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Risk-based pipeline re-assessment optimization considering corrosion defects

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ABSTRACT

Pipelines are critical assets for transporting different crucial items such as oil, natural gas, and water, and they are critical for a city's reliable, safe and secure operations. Metal loss corrosion is one of the main failure modes that pipelines suffer from that can lead to pipeline rupture or collapse. Inspections or assessments are performed periodically to assess the health conditions of pipelines. Existing methods for determining the optimal inspection interval mainly used constant fixed re-assessment interval as the decision variable during the whole service. However, pipelines with different defect sizes at the current inspection point lead to different future defect growth and failure probability, and it is more reasonable to apply different re-assessment intervals depending on pipeline health conditions. This paper proposes a method to find the optimal re-assessment intervals for pipelines subject to multiple corrosion defects, where the probability of failure (PoF) threshold is used as the decision variable for this optimization problem. Uncertainties from various sources are considered in this study to achieve an accurate and realistic prediction. A simulation-based cost evaluation approach is developed for a given re-assessment policy defined by the PoF threshold. First-order reliability method is used to calculate the PoF to improve the efficiency. The optimal PoF threshold can be obtained corresponding to the minimum expected cost rate. An example is given to demonstrate the proposed approach, and sensitivity studies are performed.

1. Introduction

Pipelines are critical assets for gathering and transporting different crucial items such as oil, natural gas, and water, and they are critical for a city's reliable, safe and secure operations. Research studies have been conducted on various topics to ensure pipeline reliability and safety, such as qualitative and quantitative risk assessment methods for urban natural gas pipeline network (Han and Weng, 2011), risk-based maintenance of petroleum pipeline systems (Dawotola, Trafalis, Mustaffa, van Gelder, & Vrijling, 2013), and optimized maintenance scheduling for water pipeline networks (Li, Ma, Sun, & Mathew, 2016a). Pipelines in the system are easily affected by surrounding environment, construction errors, natural disasters and human activities. Different kinds of defects, such as corrosion, crack, mechanical damage and third party damage, may result in reduced strength in pipeline segments, and present threat to the whole system. Hence, these defects need to be managed properly to avoid environmental hazards and costly downtime.

For some threats to pipeline integrity, like corrosion, crack and dents, the nature of the growth mechanisms are time-dependent. With the use of suitable damage propagation model, the probability of failure can be estimated for pipelines with particular types of defects. Corrosion is a major integrity threat to oil and gas pipelines. Risk analysis for metal loss corrosion defect is a vital part of pipeline integrity management. Risk is typically defined as the multiplication of probability and consequence, and it can be used as a reliability measure for pipeline systems. Qualitative and quantitative risk assessment methods are two ways for pipeline integrity management. Qualitative risk assessment methods are based on a risk analysis index system, which contains few essential data and leads to a rough estimation without giving a numerical value. However, a final descriptive ranking is given based on the index system and the results are easily presented and understood. Quantitative methods use physics models and numerical simulation to obtain quantitative assessment of risks. Han and Weng (2011) compared proposed qualitative and quantitative risk assessment methods for the natural gas pipeline system. The results for two methods were close and they could both be used in practical applications. Zhang and Zhou, (2013) proposed a method to evaluate the reliability of corroding pipeline systems.

Maintenance actions are taken for pipeline reliability and safety assurance. Inline inspection (ILI) is a typical inspection method for evaluating pipeline conditions and defect sizes using inline inspection

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tools such as magnetic flux leakage tools and ultrasonic tools. Repair actions can be taken based on inspection results. It is important to optimize maintenance activities to improve reliability, reduce risks and minimize the overall costs. Dawotola et al. (2013) proposed a data-driven method to conduct risk-based maintenance of a pipeline system. This approach estimates the failure probability of the pipeline system by fitting historical data using a homogeneous Poisson process or nonhomogeneous Poisson process. Li, Chen, and Zhu (2016b) proposed a quantitative risk analysis model for leakage failure using Bayesian networks. Optimal inspection planning for pipelines with corrosion defects has drawn lots of research attention due to its key role and the significant cost of performing ILI inspections. Bott and Sporns, (2008) provided the benefits and limitations of using risk-based inspection methods. Gomes, Beck, and Haukaas (2013), (Gomes and Beck, 2014) optimized the inspection schedule for pipelines with corrosion and crack defects respectively. Tee et al. (Tee, Khan, Chen, & Alani, 2014) gave reliability based life cycle cost optimization for pipelines using Genetic Algorithm (GA). McCallum et al., (2014) developed a model for corrosion risk assessment using Markov chain process. Zhang and Zhou (Tee et al., 2014) investigated the optimal inspection interval based on stochastic degradation models. All the methods used in these papers considered the inspection interval as the design variable, and the optimal inspection interval is fixed and constant during the whole pipeline service time once it is determined. However, pipeline defect sizes are different at different inspection points, resulting in different future defect growth and system failure probability, and thus it is more reasonable to apply different re-assessment intervals depending on pipeline health conditions.

In this paper, we develop an approach to find the optimal re-assessment intervals for pipelines subject to multiple corrosion defects, where the probability of failure (PoF) threshold is used as the decision variable for this optimization problem. Re-assessment is performed for the entire line when the predicted system PoF reaches the PoF threshold. The re-assessment interval is not constant, because it varies due to different predicted defect growth and failure probability during different stages of pipes in their life cycles, or combinations of pipes with different conditions. The framework of this study is shown in Fig. 1. First, through using detection and inspection tools like ILI tools, defects for different pipeline segments can be detected. Damage prediction models are used for predicting the growth of these defects. The entire line with multiple corrosion defects can be treated as a series system with multiple components, because it will fail if any defect meets its limit states or failure criteria. The system failure probability can be evaluated based on the structure of pipeline system and each defect's failure probability. When the failure probability for the entire line reaches the PoF threshold, different options of maintenance and rehabilitation activities may be implemented based on the corresponding criteria to ensure the safety of the whole pipeline system. Cost rate evaluation at the re-assessment point needs to be determined considering inspection cost, repair cost, potential failure cost, etc. Lastly, optimization is conducted for the pipeline system to find the optimal PoF threshold with respect to the lowest cost rate. The optimal re-assessment intervals will be determined by implementing the re-assessment policy defined by the optimal PoF.

Monte Carlo simulation technique is utilized to analyze the re-assessment policy, and uncertainties need to be considered and quantified in the simulation process. Defect identification and classification are critical for pipeline system integrity management. ILI tools have been evolving rapidly and these tools are widely used for detecting and inspecting corrosion, erosion, cracks, etc. The accuracy of ILI tools affects inspection results a lot. The inspection results contain information about types, locations and dimensions of defects and they serve as the basis for assessing a pipeline system's current condition. Therefore, the measurement error of ILI tools is necessary to be considered in the pipeline system integrity management. In this study, uncertainties in pipe geometry and material properties are also considered as important uncertainty factors in addition to the tool measurement error.

The remainder of the paper is organized as follows. Section 2 describes the damage propagation models including the limit state functions for corrosion defects as well as uncertainty quantification. Section 3 introduces the proposed re-assessment and maintenance policies, and presents the proposed pipeline re-assessment optimization approach. Section 4 presents examples to implement the proposed approach, investigates the impact of relevant parameters on the results, and compares with fixed interval method. Conclusions are presented in Section 5.

2. Damage prediction models

2.1. Limit state functions for failure due to corrosion

For pipelines with active corrosion defects, failure caused by the defects is determined by calculating the limit state functions (LSFs). There are two limit state functions representing the failure criteria for pipelines with corrosion defects. The corrosion defects are considered to be safe only when the two limit state functions are both positive.

The first LSF is defined as the difference between the burst pressure P_f and the operating pressure P_{op}, and the general form of the *LSF* is:

$$LSF_1(P_f, T) = P_f(D, t, YS, UTS, d(T), L(T)) - P_{op} \quad (1)$$

where D is the pipeline diameter; t is the pipeline wall thickness; YS and UTS are the pipeline material yield strength and ultimate tensile strength, respectively; L is the axial length of the defect; d is the depth of the defect and T is the elapsed time. This limit state function is time-dependent, and the burst pressure P_f depends on the above-mentioned parameters.

