# System for Risk Assessment in Oil and Gas Pipelines Laying Process in Single Ditch Based On Quantitative Risk Analysis

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*Abstract*— In view of the vegetation reduction caused by the continuous construction of oil and gas pipelines, the pipelines have been designed to be laid in one ditch to reduce land occupation. However, owing to the small spacing between the pipelines, the fault correlation between pipelines has been proven to increase the potential hazard of adjacent pipelines and routing environments. The neglect of failure correlation in existing risk assessment methods leads to inaccurate results, which will lead to errors in maintenance decisions. Therefore, this paper proposed a risk assessment system for pipelines using this laying method. In the risk assessment, pipelines laid in one ditch (PLOD) were regarded as a series system relative to the routing environment. Therefore, by combining the reliability theory of the engineering system with mathematical induction, a functional relationship between the overall risk of the pipeline system and the risk of each pipeline was obtained. In addition, the probability of failure of each pipeline in the system was calculated using fuzzy set theory combined with Fault Tree analysis. Event tree analysis was used to classify all possible consequences of pipeline failures and then aggregated the results in monetary terms to assess the severity of the failure consequences. Finally, we combined the two parts into a butterfly diagram to implement risk management and pipeline control. Meanwhile, risk acceptance criteria and pipeline maintenance guidelines for risk analysis have been formulated. The system provides a complete risk assessment system for pipeline systems buried in a single trench, including risk identification, risk assessment and risk analysis methods essential to ensure the safety of pipelines and the environment when using this installation.

***Keywords:*** Oil and Gas Pipelines Laid In One Ditch; Risk Assessment Analysis; Bow-Tie Model; Risk Acceptance Criteria; Fuzzy Set Theory

## I. INTRODUCTION

With the development of the global economy, the demand for oil resources and energy in various countries is increasing [1,2]. To solve the imbalance between supply and demand, many oil and gas pipelines have been built due to the cost-effectiveness and high efficiency of oil and gas transportation. However, since plants cannot be grown around the pipeline, the construction of many pipelines seriously affects the ecological environment. Therefore, operators are either constructing two or more new pipelines in the same ditch or building new pipelines along other existing pipelines in the same ditch to reduce land occupancy and comply with sustainable development principles [3]. Due to the large span of the pipeline, it is inevitable that the pipeline will be installed through an area with a complex geological environment. The use of pipeline transport is associated with many uncertainties and risks, such as natural and human factors. Available data show that numerous accidents occur each year due to soil erosion, landslides, floods, collapses, advections and earthquakes [4-9]. In addition, the safety of pipelines is simultaneously threatened by human factors such as third-party damage, terrorist attacks, misuse and design flaws [10,11]. Because oil and gas pipelines are flammable, explosive and toxic, leaks in pipelines can have catastrophic consequences such as fire, explosion and environmental pollution [12-14]. As a result, risk assessment is used to identify risk factors associated with uncertainty in pipeline operation, assess the likelihood and consequences of accidents, and comprehensively calculate risk values. Results can be used to guide pipeline maintenance [15]. In 1992, Muhlbauer proposed a comprehensive and continuously improving system for quantifying pipeline risk, which became the guideline for pipeline risk assessment [16]. Methodologies for calculating the probability of failure have gradually evolved from qualitative to quantitative methods [17], which include two types of methods. One is to evaluate failure potential based on failure databases such as the Pipeline and Dangerous Goods Safety Administration (PHMSA) database in India and the Asian Gas Pipeline Incident Data Group (AGIG) database in Asia [18].

