RELIABILITY ANALYSIS OF AGED NATURAL GAS PIPELINES BASED ON UTILITY THEORY

X. Zhang* – W. Li – Z. Luo – H. He

School of Management, Xi'an University of Architecture and Technology, Xi'an 710055, Shaanxi, China

ARTICLE INFO

***Article history*:**
Received: 27.08.2014.
Received in revised form: 08.12.2014.
Accepted: 11.12.2014.

Keywords:
Corroded pipelines
Residual life
Leakage probability
Utility theory
Reliability analysis
Natural gas pipelines

Abstract:

Pipelines are of major importance for transport of natural gas, but a lot of the current in-service pipelines are in wear-out phase. Safe and reliable operations of these pipelines are related to economic development and social stability. It is of great importance and practical significance to study when the corroded pipelines will be retired and how to guarantee that these pipelines will be operating under safe and reliable conditions. The paper proposes a model for assessing risk in natural gas pipelines, and for classifying sections of pipeline into risk categories with utility theory. It aims to help transmission and distribution companies when engaged in risk integrated assessment and decision making consider multiple dimensions of risk from pipeline leakage accidents. Firstly, we analyze the corrosion leakage probability of pipeline remaining life using the exponential distribution; secondly, we evaluate the economic loss, loss of life and damage to the environment in terms of the utility function to get the corresponding risk value of external loss. Finally, we calculate the internal economic loss when in-service pipelines are replaced ahead of scheduled time and then schedule a most optimal date to exchange the aging pipelines containing corrosion. To verify the effectiveness of the proposed methods, a numerical application based on a real case study is presented.

1 Introduction

Integrity assessment and data management is a very important activity for many facilities and process presenting technological risks, especially for transporting dangerous substances, via natural gas pipelines [1-3]. Pipelines are considered to be one of the safest methods to transfer gaseous substances, with accident frequencies lower than those with road or rail haulage and are the most efficient and economic means to transport large quantities of natural gas over long distances. But failures in pipelines may happen and sometimes they generate catastrophic consequences, especially when they have not been serviced for a long time [4]. The significant nature of the consequences of such

* Corresponding author. Tel.: (+86-29)13152031863.

accidents highlights the importance of deploying appropriate and effective risk management for this kind of facility [1, 5, 6]. For example, it was only in 1960s that natural gas pipelines began to be constructed in China, most of the existing pipelines were close to or almost exceeded their design lifetime, getting thus into an accident-prone period. Most pipeline accidents are caused either by pipeline corrosion, or are due to stress concentration on the partial wall thinning.

Pipeline corrosion problems can not only bring huge losses to the national economy, but also cause great risks to the safe operation [7]. Especially, the aged pipelines are more prone to leak because of corrosion problems. Once the leakage of gas has reached a certain concentration, and encountered an ignition source, it can easily cause a fire explosion. Moreover, it also causes property damage, personal injury and environmental pollution. For example, New Mexico natural gas pipeline explosion killed 12 people in the United States in June 10, 1999, and also brought adverse social and political implications. In November 22, 2013, in the Qingdao natural gas explosion in China, 62 people were killed, 136 injured and 9 missing, which caused a significant impact on the normal life of local people.

With respect to natural gas delivery pressure, pipelines will burst and thus cause leakage as long as a part of pipelines wall is thinning to a certain threshold. Therefore, reliable operation and functional safety of the aged pipelines need to be deeply studied. Several studies dealing with different aspects referring to assessing risk in natural gas pipelines have been published in the literatures [1, 5, 6, 8-14]. Certainly, safe and reliable operations of these pipelines are also reflected in the economic development and social stability. It is of great importance and practical significance to study when pipelines with corrosion defects are to be retired and how to guarantee safe and reliable conditions for the operation of these pipelines. .

According to European and American criteria to classify the severity of pipeline accidents, they can be generally grouped into three modes: leak, perforation and rupture, respectively [15]. Pipeline failure factors can be divided into failures caused by subjective factors (such as third party damage) and failure caused by objective factors (such as material natural corrosion). Corrosion in pipeline is one of the most common causes of pipeline failure, so we choose objective factors of leakage caused by corrosion as the main research object in this paper. In order to help decision makers from gas companies deal with this problem, the paper proposes a model used not only for assessing risk in natural gas pipelines but for classifying sections of pipeline into risk categories with utility theory as well. It aims to help transmission and distribution companies when engaged in risk integrated assessment and decision making consider the risk from pipeline leakage accidents.