As for burst pressure calculation, in the literature, various burst pressure models, including B31G (Institute, 1991), (Vieth, 2002), modified B31G (Kiefner and Vieth, 1989), Battelle (Leis and Stephens et al., 1997), DNV-99 (Veritas, 2004), Shell-92 (Ritchie and Last, 1995), can be used to calculate P_f in Eq. (1). Equations for all these methods are similar and they are all based on the NG-18 equation (Kiefner, Maxey, Eiber, & Duffy, 1973). Cosham, Hopkins, and Macdonald (2007) presented and compared these burst pressure models in the literature used to assess corrosion defects. Caleyo, González, and Hallen (2002) compared these burst pressure models when conducting the reliability assessment of corroded pipelines. Among these burst pressure models, modified B31G is the most popular one and it is relatively accurate. Hence, in this paper, we use modified B31G model to calculate burst pressure, which is shown as follows:

$$P_f = \frac{2(YS + 68.95)t}{D}\left(\frac{1 - \frac{0.85d(T)}{t}}{1 - \frac{0.85d(T)}{tM}}\right) \quad (2)$$

$$M = \sqrt{1 + 0.6275\frac{L(T)^2}{Dt} - 0.003375\left(\frac{L(T)^2}{Dt}\right)^2}, \text{ if} \frac{L^2}{Dt} \le 50$$
$$M = 0.032\frac{L(T)^2}{Dt} + 3.3, \text{ if} \frac{L^2}{Dt} > 50. \quad (3)$$

In industry practice, often times 80% of the wall thickness is used as the threshold of the defect depth. It is a conservative maximum allowable value though, which means the leaks will not occur when the defect depth reaches 80% of the wall thickness, and there is no tolerance when considering a serious pipeline integrity issue. This leads to the second LSF, which is defined using the following equation:

$$LSF_2(d, T) = 0.8t - d(T). \quad (4)$$

As indicated before, a defect failure occurs if one of the LSFs is negative. Therefore, the probability of failure associated with an individual corrosion defect PF_{defect} is computed by:

$$PF_{defect} = \Pr(LSF_1 \le 0 \quad \text{OR} \quad LSF_2 \le 0) \quad (5)$$

The corrosion growth model needs to be determined to calculate the

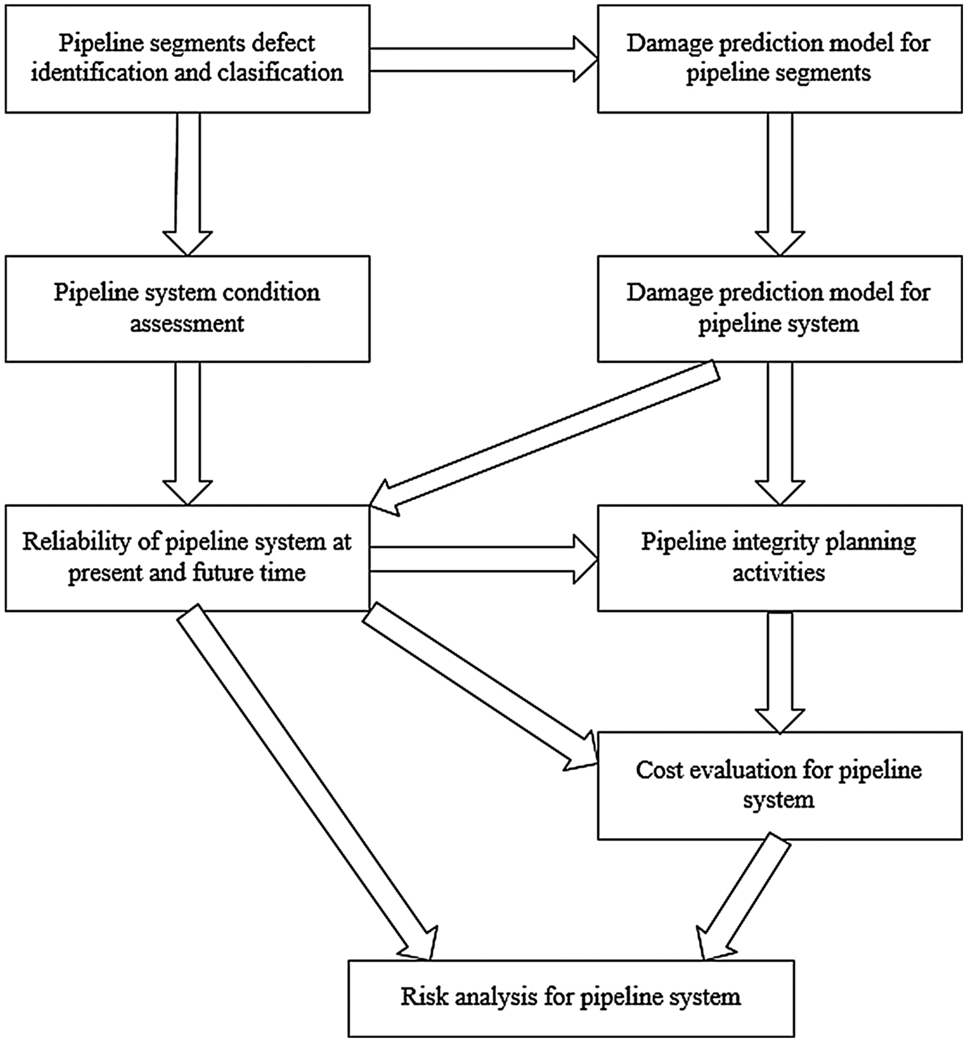


Fig. 1. Framework for the pipeline system risk assessment.

probability of failure for a single corrosion defect. The widely used corrosion degradation models for defect depth with respect to time are shown in the following equations (Caleyo et al., 2002; Fuller, 2009; Jaech, 1985).

$$d(t) = d_0 + V_r(T-T_0) \tag{6}$$

$$L(t) = L_0 + V_a(T-T_0) \tag{7}$$

where d_0 and L_0 are initial defect depth and length, respectively; V_r and V_a are radial and axial corrosion growth rate, respectively; T_0 is the time of last inspection and T is the exposure time. Substituting Eq. (1)–(4), (6), (7) into Eq. (5), we can predict the failure probability of a single corrosion defect at any future time. Thus, reliability can be calculated based on pipe geometry, defect geometry, material properties, growth rates and time.

There are many pipeline segments in a pipeline system, inspected by ILI tools. Therefore, it is very likely there are multiple corrosion defects in the pipeline. The entire pipeline is considered in this study, which is consistent with industry practice in ILI planning. Major pipelines are typically series systems over very long distance without complex network structure, and a pipeline system for which ILI assessments are planned for is typically a series system. It is also assumed that all these corrosion defects are independent, and they typically occur at different locations. The probability of failure for a pipeline segment with multiple corrosion defects PF_{pipe} is calculated by:

$$PF_{pipe} = 1 - \prod_{i=1}^{n} (1 - PF_{defect,i}) \tag{8}$$

where PF_{pipe} is failure probability of the pipeline, and n is the number of corrosion defects.

2.2. Uncertainties quantification

There are uncertainties both on load and resistance parameters, which the two limit state functions depend on due to tool performance and measurement errors. The relationship among risks, costs and tool performance need to be investigated. The information about pipe geometry and mechanical properties may have some uncertainties when measuring and testing them. Material uncertainty and geometry uncertainty will affect the burst capacity model, and as a result, will cause uncertainties in determining the limit state of corroded pipelines. Uncertainties associated with the ILI tool can be represented by the measurement error. In general, the measurement error will be affected by the resolution of ILI tool. It will affect the predicted depth a lot if the measurement error is big. σ_{ILI} is used to denote standard deviation of the measurement error in this paper.

Besides, model uncertainty of corrosion growth model should also be investigated. In the corrosion growth model, the two major parameters, corrosion growth rates V_r and V_a, depend on the surrounding environment and pipe materials. These random variables are assumed to follow normal distributions. The mean and standard deviation used

Table 1
Random variables (Zhang and Zhou, 2013).

Random variables	Mean	Standard deviation
Pipeline diameter (D)	914.4 mm	18.288
Pipeline thickness (t)	20.6 mm	0.412
Operating fluid pressure (P_{op})	7.8 MPa	1.56
Material yield stress (YS)	358 MPa	25.06
Ultimate tensile strength (UTS)	455 MPa	31.85
Defect length (L_0)	200 mm	20
Defect depth (D_0)	(10%–20%)t	0.5
Radial corrosion growth rate (V_r)	0.3 mm/year	0.03
Axial corrosion growth rate (V_a)	10 mm/year	0.5

for the basic variables in each analysis can be seen in Table 1. Some parameters of these variables were reported in (Zhang and Zhou, 2013).

3. The proposed risk-based re-assessment optimization approach

3.1. Re-assessment and maintenance policy

The proposed risk-based pipeline re-assessment and maintenance policy are described in this section. The proposed risk-based re-assessment optimization approach is used to find the optimal PoF threshold. At the current pipeline assessment point, defect information is collected based on the pipeline assessment results. Corrosion defect growth can be predicted based on the current defect information and defect growth models. Considering uncertainties in defect measurement, defect growth, pipe properties, future defect failure probability, and thus pipeline system PoF, can be predicted. The re-assessment interval is the point when the predicted system PoF first exceeds the optimal PoF threshold. Inspection cost is incurred at the predicted re-assessment interval.

