Qin et al. J Infrastruct Preserv Resil (2022) 3:19
https://doi.org/10.1186/s43065-022-00066-1

Journal of Infrastructure Preservation and Resilience

RESEARCH Open Access

An information entropy-based risk assessment method for multiple-media gathering pipelines

Guojin Qin[1,2], Shengyu Tang[3], Ruiling Li[2], Ailin Xia[2], Zhenwei Zhang[2] and Yihuan Wang[1,2*]

Abstract

Unrefined and highly corrosive upstream petroleum resources and complex operating environments pose a significant threat to the integrity and safety of gathering pipelines. The present study proposed a novelty method to perform a risk assessment for gathering pipelines. The use of historical failure data developed a fishbone diagram model of hazard factors. The risk index system was developed based on the KENT method, including failure likelihood and failure consequence coefficient models. Information entropy theory was used to determine the weight of each indicator. Combined with the area-level safety design coefficient, The welding institute (TWI) method was improved to perform risk classification for different areas. The proposed method was applied to 81 gathering pipelines. Results demonstrated that the proposed method could meet the actual conditions of gathering pipelines, improving upstream energy security.

Keywords: Gathering pipelines, Risk assessment, Information entropy, Internal corrosion, Oil and gas field infrastructures

Introduction

Gathering pipelines are the primary energy transmission infrastructure for upstream oil and gas fields [1]. Compared with long-distance pipelines, unrefined transport media can cause more serious internal corrosion [2–4]. Besides, the operating environment with high uncertainties will cause the gathering pipeline failure, seriously affecting upstream production, environmental pollution, and even casualties [5–8]. Although this is well-known in the industry, the statistical data show that failure accidents of gathering pipelines are rising [9]. Pipeline owners implement risk-based integrity management to prevent such accidents as much as possible [10, 11]. Accuracy and adaptability of risk assessment are crucial for predicting risks and reducing accidents [12].

Extensive studies have been conducted to mitigate pipeline risk [13–15]. However, those methods were developed for the risks faced by long-distance. The increasing number of accidents indicates that those methods do not apply to gathering pipelines [9]. This may be because some critical properties of the gathering pipeline were ignored, including transporting multiple corrosive and high-temperature media, small outer diameter, small wall thickness, and low operating pressure [4]. It is necessary to sort out all risk factors of the gathering pipelines. For long-distance pipelines, the semi-quantitative-based method, i.e., the KENT method, developed a comprehensive index system to implement pipeline risk assessment, including the indicators of failure likelihood and failure impacts [16]. Many variants have been generated based on the KENT method, such as the fault tree-based and the Bayesian network-based models [17, 18]. However, the KENT method can only provide a subjective expert-based evaluation. Besides,

*Correspondence: yihuan.wang@swpu.edu.cn

[2] School of Civil Engineering and Geomatics, Southwest Petroleum University, Chengdu 610500, Sichuan, China
Full list of author information is available at the end of the article

the weight of all major categories of indicators is the same, which is not enough to reflect the pipeline risk characteristics. The information entropy method could compensate for the lack of information to dynamically determine the weights of indicators according to actual pipeline conditions, which helps reduce the subjectivity of assessment. Therefore, this method has been widely used in risk assessment [19–21].

The present study developed a novelty information entropy-based risk assessment method for multiple-media gathering pipelines, including a risk calculation model and a risk classification method. The historical accidents of gathering pipelines were systematically analyzed to develop a fishbone diagram model for sorting out the risk indicators. A risk evaluation index system was developed for multiple-media gathering pipelines. The weight of each index was determined by the information entropy method. The use of the modified TWI method implemented risk classification. The applicability and accuracy of the proposed method were illustrated through a case study.

Methodology

Statistical analysis of gathering pipeline accidents

Accident statistical analysis is the premise of risk assessment. The main risk factors are sorted out through the analysis of the root causes to develop a practical risk analysis method [22]. Pipeline and Hazardous Materials Safety Administration (PHMSA) collected and analyzed the failure causes of gathering pipelines in the US in the past 20 years, and the statistical results are shown in Fig. 1(a) [23]. Alberta Energy Regulator (AER) organized the failure causes of Canadian crude oil and gas pipelines, respectively, and the statistical results are shown in Fig. 1(b) [24]. Fig. 1(c) shows the statistical failure caused by gathering pipelines in China from 2011 to 2016 [25]. From Fig. 1, corrosion is the primary failure factor of pipeline accidents in the US, specifically, 55.5% of general accidents, 28.6% of serious accidents, and 57% of major accidents. In Canada, 69% of crude oil pipeline failures were caused by internal corrosion, and 53.2% of gas pipeline failures were caused by internal corrosion. Also, for the accidents in China of crude oil pipelines, gas pipelines, water pipelines, and steam pipelines, the corrosion contribution was 69.5%, 73.43%, 70.60%, and 69.43%, respectively. It can be seen that corrosion is responsible for more than 40% of the gathering pipeline failure, in which internal corrosion-induced failure is over 24%, which becomes the leading factor. Thus, internal corrosion is the primary hazard factor of gathering pipeline failure.

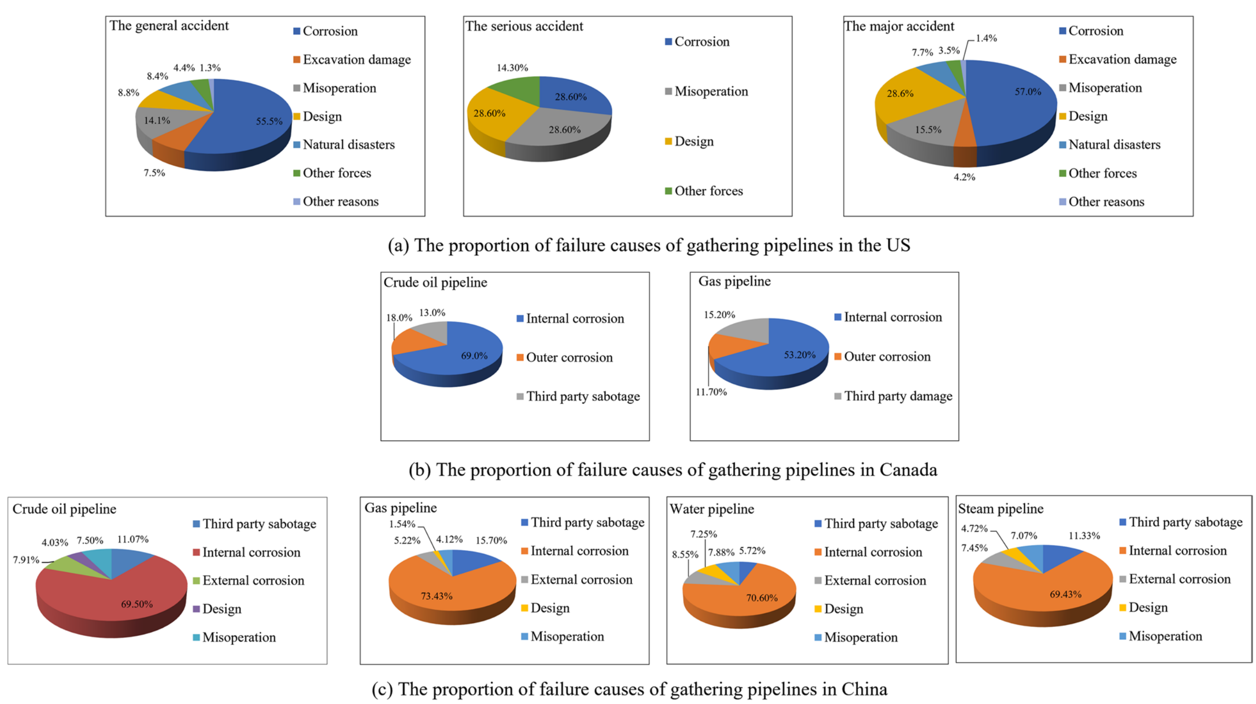

Fig. 1 Gathering pipeline accident statistics

Identification and quantitative analysis of failure factors

The Fishbone diagram is an analysis method to capture the root cause of an incident, which has been widely used in engineering failure analysis given its intuitive image and ability to mine the grounds of the accident deeply [26].

