the sensitivity of indexes, it is necessary to determine further the influencing degree of each index, which depends on the real-time geological environment and historical occurrence data of disaster in this region. Expert evaluation can be a reliable source of data if there is little data available. Nonetheless, experts can only use degree language to describe the impact due to the randomness of the hazard index. In combination with geological engineering, the degree of danger can be characterized by very low (VL), low (L), relatively low (RL), medium (M), relatively high (RH), high (H), and very high (VH) (Fig. 2) (Piadeh et al. 2018). There are ambiguity and uncertainty in these language values. Generally, fuzzy mathematics can be used to convert language values into numerical values.

Before the evaluation, multiple experts in different fields of geological engineering and pipeline engineering industries should be invited to reduce human subjectivity. Nevertheless,

they have different advantages and professional level due to the difference in personal experience and knowledge level of multiple experts. For this reason, it is not appropriate to use the mathematical mean or median of their conclusion as the evaluation result. It is necessary to assess the level of expertise to obtain reliable and objective results. In this study, the analytic hierarchy process (AHP) is introduced to developing the evaluation system to get the weights of various experts (Erdogan et al. 2017). The factors affecting the ability of experts are used to assess the weight of experts. In AHP, the target is to assess personal ability (PA), which is the first level of the system; the factors affecting expert knowledge include professional title (PT), professional experience (PE), and education background (EB), which constitute the second level of the system; the third level is the experts participating in the assessment (Li et al. 2019b).

After the analysis above, the influence degree of each factor can be carried out according to the following steps:

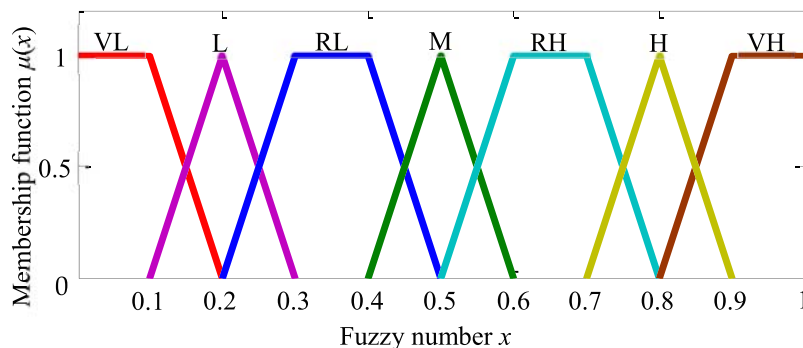
1. The assessment team composed of experts judges the impact factors

An evaluation team, including experts from different sectors of the geological engineering industry, inspects the geological environment in the evaluation area and then discusses the danger of the impact indexes.

2. Transforming language value into a fuzzy number

Fuzzy cut set theory can be used to process these uncertain language values. The membership function expressions include triangular fuzzy number membership function, trapezoidal fuzzy number membership function, and Gaussian fuzzy number membership function. Triangular and trapezoidal fuzzy numbers are widely used in fuzzy linear calculations due to their high efficiency and simplicity. They can provide more accurate descriptions and more reliable solutions, which are commonly used in real-time systems. Accordingly, these linguistic values can be replaced by fuzzy triangular numbers and trapezoidal fuzzy numbers in this work.

Fig. 2 Fuzzy numbers represent linguistic value



$$\mu(x) = \begin{cases} \frac{x-a}{b-a} & (a < x \leq b) \\ \frac{c-x}{c-b} & (b < x < c) \\ 0 & \text{otherwise} \end{cases} \tag{6a}$$

$$\mu(x) = \begin{cases} \frac{x-a}{b-a} & (a < x \leq b) \\ 1 & (b < x < c) \\ \frac{d-x}{d-c} & (c < x < d) \\ 0 & \text{otherwise} \end{cases} \tag{6b}$$

where a, b, c, and d are the upper and lower limits of the fuzzy number representing natural language, respectively.

Thus, Eq. 7 (a–g) represent membership functions at different levels:

$$\mu_{vL}(x) = \begin{cases} 1, & 0 \leq x \leq 0.1 \\ \frac{0.2-x}{0.1}, & 0.1 \leq x \leq 0.2 \\ 0, & \text{otherwise} \end{cases} \tag{7a}$$

$$\mu_L(x) = \begin{cases} \frac{x-0.1}{0.1}, & 0.1 \leq x \leq 0.2 \\ \frac{0.3-x}{0.1}, & 0.2 \leq x \leq 0.3 \\ 0, & \text{otherwise} \end{cases} \tag{7b}$$

$$\mu_{rL}(x) = \begin{cases} \frac{x-0.2}{0.1}, & 0.2 \leq x \leq 0.3 \\ 1, & 0.3 \leq x \leq 0.4 \\ \frac{0.5-x}{0.1}, & 0.4 \leq x \leq 0.5 \\ 0, & \text{otherwise} \end{cases} \tag{7c}$$

$$\mu_M(x) = \begin{cases} \frac{x-0.4}{0.1}, & 0.4 \leq x \leq 0.5 \\ \frac{0.6-x}{0.1}, & 0.5 \leq x \leq 0.6 \\ 0, & \text{otherwise} \end{cases} \tag{7d}$$

$$\mu_{rH}(x) = \begin{cases} \frac{x-0.5}{0.1}, & 0.5 \leq x \leq 0.6 \\ 1, & 0.6 \leq x \leq 0.7 \\ \frac{0.8-x}{0.1}, & 0.7 \leq x \leq 0.8 \\ 0, & \text{otherwise} \end{cases} \tag{7e}$$

$$\mu_H(x) = \begin{cases} \frac{x-0.7}{0.1}, & 0.7 \leq x \leq 0.8 \\ 1, & 0.8 \leq x \leq 0.9 \\ 0, & \text{otherwise} \end{cases} \tag{7f}$$

$$\mu_{vH}(x) = \begin{cases} \frac{0.8-x}{0.1}, & 0.8 \leq x \leq 0.9 \\ 1, & 0.9 \leq x \leq 1 \\ 0, & \text{otherwise} \end{cases} \tag{7g}$$