In addition, at a pipeline assessment point, maintenance actions, including possible excavation and repair actions, may be taken based on the collected defect information. There are mainly two types of maintenance activities: predictive maintenance and corrective maintenance. Maintenance option selection is based on the risk estimation, which means we need to calculate the probability of failure of the whole system and quantify the total consequence of the failure hazards. If a failure occurs in pipelines at any time, the corrective maintenance or replacement needs to be performed immediately. In industry, pipeline failure is highly undesirable due to the potential damage to human life and environment and huge economic loss, and it is characterized by very high failure cost in this study. As to predictive maintenance activities, it is typically performed at an inspection point and there are two main repair activities, sleeving and recoating.

If a corrosion defect is successfully detected, we can utilize certain criterion to determine repair actions. Based on monitoring programs, the mitigation programs are initiated including pipeline excavations and different repair activities if a defect meets a certain criterion. A defect will be repaired immediately after inspection if any of the following limit state functions, described in Eqs. (9) and (10), is smaller than zero (Zhou and Nessim, 2011). Here, we call it as repair criteria 1. If a defect doesn't meet the repair criteria 1, neither excavation nor repair activities need to be performed at the inspection point.

$$LSF(d) = 0.5t - d \leq 0 \tag{9}$$

$$LSF(P_f)P_f - 1.39P_{op} \leq 0 \tag{10}$$

If a corrosion defect meets repair criteria 1, excavation needs to be performed at the inspection point and we need to check whether it meets repair criteria 2 or not. Repair criteria 2 is described by the following two equations, described in Eqs. (11) and (12). If any of the following limit state functions is smaller than zero, the corrosion defect meets repair criteria 2, and this corrosion defect is repaired with a full encirclement sleeve. And if the corrosion defect doesn't meet the repair criteria 2, the defect will be recoated.

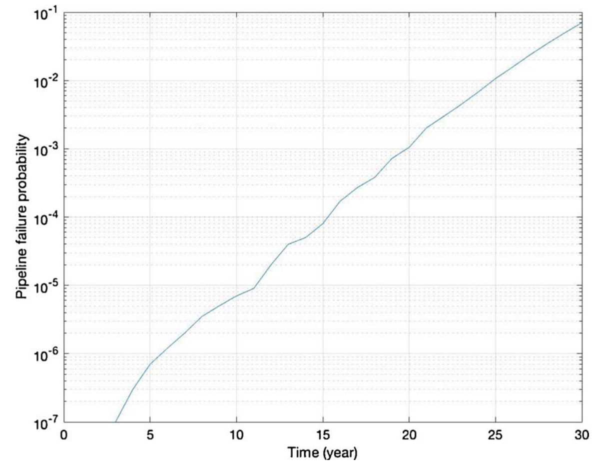


Fig. 2. Example failure probability of pipelines versus time.

$$LSF(d) = 0.75t - d \leq 0 \tag{11}$$

$$LSF(P_f)P_f - 1.1P_{op} \leq 0 \tag{12}$$

The proposed policy, defined by the system PoF threshold, leads to varying pipeline re-assessment intervals. But generally speaking, with the increase of PoF threshold, the average re-assessment interval increases, because the system failure probability that can be tolerated becomes larger. Fig. 2 is an example plot of failure probability of pipelines versus time. With the design variable PoF threshold given, we can find the re-assessment interval for next tool run. For example, if PoF threshold is 1×10^{-6}, the PoF of pipelines is smaller than the threshold until $T = 6$ years. In this way, for different PoF thresholds, we can record the corresponding re-assessment intervals and calculate the average re-assessment intervals, which is shown in Table 2. We can find that the number of years to perform next tool run increases with the decrease of PoF threshold.

3.2. Cost rate evaluation

An optimal risk-based pipeline re-assessment policy is defined by the optimal PoF threshold corresponding to the lowest cost rate, e.g. cost per year. The optimization problem can be generally formulated as follows:

$$\begin{aligned} &\min\ \mathrm{CR(PoF)} \\ &\text{s.t.}\ \ \mathrm{PoF} < \mathrm{PoF}_a \end{aligned} \tag{13}$$

where CR(PoF) is the total cost rate with a given PoF threshold; PoF_a is the acceptable threshold. In the optimization model, only the PoF threshold is the decision variable. The re-assessment or inspection intervals can be subsequently determined by the PoF threshold, using the methods described in Section 3.1. That is, at a certain inspection point, the corrosion defects are evaluated and future pipeline system failure

Table 2
Example average re-assessment interval.

Probability of Failure (PoF) threshold	Average re-assessment interval (yrs.)
1×10^{-7}	3
1×10^{-6}	6
5×10^{-6}	8
1×10^{-5}	12
5×10^{-5}	14
1×10^{-4}	15
1×10^{-3}	20
1×10^{-2}	25

probability is predicted. The next re-assessment time is the time when the predicted failure probability reaches the PoF threshold. In industry, there is an acceptable failure probability for pipelines defined before risk assessment. According to (Bai and Bai, 2014), the acceptable failure probability is defined based on safety class. The value is typically between 10^{-5} and 10^{-3} for different safety class.

In the risk-based pipeline re-assessment optimization, cost rate evaluation is a critical step. The problem is quite complex though, due to the consideration of multiple random variables, failure criteria, maintenance actions and corrosion defects. A simulation-based method is developed for cost rate evaluation given a certain PoF threshold value. The detailed procedure for cost evaluation and re-assessment interval optimization is given in the rest of the section.

3.2.1. Step 1: simulation initiation

In this stage, we consider the current inspection time at the beginning of the inspection cycle (with the predicted re-assessment time as the end of the inspection cycle). We can gather information on the size of each defect, namely depth $d_{0,i}$ and length $L_{0,i}$, pipeline geometry (OD, t), pipeline mechanical strengths (*YS*, *UTS*), etc. We need to consider defect measurement uncertainty, growth rate uncertainty and all the other uncertainties in load and resistant parameters. Then we generate all the load and resistant parameters with the consideration of uncertainties. Suppose the number of detected corrosion defect is *k*. Generate *k* initial corrosion defects considering the ILI tool measurement error. An example for uncertainties quantification is shown in Table 1. Specify the cost values, including inline inspection C_{in}, corrosion defect excavation cost C_{ev}, recoating cost C_{rc}, sleeving cost, C_{rs}, failure cost, C_f and additional fixed cost C_{af}.

3.2.2. Step 2: failure probability calculation

In each simulation iteration, grow each corrosion defect with uncertainty using Eqs. (6) and (7). With the use of corrosion growth model and limit state functions described in Section 2.1, PoF of the entire line at time *T*, i.e. PoF(*T*), can be calculated using first order reliability method (FORM) or Monte Carlo simulation method.

3.2.3. Step 3: cost evaluation in each iteration

When PoF(*T*) reaches the PoF threshold, the re-assessment point is reached. Record the total time. Costs include inspection costs, repair costs, and failure costs. The net present value (PV) evaluation is performed for the re-assessment interval to account for the time value of money. The net present value of total cost for pipeline with multiple corrosion defects when re-assessment interval is *t** can be determined as follows:

$$PV_{t^*}=PV_{\mathrm{insp},t^*}+PV_{\mathrm{repl},t^*}+PV_{\mathrm{fail},t^*}+PV_{\mathrm{main},t^*}+PV_{\mathrm{fixed},t^*} \tag{14}$$

where PV_{insp,t^*}, PV_{repl,t^*}, PV_{fail,t^*}, PV_{main,t^*}, PV_{fixed,t^*} are net present values of inspection cost, replacement cost, failure cost, maintenance cost and additional fixed cost for entire line at year *t**.

The inspection cost is given by:

$$PV_{\mathrm{insp},t^*}=\frac{C_{\mathrm{in}}}{(1+r)^{t^*}}=\frac{l_i\times C_{\mathrm{insp}}}{(1+r)^{t^*}} \tag{15}$$

where C_{in} is the inspection cost; *r* is the discount rate; l_i is the distance of the ILI tool run; C_{insp} is the unit inspection cost. In this study, the entire line is inspected when using ILI tools.

The replacement cost is given by (Li et al., 2016a):

$$PV_{\mathrm{repl},t^*}=\frac{C_{\mathrm{rp}}}{(1+r)^{t^*}}\times PF_{\mathrm{pipe}}=\frac{CL_i\times l_i+(CM_i+CSL_i)+CT_i\times s_i}{(1+r)^{t^*}}\times PF_{\mathrm{pipe}} \tag{16}$$

where C_{rp} is the replacement cost; CL_i is the length cost rate; CM_i and CSL_i are cost of machinery and skilled labor, respectively; CT_i is unit transportation cost; s_i is the transportation distance for replacing pipes; PF_{pipe} is the failure probability of pipeline.