Figure 2 shows the developed fishbone diagram model of gathering pipeline failure factors. Specifically, the causal factor can be four categories, including third-party damage, corrosion, design, and misoperation, involving the human-machine–environment, which can directly affect the safety status of gathering pipelines [5]. From the statistical analysis of the accident, corrosion is the main reason for the failure of gathering pipelines, especially internal corrosion. The mixed transportation of multiple corrosive media can produce different corrosion effects. To identify the corrosion hazard factors pertinently, this work considers four different corrosion media for internal corrosion factors, i.e., crude oil, gas, water, and steam.

Quantitative analysis of the main failure indexes regarding internal corrosion can reduce the subjectivity of risk assessment and improve accuracy. Quantitative analysis indicators include pressure, sulfur content, temperature, chloride ion, and salinity. The failure data are collected from various oil and gas fields in Northwest China (Table 1) to determine the functions of such indicators and the failure rate (Fig. 3).

Given the statistics of failure accidents, fishbone diagram model, and quantitative analysis results, combined with the analytic hierarchy process, a risk evaluation index system for gathering pipelines is developed regarding different transportation media, as shown in Table 2, 3,4,5 and 6 [3, 4, 15, 27].

Risk assessment method

Overview of KENT method

According to the KENT method, pipeline risk assessment includes the likelihood and consequences of pipeline failure [16]:

$$R = P \times C \tag{1}$$

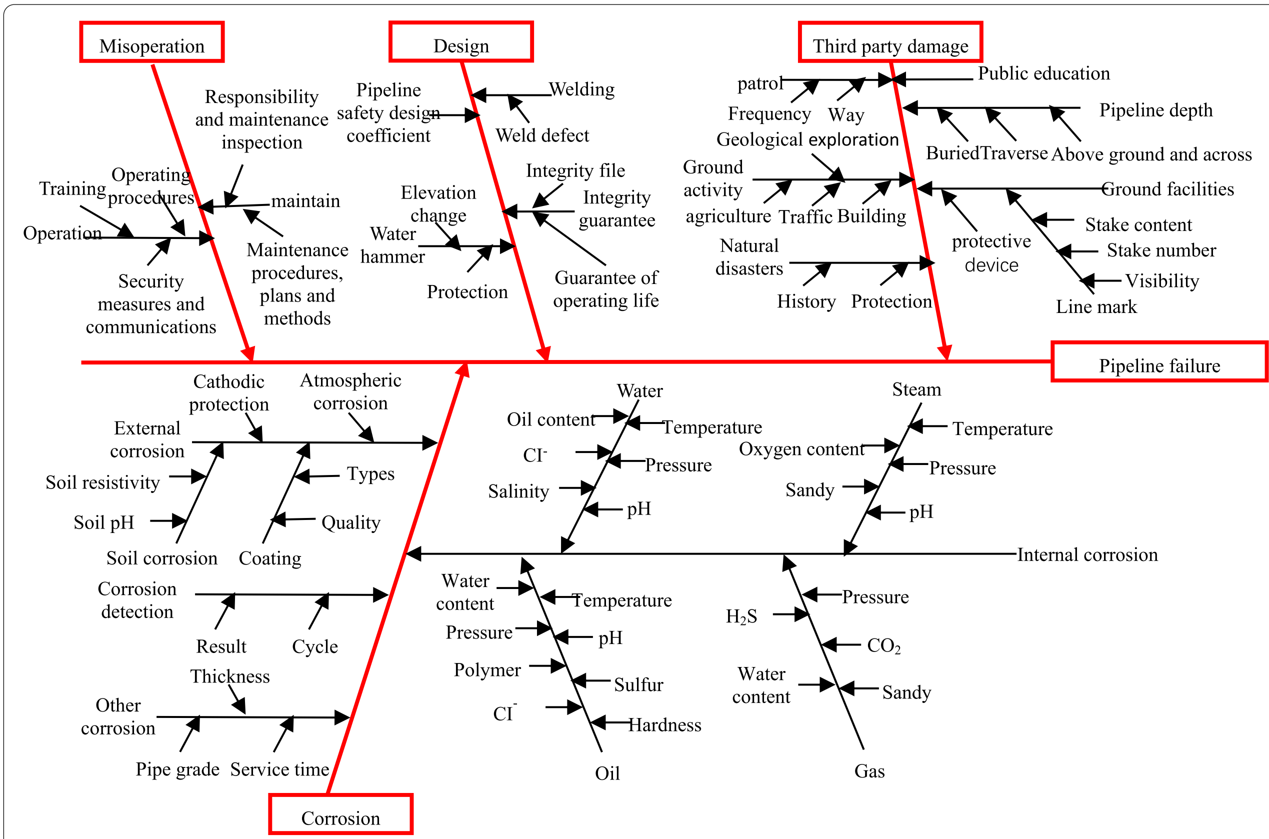

Fig. 2 Identification of hazard factors in gathering pipelines fishbone diagram. **a** Relationship between pressure and pipeline failure. **b** Relationship between sulfur and pipeline failure. **c** Relationship between salinity and pipeline failure. **d** Relationship between temperature and pipeline failure. **e** Relationship between Cl- and pipeline failure

Table 1 Pipeline failure data

(a) Relationship between pressure and pipeline failure					
Operating pressure Design pressure	Failure probability Design pressure	Operating pressure	Failure probability		
0	0.02543	0.50625	0.21564		
0.0125	0.02965	0.559375	0.22786		
0.021875	0.03032	0.634375	0.23965		
0.025	0.03989	0.690625	0.24739		
0.03125	0.04768	0.771875	0.26988		
0.0375	0.06382	0.796875	0.2779		
0.046875	0.07921	0.86875	0.29362		
0.090625	0.09102	0.9125	0.30171		
0.11875	0.11763	0.934375	0.34974		
0.146875	0.13821	0.959375	0.38416		
0.234375	0.15967	0.984375	0.43101		
0.325	0.18802	1	0.48905		
(b) Relationship between Sulfide and pipeline failure					
Sulfide (mg/L)	Failure probability	Sulfide (mg/L)	Failure probability		
0.0005	0.0167548	19.278629	0.335179		
0.001	0.0986524	25.78192	0.3652819		
0.015	0.1587651	30.267819	0.3819283		
0.1648	0.1654318	40.267812	0.4028381		
0.19876	0.1892761	53.267189	0.412312		
0.786542	0.2109763	59.271829	0.4328172		
1.347652	0.2276541	70.362718	0.4728272		
2.45632	0.289754	80.27838	0.493721		
7.263721	0.291082	100.26372	0.5019283		
10.27653	0.319864	142.26	0.51685937		
(c) Relationship between salinity and pipeline failure					
Salinity (mg/L)	Failure probability	Salinity (mg/L)	Failure probability		
0	0.053832	5000	0.180123		
500	0.102123	6000	0.185632		
900	0.14231	8000	0.189263		
1000	0.147921	9000	0.19321		
1100	0.149012	10000	0.19999		
1200	0.15112	12000	0.22031		
1250	0.156281	14000	0.242516		
1300	0.1590187	16000	0.280192		
1400	0.164961	20000	0.310212		
1600	0.169979	25000	0.3462712		
2000	0.175291	30000	0.392012		
2500	0.179021	35000	0.4602123		
4000	0.17999	40000	0.503728		
(d) Relationship between temperature and pipeline failure					
T (℃)	Failure probability	T (℃)	Failure probability	T (℃)	Failure probability
2	0.1011	9	0.15021	23	0.16999
3	0.1231	11	0.15782	25	0.17211
4	0.13217	13	0.159021	27	0.17621
5	0.13671	16	0.16021	29	0.17985
7	0.140123	19	0.16823	33	0.1821
35	0.18867	61	0.54123	220	0.35125
40	0.19012	63	0.51283	230	0.37859

Table 1 (continued)