The corresponding fuzzy numbers are defined as follows:

$$\begin{aligned} \mu_{vL}(x) &= [0, 0, 0.1, 0.2], \quad \mu_L(x) = [0.1, 0.2, 0.3], \\ \mu_{rL}(x) &= [0.2, 0.3, 0.4, 0.5], \quad \mu_M(x) = [0.4, 0.5, 0.6], \\ \mu_{rH}(x) &= [0.5, 0.6, 0.7, 0.8], \quad \mu_H(x) = [0.7, 0.8, 0.9], \\ \mu_{vH}(x) &= [0.8, 0.9, 1, 1]. \end{aligned}$$

A comprehensive discussion of expert evaluation is made using the α -cut set theory. The α -cut of the fuzzy number W can be described as:

$$W_\alpha = \{x, x \in \mathbb{R}, \mu_W \geq \alpha\} = [z_L, z_U]$$

where z_L and z_U represent the upper and lower limits of each α cut set, respectively. Hence, the upper and lower limits of the cut set and the value of α in Eq. 7 are as follows:

$$\begin{aligned} \text{When } vL_\alpha &= [vL_L, vL_U], \quad vL_L = 0, \quad vL_U = 0.2 - 0.1\alpha; \\ \alpha &= \left[0, \frac{0.2-vL_U}{0.1}\right]; \end{aligned}$$

$$\begin{aligned} \text{When } L_\alpha &= [l_L, l_U], \quad l_L = 0.1\alpha + 0.1, \quad l_U = 0.3 - 0.1\alpha, \\ \alpha &= \left[\frac{l_U-0.1}{0.1}, \frac{0.3-l_U}{0.1}\right]; \end{aligned}$$

$$\begin{aligned} \text{When } rL_\alpha &= [rL_L, rL_U], \quad rL_L = 0.1\alpha + 0.2, \quad rL_U = 0.5 - 0.1\alpha, \\ \alpha &= \left[\frac{rL_L-0.2}{0.1}, \frac{0.5-rL_U}{0.1}\right]; \end{aligned}$$

$$\begin{aligned} \text{When } M_\alpha &= [m_L, m_U], \quad m_L = 0.1\alpha + 0.4, \quad m_U = 0.6 - 0.1\alpha, \\ \alpha &= \left[\frac{m_L-0.4}{0.1}, \frac{0.6-m_U}{0.1}\right]; \end{aligned}$$

$$\begin{aligned} \text{When } rH_\alpha &= [rH_L, rH_U], \quad rH_L = 0.1\alpha + 0.5, \quad rH_U = 0.8 - 0.1\alpha, \\ \alpha &= \left[\frac{rH_L-0.5}{0.1}, \frac{0.8-rH_U}{0.1}\right]; \end{aligned}$$

$$\begin{aligned} \text{When } H_\alpha &= [h_L, h_U], \quad h_L = 0.1\alpha + 0.7, \quad h_U = 0.9 - 0.1\alpha, \\ \alpha &= \left[\frac{h_L-0.7}{0.1}, \frac{0.9-h_U}{0.1}\right]; \end{aligned}$$

$$\begin{aligned} \text{When } vH_\alpha &= [vH_L, vH_U], \quad vH_L = 0.1\alpha + 0.8, \quad vH_U = 1, \\ \alpha &= \left[\frac{vH_L-0.8}{0.1}, 1\right]. \end{aligned}$$

Different experts often have various views on risk. For this reason, it is necessary to integrate their views into a single point of view. This paper recommends using a linear opinion database, as described in reference (Clemen and Winkler 1999):

$$f(x) = \sum_{N=1}^n \omega_N \otimes A_{X_iN} \tag{8}$$

where A_{X_iN} is the linguistic value of the hazard given by expert N , and ω_N is the weight of expert N .

3. Converting the fuzzy number to fuzzy possibility value

According to the left-right fuzzy sorting method, the fuzzy number is converted into a fuzzy probability score (FPS_T). This method defines the maximum fuzzy set and the minimum fuzzy set as:

$$f_{\max}(x) = \begin{cases} x & (0 \leq x \leq 1) \\ 0 & \text{otherwise} \end{cases} \quad f_{\min}(x) = \begin{cases} 1-x & (0 \leq x \leq 1) \\ 0 & \text{otherwise} \end{cases}$$

The left and right fuzzy probability (FPS_R and FPS_L) values of the fuzzy numbers are:

$$FPS_R = \sup_x [f_W(x) \wedge f_{\max}(x^{\max})] \tag{9}$$

$$FPS_L = \sup_x [f_W(x) \wedge f_{\min}(x^{\min})] \tag{10}$$

where $f_W(x)$ is the corresponding membership function.