The failure cost considering risk to human and environmental is given by:

$$PV_{\mathrm{fail},t^*}=\frac{C_{\mathrm{fa}}}{(1+r)^{t^*}}\times PF_{\mathrm{pipe}}=\frac{C_{\mathrm{po}}+C_{\mathrm{en}}}{(1+r)^{t^*}}\times PF_{\mathrm{pipe}} \tag{17}$$

where C_{fa} is the failure cost due to damage to population and environment; C_{po} and C_{en}represent the cost converted from the damage to population and environment, respectively. The consequences of potential hazards are hard to estimate. Human safety, environmental damage, and economic loss consequences need to be quantified for further analysis. Total risk is the summation of human safety, environmental and economic risks. After converting damage to population and environment to economic loss, we can calculate the cost due to failure, $C_f = C_{fa} + C_{rp}$.

The maintenance cost is given by:

$$PV_{\mathrm{main},t^*}=\frac{\sum_{k}^{j=1}(C_{\mathrm{main},j}\times z_{t^*,j})}{(1+r)^{t^*}}$$
$$z_{t^*,j}=\begin{cases}1, \text{ if meet repair criteria 1}\\ 0, \text{ otherwise}\end{cases}. \tag{18}$$

$C_{main,j}$ is the repair cost; *k* is the number of corrosion defects. And $C_{main,j}$ can be calculated based on repair criteria 2, which is shown as follows:

$$C_{\mathrm{main},j}=\begin{cases}C_{\mathrm{ev}}+C_{\mathrm{rs}}, \text{ if meet repair criteria 2}\\ C_{\mathrm{ev}}+C_{\mathrm{rc}}, \text{ otherwise}\end{cases} \tag{19}$$

where C_{ev} is the excavation cost; C_{rs} and C_{rc} represent sleeving cost and recoating cost, respectively.

3.2.4. Step 4: cost rate calculation and optimization

With the Monte Carlo simulation, in each iteration (say *i*), we can obtain the total net present value PV_i and total time T_i. Suppose we run *N* simulation iterations. The cost rate with respect to a given PoF threshold can be calculated as:

$$\mathrm{CR(PoF)}=\frac{\sum_{i=1}^{N}\mathrm{PV_i}}{\sum_{i=1}^{N}\mathrm{T_i}} \tag{20}$$

We may also be interested in the average re-assessment interval corresponding to the optimal re-assessment policy by taking the average of each re-assessment time:

$$\overline{T}=\frac{\sum_{i=1}^{N}T_i}{N} \tag{21}$$

With different PoF thresholds, the total cost rate CR(PoF) are calculated. Based on the results, we can obtain the relationship between cost rate and PoF threshold, with the PoF threshold as the single variable. Due to the computation time required by the simulation procedure, we obtain CR values at a set of discrete PoF points, and use a spline to fit the CR(PoF) function. A simple optimization procedure can be performed subsequently to find the optimal PoF threshold. Once the optimal PoF threshold is found, the re-assessment intervals can be predicted at each assessment point using the proposed re-assessment policy, based on the inspection results, defect growth prediction and the optimal PoF threshold.

4. Examples

In this example, a pipeline with a length of 10 km will be inspected by ILI tools. The proposed methodology is utilized for assessing the entire line and finding the optimal PoF threshold value and ILI re-assessment time. The mean and standard deviation of geometry parameters and mechanical properties of the line are shown in Table 1. Ten initial corrosion defects are considered in the line within the defect depth range of 10% to 20% of wall thickness, at the beginning of

Table 3
Summary of costs (Zhang and Zhou, 2014).

Cost item	Absolute cost (CAD$)	Relative cost
Inline inspection C_{in}	40,000	2
Corrosion defect excavation C_{ev}	70,000	3.5
Recoating C_{rc}	20,000	1
Sleeving C_{rs}	35,000	1.75
Failure cost C_f	4,000,000	200
Fixed cost (labor, transportation, etc.)	10,000	0.5

inspection cycle, and later other ranges are also investigated in further analyses. Such assumptions are used in modeling the inspection cycles by considering various stages during the lives of pipe segments, and the fact that the pipeline might be a combination of pipes with different ages and lives. The ILI tool accuracy is assumed to be $\sigma_{ILI} = 0.5$ mm. And the axial and radial growth rate is set to be 10 mm/year and 0.3 mm/year in the example. The uncertainties are considered in all these parameters and they are normally distributed with the mean and standard deviation provided in Table 1. These parameters in Table 1 are set to be the baseline and will be compared with other scenarios in Section 4.2. FORM method is implemented here to calculate the probabilities that these limit state functions, described in Eqs. (5) (9)–(12), are smaller than 0, and then calculate the probabilities of sleeving, recoating, and failure associated with each corrosion defect. FORM is a reliability method that can provide accurate results but less time-consuming compared with the Monte Carlo simulation method.

Table 4
Comparison of optimal solutions with different discount rate r.

r	Optimal PoF threshold	Cost rate	Average re-assessment interval
0	1.83×10^{-4}	0.2272	13.8
2%	1.63×10^{-4}	0.1741	14.5
5%	2.21×10^{-4}	0.1073	14.8

The summary of costs of inspection, excavation, repair, failure is shown in Table 3 (Zhang and Zhou, 2014). Additional fixed costs such as costs for skilled labor and transportation fees are also considered here. The relative costs are utilized in this example. The cost data is simplified in this example. For instance, the failure cost is assumed to be 200 (corresponding to $4 million), which takes all the human, environmental, and economic loss factors into consideration. And the additional fixed cost will not change with the change of the re-assessment interval, same for the inspection cost. So in this example, the fixed cost is added to inspection cost to better compare with other cost items since they are both non-changing. We assume l_i is equal to the length of the entire line = 10 km and C_{insp} = $ 4, 000/km, and thus the

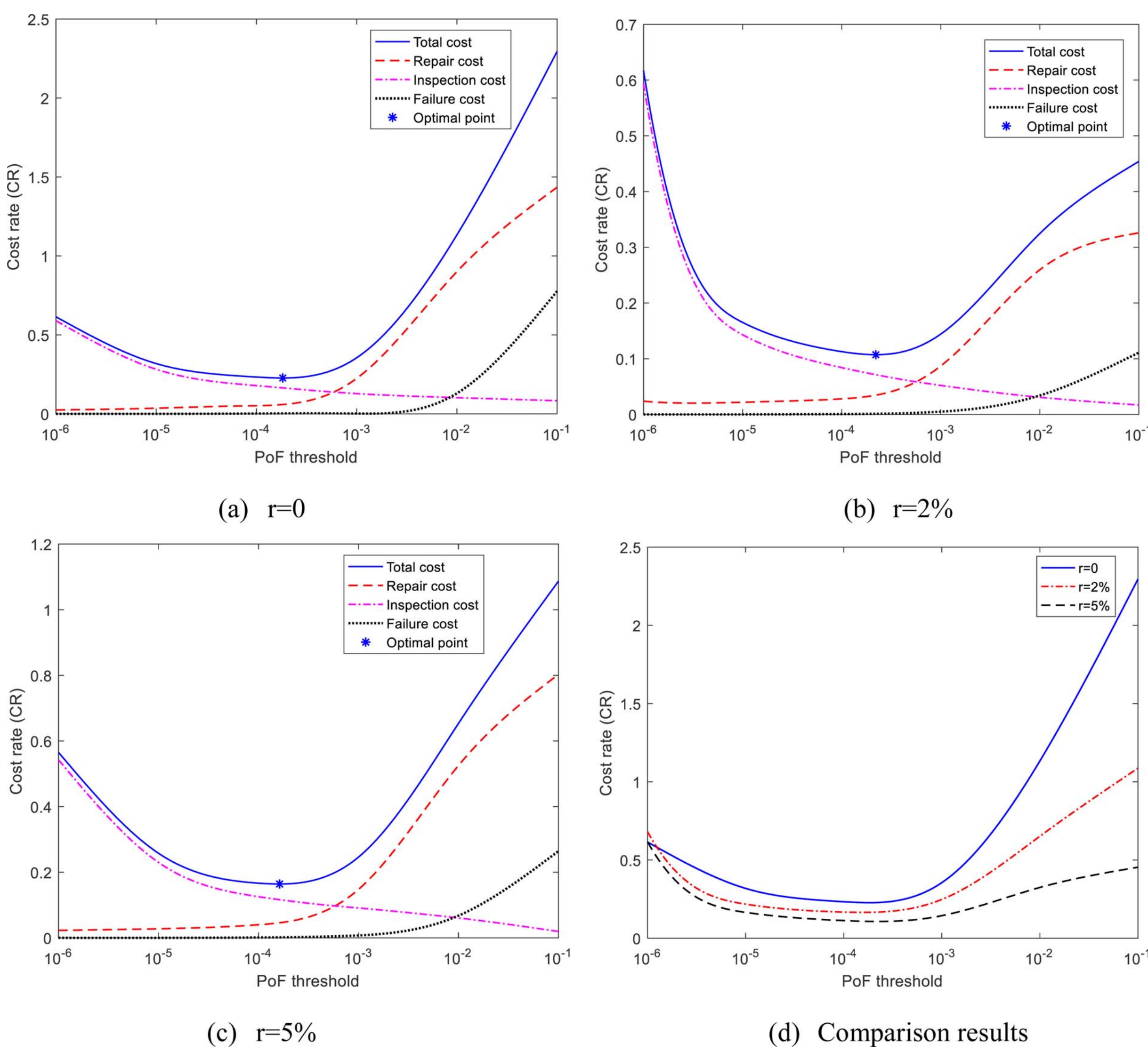


Fig. 3. Comparison of the expected cost rates associated with different cost items.