Firstly, we analyze the corrosion leakage probability of pipeline remaining life using the exponential distribution; secondly, we evaluate the economic loss, loss of life and damage to the environment in terms of the utility function to get the corresponding risk value of external loss. Finally, we calculate the internal economic loss when in-service pipelines are replaced ahead of scheduled time and then schedule a most optimal date to exchange the aging pipelines containing corrosion. To verify the effectiveness of the proposed methods, a numerical application based on a real case study is presented.

This paper is organized as follows. After introducing the pipeline leakage problem, residual strength and life evaluation methods are described in Section 2. With these residual strength and life, we then present the model for evaluating pipeline reliability with utility function in Section 3. An illustrative case study is discussed in Section 4, and conclusions are drawn in Section 5.

2 Residual strength and life evaluation

Reliability evaluation of pipeline containing corrosion mainly involves evaluation of the residual strength and prediction of residual life of pipelines [16]. An important part of assessing the residual strength of corroded pipeline is to calculate the maximum size of the allowed defects of pipeline, or to calculate the maximum safe pressure of pipeline in certain operating pressure [12, 13, 17]. Research into residual strength of corroded pipeline and evaluation of the reliability of pipeline in service will have a great theoretical significance for the maintenance and replacement of pipeline serving systems [4, 13].

The residual lifetime of corroded pipeline can be mainly predicted by analyzing the evolution trend of pipeline corrosion, effective time and reliable operation in the future in terms of the present corrosion under the residual strength assessment conditions. It is very common to evaluate the residual strength of corroded pipeline by using the criterion of B31G. We can calculate the maximum allowable corrosion depth $d_{\max}$ under the provisions of the pressure based on the residual strength model and support vector machine (SVM) prediction model [18, 23] to calculate corrosion rate of pipe section and the average corrosion rate v_a, and then using fuzzy theory and grey theory to calculate the remaining life T_r of pipeline [12].

2.1 Residual Strength

The B31G criterion (ASME 1993) is widely used to assess corroded pipelines. The main equations in the ASME B31G criteria (1993) can be summarized as follows. The maximum allowable design pressure in B31G criterion is expressed as,

$$P = \frac{2SMYS}{D} \times F \times t, \tag{1}$$

Where P is the maximum allowable design pressure, MYS is the specified minimum yield strength, F is a design factor, which is normally 0.72 and t is the wall-thickness of pipeline sections.

For a short corrosion, by corrosion region obtained parabolic approximating, the maximum safe pressure P' can be calculated with Eq.(2) ,

$$P' = 1.1P \times \left[\frac{1 - \frac{2}{3} \times \frac{d}{t}}{1 - \frac{2}{3}\left(\frac{d}{t \times \sqrt{A^2+1}} \right)} \right], \; P' \le P \text{ and } A \le 4. \tag{2}$$

For the long corrosion, by corrosion region obtained parabolic approximating, the maximum safe pressure, the maximum safe pressure P' can be calculated with Eq. (3),

$$P' = 1.1P \times \left[\frac{1 - \frac{d}{t}}{1 - \left(\frac{d}{t \times \sqrt{A^2+1}} \right)} \right], \; P' \le P \text{ and } A \le 4. \tag{3}$$

If corrosion is very long, namely A is big, the maximum safe pressure P' is calculated with Eq. (4),

$$P' = 1.1P\left(1 - \frac{d}{t}\right), \; P' \le P \text{ and } A > 4, \tag{4}$$

Where $A = 0.894\left(\frac{L}{\sqrt{Dt}}\right)$.

The maximum allowable operating pressure ($MAOP$) is not more than the maximum allowable design pressure P given with Eq.(1), *i.e.* $MAOP \le P$. Given that the Safe Maximum Pressure Level P' is equal to the $MAOP$, the maximum allowable defect depth d_{allow} can be obtained as,

1) When corrosion is approximately parabolic shape and $A \le 4$,

$$d_{allow} = \frac{3t}{2}\left[\frac{1 - MAOP/1.1P}{1 - MAOP/\left(1.1P\sqrt{A^2+1}\right)} \right]; \tag{5}$$

2) When corrosion is approximately rectangular shape and $A > 4$,

$$d_{allow} = \left[1 - \frac{MAOP}{1.1P}\right] \times t \tag{6}$$

2.2 Remain Life Evaluation

2.2.1 Basic theory

After a pipeline is corroded, its wall becomes thin, which will result in reducing the ability of withstanding the internal pressure and also of decreasing the ability of resistance leak and rupture of pipelines. When the internal pressure is bigger than the limit of the carrying capacity of the corroded pipeline, it will leak or be ruptured. That is to say, a pipeline current wall thickness d is less or equal to the allowed minimum wall thickness $d_{\min}$, and the pipeline will reach its service life. The difference between the expected service life and the current service life is the remaining life Tr, which can be calculated as ,

$$T_r = \sum_{i=1}^{n} \frac{d_i}{v_i} = \frac{d - d_{\min}}{v_a}, \quad (7)$$

where v_i is the corrosion rate of time i, d_i is the corrosion value corresponding to v_i, v_a is an average corrosion rate and d is the remaining wall thickness of corroded pipelines.