However, in situations where data to support a quantitative risk assessment are scarce, data-dependent methods of determining the probability of failure can be applied. Therefore, techniques such as fuzzy mathematics, expert judgment, and fault tree analysis have been developed in this area [19-22]. However, from the point of view of evaluating the consequences of failure, event tree analysis proved to be the most effective tool [23,24]. In terms of risk, PLOD is susceptible to failure factors in one pipeline as well as failure outcomes in adjacent pipelines, which scientists have demonstrated through numerical simulations and experiments. Studies have shown that blast and blast shock waves from pipeline damage affect adjacent pipelines, i.e. there is a correlation of failures between pipelines [25-28]. As a result, it can increase the potential risk to the pipeline and route environment. However, the existing risk assessment method does not consider the effect of the failure correlation, resulting in failure to reflect the true value of risk, leading to inadequate maintenance [29]. In order to avoid uncertainty due to risk underestimation, this article presents a quantitative risk assessment method suitable for PLOD. In this article, we did the following: A relationship has been established between the routing environment and the risk in the pipeline. We propose a risk assessment method suitable for pipelines that are failure-correlated. In addition, the risk reduction was induced by evaluating the risk assessment results using the curve method and the ALARP principle. These three parts thus form the framework for risk

## II. Risk Assessment Method for Pipeline Systems to be Laid in Single Ditch

Pipeline risk assessment is used to determine the risk level of each segment as the basis for maintenance work by comprehensively assessing the severity of the consequences of failure and the internal and external factors that influence pipeline failure. When pipelines are laid in one ditch, the distance between adjacent pipelines is small, so failure of adjacent pipelines can damage each pipeline, making it more susceptible to failure than the single pipeline approach. As a result, the potential risk to the routing environment affected by pipeline failure also increases. Therefore, to assist operators in managing and controlling pipeline risk using this laying method, this section describes a risk assessment method.

### *A. Risk Assessment of Pipeline System*

Given the small distance between pipelines, pipelines can be viewed as an engineering system (PLOD system) associated with a routing environment, where a two-pipe system is an example (Figure 1). Failure of pipe A or B in this system will have some impact on the routing environment. From the reliability design point of view, this system can be viewed as a sequential system linked to the routing environment, and any block (pipeline) failure affects the routing environment. Therefore, the serial system calculation method can be used to calculate the risk of that system.

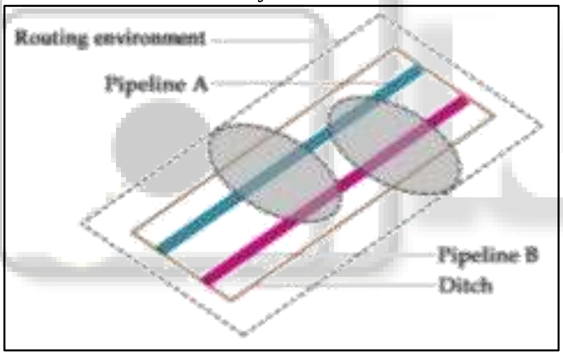


Fig. 1: The diagram of the pipelines laid in one ditch (PLOD) system

On the other hand, a failure correlation between pipelines A and B has been demonstrated given the small distance between pipelines. In addition to single pipeline failure factors, when evaluating the likelihood of pipeline A failure in a system from a risk point of view, the impact of failure of adjacent pipeline B on pipeline A must also be considered.

That is,

the failure probability $P_{fA}$ is

$$P_{fA} = (I_1, I_2, \ldots, I_{BA}, I_n) \tag{1}$$

where $Ii$ is the failure factor, $i$ = 1, 2, 3,, $n$; $I$BA is the influence of the adjacent pipeline B on A.

When the failure consequences of pipeline A are evaluated, in addition to the failure consequences of the single pipeline, the influence of A's failure on the adjacent pipeline B should be considered. That is, the failure consequences $C$A are

$$C_A = (C_1, C_2, \ldots, C_{AB}, C_n) \tag{2}$$

where $Cj$ is the possible consequence of failure, $j$ = 1, 2, 3,…, $n$; $C$AB is the influence of pipeline A'sfailure on the adjacent pipeline B. On this basis, a risk assessment system that is suitable for the PLOD system will be deduced.