Then, FPS_T can be:

$$FPS_T = [FPS_R + 1 - FPS_L] / 2 \quad (11)$$

4. Converting FPS_T to fuzzy hazard occurrence probability (HOP) as the approach proposed in literature (Onisawa 1990)

The value can be converted into the HOP as follows:

$$HOP = \begin{cases} \frac{1}{10^k} & (FPS_T \neq 0) \\ 0 & (FPS_T = 0) \end{cases} \quad (12)$$

where

$$k = 2.301 \times \left[\frac{1 - FPS_T}{FPS_T} \right]^{1/3} \quad (13)$$

The hazard degree of regional geological hazards can be expressed by the hazard index H . The occurrence possibility of geological hazards rises as the H increases, which can be expressed by the following formula combined with the sensitivity assessment.

$$H = \sum_{m=1}^n S_m \cdot HOP_m \quad (14)$$

Evaluation of pipeline vulnerability

Assessing leakage probability under the action of geological hazards should include two parts of work. One is to evaluate the occurrence likelihood of geological hazards; the other is to assess the possible damage to the pipeline. This section will discuss the second task.

In the civil industry, the vulnerability can characterize the extent to which structures (such as building, bridge) are affected by disasters (Ye and Jiang 2018; Jiang et al. 2019). Similarly, this index can also be used to predict the degree of damage to pipeline structures due to geological hazards.

Damage factors of buried pipelines

Geological disasters can cause soil movement and ground deformation, resulting in underground pipeline bending and fracture. Researches show that the damage of buried pipes is affected by the following factors under the external force of the natural environment: (1) the resistance of the pipeline decreases with the increase of service time (Younsi and Smati 2017). (2) The damage of underground pipes is strongly related to the site conditions (Manolis et al. 2020; Wang et al. 2019). Covering soil plays a critical role in protecting pipes. The possibility of pipeline

damage decreases with increasing soil hardness. (3) The geometry of the tube has a significant influence on its load-carrying capacity; the failure probability of pipe decreases with wall thickness and diameter increase (Liu et al. 2017). (4) Complex lateral vibration is generated under the action of the high-speed and high-pressure fluid. The effect of external environmental forces will be more significant in this state. The study found that the disaster resistance of the pipeline decreases with the increase of fluid flow velocity and fluid density (Khudayarov and Komilova 2019; Zhang et al. 2019c).

Assessment system for pipeline geological disaster vulnerability

Based on the analysis last section, the main factors that affect the damage of the pipeline system include such as site conditions, pipeline materials, and geometry of the pipe. According to the analysis of the mechanical behavior of steel pipelines under geological disasters and the relevant literature, the following hazard indexes are selected to comprehensively reflect the vulnerability of pipelines to geological disasters in this paper: site conditions (V_1), friction coefficient of pipe soil (V_2), pipe steel grade (V_3), pipe diameter (V_4), wall thickness (V_5), buried depth (V_6), fluid velocity (V_7), fluid density (V_8), tube age (V_9). An assessment system is established to quantify the contribution of each hazard index to pipeline disaster resistance using combined with accident records of pipelines and the previous study. The system includes two-layer factors, which represent the hazard factors and specific evaluation factors, respectively, as shown in Table 1 (Alvarado-Franco et al. 2017; Wu et al. 2019; Zhang et al. 2019b; Mou et al. 2019; Li et al. 2017).

There are significant uncertainty and ambiguity in the damage to buried pipelines when geological disasters occur. It is difficult to quantify the disaster-causing factors with a deterministic method. Thus, the fuzzy comprehensive analysis method is introduced to evaluate and analyze them following objective reality. Quantifying the hazards can follow steps:

- (1) Using three-demarkation method

$$f_{ij} = \begin{cases} 0 & , s(i) < s(j) \\ 0.5 & , s(i) = s(j) \\ 1 & , s(i) > s(j) \end{cases}$$

where $s(i)$ and $s(j)$ represent the relative importance of indicators f_i and f_j , respectively. Then a complementary fuzzy judgment matrix $F = (f_{ij})_{n \times n}$ can be established.

In the following, the hazard factor “tube age” is taken as an example. According to the above principles, the relative importance of each index is compared; a fuzzy judgment matrix F_{V_9-v} for the second-order hazard factor of tube age can be established as shown in Table 2.

Table 1 Vulnerability assessment system of the buried pipelines under the action of geological hazards