2.2.2 Method of prediction

1) Determine the minimum allowable thickness
The minimum allowable thickness $d_{\min}$ is a limit state of pipeline in reliable operation obtained by substituting Eq.(5) and Eq.(6) into $d_{\min} = t - d_{allow}$.

2) Predict corrosion rate
The corrosion rate can be statistical analysis on the basis of accumulated on-site data. There are two ways to obtain these data. The first method is to make statistics and analysis pipeline repair records of the past years, which is more accurate. But those data are always rarely obtained so that it cannot fully reflect the situation of corrosion in pipelines. The second method is to detect pipeline by smart pigging, based on the statistics and analysis of previous test data, and this method can reflect the overall condition of the pipeline corrosion, which is a reasonable source of pipeline corrosion rate across the board.
For the overall condition of the pipeline corrosion, with the first method we can get the accurate data, but in the case of sudden changes in the environment, pipeline corrosion or pipeline impending situation, the second method may be a good choose.
The time-interval data test mechanism can be established to examine the severe corrosion of the pipeline or the unfavorable pipeline environment. Here we use gray prediction model - GM (Grey Model) to predict it. GM models are divided into GM (1, n) model and GM (1, 1) model. GM (1, 1) is the most common kind of gray models and only contains a single variable defined by a first-order differential equation, which is a special case of GM (1, n). The basic theory of gray model GM (1, 1) is established on the basis of the test data. Moreover, it can perform a good prediction on the strictly increasing or decreasing data series (such as corrosion pipe wall thickness).
Suppose we have an original to-be-detected time series data of wall thickness obtained from one pipeline,

$$x^{(0)} = \left(x^{(0)}(1), x^{(0)}(2), \dots, x^{(0)}(k), \dots, x^{(0)}(n)\right), \quad (8)$$

it would be a random process, and sometimes it may not be stable, so the cumulative numbers are generated as

$$x^{(1)} = \left(x^{(1)}(k), k = 1, 2, \dots, n\right), \quad (9)$$

Where

$$x^{(1)}(k) = \sum_{k=1}^{k} x^{(0)}(i). \quad (10)$$

After the above processing, the randomness of the data series will be weakened. As $x^{(1)}(k)$ fits exponential growth law, the solution is just first-order differential equations in the form of the exponential growth of the solution. We can assume that the sequence of $x^{(1)}$ satisfies the following first-order differential equations law model,

$$\frac{dx^{(1)}}{dt} + ax^{(1)} = u \ . \quad (11)$$

According to the definition of the derivative, we can get

$$\frac{dx}{dt} = \lim_{\Delta t \to 0} \frac{x^{(1)}(t + \Delta t) - x^{(1)}(t)}{\Delta t} \ . \quad (12)$$

By using the discrete form, the differential term could be

$$\begin{aligned} \frac{\Delta x}{\Delta t} &= \frac{x^{(1)}(k+1) - x^{(1)}(k)}{(k+1) - k} \\ &= x^{(1)}(k+1) - x^{(1)}(k) \quad , \\ &= a^{(1)}\left[x^{(1)}(k+1)\right] \end{aligned} \quad (13)$$

Where $x^{(1)}$ is the average value of the time k and $k+1$. And thus we can get,

$$a^{(1)}\left[x^{(1)}(k+1)\right]+\frac{1}{2}a\left[x^{(1)}(k+1)+x^{(1)}(k)\right]=u. \quad (14)$$

Then, we can write the above equation in the matrix form,

$$\begin{bmatrix} x^{(1)}(2) \\ x^{(0)}(3) \\ \cdot \\ x^{(0)}(n) \end{bmatrix} = \begin{bmatrix} -\frac{1}{2}\left[x^{(1)}(1)+x^{(1)}(2)\right] & 1 \\ -\frac{1}{2}\left[x^{(1)}(2)+x^{(1)}(3)\right] & 1 \\ \cdot & \cdot \\ -\frac{1}{2}\left[x^{(1)}(n-1)+x^{(1)}(n)\right] & 1 \end{bmatrix} \begin{bmatrix} a \\ u \end{bmatrix}. \quad (15)$$