### *B. Double-Pipeline System:*

The PLOD system consists of A and B. According to the theory of the series system, there arethree situations of system failure:

1) A fails but B does not, the failure probability of the system is $P_{fA}(1-P_{fB})$;
2) B fails but A does not, the failure probability of the system is $P_{fB}(1-P_{fA})$;
3) A and B fail at the same time, the failure probability of the system is $P_{fA}P_{fB}$

Correspondingly, each of the three failure situations will bring three consequences:

1) Failure consequences of the A;
2) Failure consequences of the B;
3) Sum of the failure consequences of A and B.

Therefore, the total risk of thesystem can be calculated as follows:

$$R_{AB} = P_{fA}(1-P_{fB})C_A + P_{fB}(1-P_{fA})C_B + P_{fA}P_{fB}(C_A + C_B) \tag{3}$$

where $R$AB is the total risk of double-pipeline system; $Pf$A is the failure probability of A; $Pf$B is thefailure probability of B; $C$A is failure consequences of A; $C$B is failure consequences of B.

expand equ. (3)

$$R_{AB} = P_{fA}(1-P_{fB})C_A + P_{fB}(1-P_{fA})C_B + P_{fA}P_{fB}(C_A + C_B) \tag{4}$$

Collate

$$R_{AB} = P_{fA}C_A + P_{fB}C_B \tag{5}$$

Therefore, the risk of the double-pipeline system is equal to the sum of the risks of the two pipelines.

Similarly, for triple pipeline system risk equation will be

$$R_{ABC} = P_{fA}(1-P_{fB})(1-P_{fC})C_A + P_{fB}(1-P_{fA})(1-P_{fC})C_B + P_{fC}(1-P_{fA})(1-P_{fB})C_C + P_{fA}P_{fB}(1-P_{fC})(C_A + C_B) + P_{fA}P_{fC}(1-P_{fB})(C_A + C_C) + P_{fB}P_{fC}(1-P_{fA})(C_B + C_C) + P_{fA}P_{fB}P_{fC}(C_A + C_B + C_C) \tag{6}$$

where $R$ABC is the total risk of the triple-pipeline system; $Pf$C is the failure probability of C; $C$C is failureconsequences of C.

expand equ. (6)

$$R_{ABC} = P_{fA}C_A + P_{fB}C_B + P_{fC}C_C \tag{7}$$

### *C. Quantitative Risk Assessment for Pipelines Considering Failure Correlation among Pipelines*

As the number of pipelines in the ditch increases, the overall engineering system becomes more complex and the potential for damage to the environment increases. Therefore, there is a need for a method with visualization, communication and display convenience characteristics that can guide maintenance personnel to reduce the occurrence and spread of accidents. Pipeline risk assessment methodologies have evolved progressively to include key content from the risk assessment process in the model. The bow tie model uses intuitive graphics to represent possible causes and consequences of accidents. Accident prevention and mitigation measures can be clearly charted by establishing barriers to achieve dynamic management consistent with the development goals of risk assessment methods in petroleum engineering [32]. Therefore, the butterfly model has become a hotspot in the application and research of risk assessment methods [33]. The centerpiece of the butterfly diagram is the unwanted event. On the left are the cause of the incident and preventive control actions, and on the right are the potential consequences and mitigating actions of the incident. Bow tie diagrams are used to facilitate team discussions to reduce risks to acceptable levels by systematically identifying risks, assessing and controlling risks, and taking appropriate risk mitigation actions in appropriate locations [34]. In the butterfly model, Fault Tree Analysis (FTA) is a logical deduction analysis tool that can be used to analyze the causes and effects of all major events leading to pipeline failures and their combinations [35]. In analyzing pipeline failure factors using FTAs, in addition to third-party damage, corrosion, pipeline quality defects, misuse, and irrational design, the consequences of adjacent pipeline failures must also be considered. It can be identified as Key events affecting the evaluated pipeline. The consequences of pipeline failures in PLOD systems are complex and uncertain. Event tree analysis (ETA) can be used to classify all possible consequences of pipeline failures, identify root causes of accidents, and provide a reliable basis for defining safety measures to achieve accident prediction and prevention goals. can. Furthermore, this paper proposed a novel approach that can combine different outcomes of pipeline failures to evaluate the overall consequences of failures and finally express the results in the form of currency. Therefore, Figure 2 shows the pipeline failure accident.