43	0.19701	65	0.47891	240	0.401293
46	0.19989	66	0.43212	250	0.43128
49	0.20001	69	0.40105	260	0.45752
50	0.21012	70	0.39211	270	0.47291
51	0.26012	80	0.35102	280	0.49128
52	0.3012	90	0.21021	290	0.51965
54	0.38102	100	0.1921	300	0.542712
55	0.41219	130	0.22103	310	0.54123
56	0.46961	140	0.23104	320	0.501293
57	0.49989	160	0.26109	330	0.482731
58	0.52012	180	0.28473	340	0.402483
59	0.53129	200	0.29386	350	0.353921
60	0.56125	210	0.280192		
(e) Relationship between Cl- and pipeline failure					
Cl^-(mg/L)	Failure probability	Cl^-(mg/L)	Failure probability		
1	0.1021	430	0.34652		
2	0.1212	500	0.31203		
3	0.1523	550	0.31293		
4	0.17382	600	0.31238		
5	0.19382	700	0.3283		
6	0.210334	800	0.32993		
7	0.250234	900	0.33102		
8	0.278392	1000	0.33765		
9	0.29832	1200	0.33989		
10	0.319389	1300	0.412031		
15	0.33234	2500	0.431342		
20	0.364283	3700	0.431723		
50	0.36431	5000	0.449872		
100	0.35218	6100	0.462341		
200	0.35281	8000	0.48997		
250	0.35102	8600	0.501283		
300	0.350123	9000	0.523898		
350	0.349921	10000	0.563742		

where R is the pipeline risk value; P is the failure likelihood score; C is the consequence score. The risk assessment model for failure likelihood in the KENT method can be

$$P = P_{third\ party} + P_{corrosion} + P_{design} + P_{misoperation} \tag{2}$$

where $P_{third\ party}$, $P_{corrosion}$, P_{design} and $P_{misoperation}$ are the score of the third-party damage indicator, the corrosion indicator, the design indicator, and the misoperation indicator, respectively. The failure consequence calculation model can be

$$C = K_w \times LV \times D \times S \tag{3}$$

where K_w is the hazard of the product; LV is the leakage volume; D is the diffusion coefficient; S is the receptor coefficient.

An information entropy-based method of failure likelihood for gathering pipelines

When evaluating the failure likelihood, different causal factors have individual effects on pipeline safety. Therefore, the weight of each factor needs to be determined. Then, Eq. (2) can be

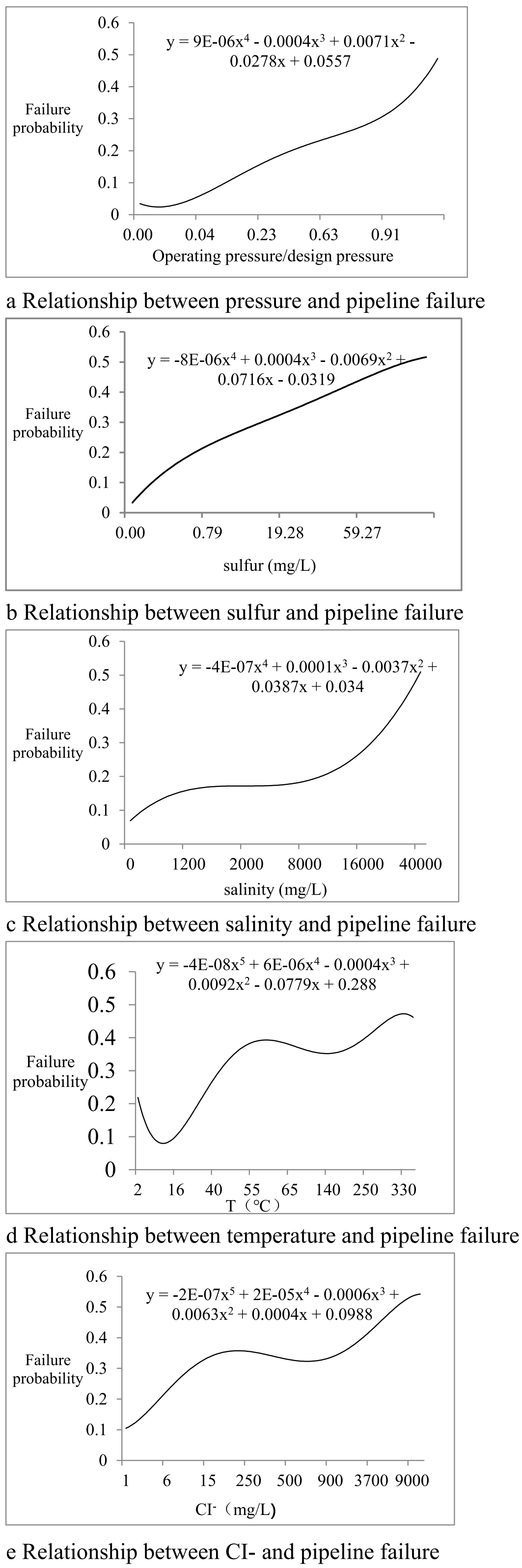

Fig. 3 Relationship between quantitative index and failure probability

$$P = L_1 P_{third\ party} + L_2 P_{corrosion} + L_3 P_{design} + L_4 P_{misoperation} \tag{4}$$

where L_1, L_2, L_3, and L_4 are the weights of third-party damage, corrosion, design, and misoperation, respectively, $L_1 + L_2 + L_3 + L_4 = 1$.

It should be noted that the L_1, L_2, L_3, and L_4 are dynamically determined based on the actual situation. Ignoring that will reduce the accuracy of the risk assessment. In this work, the dynamic weights can be determined by the information entropy method combined with failure frequency [28, 29], following the steps:

a. According to the actual situation of the oil and gas field, the information matrix AT is developed by the experts:

$$AT = \begin{bmatrix} t_{11} & t_{12} & \cdots & t_{1n} \\ t_{21} & t_{22} & \cdots & t_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ t_{m1} & t_{m2} & \cdots & t_{mn} \end{bmatrix}$$

b. Define the membership function $\mu(t_{ij})$:

$$\mu\left(t_{ij}\right) = -\lambda p_n\left(t_{ij}\right) \ln p_n\left(t_{ij}\right) \tag{5}$$

$$\mathrm{s.t.p_n}\left(\mathrm{t_{ij}}\right) = \frac{\mathrm{t_{ij}} + \gamma}{\mathrm{k} + \gamma} \tag{6}$$

$$\lambda = \frac{1}{\ln\left(k + \gamma\right)} \tag{7}$$

where $k=n$ is the conversion parameter; γ (1, 2,..., n) is the adjustment coefficient; t_{ij} is the recommendation trust degree of the i-th recommended entity for the j-th attribute index.

c. Develop membership matrix B:

$$B = \begin{bmatrix} b_{11} & b_{12} & \cdots & b_{1n} \\ b_{21} & b_{22} & \cdots & b_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ b_{m1} & b_{m2} & \cdots & b_{mn} \end{bmatrix}$$

d. Determine the initial weight by Eqs. (8-11), as follows:

$$t_j = \frac{\sum_{i=1}^{m} b_{ij}}{m} \tag{8}$$

Table 2 Failure factors of gathering pipelines regarding third-party damage

First level	Second level	Weight	Description
Third party damage	Buried depth	Buried (28)	>160cm (7); 100cm~160cm (14); 50cm~100cm (21); <50cm (28)
		Above ground and across (28)	Well protection (5); A degree of protection (16); None (28)
	Ground facilities	[a] Line mark (15)	100% (3); 80%-100% (5); 60%-80% (8); 40% -60% (10); <40% or none (15)
		[b] Building facilities (7)	None (2); 1-3 (3); >3 (5)
	Activity level	[c] Construction (6)	None (1); 0~3 months (2); 3~12 months (4); >12 months (6).
		Transportation (8)	None (2); Traffic branch (4); Traffic artery/main road (6); Rail or road traffic trunk lines (8)
	Patrol efficiency	Frequency (10)	Once a day (2); Once every two days (5); Once a week (7); Once a month (10)
		Method (7)	Step by step (1); High-risk pipe section (3); Valve chamber (7)
	Malicious damage	Possibility (6)	Low (2); Medium (3); High (6)
	Natural disasters	History (5)	None (0); Occurred but did not cause incident (2); Occurred and caused pipeline failure (5)
		Protection (8)	Disaster monitoring and normal operation (1); In-line inspection (4); Pigging and corrosion inhibitor (8)
Total	100		

[a] Completeness of warning signs

[b] The evaluation range is 7 meters on both sides of the pipeline

[c] Construction duration

$$\xi_j = \sqrt{\frac{\sum_{i=1}^{m} \left(b_{ij}\text{-}t_j\right)}{m}} \geq 0 \tag{9}$$

$$g_j = t_j\left(1\text{-}\xi_j\right)\left(g_j > 0\right) \tag{10}$$

$$\omega_j = \frac{g_j}{\sum_{i=1}^{n} g_j} \tag{11}$$

where the initial weight is $G=[g_1,g_2...,g_n]$, there are four indexes, including third-party damage, corrosion, design and misoperation in this work, n is 4. The initial weight is g_1, g_2, g_3 and g_4, respectively; t_j is the average recommendation, representing recommend the entity's consistent views on attribute indicators; b_{ij} is the degree of membership of trust t_{ij}; m is the number of recommended subjects; ζ_j is the recommended blindness, i.e., uncertainties due to differences in recommendations.