That is

$$Y_n = BA. \quad (16)$$

In the above equation, Y_n and B are known variables, A is an undetermined parameter. Using matrix derivation formula, we can get

$$A=\left(B^T\ B\right)^{-1}B^T Y_n = \begin{bmatrix} \hat{a} \\ \hat{u} \end{bmatrix} \quad (17)$$

Substitute the obtained $\hat{a}$ and $\hat{u}$ back to Eq. (15) (17), we can get

$$\frac{dx^{(1)}}{dt}+\hat{a}x^{(1)}=\hat{u}. \quad (18)$$

And thus,

$$x^{(1)}(t)=\left[x^{(1)}(1)-\frac{\hat{u}}{\hat{a}}\right]e^{-\hat{a}t}+\frac{\hat{u}}{\hat{a}}. \quad (19)$$

Let $x^{(1)}(1)=x^{(0)}(1)$, we can get

$$x^{(1)}(k+1)=\left[x^{(0)}(1)-\frac{\hat{u}}{\hat{a}}\right]e^{-\hat{a}k}+\frac{\hat{u}}{\hat{a}}. \quad (20)$$

To do this type regressive reduction on Eq.(20), we get the gray prediction model of $x^{(0)}$ as

$$\begin{aligned}\hat{x}^{(0)}(k+1)&=\hat{x}^{(1)}(k+1)-\hat{x}(k)\\&=\left[x^{(0)}(1)-\frac{\hat{u}}{\hat{a}}\right]e^{-\hat{a}k}\left(1-e^{a}\right)\end{aligned}. \quad (21)$$

With the GM (1, 1) model, we can determine the average corrosion rate of the pipeline external surface, and then use the established support vector machines (SVMs) [19, 20] to obtain the accurate numerical corrosion rate.

3 Pipeline reliability analysis based utility function

3.1 Utility Function Theory

Utility is a way used by economists for measuring pleasure or happiness and for relating it to the decisions made by people. Utility measures the benefits (or drawbacks) not only obtained from consuming a good or services but also from working. The optimal action choice was the option that maximized the expected monetary value. Although utility is not directly measurable, it can be inferred from the decisions that people make. Utility in economics is usually described with a function [21]. In our context, utility function is to quantify the consequences decided by the decision a and the possible occurred status θ when the decision maker makes a decision, which is a function of two variables, known as $u=u(a,\theta)$.

Corroded pipeline segments will have two statuses in the operation process: no leakage a_1 and leakage a_2, with the probability P_1 and P_2, respectively. When a corroded pipeline leaks, gas leak consequences are generally divided into steam clouds θ_1, jet and pool fires θ_2 and explosions θ_3. And the probabilities of no burning vapor cloud, no jet fire and no explosion are P_{21}, P_{22} and P_{23}, respectively, where P_{21} is the probability of leaking state vapor cloud conditions, P_{22} is the probability of leaking state jet fire and pool fire and P_{23} is the probability of leaking state explosion under the occurrence of a_2 leaking state, $P_{21}+P_{22}+P_{23}=P_2$ and $P_1=1-P_{21}-P_{22}-P_{23}$. Then in the case of decision a_2, utility functions of pipeline segments with all sorts of statuses can be defined as,

$$u_{21}=u(a_2,\theta_1), \tag{22}$$

$$u_{22}=u(a_2,\theta_2), \tag{23}$$

$$u_{23}=u(a_2,\theta_3). \tag{24}$$

The expect utility function of pipe leakage can be obtained with Eq. (25),

$$\mathrm{E_u}(\mathrm{a}_2)=\mathrm{E}\left[\mathrm{u}(\mathrm{a}_2,\theta)\right] =\mathrm{u}(\mathrm{a}_2,\theta_1)p_{21}+\mathrm{u}(\mathrm{a}_2,\theta_2)p_{22}+\mathrm{u}(\mathrm{a}_2,\theta_3)p_{23}. \tag{25}$$

3.2 Analysis of the Consequences After Pipelines Failed

Experience and theory prove that service life of pipeline segments is subject to a probability distribution before leak [22],

$$P_s=e^{-(T_r/\nu)\alpha}, \tag{26}$$

where T_r is the remaining life of pipelines, P_s is a probability when service life reaches T_r, ν is a statistical parameter named as 'characteristic life' and α is a statistical parameter.

According to Eq. (12), when $T_r=\nu$, then $P_s=e^{-1}=0.368$, that is to say, there is 36.8% of the whole pipelines are not corroded to leak when remaining life is equal to characterized life. Using log function on both sides of Eq. (12), $\ln T_r$ and $\ln\{\ln[1/P_s(T_r)]\}$ is a linear relationship. Statistical probability data of the residual life of a pipeline are shown in Table 1.