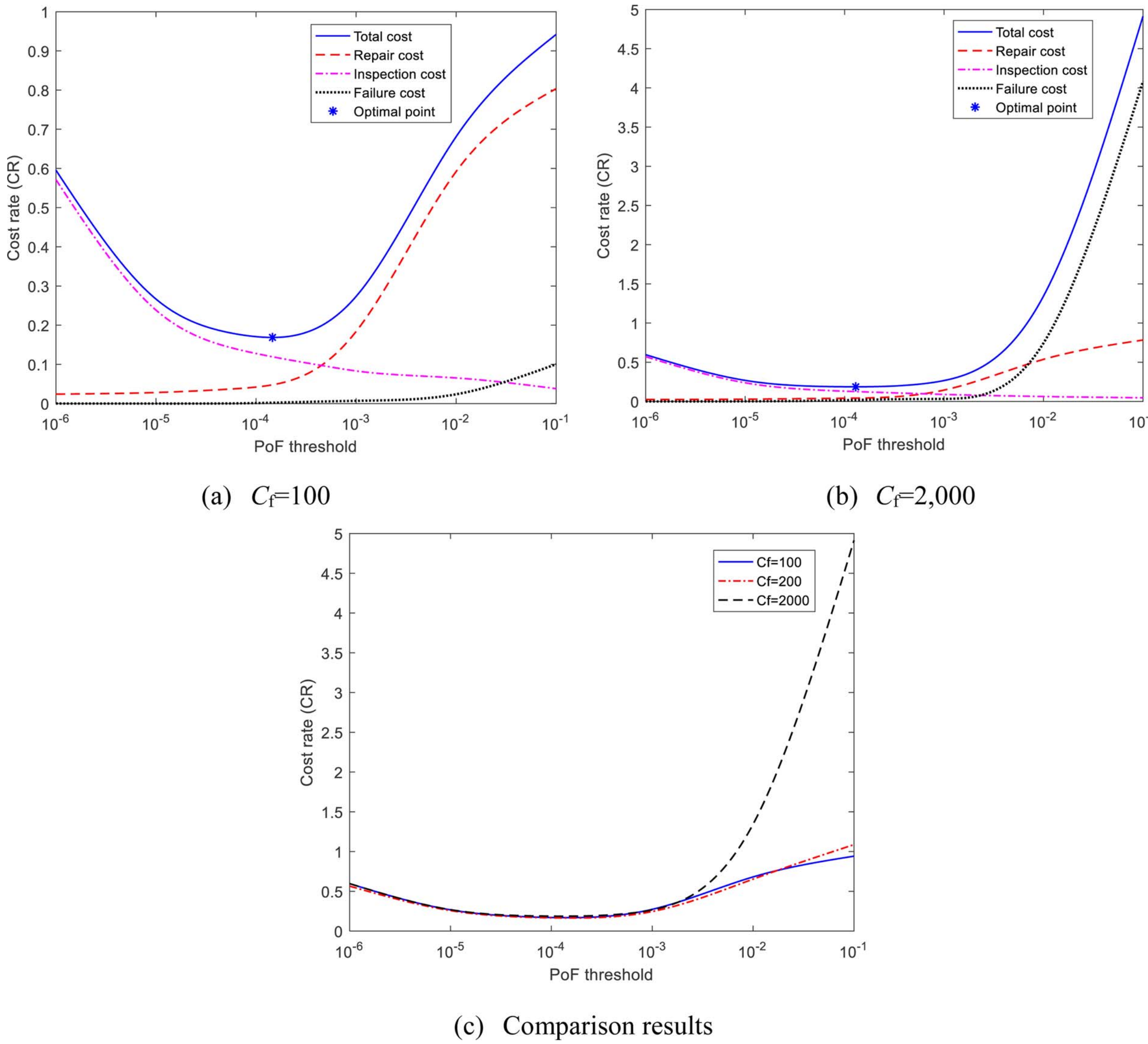


Fig. 4. Cost rate vs. PoF threshold in term of C_f = 100, 200, 2000.

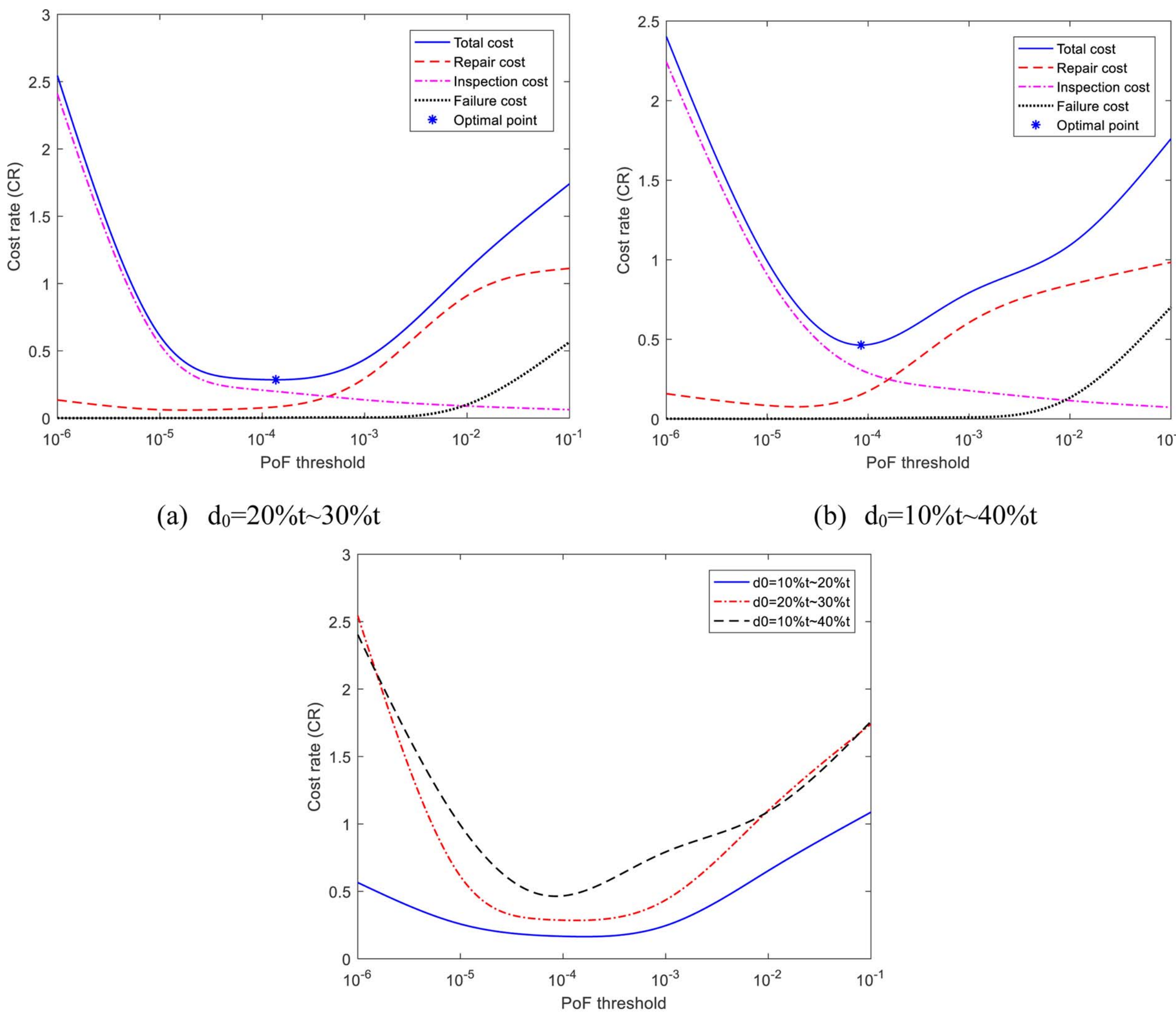
Table 5
Comparison results of optimal solutions for each scenario.

Scenario #	Parameter Value	Optimal PoF threshold	Cost rate
Scenario 1: Failure cost	100	1.46×10^{-4}	0.1687
	200	1.63×10^{-4}	0.1741
	2000	1.29×10^{-4}	0.1868
Scenario 2: Initial defect depths	(10%–20%)t	1.63×10^{-4}	0.1741
	(20%–30%)t	1.36×10^{-4}	0.2850
	(10%–40%)t	0.85×10^{-4}	0.4526
Scenario 3: Corrosion radial growth rate	0.2 mm/yr.	2.20×10^{-4}	0.1188
	0.3 mm/yr.	1.63×10^{-4}	0.1741
	0.4 mm/yr.	1.30×10^{-4}	0.2206
Scenario 4: ILI tool measurement error	0.3 mm	1.40×10^{-4}	0.1704
	0.5 mm	1.63×10^{-4}	0.1741
	0.7 mm	1.61×10^{-4}	0.1786

inspection cost is $40,000. C_f is assumed to be $4,000.000 as the baseline. Table 3 is utilized as the baseline to compare with other scenarios in the sensitivity analysis.