Subsequently, according to the failure rate of various indexes from different oil and gas fields, the dynamic weight can be determined by

$$\mathrm{L_i} = \frac{\mathrm{g_i} + \frac{\mathrm{F_i}}{\mathrm{F}}}{2} \ (\mathrm{i} = 1, 2, 3, 4) \tag{12}$$

where F_i $(i=1,2,3,4)$ is the number of accidents caused by third-party damage, corrosion, design, and misoperation, respectively; F is the number of failures of gathering pipelines; a_i $(i=1,2,3,4)$ is additional weights determined by the evaluator for third-party damage, corrosion, design, and misoperation, respectively, $a_1+a_2+a_3+a_4=0$.

Failure consequence assessment model

The failure consequences of gathering pipelines can be assessed by medium harmfulness and receptors. The KENT method-based failure consequence assessment model can be

$$C = \frac{K_w}{K_{w\mathrm{sum}}} \times \frac{S}{S_{sum}} \tag{13}$$

where K_w is the medium hazard score; S is the receptor score; K_{wsum} is the total score of medium hazards; S_{sum} is the total score of the receptors. The failure consequence coefficient is within [0.3117,1].

Risk classification

According to the population density of different areas and China standard GB 50251-2015: Code for the design of gas transmission pipeline engineering [30], the surroundings can be defined as level 1 first-class area, level 1 second-class

Table 3 Failure factors of gathering pipelines regarding corrosion

First level	Second level	Weight	Third level	Weight	Description
Corrosion	External corrosion	Heavy oil (13/20)[a]; Thin oil (2/5); Gas (21/20); Water, Steam (13/20)	Soil corrosion	Resistivity (7)	>50Ω•m (2); 20~50Ω·m (4); <20Ω·m or none (7)
				pH (8)	6.5~8.5 (2); 4.5~6.5 (4); <4.5 (8)
			External coating	Type (6)	3-Layer Polyethylene (1); Coal tar enamel/coal tar epoxy/epoxy powder (2); Yellow jacket polyurethane foam/polythene (3); Asphalt glass fabric/phenolic resins (4); Anti-rust oil (5), None (6)
				Quality (9)	Complete (2); Partial loss (5), Mass shedding (9)
			Cathodic protection (10)		Normal use (3); Not used (6); None (10)
	Internal corrosion	Heavy oil (24/29) Thin oil (1) Gas (4/8) Water/Steam (1)	Oil (58)	Water (6)	<50% (2); 50%~75% (3); 75%~95% (5); >95% (6)
				Pressure (5)	<0.6 MPa (1); 0.6~0.8 MPa (3); 0.8~1.5 MPa (4); >1.5MPa (5)
				Cl^- (10)	<1000mg/L (2); 1000~3000mg/L (3); 3000~5000mg/L (5); 5000~7000mg/L (7); 7000~9000 (8); >9000 mg/L (10)
				H2S (10)	<0.005mg/L (2); 0.005~0.01mg/L (4); 0.01~0.015mg/L (7); >0.015mg/L (10)
				Temperature (4)	<50°C (2); 50~70°C (3); >70°C (4)
				pH (8)	7~10 (2); 4~7 (4); <4 (6); >10 (8)
				Hardness (5)	<100 mg/L (2); 100~300 mg/L (4); >300 mg/L (5)
			Gas (40)	Water (10)	<5% (4); 5%~10% (6); 10%~15% (8); >15% (10)
				Pressure (8)	<1MPa (1); 1~4 MPa (2); 4~10 MPa (4); 10~20 MPa (6); >20 MPa (8)
				Sulfide (12)	<42.68mg/L (3); 42.68~142.26mg/L (6); >142.26 mg/L (12)
				CO2 (10)	<0.207%mol/mol (3), 0.207%~2.073%mol/mol (7), >2.073% mol/mol (10).
			Water (38)	Oil content (6)	<2 mg/L (2); 100~500 mg/L (4); 2~100 mg/L (6)
				Cl^- (6)	<5 mg/L (2), 5~10 mg/L (4), >10 mg/L (6).
				Salinity (9)	<1000mg/L (1), 1000~3000 mg/L (3), 3000~10000 mg/L (5), 10000~50000 mg/L (7), >50000 mg/L (9).
				pH (5)	7~10 (1); 4~7 (3); <4 (4); >10 (5)
				Temperature (6)	<50°C (2), >60°C (3), 50~60°C 6.
				Pressure (6)	<1 MPa (1); 1~2.5 MPa (2); 2.5~16 MPa (3); 16~20 MPa (4); 20~25 MPa (5); >25 MPa (6)
			Steam (38)	Pressure (9)	<2.5MPa (2); 2.5~10 MPa (4); 10~12 MPa (5) 12~14 MPa (6); >14 MPa (9)
				Cl^- (12)	<5mg/L (4); 5~10mg/L (7); >10mg/L (12)
				pH (9)	7~8 (3); 6~7 (5); 5~6 (6); <5 (8); >8 (9)
				Temperature (8)	<200°C (3); 200~300°C (5); >300°C (8)
	Other corrosion factors (17)		Pipe grade (3)		X70 (1); X52 (1.5); X42 (2); Lower grade (3)
			Service years (8)		<5 years (2); 5~10 years (4); 10~20 years (6); >20 years (8)
			Corrosion-induced failure history (6)		≤1 (2); 1~3 (4); >3 (6)
	Corrosion inspection (9)		External inspection (4)		<1 per 1 year (1); 1 per 1~2 years (2); 1 per > 2 years (4)
			In-line inspection (5)		<1 per 1 year (2); 1 per 1~2 years (4); 1 per >2 years (5)
Total	**100**				

[a] For different media, the weight should be multiplied after the evaluation, e.g., it is necessary to multiply the weight 26/40 after evaluating the external corrosion of the heavy oil pipeline

Table 4 Failure factors of gathering pipelines regarding design

First level	Second level	Weight	Description
Design	Pipeline strength	Safety design factor (34)	$\frac{\text{Actual wall thickness}}{\text{Design wall thickness}}$: >1.8 (0); 1.61~1.8 (3.5); 1.41~1.6 (7); 1.20~1.4 (14); 1.1~1.20 (21); 1.0~1.1 (28); <1 (34)
	Water hammer	Elevation change (9)	Gently topography (0); Design pressure - MAOP > Maximum elevation pressure (4); Design pressure - MAOP < Maximum elevation pressure (9)
		Protective (6)	Slow closing device (2); Pressure relief valve (3); Buffer tank (5); Operating procedures for preventing water hammer (6)
	Integrity assurance	Usage time (10)	0~5years (2), 5~15 years (4), 15~20 years (6), 20~25 years (8), >25 years (10).
		Inspection time (7)	<1 year (1); 1~2 years (2); 2~3 years (3); 3~4 years (4); > 4 years (7)
	Welding quality	Welding level (10)	Strictly follow the operation procedure, i.e., high quality (2); According to the operation procedure, i.e., average quality (6); Random welding, i.e., poor quality (10)
		Inspection rate (10)	100% (2); 80%~100% (6); 60%~80% (8); <60% (10)
	Backfill quality	Backfill depth (8)	>76.2 cm (2); 7.62~76.2cm (4); <7.62cm or uncovered (8).
		Backfilling method (6)	Both process and method are correct (2); Process is correct but the method is incrorrect (4); Both backfill process and method are incorrect (5); None (6).
Total		**100**	

Table 5 Failure factors of gathering pipelines regarding misoperation

First level	Second level	Weight	Description
Misoperation	Misoperation during operation	Operating procedures (20)	Equipment operation, maintenance and calibration procedures are complete and strictly followed (5); Regulations have not been implemented (13); None (20)
		Communication (10)	Dedicated communication tool (4); Communication equipment is not dedicated (6); Communication equipment failure (10)
		Staff training 10	Regular training (3); Occasional training (7); None (10)
		Safety measures (10)	Safety responsibility system is sound and strictly implemented (3); There is a safety responsibility system but not implemented (7); None (10)
	Maintenance misoperation	Maintain documentation (10)	Complete (3); Incomplete (6); None (10)
		Maintenance measurement (10)	Replacement or no need for repairing (3); Repairment (5); Maintenance (8); None (10)
		Maintenance plan (10)	Regular maintenance (3); Irregular maintenance (7); None (10)
		Maintenance procedures (10)	Strict implementation of maintenance procedures (2); Maintenance procedures are not fully implemented (5); No procedures but maintenance records (8); None (10)
		Maintenance personnel ability (10)	Maintenance personnel are of high quality and strong sense of responsibility, and no accident occurred (3); Maintenance personnel are competent for their jobs, and only one accident occurred (6); Maintenance personnel are unqualified and irresponsible and there were more than 2 liability accidents (10)
Total		**100**	

area, level 2 area, level 3 area, level 4 area, with safety design coefficients of 0.8, 0.72, 0.6, 0.5 and 0.4, respectively [30].