Hazard factors	Index	Vulnerability impact factor system
Site conditions	V_1	$\{v_{11}, v_{12}, v_{13}, v_{14}\} = \{\text{Hard soil, Medium hard soil, Medium soft soil, Soft soil}\}$
Coefficient of soil friction	V_2	$\{v_{21}, v_{22}, v_{23}, v_{24}\} = \{0, (0, 0.3], (0.3, 0.4], (0.4, 0.5]\}$
Steel grade	V_3	$\{v_{31}, v_{32}, v_{33}, v_{34}, v_{35}, v_{36}, v_{37}\} = \{X80, X70, X65, X60, X56, X52, X46\}$
Pipe diameter/mm	V_4	$\{v_{41}, v_{42}, v_{43}, v_{44}, v_{45}, v_{46}, v_{47}\} = \{[1050, 1200), [900, 1050), [750, 900), [600, 750), [450, 600), [300, 450), [150, 300)\}$
Wall thickness/mm	V_5	$\{v_{51}, v_{52}, v_{53}, v_{54}, v_{55}, v_{56}, v_{57}, v_{58}\} = \{[46, 52), [40, 46), [34, 40), [28, 34), [22, 28), [16, 22), [10, 16), (4, 10)\}$
Buried depth/m	V_6	$\{v_{61}, v_{62}, v_{63}, v_{64}, v_{65}, v_{66}\} = \{(0, 0.6), [0.6, 1.2), [1.2, 1.8), [1.8, 2.4), [2.4, 3.0), [3.0, + \infty)\}$
Fluid velocity/ $m \cdot s^{-1}$	V_7	$\{v_{71}, v_{72}, v_{73}, v_{74}, v_{75}, v_{76}, v_{77}, v_{78}, v_{79}\} = \{[0.5, 1.0), [1.0, 1.5), [1.5, 2.0), [2.0, 2.5), [2.5, 3.0), [3.0, 3.5), [3.5, 4.0), [4.0, 4.5), [4.5, 5.0)\}$
Fluid density/ $g \cdot cm^{-3}$	V_8	$\{v_{81}, v_{82}, v_{83}, v_{84}, v_{85}, v_{86}\} = \{(0.70, 0.75), [0.75, 0.80), [0.80, 0.85), [0.85, 0.90), [0.90, 0.95), [0.95, 1.0)\}$
Usage time/year	V_9	$\{v_{91}, v_{92}, v_{93}, v_{94}, v_{95}, v_{96}\} = \{(0, 10), [10, 20), [20, 30), [30, 40), [40, 50), [50, + \infty)\}$

(2) Seeking row sum $r_i = \sum_{j=1}^n f_{ij}$. The formula of $r_{ij} = \frac{r_i - r_j}{2n} + 0.5$ is used to transform the fuzzy judgment matrix of $F = (f_{ij})_{n \times n}$ into a fuzzy consistency judgment matrix of $B = (r_{ij})_{n \times n}$. According to that, the fuzzy judgment matrix F_{V_9-v} of the subfactors of the tube age shown in Table 2 can be transformed into a fuzzy consistency judgment matrix of B_{V_9-v} :

$$B_{V_9-v} = \begin{bmatrix} 0.500 & 0.583 & 0.667 & 0.750 & 0.833 & 0.917 \\ 0.417 & 0.500 & 0.583 & 0.667 & 0.750 & 0.833 \\ 0.333 & 0.417 & 0.500 & 0.583 & 0.667 & 0.750 \\ 0.250 & 0.333 & 0.417 & 0.500 & 0.583 & 0.667 \\ 0.167 & 0.250 & 0.333 & 0.417 & 0.500 & 0.583 \\ 0.083 & 0.167 & 0.250 & 0.333 & 0.417 & 0.500 \end{bmatrix}$$

(3) Normalization with $W^{(0)} = (w_1, w_2, \dots, w_n)^T = \left(\frac{\sum_{j=1}^n r_{1j}}{\sum_{i=1}^n \sum_{j=1}^n r_{ij}}, \frac{\sum_{j=1}^n r_{2j}}{\sum_{i=1}^n \sum_{j=1}^n r_{ij}}, \dots, \frac{\sum_{j=1}^n r_{nj}}{\sum_{i=1}^n \sum_{j=1}^n r_{ij}} \right)^T$ to get the ordering

Table 2 Fuzzy judgment matrix of index for tube age of F_{V_9-v}

V_9	v_{91}	v_{92}	v_{93}	v_{94}	v_{95}	v_{96}
v_{91}	0.5	1	1	1	1	1
v_{92}	0	0.5	1	1	1	1
v_{93}	0	0	0.5	1	1	1
v_{94}	0	0	0	0.5	1	1
v_{95}	0	0	0	0	0.5	1
v_{96}	0	0	0	0	0	0.5

vector $W_{V_9-v}^{(0)} = (0.2361, 0.2083, 0.1806, 0.1528, 0.1250, 0.0972)^T$.

(4) Use the conversion function $e_{ij} = \frac{r_{ij}}{r_{ji}}$ to transform the fuzzy consistency judgment matrix $B = (r_{ij})_{n \times n}$ into a reciprocal matrix $E = (e_{ij})_{n \times n}$; afterwards, turn the fuzzy consistency judgment matrix B_{V_9-v} of the secondary disaster factor of “tube age” into a reciprocal matrix E_{V_9-v} :

$$E_{V_9-v} = \begin{bmatrix} 1.000 & 0.1400 & 2.000 & 3.000 & 5.000 & 11.000 \\ 0.714 & 1.000 & 0.1400 & 2.000 & 3.000 & 5.000 \\ 0.500 & 0.714 & 1.000 & 1.400 & 2.000 & 3.000 \\ 0.200 & 0.333 & 0.500 & 0.714 & 1.000 & 1.400 \\ 0.091 & 0.250 & 0.333 & 0.417 & 0.500 & 0.583 \\ 0.091 & 0.200 & 0.333 & 0.500 & 0.714 & 1.000 \end{bmatrix}$$

(5) The ordering vector $W_{V_9-v}^{(0)}$ obtained by the normalization method is used as the initial value of the eigenvalue method. After seven iterations, the sorting vector is obtained $W_{V_9-v}^{(7)} = (0.3735, 0.2335, 0.1593, 0.1104, 0.0751, 0.0481)^T$. The calculation accuracy is 0.00001.