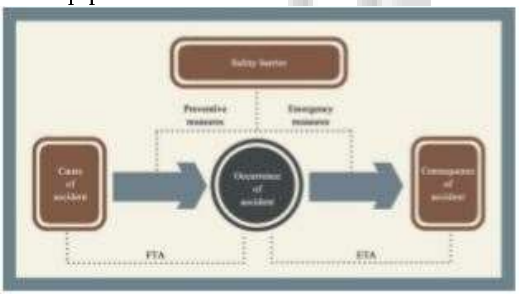


Fig. 2: Bow-tie model of pipeline failure accidents

There are two types of pipeline failures: cracks and perforations [36], and both types of failure can lead to leaks. Consequently, the major event in the butterfly pattern is the intermediate leak. To estimate the likelihood that a major event will occur, you need to know the probabilities of all major events. Determining the probability of a major event can refer to historical failure data. However, it is difficult for all pipeline operators to quantify risk because there is not enough information on pipeline failures and judgment and expert judgment become the main data sources [37]. However, because the occurrence of key events in a pipeline failure tree is ambiguous and random, even experts cannot accurately predict the likelihood of each event. Fuzzy mathematics is therefore used to quantify expert opinions to determine the likelihood of a key event [38]. Exact figures may not be provided directly during the peer review process, but some language is used to indicate the likelihood of an event occurring. When combined with pipeline engineering, natural language values can be divided into 7 stages: very small (VS), small (S), relatively small (RS), medium (M), relatively large (RL), and large (L). , and very large ( VL) [24]. In practice, it is necessary to select experts in various fields of pipeline design to achieve the goal of assessing trends in data. However, different professionals have different strengths and knowledge gaps due to differences in personal experience and knowledge level. Therefore, the evaluation ability of experts is also different. It is inappropriate to combine mathematical or geometric means in the judgment of an expert. In order to obtain more reliable results, it is necessary to evaluate the personal abilities of the experts before reaching conclusions. Therefore, the Analytical Hierarchy Process (AHP) is used to evaluate an expert's ability to improve the objectivity of expert judgment [39]. AHP uses factors that influence expert competency to determine the weight of expert competency (Figure 3). The overall goal is personal competence (PA), which is the first tier of the model. Factors affecting the ability of experts include PK (Personal Knowledge), IS (Source of Information), UB (Objectivity), PE (Personal Experience), etc., which constitute the second-level model [40]. The third level is the expert who involved in the assessment.

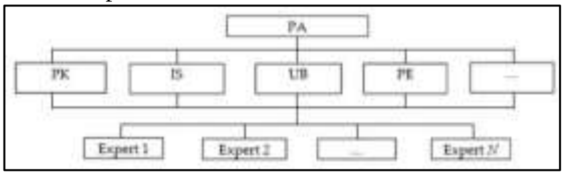


Fig. 3: Expert ability assessment analytic model

The possibility of a basic event (Xi) can be calculated as follows:

- An expert evaluation team makes a subjective judgment on Xi. An evaluation team is formed by inviting experts from various fields such as design, construction, installation, maintenance, and pipe management. The pipeline manager informs the expert about the key status of the pipeline and invites the expert to inspect the pipeline. Then, experts are organized to discuss possible major events in Xi.
- Convert linguistic values into fuzzy numbers Fuzzy set theory is used to treat these linguistic meanings as uncertainties. There are many member function expressions, such as member functions of triangular fuzzy numbers, member functions of trapezoidal fuzzy numbers, and member functions of fuzzy Gaussian numbers. Triangular and trapezoidal fuzzy numbers are widely used in linear fuzzy calculations because of their efficiency and simplicity. It is widely used in real-time systems to provide more accurate descriptions and more accurate solutions [41]. Thus, triangular fuzzy numbers (Equation (10)) and trapezoidal fuzzy numbers (Equation (11)) are used to replace these linguistic meanings (Figure 4)