In combination with the TWI risk classification method [31], taking $[Min, (Min+(Max-Min)\times 6/25\times b]$ as the low-risk level, $[Min+(Max-Min)\times 6/25\times b, Min+(Max-Min)\times 13/25\times b]$ as the medium risk level, $[Min+(Max-Min)\times 13/25\times b, Max]$ as the high-risk level, where Min is the minimum risk value, while Max is the maximum risk score. The value differs for various oil and gas fields, and b is the safety design factor. The risk ranking is shown in Fig. 4, where the high-risk level is in red, the medium-risk level is in yellow, and the low-risk level is in green.

A framework of risk assessment for gathering pipelines

This section analyzes the failure data of gathering pipelines to develop a fishbone diagram model of failure

Table 6 Consequences of failure

First level	Second level	Weight	Description
Consequences of failure	Medium hazard	Combustibility (20)	None (2); Flash point>93°C (4); 38°C<Flash point>93°C (8); Flash point<38°C and ignition point<38°C (12); Flash point<23°C and ignition point<38°C (20)
		Toxic hazard (20)	None (2); Minor chronic injuries (5); To avoid temporary incapacity, medical measures must be taken immediately (10); Can cause severe temporary or sequelae injuries (15); Short-term exposure can cause death or serious injury (20)
	Receptor	Population density (26)	Level 1 first class region (5); Level 1 second class area region (8); Level 2 region (15); Level 3 region (20); Level 4 region (26)
		Environmental sensitivity [a] (22)	None (8); Vegetation or farmland (14); Culverts, rivers, fresh water, marshes and silted land, wetlands (18); Animal sanctuary, scenic spot or scenic area sanctuary (22)
		Internal influence in oil and gas filed [b] (12)	Well-metering station/metering station-well/water supply-injection branch (6); Metering station-transfer station/transfer station-metering station/metering station-processing station/metering station-pull station/gathering station-transfer station (8); Transfer station-processing station/transfer station-transfer station/empty station-processing station/processing station-empty station (9); Oil depot-oil depot/oil depot-outside the station/processing station-oil depot (12)
Total		**100**	

[a] The range of influence is within 200m;

[b] Gathering pipeline connects the two stations or facilities, e.g., well-metering station represents the well and the metering station are connected by a pipeline

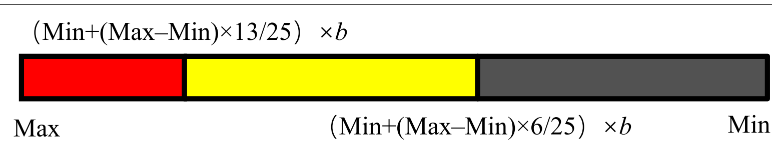

Fig. 4 Risk classification of gathering pipelines

factors. The primary failure indicators are quantitatively analyzed to ensure the objectivity of evaluation indexes. Further, this section develops a novelty risk assessment method for gathering pipelines combined with the KENT method and information entropy theory. Also, the risk classification method is proposed to judge the pipeline's safety status in different regions. The proposed risk assessment framework for gathering pipelines is shown in Fig. 5.

Case study

Site description and pipeline selection

The proposed method is implemented in gathering pipelines of an oil and gas field in Northwest China. As shown in Fig. 6, the operating environment of the gathering pipelines is complex with high uncertainties, including deserts, gobi, cross railways, highways, national highways, woods, rivers, and scenic spots. Three operating regions are selected and marked in blue. The selected pipelines pass through the World Devil City Scenic spot (See pink label), farmland (See white label), and river (See black label). Roads route the operation area (See yellow label) and the main traffic road inside the oil field (See green label).

81 double-high (A term that denotes high failure likelihood and high failure consequences) pipelines transporting four different media, including crude oil, gas, water, and steam, are selected for the case study. The characteristics of the pipelines chosen are shown in Table 7.

Method implementation

Each pipeline can be assessed according to the risk index system developed in Section 2.2. Then, the score of pipeline failure likelihood can be determined given the method in Section 2.3.2. Further, according to the pipeline inspection data and the opinions of oil and gas field experts, the pipeline trust recommendation matrix *AT* can be

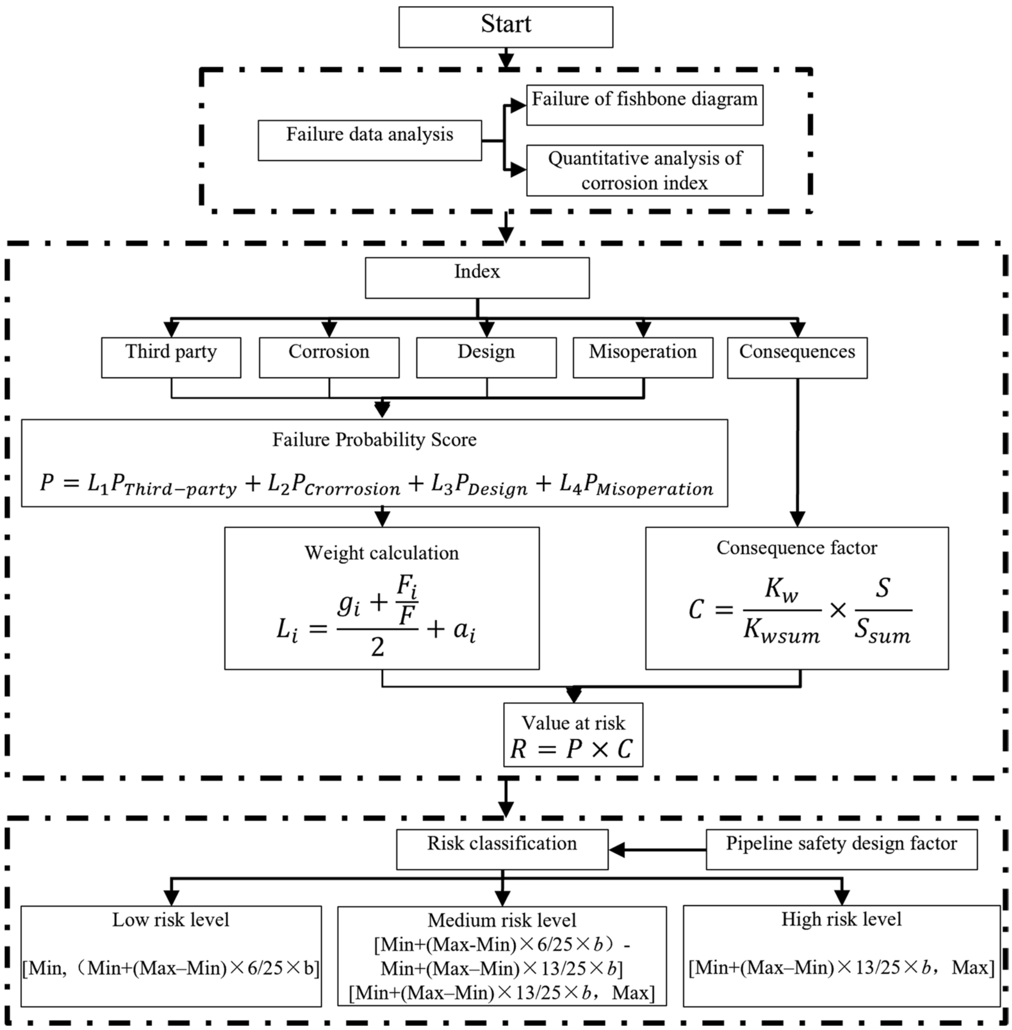

Fig. 5 Risk assessment framework proposed in this work

$$AT = \begin{bmatrix} 1.0000 & 7.0000 & 0.1670 & 0.2000 \\ 0.1420 & 1.0000 & 0.1100 & 0.1250 \\ 6.0000 & 9.0000 & 1.0000 & 4.0000 \\ 5.0000 & 8.0000 & 0.2500 & 1.0000 \end{bmatrix}$$

According to Eqs. (5), (6) (7), the membership matrix B is

$$B = \begin{bmatrix} 0.4306 & 1.2920 & 0.0957 & 0.1132 \\ 0.0829 & 0.4306 & 0.0654 & 0.0731 \\ 1.2090 & 1.4307 & 0.4306 & 1.0000 \\ 1.1132 & 1.3653 & 0.1386 & 0.4306 \end{bmatrix}$$

At this time, $n = 4$, $m = 4$, $k = 4$, and $\gamma = 1$. Then, the initial weight can be determined by Eqs. (8), (9), (10), (11), i.e., $G = [0.1123\ 0.8353\ 0.009\ 0.0404]$.