Table 1. Statistical probability data of the residual life of a pipeline

The remaining life T_r, a	Statistical probability of life $P_s(T_r)$	$\ln T_r$	$\ln\{\ln[1/P_s(T_r)]\}$
1	0.942	0.000	-2.78
2	0.861	0.693	-1.89
3	0.721	1.098	-1.11
4	0.505	1.386	-0.37
5	0.303	1.609	0.19
6	0.242	1.792	0.36
7	0.141	1.946	0.68
10	0.072	2.302	0.98

Given $x=\ln T_r$ and $y=\ln\{\ln[1/P_s(T_r)]\}$, with the least squares $y=a+bx$ curve fitting, we can solve it and get $\alpha=b=1.77$, $a=-2.90$, $\nu=e^{-a/b}=5.16$. The results showed that about 63% of corroded pipeline will leak with perforation after 5 years and two months. The probability of pipeline residual life is,

$$P_f(T_r)=e^{-(T_r/5.16)^{1.77}}. \tag{27}$$

With the prediction of residual life of corroded pipeline, we can get the residual life T_r of segments of the pipeline, and substitute T_r into Eq.(27). We can get the probability to continue using this pipeline sections, and the probability of leakage is $P_f(T_r)=1-P_s$ under the above residual life.

3.2.2 Pipeline Failure Loss

Pipeline leakage failure leads to the internal and external loss of the gas pipeline company.

1) Internal loss V_A of pipeline company

Replacement of serious corroded pipeline, at the time of its residual life, i.e., at time of T_r will cause some economic losses to the pipeline company, increase in depreciation costs per unit length of the pipeline, and also reduced service revenue per unit length of pipeline.

Early replacement of pipelines with remaining life T_r will cause a certain degree of depreciation costs, so the corresponding pipeline depreciation costs can be calculated as

$$\frac{C}{a_1 + T_r} \times T_r \times l, \tag{28}$$

Where C is the total unit cost of pipeline construction, a_1 is the past operation years; T_r is the remaining life which has been calculated.

The pipeline, which should be replaced, can create value for the company in the remaining life T_r, which can be obtained by

$$\frac{l}{L} \times R_{pr} \times T_r + V_{j-k} \tag{29}$$

Where l is the total length of pipelines in advance replacement with remaining life T_r, L is the total length of the pipeline, R_{pr} is annual average margin net profit of pipelines, V_{j-k} and is the value of natural gas between two adjacent valves. So, in order to prevent aged pipelines with remaining life T_r to leak, we should exchange them in advance, and thus the expected utility function of such internal losses can be expressed as,

$$V_A = \left[\frac{C}{a_1 + T_r} \times T_r \times l + \left(\frac{l}{L} \times R_{pr} \times T_r + V_{j-k} \right) \right] \times \times P_f(T_r) \tag{30}$$

2) External loss V_B of pipeline company

When the corroded pipeline fails, the external consequences of the failure will be considered through three parameters, namely economic losses, loss of life and environmental damage [23].

▪ *Economic loss m*. Property losses caused by the accident mainly refer to the value of equipment loss, housing loss and leakage of natural gas loss.

▪ *Loss of life n*. *Pipeline* leakage accidents caused by casualties are mainly divided into the number of staff deaths N_1, the number of injured personnel N_2 and the number of people with minor injuries N_3. Measurement of the loss of life or personal injury after pipeline leaks caused by accidents will be considered and combined with the local economy status as a reference to financial compensation to the victim families according to the case type.

▪ *Environmental damage h*. Natural gas contains toxic and harmful gases, such as H_2S, in the leakage accident, damages to the environment, and it is very difficult to calculate with one appropriate calculation method. Depending on the circumstances, we can use the pipeline company fined value given by government as a reference. *h* is the environmental damage value.

By determining the multi-criteria utility function, we can equivalently turn the multiple criteria into a single criterion. Therefore, it can be turned into a single-criteria decision problem from multi-criteria decision problems. We can transform multiple criteria utility function into linear combination of single criterion utility function by weighting coefficient, and make decision through a single utility value. Thus, a rule preference degree of a decision maker is not affected by other standards criteria, namely these 3 criteria are independent from each other, and then we can get,

$$e = m + n \times \xi_1 + h \times \xi_2 \tag{31}$$

Where ξ_1 is the economic loss of the loss of life per unit; ξ_2 is environmental economic loss per unit caused by the leakage volume. The parameters, m, n and h can be determined by the decision-maker's risk attitude and the actual situation.