The service life of buried pipelines has a significant impact on the disaster resistance performance of pipes. It is restricted by many factors, such as the composition of the transmission medium, temperature, pressure, and anti-corrosion conditions. The pipeline is gradually aging with the increase of the service time, leading to the disaster resistance getting weaker. Therefore, the second-grade factors of $V_9 - v$ are following the actual situation so that the weight value can reflect the vulnerability of pipelines under natural disasters. It can be observed the vulnerability decreases with the increase of the weight value.

Table 3 Weights of hazard factors at all levels in the evaluation model

Hazard factor	Weight	Hazard factor	Weight	Hazard factor	Weight	Hazard factor	Weight
V_1	0.0274	V_4	0.0976	V_6	0.1416	V_8	0.2389
v_{11}	0.4952	v_{41}	0.3337	v_{61}	0.3735	v_{81}	0.3735
v_{12}	0.267	v_{42}	0.2178	v_{62}	0.2335	v_{82}	0.2335
v_{13}	0.1541	v_{43}	0.1551	v_{63}	0.1593	v_{83}	0.1593
v_{14}	0.0837	v_{44}	0.1131	v_{64}	0.1104	v_{84}	0.1104
V_2	0.0492	v_{45}	0.0823	v_{65}	0.0751	v_{85}	0.0751
v_{21}	0.4952	v_{46}	0.0585	v_{66}	0.0482	v_{86}	0.0482
v_{22}	0.267	v_{47}	0.0395	V_7	0.1769	V_9	0.117
v_{23}	0.1541	V_5	0.0821	v_{71}	0.2760	v_{91}	0.3735
v_{24}	0.0837	v_{51}	0.3019	v_{72}	0.1911	v_{92}	0.2335
V_3	0.0693	v_{52}	0.2037	v_{73}	0.1440	v_{93}	0.1593
v_{31}	0.3337	v_{53}	0.1497	v_{74}	0.1116	v_{94}	0.1104
v_{32}	0.2178	v_{54}	0.1131	v_{75}	0.0874	v_{95}	0.0751
v_{33}	0.1551	v_{55}	0.0859	v_{76}	0.0683	v_{96}	0.0482
v_{34}	0.1131	v_{56}	0.0647	v_{77}	0.0528		
v_{35}	0.0823	v_{57}	0.0476	v_{78}	0.0398		
v_{36}	0.0585	v_{58}	0.0334	v_{79}	0.029		
v_{37}	0.0395						

Weight values of other second-grade factors can be calculated by the above method. The weight values of other first-level indicators can be obtained through the same process. Thus, the influence degree of various factors in the assessment system on the vulnerability of pipeline geological hazards is obtained, as shown in Table 3.

The vulnerability of the pipeline under geological disasters can be expressed by the weight combination value V of each factor. The calculation formula is:

$$V = \sum_{i=1}^n W_{V_i} W_{V_i-v_j} \quad (i = 1, 2, \dots, 9) \tag{15}$$

where W_{V_i} is the weight value of the first-grade factor, and $W_{V_i-v_j}$ is the weight value of the second-level hazard factor.

Evaluation of environmental loss

Oil leakages will cause damage to the surrounding environment, including the social environment and the ecological environment. The former includes such as human health, property damage; besides, the latter includes such as soil, freshwater resources, forests, and air. Environmental damage

often attracts media and public attention, and its impact on corporate reputation far outweighs direct economic losses (Chen et al. 2019b; Lu et al. 2019; Li and Xi 2019). At present, it is challenging to obtain the total environmental losses in the consequence assessment due to the inconsistent dimensions of the evaluation items. In fact, economic measures such as compensation and maintenance are required after leakage for operators (Zhang et al. 2019a; Li et al. 2019a). According to this idea, combined with specific market conditions, investigating market prices, and using methods such as property statistics, environmental value assessments, and environmental restoration costs, currency can be used to unify generalized environmental losses. Table 4 shows the factors that should be considered when quantifying the consequences of pipeline leakage (Heinrich 1931; Coent et al. 2017; Jou and Chen 2015; Bonvicini et al. 2018). Note that it is necessary to determine according to specific circumstances in the assessment.

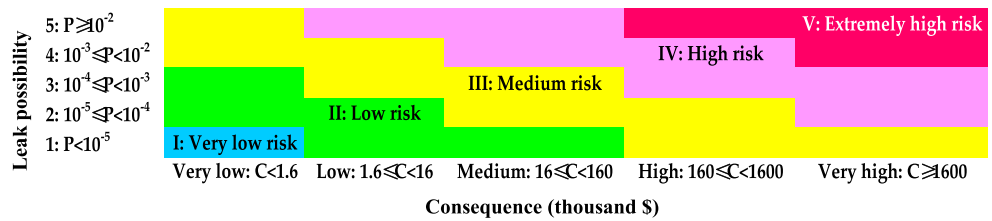
Thus, the consequences of oil leakage can be calculated from complex functional expressions into a linear addition formula:

$$C = f(c_1, c_2) = c_1 + c_2 \tag{16}$$

Table 4 Factors considered in monetary quantification

Type	Assessment index
Human environment c_1	Death; poisoning; building destruction; crop spoilt...
Ecosystem loss c_2	Air pollution; water pollution; soil pollution; forest resources...