The number of gathering pipelines failure are statistically analyzed in this oil and gas field. In the past six years, there have been 463 pipeline incidents, where third-party damage caused 21 pipeline failures, corrosion caused 423 pipeline failures, the design caused six pipeline failures, and misoperation caused 13 pipeline failures. The failure rate of pipelines caused by such factors were 0.0454, 0.9135, 0.0130, and 0.0281, respectively.

The dynamic weight of failure indicators can be determined based on Eq. (11). As the evaluation was jointly participated by staff and experts, the evaluation result was highly accurate and ai is 0. Thus, the dynamic additional weights of failure likelihood indicators can be $L = [0.0803\ 0.8744\ 0.0110\ 0.0343]$.

Then, the failure likelihood can be determined by

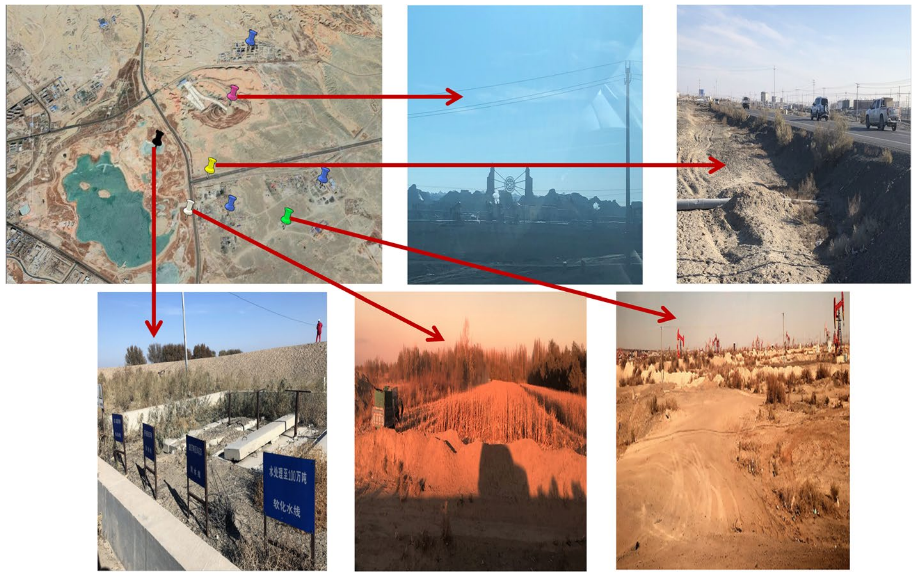

Fig. 6 Area and environment

Table 7 Pipeline features

Medium	Number	Service years (year)	Pipe material	Outer diameter (mm)	Wall thickness (mm)	Design pressure (MPa)	Operating pressure (MPa)	Description
Thin oil	18	5~20	20#	159~273	3.5~13	2.5~6	0.7~3.5	The soil along the pipeline is soft, making it difficult for vehicles to pass. Due to wind erosion, the content of the pipeline marker piles is blurred. The embankment along the pipeline is flush with the ground and cannot protect the pipeline.
Heavy oil	25	10~20	20#	60~273	3.5~7	1.6~16	0.6~10.5	There is a main traffic line near the pipeline, some marker piles along the line are inclined and collapsed, some pipe trenches are not backfilled, and large construction machinery is nearby.
Gas	18	10~20	20#	114~508	5~27	1.6~32	0.~29	Part of the pipeline through provincial roads, agricultural areas, a desert oasis ecological park, the railway, a parking lot, and some signs along with the pipeline collapse.
Water	12	5~25	20#	159~219	5	1~20	0.~16	Pipeline elbows are used to cross roads. There are marks of rolling over the pipeline, and the pipe dike is damaged.
Steam	8	10~20	20#	114	10	14	3~13.5	There is no internal anti-corrosion method for pipeline laying. The pipeline crosses the aisle, the traffic flow is large, the marking pile along the line is incomplete, and the marking content is unclear. The insulation layer of the pipeline has fallen off.

$$P = 0.0803P_{third\ party} + 0.8744P_{corrosion} + 0.011P_{design} + 0.0343P_{misoperation} \tag{14}$$

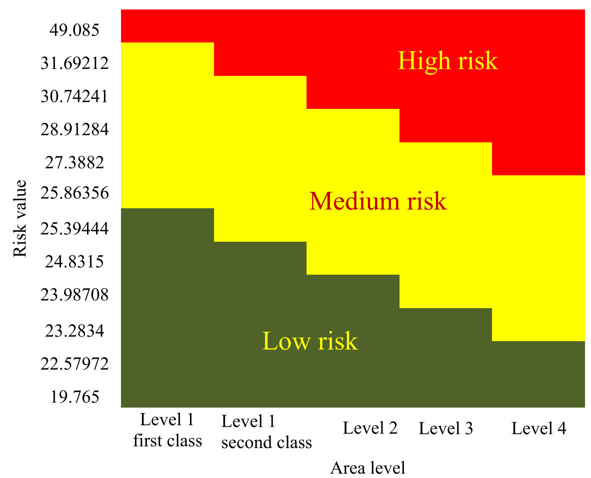

Fig. 7 Risk matrix of gathering pipelines

The failure consequence coefficient can be determined by Eq. (13). The use of Eq. (1) can assess the risk of each pipeline.

Results and discussion

Results show that the lowest risk value is 19.765, while the highest is 49.085. The risk grade boundary can be determined by the safety design coefficients of different areas. The risk level boundary of the level 1 first-class area is between 25.39444 and 31.96212. The risk level boundary of the level 1 second-class area is between 24.831496 and 30.742408. The risk level boundary of the level 2 area is between 23.98708 and 28.91284. The risk level boundary of the level 3 area is between 23.2834 and 27.3882. The risk level boundary of the level 4 area is between 22.57972 and 25.86356. The risk matrix is shown in Fig. 7.

The risk level of each pipeline is determined given the proposed risk matrix, as shown in Table 8. The risk value of the selected pipeline is between 19.765 and 49.085, where 8 pipelines are low-risk level, accounting for 9.88%; 34 pipelines are medium-risk, accounting for 41.96%; There are 39 high-risk pipelines, accounting for 48.16%. Among the four kinds of transmission medium pipelines, the risk value of water transmission pipelines is the lowest, most are at medium risk level, and a few are at low-risk level, but there is no high-risk level. The gas transmission pipeline with the highest risk value is located in densely populated areas and has serious failure consequences. 72% of thin oil pipelines are high risk, 28% are medium risk, and there is no low risk; 36% of heavy oil pipelines were rated as high risk, 56% as medium risk and 8% as low risk.

The proposed method (i.e., method 1) is compared with a previous method (i.e., method 2), see Appendix [30], as shown in Fig. 8. The previous risk assessment method used in the case of oil and gas fields mainly refer to a China Code (GB-32167-2015). The gathering pipelines are scored using the semi-quantitative risk assessment index system to determine the failure likelihood and consequence scores. The semi-quantitative failure lilelihood index and failure consequence index are shown in Table 1 A and Table 2.