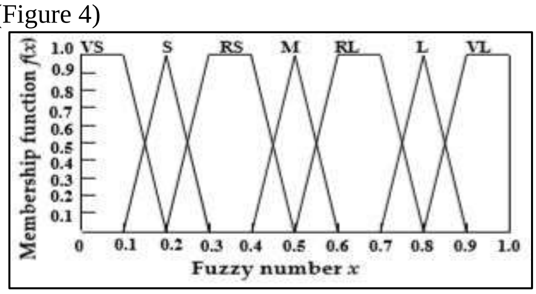


Fig. 4: Fuzzy numbers represent linguistic value

$$f(x)=\begin{cases}0 & (x>a)\\ \frac{x-a}{b-a} & (a<x\le b)\\ \frac{c-x}{c-b} & (b<x<c)\\ 0 & (x>c)\end{cases} \quad (10)$$

$$f(x)=\begin{cases}0 & (x>a)\\ \frac{x-a}{b-a} & (a<x\le b)\\ 1 & (b<x<c)\\ \frac{d-x}{d-c} & (c<x<d)\\ 0 & (x>d)\end{cases} \quad (11)$$

## III. MONETARY QUANTIFICATION OF PIPELINE FAILURE CONSEQUENCES

ETA is used to classify all possible consequences of pipeline failure according to the evolution of the incident and then determine the cause of the hazard. Finally, mitigation barriers are established. A quantitative analysis should be performed to comprehensively assess the severity of the failure consequences. In general, the consequences of pipeline failure are considered in three aspects: accidents (n), environmental damage (v), and property loss (c). Accident (life) refers to an accident that may cause damage to people around you due to fire, explosion, or poisoning due to pipe failure. Environmental damage (m3) is used to assess the amount of a pollutant to determine the severity of the impact. Environmental damage often gets a lot of media and public attention, which is far more serious to a company's reputation than direct economic damage. The economic loss ($) includes the cost of maintenance, the cost of reinstalling damaged equipment, and the cost of shutdown. You must also evaluate the impact of pipeline failures on adjacent pipelines, including losses due to pipe losses, fluid losses, and downtime. However, it is difficult to comprehensively assess losses from pipeline failures given the incompatible dimensions of the three failure outcomes. In fact, pipeline accidents for pipeline operators are accompanied by economic losses such as compensation and maintenance. In keeping with this idea, this study incorporated currency quantified loss measurement that requires learning from different methods of market price research, real estate statistics, life safety and environmental valuation combined with specific pipeline conditions. Loss of life c1($), loss of environment c2($), loss of property c3($) and loss of adjacent pipeline c4($) are recorded respectively. Factors to consider when quantifying the failure of a piping system in a single trench are shown in Table 1 [46-48]. In a particular assessment, it should depend on the situation.

| Type | Assessment index | Type | Assessment index |
|---|---|---|---|
| Life loss $c_1$ | Death; Injury; | Property loss $c_3$ | Construction property; Repair cost; Medium loss; Equipment property loss; Downtime loss |
| Environmental loss $c_2$ | Air pollution; Water pollution; Soil pollution; Forest resources | Adjacent pipelines loss $c_4$ | Pipe loss; Medium loss; Downtime loss |

Table 1: Factors considered in monetary quantification.