Fig. 3 5 × 5 risk matrix; there are 5 levels of pipeline failure probability and consequences, and the risk is also categorized into 5 levels



Risk matrix

The risk matrix method can comprehensively evaluate the probability and consequence severity of pipeline leakage to make further maintenance plans. The corresponding relationship among risk level, failure probability, and the consequence is shown in Fig. 3 (Hong et al. 2007).

Decision-makers can determine the risk level based on the results of risk calculation and risk matrix so that they can make targeted plans to reduce environmental risks. Table 5 presents the decision suggestions corresponding to varying levels of risk (Lu et al. 2015).

A framework for leakage-induced environmental risk assessment

This section presents the hazard assessment for pipeline leakage under the common threat of multiple natural hazards. Moreover, the vulnerability index is used to discuss the disaster resistance of the pipe. In terms of consequences, monetary quantification is used to unify the dimensions of the general environmental loss from the perspective of the pipeline company. Afterward, the value of risk in currency units can be obtained in this way. Thus, leakage-induced environmental risk can be defined as the expectation of environmental loss. The risk *R* can be calculated as follows:

$$R = H \cdot V \cdot C \tag{17}$$

A probability-currency risk matrix is developed to define the risk level. After maintaining, it is necessary to re-evaluate for ensuring the reliability of the pipeline until the risk can be acceptable. Thus, a sustainable risk assessment framework for environmental management under natural disasters is proposed, as shown in Fig. 4.

Results and discussion

Leakage probability

Hazard assessment of natural disasters

According to the geological hazard investigation data of 2018, there are three types of geological hazards developed in the study area, including landslide, flood damage at slope, and waterlogging. As an information processing technology, GIS spatial analysis can provide effective support for risk assessment and significantly improve the accuracy and speed of evaluation (Cai et al. 2019). The impact factors system is developed from landform, geological environment, and power source of hazard occurrence by collecting the geological hazard information, remote sensing image, and existing literature (Table 6).

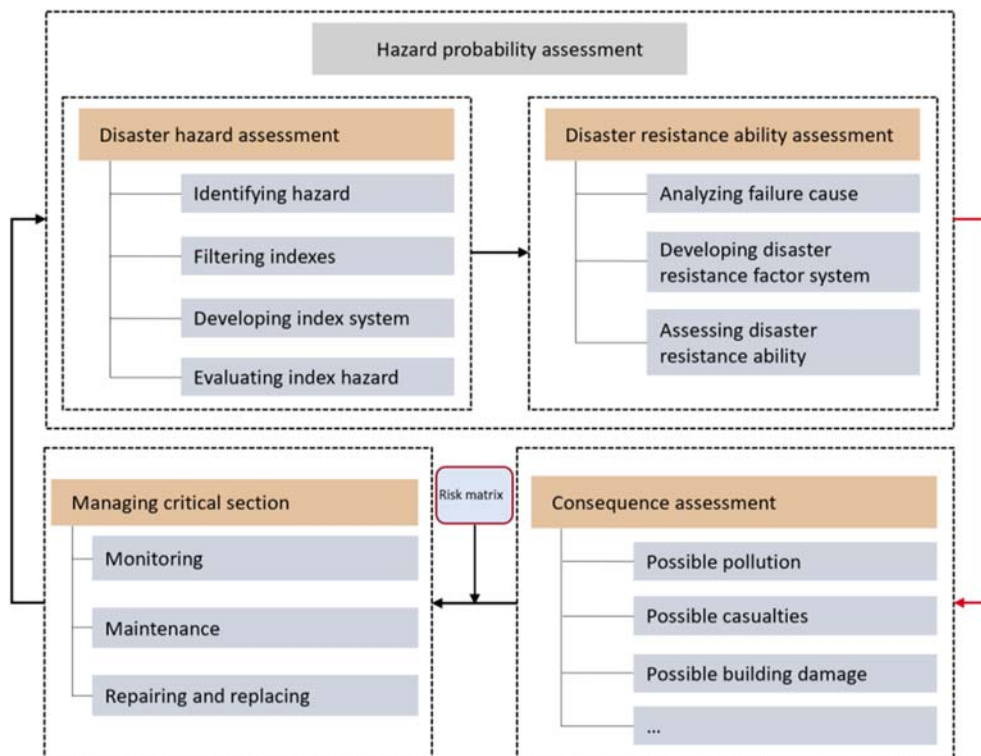
Sensitivity analysis of influencing factors The contribution rate model is used to evaluate the sensitivity of influencing indexes in this paper. The factor “altitude difference” of the landslide is taken as an example to show the method.

The altitude difference, defined as the difference between the maximum value and the minimum value in the area, is a quantitative factor to describe the relief of a certain area. This index can provide kinetic energy conditions for slope sliding. Two hundred fifty-two landslides in this area were processed using the ArcGIS neighborhood analysis function. Specifically, (i) extract the maximum and minimum values in each evaluation unit through DEM data, (ii) generate the altitude difference data by using grid calculator, and (iii) adopt the natural breakpoint method to reclassify the altitude difference data and divide it into ten levels to analyze the distribution of landslides in each altitude difference classification. Then, the number of landslides, distribution area, and volume scale of landslides in each altitude difference classification can

Table 5 Maintenance strategy

Risk level	Suggestions
I	Risk is acceptable
II	Strengthening the monitoring
III	Taking proper maintenance measures
IV	Strengthening pipeline reinforcement and hydrological protection
V	Unacceptable risk, suggesting rerouting

Fig. 4 Framework for sustainable risk assessment under natural disasters



be calculated, and the sensitivity of the internal index is obtained by combining the contribution rate conversion model (Table 7).