Results show that high, medium and low risk accounted for 48.16%, 41.96% and 9.88%, respectively, by using the method 1. Meanwhile, the results using the method 2 show that all pipelines are at high risk where the lowest risk value is 6.4827, and the highest one is 185.8968, demonstrating risk threshold is quite different between the two methods.

Further, 81 double-hight pipelines are investigated onsite to examine the accuracy of the two methods. The results show that some pipelines are not featured with high risk, e.g., thin oil pipeline #9, heavy oil pipeline #33, gas pipeline #52, water pipeline #64, and steam pipeline #79. They all have a 5cm thick concrete protective layer, intact pipe embankment, and marker piles. A staff patrols the pipelines daily. The pipelines are equipped with a real-time monitoring system. Also, heavy oil pipeline #41, gas pipeline #46, and water pipeline #69 have a 10cm protective layer. Staff patrol the pipelines daily, fill corrosion inhibitor and pigging regularly, set up real-time monitoring and automatic cutting system, carry out staff training regularly, and set up protection devices when routing densely populated and scenic areas. Therefore, it can be explained that method 2 cannot accurately reflect the actual risk status of the pipelines, which provides too conservative protective measures, increasing maintenance costs.

Conclusions

In this work, a comprehensive risk assessment framework was proposed to effectively avoid the environmental hazards and economic losses caused by the failure of gathering pipelines. A risk index system for multiple media gathering pipelines was developed based on the KENT method. The information entropy method was used to determine the weights of the failure likelihood indicators to improve the accuracy and applicability of the method. An improved risk classification method for different regions was proposed by introducing the safety design coefficient, reflecting the actual risk status in different areas. The proposed risk assessment method was

Table 8 Evaluation results [33]

Number	Medium	Area	Value	Grade	Number	Medium	Area	Value	Grade	Number	Medium	Area	Value	Grade
1	Thin oil	Level 2	34.064	High	28	Heavy oil	Level 1 second class	29.611	Medium	55	Gas	Level 4	30.211	High
2	Thin oil	Level 1 first class	33.159	High	29	Heavy oil	Level 1 second class	29.278	Medium	56	Gas	Level 4	31.08	High
3	Thin oil	Level 1 first class	34.969	High	30	Heavy oil	Level 2	28.129	Medium	57	Gas	Level 1 first class	28.295	Medium
4	Thin oil	Level 1 first class	34.0641	High	31	Heavy oil	Level 2	29.954	High	58	Gas	Level 3	29.871	High
5	Thin oil	Level 1 first class	33.7361	High	32	Heavy oil	Level 3	28.438	High	59	Gas	Level 2	28.195	Medium
6	Thin oil	Level 1 first class	38.786	High	33	Heavy oil	Level 1 first class	29.298	Medium	60	Gas	Level 1 second class	29.195	Medium
7	Thin oil	Level 1 first class	32.7806	High	34	Heavy oil	Level 1 first class	28.937	Medium	61	Gas	Level 1 second class	23.195	Low
8	Thin oil	Level 1 first class	32.78	High	35	Heavy oil	Level 1 first class	28.195	Medium	62	Water	Level 1 first class	22.36	Low
9	Thin oil	Level 1 first class	31.141	Medium	36	Heavy oil	Level 1 first class	27.195	Medium	63	Water	Level 1 first class	28.195	Medium
10	Thin oil	Level 1 first class	31.244	Medium	37	Heavy oil	Level 1 first class	37.892	High	64	Water	Level 1 first class	27.195	Medium
11	Thin oil	Level 1 first class	30.527	Medium	38	Heavy oil	Level 1 first class	31.937	High	65	Water	Level 1 first class	31.273	Medium
12	Thin oil	Level 1 first class	31.372	Medium	39	Heavy oil	Level 1 first class	30.047	Medium	66	Water	Level 1 first class	30.192	Medium
13	Thin oil	Level 1 first class	33.22	High	40	Heavy oil	Level 1 first class	28.195	Medium	67	Water	Level 1 first class	29.273	Medium
14	Thin oil	Level 1 first class	43.483	High	41	Heavy oil	Level 1 first class	23.163	Low	68	Water	Level 1 first class	28.947	Medium
15	Thin oil l	Level 3	29.162	Medium	42	Heavy oil	Level 1 first class	30.165	Medium	69	Water	Level 1 first class	19.765	Low
16	Thin oil	Level 3	29.455	High	43	Heavy oil	Level 1 first class	22.462	Low	70	Water	Level 1 first class	28.136	Medium
17	Thin oil	Level 4	36.208	High	44	Gas	Level 1 first class	48.308	High	71	Water	Level 1 first class	27.362	Medium
18	Thin oil	Level 4	40.261	High	45	Gas	Level 1 first class	22.57	Low	72	Water	Level 1 first class	27.561	Medium
19	Heavy oil	Level 4	37.892	High	46	Gas	Level 1 first class	21.82	Low	73	Water	Level 1 first class	29.162	Medium
20	Heavy oil	Level 1 first class	31.937	Medium	47	Gas	Level 2	22.642	Low	74	Steam	Level 1 first class	47.56	High

Table 8 (continued)

Number	Medium	Area	Value	Grade	Number	Medium	Area	Value	Grade	Number	Medium	Area	Value	Grade
21	Heavy oil	Level 1 second class	31.937	Medium	48	Gas	Level 2	49.085	High	75	Steam	Level 1 first class	47.752	High
22	Heavy oil	Level 1 second class	35.538	High	49	Gas	Level 3	47.835	High	76	Steam	Level 1 first class	35.564	High
23	Heavy oil	Level 1 second class	34.681	High	50	Gas	Level 2	48.226	High	77	Steam	Level 1 first class	38.869	High
24	Heavy oil	Level 1 second class	33.41	High	51	Gas	Level 1 second class	29.296	High	78	Steam	Level 1 first class	39.135	High
25	Heavy oil	Level 1 second class	33.41	High	52	Gas	Level 1 second class	30.747	Medium	79	Steam	Level 1 first class	29.455	Medium
26	Heavy oil	Level 1 second class	33.791	High	53	Gas	Level 3	29.296	High	80	Steam	Level 1 first class	36.208	High
27	Heavy oil	Level 1 second class	29.611	Medium	54	Gas	Level 2	28.117	Medium	81	Steam	Level 1 first class	40.261	High

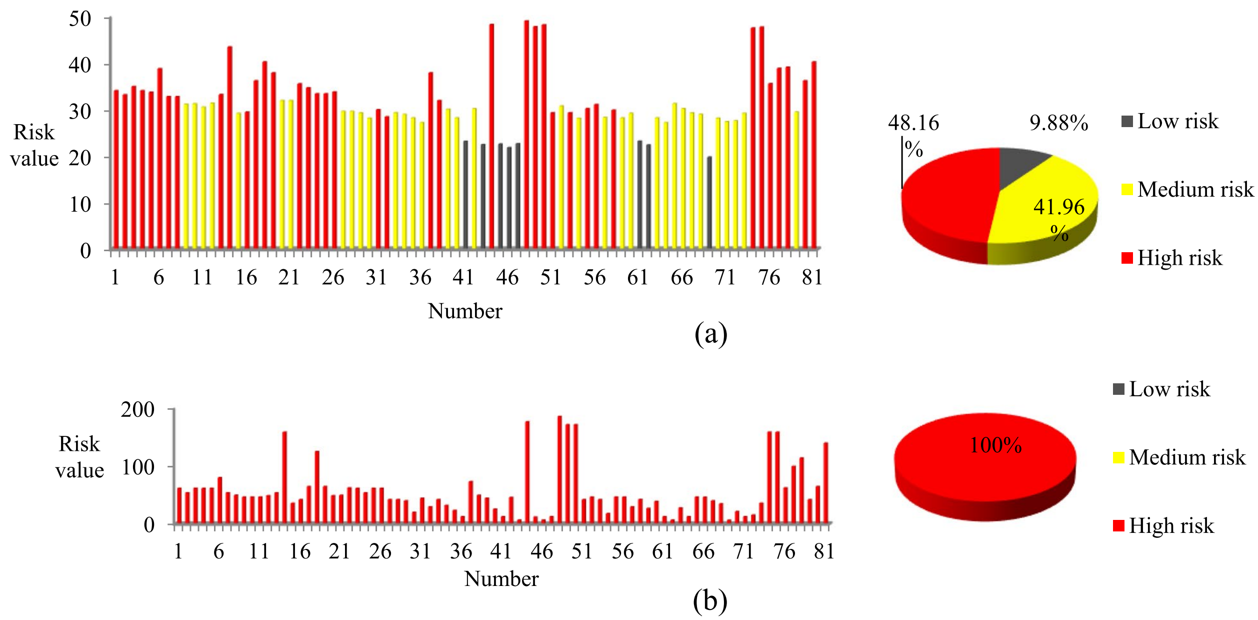

Fig. 8 Comparison of assessment results of (**a**) method 1 and (**b**) method 2

applied to a case study. Results showed that high-risk pipelines account for 48.16%, medium-risk pipelines account for 41.96%, and low-risk pipelines account for 9.88%, consistent with the pipeline's actual operating conditions. Meanwhile, it demonstrated that the proposed method could guide risk operators to improve the effectiveness of risk management. However, the proposed method is essentially an expert-based system with subjectivity. A Bayesian network model could be established based on the index system proposed in this work to perform a more accurate quantitative risk assessment.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s43065-022-00066-1.