4.1. Results with the proposed approach

In this study, the total cost rate is broken down into different cost rate components, including inspection, repair and failure cost rates, respectively. It should be pointed out that the additional fixed cost is included in the inspection cost, the excavation cost is included in the failure cost, and the replacement cost is included in the failure cost. The cost evaluation and optimization results are shown in Fig. 3. The results for the comparison of different cost rate components in term of different discount rate r are shown in Fig. 3a–c, respectively. The results indicate that the inspection cost rate decreases with the increase of the PoF threshold, while it is the opposite for both repair cost rate and failure cost rate. It is reasonable because the inspection cost is a fixed cost in this example, and the inspection cost rate will decrease as T and PoF increase. And with the increase of PoF threshold, the possibility of repair actions and failure damage is increasing, which results in the increase of relevant cost rate. Besides, from the observation of these three figures, the inspection cost rate has the highest contribution to the total cost rate when the PoF threshold is smaller than around 5×10^{-3}, followed by repair cost rate and failure cost rate. The failure cost rate is negligible compared with other components of the total cost rate. This is because when the PoF threshold is small, pipeline is unlikely to fail and the corresponding inspection interval is also small, which gives a relatively big inspection cost rate and low repair and failure cost rate. When the PoF threshold becomes bigger, repair cost rate becomes higher and eventually the highest one. The comparison result for total cost rate of r = 0, 2%, 5% is shown in Fig. 3d. The figures show that the



(a) d_0=20%t~30%t

(b) d_0=10%t~40%t

(c) Comparison results

Fig. 5. Cost rate vs. PoF threshold in term of d_0 = 10%t–20%t, 20%t–30%t, 10%t–40%t.

shapes of total cost rate plots with different discount rate are similar and the cost rate increases with the decrease of the discount rate. The optimal solutions for the PoF threshold, and the corresponding average re-assessment intervals and cost rates are shown in Table 4. And the results suggest that the optimal solution for the PoF threshold and average re-assessment interval doesn't change much with the discount rate. r is assumed to be 2% in all following studies. And the results for r = 2% with the parameters described previously will set to be the baseline and utilized in the parametric analysis. All the horizontal axis in the following figures are in logarithmic scale.

4.2. Sensitivity analysis

There are four scenarios considered in sensitivity analysis, and the studied parameters are failure cost, initial defect depths, corrosion radial growth rate, and measurement error of ILI tools, respectively. For each scenario, three different values of that parameter are chosen. The values of total cost rate and its components as functions of PoF threshold are plotted for each scenario and the results for the cost rate vs. PoF threshold are studied and compared. The plots for comparison results are depicted in Figs. 4–7, and the optimal solutions are shown in Table 5. Note that the optimal PoF threshold and its corresponding re-assessment interval are further summarized and discussed in Section 4.2.5.

4.2.1. Scenario 1: failure cost

Because it is difficult to convert the failure damage of population and environment into economic loss, the value for failure cost is difficult to determine. It depends on many factors such as the density of population, the recovery time of environmental damage, etc. Different risk factors, like stringent and conservative, may result in a very big difference in the value of failure cost. Hence, it is necessary to investigate the influence of failure cost on the results. Three different values are selected for analyzing the impact of failure cost, with relative cost 100, 200, 2000, respectively. The failure cost equal to 200 is the baseline and the result is shown in Fig. 3b. The plots for the total cost rate along with different components as functions of PoF threshold for C_f = 100 and C_f = 2000 are shown in Fig. 4a and Fig. 4b, respectively. The failure cost rate increases as C_f increases. And for C_f = 2000, the failure cost rate has the highest contribution to total cost rate when PoF threshold is bigger than around 10^{-2} while the repair cost rate is the highest components for the other two. Fig. 4c suggests that the optimal PoF remains close. And the total cost rates are close when the PoF threshold is smaller, the one with C_f = 2000 differs notably from the rest when the PoF threshold becomes big.

4.2.2. Scenario 2: initial defect depth

Three initial defect depths scenarios are chosen for comparison, 10%–20%, 20%–30%, 10%–40% of the wall thickness, respectively.

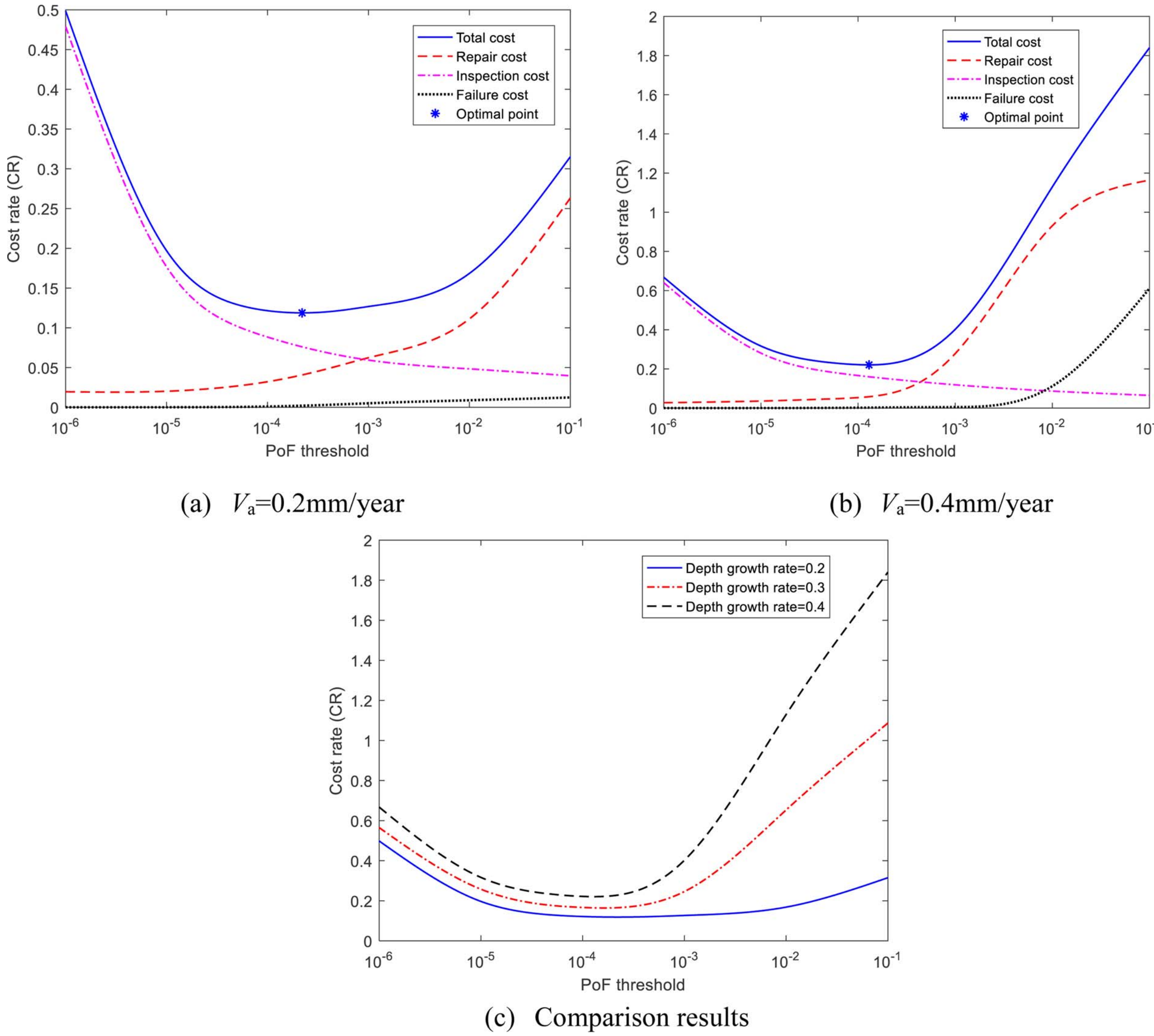


Fig. 6. Cost rate vs. PoF threshold in term of V_a = 0.2, 0.3, 0.4 mm/year.

And the values corresponding to (10%–20%)*t*, (20%–30%)*t*, (30%–40%)*t* are shown in Fig. 3b, Figs. Fig. 5a, Fig. 5b, respectively. The shapes of curves for repair cost rate and total cost rate are different with the change of the initial defect depths. The PoF threshold at the intersection point of repair cost rate and inspection cost rate decreases as initial defect depths increase. Fig. 5c suggests that initial defect depths have a large impact on the total cost rate. Higher initial defect depths lead to higher probability of repair actions and failure damage. Therefore, less time will be needed for higher defect depths to reach the certain threshold, and it results in higher repair cost rate, failure cost rate and total cost rate.