From Table 7, the number of landslides in this area does not increase with the increase of elevation difference. There are few geological disasters developed on slopes with elevation difference more than 32 m, most of which are distributed within the range of elevation difference less than 32 m, mainly within 25 m. In the study area, the areas with high sensitivity are primarily distributed in the field of 4.94–24.72 m, which is the main range of altitude difference for the development of landslide disasters. The sensitivity value of the internal index of the factors of the landslide can be calculated in the same way. After that, the sensitivity value of each factor can be obtained (Table 8). According to this method, the sensitivity of different evaluation factors of various disasters, in this case, can be obtained. Then the weight of evaluation factors can be obtained by normalization (Table 9).

Hazard of influencing factors After the sensitivity calculation, it is necessary to invite experts to investigate the geological

environment near the evaluation pipe segment and hold a meeting to discuss the hazard of factors. Three experts from geological engineering and two from pipeline engineering are invited to form an expert team for evaluation (Table 10). The weights ω of experts obtained by AHP are 0.255, 0.236, 0.2, 0.145, and 0.164, respectively. The judgements of experts on the hazard assessment of altitude difference are RL, VL, RL, M, and L, respectively.

By Eq. 8, the comprehensive fuzzy number can be:

$$f(x) = \max[\omega_1\mu_{RL}(x)\wedge\omega_2\mu_{VL}(x)\wedge\omega_3\mu_{RL}(x)\wedge\omega_4\mu_M(x)\wedge\omega_5\mu_L(x)]$$

$$= [0.0764\alpha + 0.1654, 0.4109 - 0.1\alpha]$$

Then, the corresponding membership function is:

$$\mu_w(x) = \begin{cases} \frac{x-0.1654}{0.0764} & (0.1654 \leq x \leq 0.2418) \\ 1 & (0.2418 \leq x \leq 0.3109) \\ \frac{0.4109-x}{0.1} & (0.3109 \leq x \leq 0.4109) \\ 0 & (\text{otherwise}) \end{cases}$$

Table 6 Influencing factors of geological hazards in study area

Disaster	Index
Landslide	Slope shape, slope, altitude difference, 24-h maximum rainfall, geotechnical type
Flood damage at slope	Slope shape, slope, altitude difference, drainage area, 24-h maximum rainfall, surface water
Waterlogging	Slope, drainage area, 24-h maximum rainfall, surface water, geotechnical type

Table 7 Sensitivity of the internal index of altitude difference factor

Altitude difference interval/m	Number of landslides	Landslide area /m ²	Landslide volume /m ³	Sensitivity value/%
0~4.94	12	365,263	2,850,862	1.11
4.94~12.36	102	3,429,968	13,883,761	15.42
12.36~18.54	88	2,069,587	6,599,400	7.66
18.54~24.72	37	1,165,628	5,775,529	2.30
24.72~32.14	11	225,866	1,065,000	0.20
32.14~44.50	1	28,178	45,000	0.00
44.50~71.70	1	6916	13,832	0.00
71.70~117.44	0	0	0	0.00
117.44~186.67	0	0	0	0.00
186.67~316.47	0	0	0	0.00

Left and right fuzzy probability values of fuzzy numbers are calculated according to Eq. 9 and Eq. 10.

$$FPS_L = 0.8463, FPS_R = 0.3454.$$

Then substitute the result into Eq. 11 to calculate $FPS_T = 0.24955$. Further, $k = 2.301 \times \left[\frac{1-0.24955}{0.24955} \right]^{1/3} = 3.3213$.

Finally, HOP of the altitude difference is 4.772×10^{-4} using Eq. 12. The hazard of other influencing factors can be calculated according to this method, as shown in Table 11. Next, H can be calculated by Eq. 14 of 3.16×10^{-3} .

Pipeline vulnerability assessment

The weight value of each disaster causing factor can be obtained based on the parameters and geological environment of the Lan-Cheng crude oil pipeline (Table 12). Next, the vulnerability of the pipeline under natural disasters can be calculated using Eq. 15. At last, the pipeline failure probability can be calculated combined with the hazard of geological disasters.

$$P = H \times V = 5.726 \times 10^{-4}$$

Environmental loss assessment

The monetary quantification method is used to evaluate the consequences of pipeline leakage according to the way mentioned in the “Evaluation of environmental loss” section. There are residential buildings, forests, cultivated land, and freshwater reservoirs in the pipeline section. The expert team and operators conclude that the total loss between \$100,000

and \$150,000 through the investigation of local price, per capita wage, medical level, environmental compensation, etc.

Assessment results and discussion

As mentioned above, the pipeline leakage probability is level 3, and the consequence level is medium. It can conclude that the risk level is III based on the risk matrix. The results demonstrate that the pipeline is at medium risk. For this reason, risk engineers should be organized to make detailed analyses and formulate countermeasures to mitigate risks. Note that the assessment result shows that the study area is at high risk if ignoring the resistance of pipeline structure to natural disasters. Such an evaluation result is conservative, which will cause a waste of maintenance resources. Thus, pipeline vulnerability evaluation should be introduced into the risk assessment.