Additional file 1.

Authors' contributions

Guojin Qin: Conceptualization, Methodology, Investigation, Writing - original draft, Writing - review & editing, Project administration, Funding acquisition. Shengyu Tang: Methodology, Investigation, Writing - original draft. Ruiling Li: Writing - review & editing. Ailin Xia: Writing - review & editing. Zhenwei Zhang: Writing - review & editing. Yihuan Wang: Validation, Writing - review & editing, Supervision. All authors reviewed the manuscript. The authors read and approved the final manuscript.

Funding

This work was supported by Open Fund (PLN2022-40) of State Key Laboratory of Oil and Gas Reservoir and Exploitation (Southwest Petroleum University).

Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

Not applicable.

Competing interests

The authors declare that they have no competing interests.

Author details

[1]State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation, Southwest Petroleum University, Chengdu 610500, China. [2]School of Civil Engineering and Geomatics, Southwest Petroleum University, Chengdu 610500, Sichuan, China. [3]Systems Engineering Research Institute, China State Shipbuilding Corporation Limited, Beijing ,100000, China.

Received: 25 September 2022 Revised: 19 November 2022 Accepted: 21 November 2022
Published online: 27 December 2022

References

1. Zhang H, Liang Y, Zhang W, Wang B, Yan X, Liao Q (2017) A unified MILP model for topological structure of production well gathering pipeline network. J Petrol Sci Eng 152:284–293
2. Wang H, Duncan IJ (2014) Understanding the nature of risks associated with onshore natural gas gathering pipelines. J Loss Prevent Proc 29:49–55
3. Liao K, Yao Q, Wu X, Jia W (2012) A numerical corrosion rate prediction method for direct assessment of wet gas gathering pipelines internal corrosion. Energies 5:3892–3907
4. Zhang P, Chen X, Fan C (2020) Research on a safety assessment method for leakage in a heavy oil gathering pipeline. Energies 13:1340
5. Wang Y, Li R, Xia A, Ni P, Qin G (2023) An integrated modeling method of uncertainties: application-orientated fuzzy random spatiotemporal analysis of pipeline structures. Tunn Undergr Sp Tech 131:104825
6. Sun H, Zhou W, Kang J (2021) A review of crack growth models for near-neutral pH stress corrosion cracking on oil and gas pipelines. J Infrastruct Preserv Resil 2:1–15

7. Salemi M, Wang H (2020) Fatigue life prediction of pipeline with equivalent initial flaw size using Bayesian inference method. J Infrastruct Preserv Resil 2:1–15
8. Cheng YF (2016) Monitor safety of aged oil pipelines. Nature 529:156
9. Wises JD (2012) Pipeline safety: information collection activities, revision to gas transmission and gathering pipeline systems annual report, gas transmission and gathering pipeline systems incident report, and hazardous liquid pipeline systems accident report, vol 77. Federal Register (National Archives & Records Service, Office of the Federal Register), pp 58616–58622
10. Adumene S, Khan F, Adedigba S, Zendehboudi S, Shiri H (2021) Offshore pipeline integrity assessment considering material and parametric uncertainty. J Pipeline Sci Eng 1:265–276
11. Kraidi L, Shah R, Matipa W, Borthwick F (2021) An investigation of mitigating the safety and security risks allied with oil and gas pipeline projects. J Pipeline Sci Eng 1:349–359
12. Khan F, Yarveisy R, Abbassi R (2021) Risk-based pipeline integrity management: A road map for the resilient pipelines. J Pipeline Sci Eng 1:74–87
13. Wang Y, Hou X, Zhang P, Qin G (2020) Reliability assessment of multistate reconfiguration pipeline system with failure interaction based on Cloud inference. Process Saf Environ 137:116–127
14. Wang Y, Zhang P, Hou X, Qin G (2020) Failure probability assessment and prediction of corroded pipeline under earthquake by introducing in-line inspection data. Eng Fail Anal 115:104607
15. Zhang P, Wang Y, Qin G (2018) Fuzzy damage analysis of the seismic response of a long-distance pipeline under a coupling multi-influence domain. Energies 12(1):62
16. Muhlbauer WK (2004) Pipeline risk management manual, 3rd edn. Gulf Publishing Companies, Houston
17. Cui Y, Quddus N, Mashuga CV (2020) Bayesian network and game theory risk assessment model for third-party damage to oil and gas pipelines. Process Saf Environ 134:178–188
18. Badida P, Balasubramaniam Y, Jayaprakash J (2019) Risk evaluation of oil and natural gas pipelines due to natural hazards using fuzzy fault tree analysis. J Nat Gas Sci Eng 66:284–292
19. Liu Y, You M, Zhu J, Wang F, Ran R (2019) Integrated risk assessment for agricultural drought and flood disasters based on entropy information diffusion theory in the middle and lower reaches of the Yangtze River, China. Int J Disast Risk Re 38:101194
20. Zhao R, Liu Q, Wang Y, Jia P, Li C, Ma Y, Zhu W (2022) Dynamic Crowd Accident-Risk Assessment Based on Internal Energy and Information Entropy for Large-Scale Crowd Flow Considering COVID-19 Epidemic. IEEE T Intell Transp 23:17466–17478
21. Huang W, Zhang Y, Yu Y, Xu Y, Xu M, Zhang R, De Dieu G, Yin D, Liu Z (2021) Historical data-driven risk assessment of railway dangerous goods transportation system: Comparisons between Entropy Weight Method and Scatter Degree Method. Reliab Eng Syst Safe 205:107236
22. Zhang P, Qin G, Wang Y (2019) Risk assessment system for oil and gas pipelines laid in one ditch based on quantitative risk analysis. Energies 12:981
23. PHMSA (2016) About data & statistics. http://www.phmsa.dot.gov/pipeline/library/data-stats.
24. Alberta Energy Regulator (AER) (2013) Report 2013-B: Pipeline Performance in Alberta, 1990-2012.
25. Yang L, Li Y, Gong Z et al. (2019) Xinjiang Oilfield Company, CNPC Research Report 2019. Risk assessment method of oil and gas gathering pipeline.
26. Shinde DD, Ahirrao S, Prasad R (2018) Fishbone diagram: application to identify the root causes of student–staff problems in technical education. Wireless Pers Commun 100:653–664
27. Qiao Q, Cheng G, Wu W, Li Y, Huang H, Wei Z (2016) Failure analysis of corrosion at an inhomogeneous welded joint in a natural gas gathering pipeline considering the combined action of multiple factors. Eng Fail Anal 64:126–143
28. Geng X, Wanyuan M (2017) Interval-valued intuitionistic vikor considering unknown attribute weights. Comput Eng Appl 53:257–262
29. Liang G, Li Y (2017) Spectral Clustering Algorithm Based on Attribute Weight of Information Entropy. In: Recent Developments in Intelligent Computing, Communication and Devices. Springer, Singapore, pp 137–142
30. Ministry of Housing and Urban-Rural Development (MOHURD) (2015). GB 50251-2015: Code for design of gas transmission pipeline engineering.
31. The welding institute (TWI) (2017) RiskWISE® for pipelines, Cambridge https://www.twisoftware.com/software/integrity-management-software/riskwise-for-pipelines/
32. Administration of Quality Supervision,Inspection and Quarantine (AQSIQ) (2015) Standardization Administration of China (SAC). GB 32167-2015: Oil and gas pipeline integrity management specification.

Publisher's Note