4.2.3. Scenario 3: corrosion radial growth rate

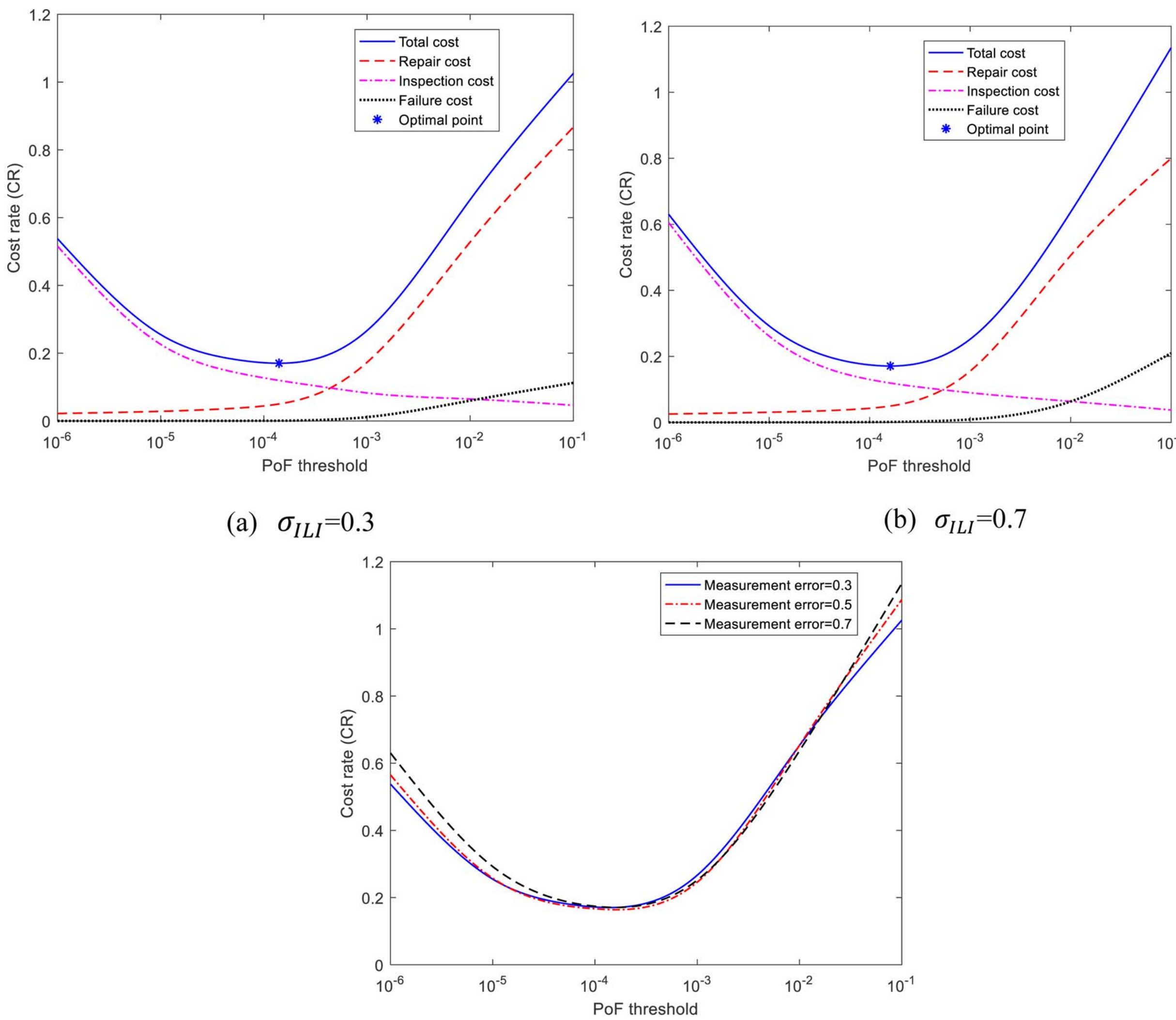
Three cases are considered in this scenario, namely 0.2, 0.3, 0.4 mm/year, respectively. The results shown in Fig. 6 illustrate the impact of corrosion radial growth rate on total cost rate and its components. The corrosion radial growth rate affects failure cost rate and repair cost rate a lot, and with the increase of growth rate, the repair, failure and total cost rates increase at a given re-assessment interval. The failure cost rate increases significantly as the growth rate increases from 0.3 to 0.4 mm/year. It is mainly due to the fact that a higher corrosion radial growth rate leads to larger corrosion depth, and therefore, shorter time to reach the PoF threshold, which leads to higher cost rate with the same PoF threshold. From Fig. 6c, when the PoF threshold is small, the shapes of curves for the total cost rate are similar, and it can reach a higher total cost rate with a higher depth growth rate, as expected. The differences among three curves keep increasing as the PoF threshold increases.

4.2.4. Scenario 4: ILI tool measurement error

The impact of ILI tool measurement error on cost rate items is illustrated in Fig. 7. Three cases are considered in this scenario, namely σ_{ILI} = 0.3, 0.5 and 0.7, respectively. The shapes of the curves for total cost rate and its different components are similar with the change of ILI tool measurement error. Overall, from the trend of three curves in Fig. 7c, the total cost rate increases as the measurement error of ILI tool increases. This is mainly because the real corrosion depth could be bigger if the standard deviation of the tool measurement error is bigger, which results in a higher total cost rate. The impact of ILI tool measurement error on the total cost rate and its components are relatively small, and the total cost rate corresponding to different ILI tool measurement error become very close when the PoF threshold is around the optimal solution. This is mainly because the measurement error of ILI tool in this example is relatively small compared to corrosion depth and wall thickness (20.6 mm).

4.2.5. Summary of the four scenarios

The comparison results of optimal PoF threshold and corresponding



(a) σ_{ILI}=0.3 (b) σ_{ILI}=0.7

(c) Comparison results

Fig. 7. Cost rate vs PoF threshold in term of σ_{ILI} = 0.3, 0.5, 0.7.

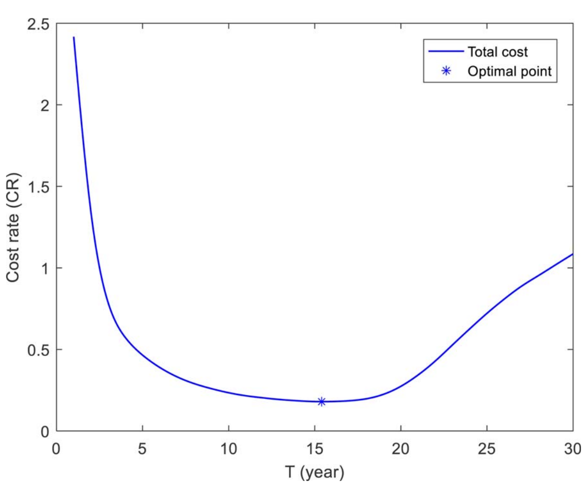


Fig. 8. Cost rate vs. T for baseline using fixed interval method.

cost rate for each scenario are summarized and compared in Table 5. The optimal PoF threshold is obtained by finding the lowest total cost rate. Note that in this study, we use the normal safety class and acceptable failure probability is 5×10^{-4}, and in this way, our optimal PoF threshold should be smaller than this value. All the obtained

Table 6
Comparison results of the proposed method and fixed interval method.

Parameter Value	Cost rate (Fixed interval method)	Cost rate (Proposed method)	Improvement of proposed method
d_0 = (10%–20%)t C_{in} = *2.5, C_f–100*	0.1782	0.1687	5.6%
d_0 = (10%–20%)t C_{in} = *2.5, C_f–2000*	0.1991	0.1868	6.6%
d_0 = (10%–40%)t C_{in} = *2.5, C_f–200*	0.4942	0.4526	9.1%
d_0 = (30%–40%)t C_{in} = *2.5, C_f–200*	0.7264	0.6453	12.6%
d_0 = (10%–20%)t C_{in} = *5, C_f = 200*	0.2712	0.2516	7.8%
d_0 = (10%–20%)t C_{in} = *15, C_f = 200*	0.7486	0.6730	11.2%
d_0 = (10%–20%)t C_{in} = *25, C_f = 200*	0.9609	0.9060	6.1%
d_0 = (30%–40%)t C_{in} = *15, C_f = 500*	2.1364	1.9534	9.4%
d_0 = (30%–50%)t C_{in} = *5, C_f = 200*	2.7115	2.4533	10.5%
d_0 = (30%–50%)t C_{in} = *15, C_f = 500*	4.4564	3.8780	14.9%

Table 7
Comparison results of the proposed method and fixed interval method.