Even though the possibility of pipeline leakage is very low, the harm to the environment can be enormous. In conclusion, it is urgent to promote prevention and early warning to reduce the possibility of accidents. The most effective method is to make appropriate adjustments from the aspects of pipeline planning, construction, geological environment monitoring, and operation management. The following preventive and emergency measures are proposed for this case:

- (1) Use unmanned aerial vehicle (UAV) patrol

In the area with a complex geological environment, it is not suitable to use the artificial patrol to check the hazard. UAV is a safe and more effective way. The real status of the geological

Table 8 The inter-sensitivity of all factors of landslides

Index	Slope shape	Slope	Altitude difference	Geotechnical type	24-h maximum rainfall
Inter-factor sensitivity/%	31.49	28.14	26.69	18.66	33.40

Table 9 Determination of evaluation factor weight

Index	Sensitivity (%)			Mean sensitivity (%)	Weights (%)
	Waterlogging	Flood damage at slope	landslide		
Slope shape		34.76	31.49	22.08	16.60
Slope	15.81	31.9	28.14	25.28	19.00
Altitude difference		18.11	26.69	14.93	11.22
Drainage area	33.78	14.37		16.05	12.06
24-h maximum rainfall	11.19	34.46	33.40	26.35	19.81
Surface water	33.77	12.5		15.42	11.59
Geotechnical type	20.13		18.66	12.93	9.72

environment can be observed clearly by using UAV. Alongside this, further hazard analysis can be made through the recorded image data, thus dramatically improving monitoring efficiency.

(2) Establish an oil leakage emergency mechanism

An emergency command post should be built near the freshwater reservoir. Professional training is planned to deepen the understanding of emergency control procedures, master emergency prevention measures and operation of equipment used, and enhance the ability to deal with accidental oil leakage. Emergency response drills of the oil spills can be regularly carried out to train the emergency response ability of staff, to reduce environmental pollution ultimately.

(3) Prepare an oil leakage emergency plan

According to the characteristics of the study area, the emergency plan is formulated to implement the command procedure more effectively. The emergency plan may include river oil spill, soil remediation, emergency command, communication and cooperation, environmental impact scope, environ-

mental sensitivity analysis, and social stability assessment. Meanwhile, accident response may also include indirect factors surrounding environmental recovery, such as claims and public relations coordination.

Conclusions

Risk assessment plays a vital role in environmental protection. Oil pipelines in mountain areas are threatened by natural disasters, which may lead to leaks, resulting in devastating environmental accidents and significant economic losses. Therefore, this study proposed a method to assess the impact of the pipeline leakage on the surrounding environment under the common threat of multiple natural disasters, thereby developing a comprehensive risk assessment framework for effective management.

The hazard assessment index system was developed by identifying natural disasters in the study area. The sensitivity of each influencing factor was determined based on the GIS technology and contribution rate model. Next, the linguistic judging value of experts was transferred to a numerical probability using the fuzzy set theory. Meanwhile, the vulnerability

Table 10 Composition of assessment expert group

Expert number	PT	PE (year)	EB
E_1	Senior	20~29	PhD
E_2	Senior	20~29	Master
E_3	Vice Senior	20~29	Undergraduate
E_4	Mid-level	6~9	Undergraduate
E_5	Mid-level	20~29	College

Table 11 Hazard of impact indexes of natural disasters

Slope shape	Slope	Altitude difference	Drainage area	24-h maximum rainfall	Surface water	Geotechnical type
8.18×10^{-3}	4.21×10^{-3}	4.772×10^{-4}	1.14×10^{-4}	2.54×10^{-4}	4.07×10^{-4}	8.57×10^{-3}

Table 12 Section and the value of vulnerability

Site conditions	Coefficient of soil friction	Steel grade	Pipe diameter/mm	Wall thickness/mm	Buried depth/m	Fluid velocity/m · s ⁻¹	Fluid density/g · cm ⁻³	Usage time/year
v ₁₃	v ₂₃	v ₃₃	v ₄₄	v ₅₈	v ₆₂	v ₇₂	v ₈₃	v ₉₁

$$\begin{aligned}
 V &= \sum W_{V_i} W_{V_i, v_j} \\
 &= 0.0274 \times 0.1541 + 0.0492 \times 0.1541 + 0.0693 \times 0.1551 + 0.0976 \times 0.1131 \\
 &+ 0.0821 \times 0.0334 + 0.1416 \times 0.2335 + 0.1769 \times 0.1911 + 0.2389 \times 0.1593 + 0.1170 \times 0.3735 \\
 &= 0.1812
 \end{aligned}$$

evaluation system was developed to assess the resistance of pipeline structure under the action of natural disasters. For environmental impact assessment, leakage-induced environmental losses were transformed into currency from the perspective of operators. Finally, a 5×5 possibility-currency matrix was used to define the risk level. The case study of the Lan-Cheng crude oil pipeline was studied in detail. The result showed that this approach can help environmental managers in mountainous areas to identify risk factors and comprehensively assess the consequences.

This research is a part of environmental management under the specificity condition. It connects the geological survey and data collection and is the basis of risk decision-making. It can not only mitigate the uncertainty caused by oil leakage in the complex geographical environment but also help non-environmental professionals better understand environmental risk.

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