## IV. RISK ACCEPTABILITY CRITERIA:

The bow tie model is good for preventing the occurrence and spread of undesirable phenomena. However, there is a limitation in that quantitative conclusions for decision-making about risk cannot be obtained. Leadership is needed to make risk decisions. Consequently, risk acceptability is introduced to further assess risk and guide the implementation of risk mitigation measures. The sociological concept of risk acceptability was introduced into engineering analysis in the 1960s to see if "safety is safe enough" [49]. Risk acceptance criteria have been studied by scientists since the 1970s as a bridge between risk assessment and risk decision-making. The book "Acceptable Risk" proposes risk acceptance criteria to protect the interests of all parties as a risk can only be accepted if the gains obtained can compensate for the risk loss [50]. Pipeline risk acceptance criteria can be divided into two categories. The first is the risk acceptance criteria for pipeline operators formulated in terms of economic benefits. To achieve this benefit, operators must find a balance between safety and efficiency [51]. ALARP principles and cost-benefit analysis are used to formulate risk acceptance criteria [52]. The second was established from the perspective of protecting the lives and environment of surrounding residents as a standard for taking risks to society [53].

We use history data of deaths and environmental pollution due to pipeline failure as reference data, and prepare social risk acceptance standards in consultation with relevant departments and labor unions. In this document, the risk acceptance criteria have been described using a curved method to facilitate communication with local managers. Given that the consequences of pipeline failure are quantified uniformly in terms of money, we used functional images of pipeline failure probability (P) and property loss (L) combined with ALARP principles to formulate acceptance criteria. Risk of economic loss. The two ALARP boundaries (negligible risk values (NVAR) and invalid values (IRV)) divide the risk into three domains: unacceptable risk, non-critical, and ALARP domains (Figure 5). Ideas for maintenance decisions may vary.

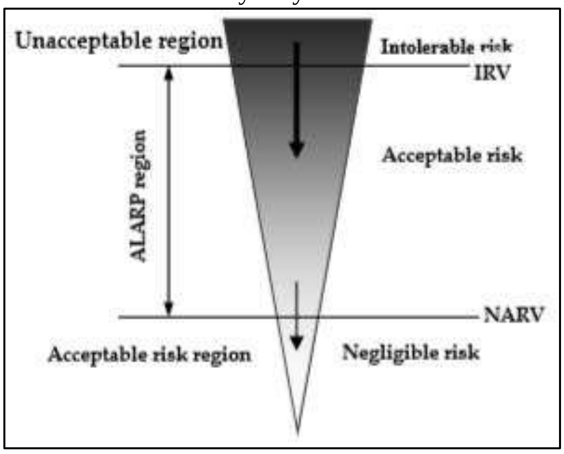


Fig. 5: Level of risk and the as low as reasonably practicable (ALARP) region

The risk boundary P-L curve is expressed as follows,

$$P_f(x) = 1 - F_L(x) < \frac{B}{x^n}$$

 

$P_f(x)$is the probability of accidents; $x$ is the loss caused by the accident; $F_L(x)$is the probability distribution function of the annual economic loss from an accident; $B$ is a constant to determine the position of the $P$-$L$ curve, referring to the risk acceptability criteria for dangerous goods transportation (HSE), the $B$ of the IRV line is $10^{-4}$, and the $B$ of NVAR is $10^{-6}$ [55,56]; $n$ is the slope of the $P$-$L$ curve, the value of $n$ is based on the acceptable risk level and the degree of risk control. The level of accident property loss is classified as shown in Table 2.

| No. | Amount of loss (thousand $) | Level |
|---|---|---|
| 1 | <1.6 | Very low |
| 2 | 1.6–16 | Low |
| 3 | 16–160 | Medium |
| 4 | 160–1600 | High |
| 5 | >1600 | Extremely high |

Table 2: Ranking criteria of consequences

Therefore, an acceptable criterion for the risk of loss of pipeline assets is shown in Figure 6. After risk assessment, pipeline failure probabilities and potential losses are represented by dots on the PL diagram. If the points fall into the non-critical area, the risk is considered negligible and there is no need to reduce the risk. If a point falls into an unacceptable area, the risk is deemed unacceptable and action must be taken by all means to reduce the risk below the IRV line. A cost-benefit analysis should be performed to determine whether action should be taken if a point falls within the ALARP area.