Test	Pipeline diameter (D) [mm]	Pipeline thickness (t) [mm]	Operating fluid pressure (P_{op}) [MPa]
1	660.4 (std. = 13.208)	12.7 (std. = 0.254)	5.6 (std. = 1.12)
2	508.0 (std. = 10.160)	7.9 (std. = 0.158)	4.3 (std. = 0.86)
3	406.4 (std. = 8.128)	7.9 (std. = 0.158)	3.9 (std. = 0.78)

Table 8
Comparison results of the proposed method and fixed interval method.

Test	Cost rate (Fixed interval method)	Cost rate (Proposed method)	Improvement of proposed method
1	0.2766	0.2554	8.3%
2	0.5223	0.4671	11.8%
3	0.5134	0.4602	11.6%

optimal PoF thresholds meet the acceptance criteria in this example. Overall, the optimal PoF threshold for each case is obtained and the minimum and maximum ones are 0.85×10^{-4} and 2.20×10^{-4}, respectively. This means the optimal PoF threshold doesn't change too much with the investigation on these scenarios. That may be because the overall geometry and mechanical properties of the line are same for each scenario. For example, if a different pipeline with different geometry and mechanical properties is used in this example, the optimal PoF thresholds may change to different values. Besides, the total cost rate increases with the increase of the parameters given in all scenarios. The initial defect depths affect the total cost rate the most, followed by corrosion radial growth rate and the failure cost. It should also be pointed out that a large number of random variables are considered, as listed in Table 1, and the variations they introduced may also have impact on the analysis results in this section.

4.3. Comparison between the proposed method and the existing fixed interval method

4.3.1. Investigation on different cost values

The main difference between the proposed method with the existing fixed interval method is in the design variables. The fixed interval method uses inspection time T as the design variable while in the proposed method, the PoF threshold is used as the design variable. To compare these two methods, we use the same input parameters as the ones used above to obtain the CR (T) curve for fixed interval method. Fig. 8 shows the plot of total cost rate and optimal point for the baseline. Table 4 shows the comparison results of the proposed method and

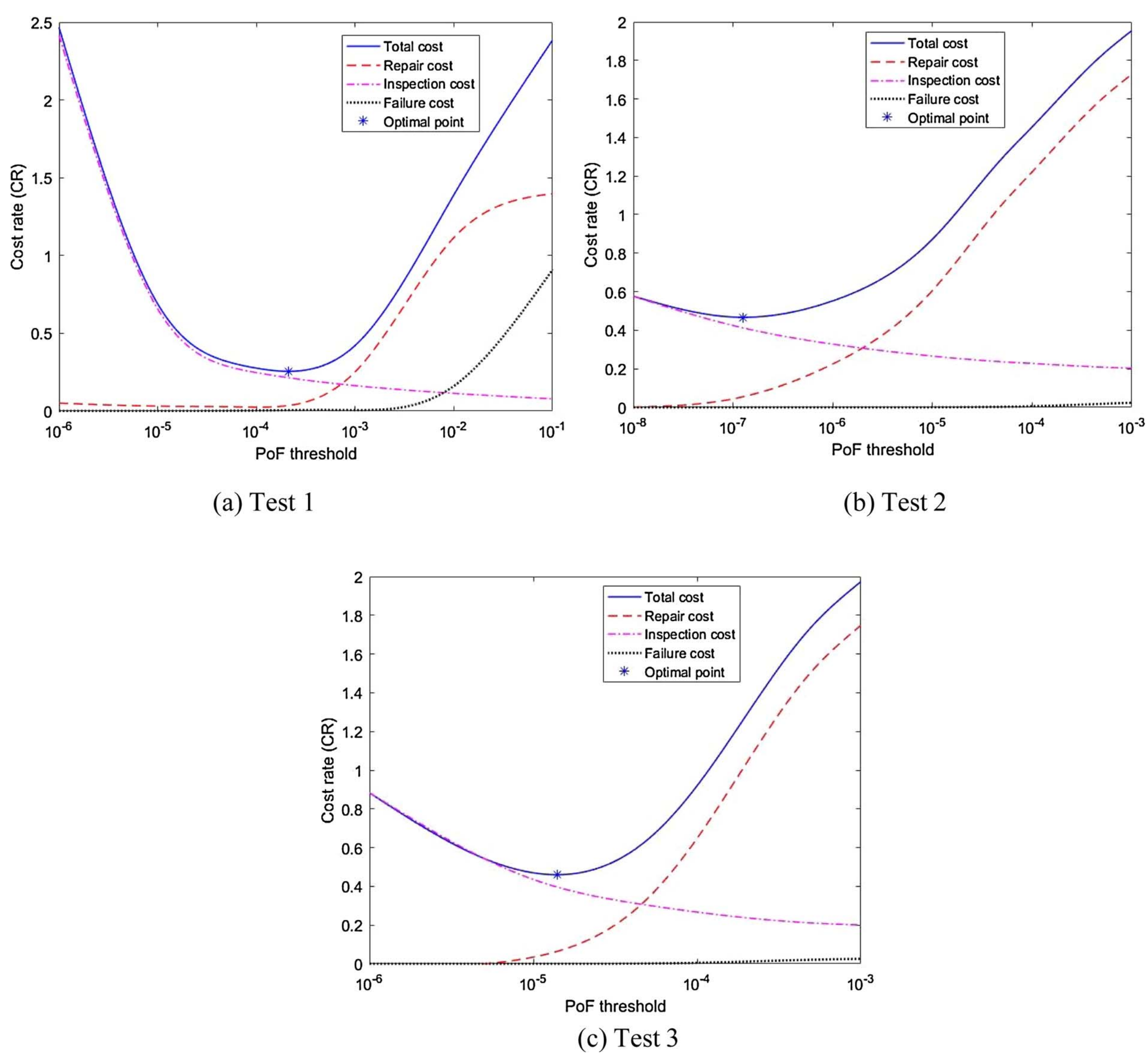


Fig. 9. Cost rate vs PoF threshold in term of different pipeline test sets.

fixed interval method. For pipelines with the same geometry, the inspection cost and failure cost may be different due to different locations and the surrounding environment. Besides, the defect size in the entire line may also vary for different pipeline segments. Therefore, we did investigations on these three parameters and compared our proposed method with the traditional fixed interval method. Ten cases with different d_0, C_{in}, C_f are used for comparison. From Table 6, we can find that for all scenarios, the optimal cost rates obtained by the proposed method are smaller than the ones obtained by fixed interval method. The improvement of the proposed method compared with the fixed interval method is in the range of 5.6% to 14.9% in these cases. And typically with a higher cost rate, the improvement is bigger. With the comparisons, we can conclude that the proposed pipeline re-assessment optimization approach is more cost-effective compared to the traditional fixed interval methods.

4.3.2. Investigation on different pipeline geometry

To demonstrate if the proposed model is applicable to other pipelines, we change parameters for geometry and physical properties in Table 1, and the new sets of random variables including pipeline diameter, thickness and operating fluid pressure are shown in Table 7. For other parameters, we use the baseline parameters, $d_0 = (10\% \sim 20\%)$ t, $C_{in} = 2.5$, $C_f = 200$. And we assume the ILI tool measurement error to be 0.5 mm. The plots for cost rates vs. PoF threshold in term of three different sets of pipeline geometry are shown in Fig. 9. Table 8 shows the comparison results of the proposed method and fixed interval method for these three cases. From Table VIII, we can find that for all these cases, the minimal cost rates obtained by the proposed method are smaller than the ones obtained by fixed interval method by 8.3% to 11.8%, which indicates that the proposed model is applicable to pipelines with different geometry and physical properties.

5. Conclusions

This paper proposes a method to find the optimal re-assessment policy for pipelines subject to multiple corrosion defects, where the system PoF threshold is used as the decision variable for this optimization problem. Uncertainties from various sources are considered in this study to make an accurate prediction, including uncertainties in pipeline geometry, mechanical properties, defect size, growth rates, and the ones associated with ILI tools. A simulation-based cost evaluation approach is developed for a given re-assessment policy defined by the PoF threshold. First-order reliability method is used to calculate the PoF to improve efficiency. The optimal PoF threshold can be obtained corresponding to the minimum expected cost rate.

An example is given for illustrating the proposed approach. Sensitivity analysis is performed for four scenarios. The following conclusions can be drawn based on observations and analysis. The optimal PoF threshold doesn't vary too much with the change of failure cost, initial defect depths, radial corrosion growth rate and ILI tool measurement error. The initial defect depths have a remarkable impact on total cost rate, followed by depth growth rate and failure cost. The total cost rate increases with the increase of these parameters.

This approach with the PoF threshold as decision variable can be used to cooperate with the acceptable risk level, and it will help to make decisions with the flexibility of adopting varying re-assessment intervals, rather than being limited to predetermined fixed inspection interval. The uncertainties from all sources are considered here to make a better and more realistic prediction and that support decision making in industry.

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