The value of ξ_1 can be referred to requirement of the relevant national injury regulations "enterprise workers casualty classification standards". With these rules: minor injuries less than 105 days of work loss days, injured more than 105 and less than 6,000 days of work loss days, job losses of death as 6,000 days, we can conduct workday of personnel injuries.

$$N = 6000N_1 + 3000N_2 + 105N_3, \tag{32}$$

$$\xi_1 = \frac{N \times \psi}{n}, \tag{33}$$

where ψ is the average daily wage of casualties.

Substitute Eq. (18) into Eq. (19), we can obtain ξ_1.

With 17,18,19 Equation, based on multi-criteria utility function, we can get the pipeline utility function of the risk of financial loss. $u = u(\varepsilon)$

In table 2, we can set up evaluation index system and calculate leak external pipeline expected loss utility function according to the above stated corrosion.
According to data listed in Table 2, we can get the expected utility function of external loss caused by corroded pipeline leakage,

$$\begin{aligned} V_B = E_u(a_2) = E[u(a_2,\theta)] \\ = u(a_2,\theta_1)P_{21} + u(a_2,\theta_2)P_{22} + u(a_2,\theta_3)P \\ = (m_1 + n_1 \times \xi_1 + h_1 \times \xi_2) \times P_{21} \\ + (m_2 + n_2 \times \xi_1 + h_2 \times \xi_2) \times P_{22} \\ + (\mathrm{m}_3 + n_3 \times \xi_1 + h_3 \times \xi_2) \times P_{23}. \end{aligned} \tag{34}$$

Table 2. Established state evaluation index system

Level #1	Level #2	Level #3
1 The expected value of the utility function E(u)	1.1 Steam clouds θ_1 Probability P_{21}	1.1.1 Economic loss m_1
		1.1.2 Loss of life n_1
		1.1.3 Environmental damage h_1
	1.2 Jet fires θ_2 Probability P_{22}	1.2.1 Economic loss m_2
		1.2.2 Loss of life n_2
		1.2.3 Environmental damage h_2
	1.3 Explosions θ_3 Probability P_{23}	1.3.1 Economic loss m_3
		1.3.2 Loss of life n_3
		1.3.3 Environmental damage h_3
	1.4 No leak $P_1 = 1 - P_{21} - P_{22} - P_{23}$	1.4.1 No loss

4 Experimental results

In this section, the method discussed in the previous sections referring to reliability analysis of one natural gas pipeline is used. A natural gas pipeline has been employed for about 40 years with the total length of 210km, and it is divided into 25 pipeline valve groups, with the average transmission rate of about $6.0\times10^6 \mathrm{m}^3$ per day every year. Using API 5L X52, we calculate the threshold of defect size, with outside diameter D =720mm, pipeline wall thickness t =10mm , minimum yield strength $SMYS$ = 325 MPa, extreme pressure P = 1.6 MPa, without considering the region category of pipeline sections.

Based on Eq. (1), we can get the minimum allowable wall thickness according to rectangular pipeline defects $d_{\min} = P \times D / (2 \times SMYS) \times 1.1 = 1.95$. Therefore, the maximum corrosion depth is $d - d_{\min} = 8.05\ mm$.
Using ultrasonic guided wave method and intelligent pigging of the entire pipeline, various outer surface defect locations and sizes can be accurately tested. The resulting data can then be grouped and analyzed. Choose out several groups of serious corrosion damages of each pipe segment between two adjacent segments valve and classify them into different groups according to corrosion size, and corrosion induced failures. After classification analysis we get results in 15 sets of data listed in Table 3. According to the SVM model from the literature [8, 24], the rate of corrosion of the pipeline can be derived. And then we can substitute these results into Eq. (7) to obtain the remaining life. The general price of natural gas is about 5,000 Yuan/ton and every ton of natural gas is equal to 1,390 m^3. We choose the average annual net profit for three consecutive years as a computation basis, which is about $1.0\text{x}10^9$ Yuan. Pipeline construction investment cost is 10 billion/km. The selected length between the two valves is 10,000m. The total length of severe corrosion area (e.g., fifth, ninth, fifteenth group detection area in Table 3) is 1,000 meters. According to statistics, various status values are listed as follows:

$m_1 = 1\times 10^6, n_1 = 0, h_1 = 1;$

$m_2 = 2\times 10^7, n2 = 3, h2 = 1;$

$m_3 = 7.5\times 10^7, \mathrm{n}_3 = 14, \mathrm{h}_3 = 3;$

$\xi_1 = 6\times 10^6, \xi_2 = 1\times 10^7.$

The main forms of natural gas pipeline leakage accident are toxic gas clouds of steam, jet fire and explosion. USA petroleum association data shows that all above accident probability is 0.8, 0.16 and 0.04, respectively [19]. Then we can get

$$V_A = \left[\frac{C}{a_1+T_r}\times T_r\times l + \left(\frac{l}{L}\times R_{pr}\times T_r + V_{j-k}\right)\right]\times \times P_f(T_r) = \left[\frac{1\times 10^8}{40+T_r}\times T_r\times 10^3 + \left(\frac{1}{210}\times 10^{10}\times T_r + 1.38\times 10^3\right)\right]\times \times(1-P_s)$$

and

$$\begin{aligned} V_B &= E_u(a) \\ &= \left(1\times 10^6 + 1\times 10^7\right)\times 0.8 \\ &+ \left(2\times 10^7 + 3\times 6\times 10^6 + 1\times 10^7\right)\times 0.16 \\ &+ \left(7.5\times 10^7 + 14\times 6\times 10^6 + 3\times 10^7\right)\times 0.04 \\ &= 2.404\times 10^7. \end{aligned}$$

Given that $V_A = V_B$, substitute Eq. (6) into Eq. (12), we can get $T_r \approx 0.51$, $P_f(T_r) \approx 0.984$. So, when the internal loss V_A is greater than the external loss V_B, it should replace corrosion in pipeline in advance in order to prevent the external losses. According to the listed statistics in Table 3, the fifth, ninth, fifteenth group of detecting corrosion degree totally similar to 1,000 meters of pipeline should be replaced when the residual life is 0.51.

Table 3. Statistics of the corrosion situation between two valve groups and results of evaluation

Pipeline section number #	Remaining wall thickness mm	Corrosion wall thickness mm	The average corrosion rate mm/a	Remaining life a
1	2.72	7.28	0.228	3.38
2	2.67	7.33	0.215	3.35
3	2.65	7.35	0.230	3.04
4	2.62	7.38	0.226	2.96
5	2.56	7.44	0.215	2.84
6	2.58	7.42	0.210	3.00
7	2.60	7.40	0.211	3.08
8	2.63	7.37	0.214	3.18
9	2.57	7.43	0.217	2.86
10	2.66	7.34	0.220	3.23
11	2.69	7.31	0.225	3.29
12	2.70	7.30	0.227	3.30
13	2.59	7.41	0.217	2.95
14	2.68	7.32	0.219	3.33
15	2.55	7.45	0.209	2.87

5 Conclusion and discussion

This paper has presented a new approach to reliability and risk analysis of natural gas pipelines, which incorporates the utility theory into the reliability analysis method in order to evaluate the risk of eroded pipeline sections to help transmission and distribution companies engaged in risk integrated assessment and decision making consider risks from pipeline leakage accidents. Experiments show that the proposed method can give the correct result for decision makers.

For risk based decision-making problems, subjectivity is an important feature of utility. The value of the relevant amount depends on the preferences of the decision-maker in utility function, which is very subjective. Therefore, different decision-makers using the same utility function to solve the same problem of risk decision may draw different conclusions. With utility function analysis, the occurrence of risks can be avoided to a certain extent. And also it has a role of early warning and providing reasonable reference for pipeline maintenance and repair to pipeline companies.

The life of a pipeline before it has leaked is subject to exponential distribution function derived from the combination of experience and theory. In the paper, there are some limitations by using intelligent pigging to regularly acquaint data. We can not collect data in a very short interval, because it will influence the enterprise benefit during the period of producing gas normally. If the two intervals of acquisition data are too long, the prediction result will not be very precise. Therefore we suggest that we should develop a reasonable method to collect test data which can obtain data at any time in the inner or external corroded pipeline so as to improve the prediction result.

We consider only the direct economic losses as the amount of external economic losses of pipeline leakage, without taking into account the secondary economic losses caused by the impact of the spill. Since the value of life is immeasurable,, the natural gas containing toxic gases may have long-term damages to the human body, and natural gas leakage always causes a long-term damage to the environment. It is hence unreasonable, when we simply use economic measures to calculate losses of a leakage accident. Therefore, conclusions drawn from this paper are a little more conservative, but they are predispositions to be undertaken and to be favorable to safer pipelines.

Acknowledgements

Research work reported in this paper are supported in part by the National Natural Science Foundation (No.: 61271278, The Research on Assessment Technology of Onshore Oil & Gas pipelines) and by the key discipline of Shaanxi Province (E08001). The authors are also extremely grateful to the anonymous reviewers who have made a lot of constructive comments.

References

[1] Papadakis, G. A.: *Assessment of requirements on safety management systems in EU regulations for the control of major hazard pipelines*, Journal of hazardous materials, 78(2000), 1, 63-89.