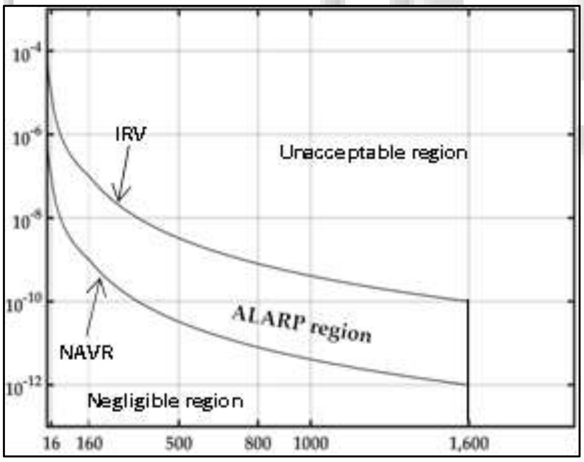


Figure 6: Pipeline property loss risk acceptable criteria

In summary, this section proposed the following risk assessment system for the PLOD (Figure 7):

1) Identifying risk factors to determine the basic events, and carding the possible failureconsequences of each pipeline;
2) Calculating the probability and consequences of each pipeline failure to obtain the total risk of the PLOD system;

Judging the risk acceptability to determine whether to maintain the system

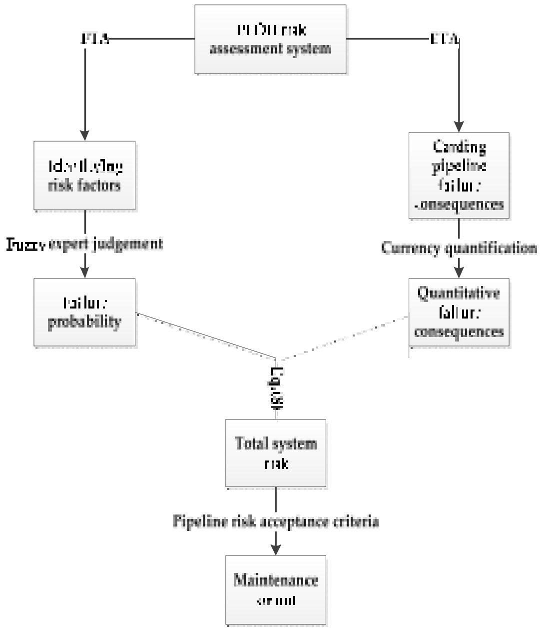


Fig. 7: Assessment process of the PLOD system

## V. CONCLUSION:

In this article, we performed a risk analysis of the PLOD system and proposed a risk assessment framework. Some conclusions were drawn after that. Piping using this routing mode can be viewed as a consistent engineering system with respect to the routing environment. In a pipeline system, the probability of pipeline failure depends on the adjacent pipelines. Meanwhile, pipeline failures affect adjacent pipelines. Combining the reliability analysis of the engineering system with mathematical induction, the risk of the pipeline system is equal to the sum of the pipeline risk and the failure correlation. A fuzzy bow-tie model combined with risk acceptance criteria was then used to provide a quantitative risk assessment that could directly guide operators in making risk decisions. When repairing pipelines, in order to prevent the influence of adjacent pipelines, it is necessary to increase the strength of the pipeline and coat the surface of the pipeline with a flame retardant coating. In addition, the frequency of surveillance and patrols should be increase to avoid accidents.

### A. *Nomenclature*

PLOD Pipelines laid in one ditch
PLOD system Pipeline laid in one ditch system
PHMSA Pipeline and hazardous materials safety administration
EGIG European Gas Pipeline Incident Data Group
ALARP As low as reasonable practical
ETA Event tree analysis
FTA Fault tree analysis
AHP Analytic hierarchy process
NAVR Negligible value at risk
IRV Intolerable value

 

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