[2] Brito, A. J., De Almeida, A. T.: *Multi-attribute risk assessment for risk ranking of natural gas pipelines*, Reliability Engineering & System Safety, 94(2009), 2, 187-198.

[3] Ashrafizadeh, H., Karimi, M., Ashrafizadeh, F.: *Failure analysis of a high pressure natural gas pipe under split tee by computer simulations and metallurgical assessment*, Engineering Failure Analysis, 32(2013), 188-201.

[4] Singh, R.: *Pipeline Integrity Handbook: Risk Management and Evaluation*, Gulf Professional Publishing, 2013.

[5] Jo, Y.-D., Ahn, B. J.: *Analysis of hazard areas associated with high-pressure natural-gas pipelines*, Journal of Loss Prevention in the Process Industries, 15(2002), 3, 179-188.

[6] Yang, Z.-P., Mei, Y.-X., Shuai, J., Meng, K.-L.: *Corrosion of pipeline safety assessment*, Gas Storage and Transportation, 22(2003), 5, 1-6.

[7] Yang, X.-H.: *Oil and Gas Pipeline Safety Engineering* China Petrochemical Press, Beijing, 2005.

[8] Jo, Y.-D., Ahn, B. J.: *A method of quantitative risk assessment for transmission pipeline carrying natural gas*, Journal of hazardous materials, 123(2005), 1, 1-12.

[9] Han, Z., Weng, W.: *An integrated quantitative risk analysis method for natural gas pipeline network*, Journal of Loss Prevention in the Process Industries, 23(2010), 3, 428--436.

[10] Jo, Y.-D., Crowl, D. A.: *Individual risk analysis of high-pressure natural gas pipelines*, Journal of Loss Prevention in the Process Industries, 21(2008), 6, 589--595.

[11] Yuhua, D., Datao, Y.: *Estimation of failure probability of oil and gas transmission pipelines by fuzzy fault tree analysis*, Journal of Loss Prevention in the Process Industries, 18(2005), 2, 83--88.

[12] Wu, M.-L., Hao, D., Liu, J.-K.: *The remaining life of the oil and gas pipeline corrosion gray prediction based on the theory of Markov*,

Pipeline Technology and Equipment, (2008), 5, 43-45.

[13] Liu, Y.-S., Wang, W., Feng, Z.-Z., Wang, F.-S., Yue, Z.-F.: *The remaining strength and Reliability of corroded pipeline Analysis* Strength and Environment, 35(2008), 3, 52-57.

[14] Garmsiri, S., Rosen, M. A., Smith, G. R.: *Integration of Wind Energy, Hydrogen and Natural Gas Pipeline Systems to Meet Community and Transportation Energy Needs: A Parametric Study*, Sustainability, 6(2014), 5, 2506--2526.

[15] Wang, Y.-M., Guo, S.-P.: *Wang Yu-mei, Guo Shu-ping*, Gas Storage and Transportation, 19(2000), 7, 5-10.

[16] Su, X., Yang, J., Yuan, Z.-M., Hu, A.-X.: *Reliability evaluation of pipeline corrosion*, Petroleum Construction Engineering, 31(2006), 6, 9-12.

[17] Bai, Y., Bai, Q.: *Subsea engineering handbook*, Gulf Professional Publishing, 2012.

[18] Luo, Z.-S., Gao, Y., Wang, H.-C., Liu, Q.-C.: *Comprehensive quantitative risk assessment of urban natural gas pipeline*, Fire Science and Technology, 6(2013), 38-43.

[19] Luo, Z.-S., Gao, Y.: *Corrosion of wet gas gathering pipeline based on gray support vector machines*, China Safety Science, 23(2013), 5, 62-67.

[20] Yan, Y -X., Shen, J.-T.: *Grey theoretical model used in grid electricity demand forecast in Yunnan*, YUNNAN ELECTRIC POWER, 34(2006), 8.

[21] Zhang, P., Chen, L.-Q., Hou, X.-Q.: *Optimal risk-based oil and gas pipeline integrity maintenance decision*, Natural Gas Industry, 24(2004), 10, 143-147.

[22] Guo, S.-W., Yuan, P.-B.: *Transmission pipeline integrity testing, evaluation and repair techniques*, Petroleum Industry Press, Beijing, 2009.

[23] Chen, L.-Q., Fan, Z.-G., Liu, K., Zhang, P., Zhao, C.-L.: *Utility function maintenance decision Optimization in Pipeline Integrity*, Gas Storage and Transportation, 6(2004), 22-25.

[24] Wagmann, L., Benčić, Z.: *Stochastic deterministic method of monte carlo simulation of harmonic currents at mv/lv transformer stations*, Engineering Review, 30(2010), 1, 23-34.