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Investigation on the Effects of Uncertainties in Construction Quality on the Bursting Capacity of Submarine Pipelines

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ABSTRACT

Construction quality plays an important role in the integrity of submarine oil and gas pipelines during their lifetime. Quality of material and quality of construction contractors are two major contributors to the durability of the pipelines. The risk regarding quality of material and fabricators accuracy creates major concerns in durability of pipelines and has a significant impact on the optimized balance between CAPEX and OPEX in Risk-based integrity management of pipeline. In this study, the impacts of construction quality and corresponding uncertainties on the probability of failure of submarine pipelines are investigated in a reliability analysis using Monte Carlo Simulation. A sensitivity analysis is also conducted to show the important parameters within the study. The results show construction quality (i.e. standard deviation) decreases to 1/3 from 1/2, the probability of failure highly reduces from 5.9e-2 to 7e-5. This indicates a high sensitivity of the probability of failure to structural uncertainty.

1. Introduction

Subsea pipelines have a remarkable role in offshore energy production chain. They are utilized to transfer hydrocarbons, water, or chemical materials between wellheads, platforms, and onshore terminals. Although subsea pipelines are cost-effective and environmental-friendly means of transferring production, they are still subjected to likelihood of failure.[1,2]. Failure of these pipelines can result in severe economic consequences and safety and health hazard.

In accordance with the UK Health and Safety Executive (HSE UK) there were almost 1970 incidents including offshore hydrocarbon releases between 2001 and 2011 in UK continental shelf [3]. As per US Pipeline & Hazardous Material Safety Administration (PHMSA), there were about 300 subsea pipeline incidents in the U.S between 2004 and 2014. Out of these incidents, 71 included hydrocarbon releases [4]. The worst influence of all is the exposure of the public to danger in the proximity of residential areas located nearby the shoreline[5].

Failure sources of offshore pipelines can be caused by degradation mechanisms and third party (shipping activity). Degradation can be defined as the loss of capacity (i.e., strength) in the structural components as a result of fatigue, crack generation, corrosion, etc. during their lifetime. Risk of degradation depends on numerous physical and environmental factors such as uncertainty in values/ homogeneity of materials properties, uncertainty in external and internal loads, fabrication quality, and temperature fluctuations [6]. Degradation in offshore facilities will lead to failure if it is not treated with extreme care.

Rupture is one of the common failure modes in subsea pipeline structure may occur as a result of the degradation process. Bursting of pipelines leads to large leak or even to rupture of the pipeline [7]. This catastrophe not only exposes public and the environment to health and safety hazards, but also results in a partial or complete shutdown in the oil and gas production that imposes enormous economic impacts [5]. On the other hand, replacement or repair procedure of pipelines is extremely expensive and time-consuming process[8].

To address this issue, a risk-based approach (considering structural uncertainties) is used for assessment of pipelines and maintenance scheduling. Several authors have contributed to this subject. The probability of failure is estimated by using the Bayesian prior-posterior analysis as well expert elicitation

methods to develop risk-based integrity model and predict the cost consequences of pipeline failures [7, 8, 9]. Joint probability of failure of pipeline failure (burst and leak) and Leak Detection System(LDS) have been considered to estimate critical failure year and critical risk year in pipelines via Monte Carlo simulation[5]. Risk-based assessment methods have been used to examine the optimal replacement of subsea facilities, based on the likelihood of failure caused by time-dependent degradation mechanisms [10]. Bayesian theory along with risk-based assessment have been applied to update the probabilistic pipelines deterioration [11, 12, 13] and to examine the optimal inspection plans [8]. Moreover, risk-based methodology has been used in conjunction with other techniques such as fuzzy logic to address uncertainty. Risk-based assessment methodology based on fuzzy logic has been used to perform risk-based assessment for pipelines [14]. Also, risk-based methodology has been used in conjunction with Analytical Hierarchy Process (AHP) to opt a maintenance strategy [15, 16].
As per reviewed literature, the structural uncertainty induced by construction quality during manufacturing procedure was not specifically addressed in approximating the POF and risk based integrity assessment as a distinct component. The objective of this paper is to investigate the impact of structural uncertainties resulted from construction on estimation of POF of subsea pipeline. These uncertainties are modeled in limit state formulations that are normally used to design the pipelines [17]. In this study bursting failure mode is only considered as it is the most probable failure mode and has the most severe consequences [7, 9]. Reliability analysis is executed for pipeline using MCS method. Likewise, sensitivity analysis is performed to investigate the impact of uncertainty of parameter on POF calculation of pipeline considering bursting mode of failure.

2. Methodology for POF calculating

Reliability analysis and risk assessment are parts of main framework named Life Cycle Cost estimation. There is a 10-steps methodology to estimate Life Cycle Cost of any project in which the first six steps are directly related to probability of failure calculation. In this research, the procedure is adjusted to these six steps as follow [18]:

1. Identifying the structure or system to be considered
2. Identifying the quality item(s) to be considered for the system
3. Identifying the principal failure mode(s) for the structure or system to be considered
4. Writing the limit state equation for the specified failure mode(s)
5. Collecting all of the statistical data for each parameter in the limit state function consisting pipeline, operational and environmental data.
6. Computing POF

The limit state function (LSF), Eq. (1), forms the basis for the reliability calculations. This function expresses Resistance- Load as a function of X, where X is n-dimensional vector of random variables which is described by probability density function (PDF) $f_x(\mathrm{x})$. The criterion for none-acceptance or failure is defined as g(X) < 0, with the corresponding probability [18].

$$P[g(X) < 0] = \int_V f_x(\mathrm{x})dx \tag{1}$$

and V is failure domain corresponding to g(X) < 0.

2.1. Mont Carlo Simulation (MCS)

MCS is an accurate and common approach to calculate POF. Two different methods can be used when using MCS; the counting and the sample statistics methods. In the counting method, as Eq. (2), sum of number of simulation trials that results in g(X) < 0 (N_f) is computed and divided by the number of simulation trials (N) [5].

$$PoF = \frac{N_f}{N} \tag{2}$$

In the second method, the reliability index (β) is calculated as Eq.3 and eventually it yields POF as expressed in Eq.4

$$\beta = \frac{\mu_Z}{\sigma_Z} \tag{3}$$

Wherein μ_Z and σ_Z are mean value and standard deviation of the LSF, respectively. μ_Z is taken as the summation of the LSF divided by the number of simulation trials [5].

$$PoF = 1 - \phi(\beta) \tag{4}$$

Where ϕ is standard normal density function.

2.2. Reliability sensitivity analysis with MCS

To use Monte Carlo methods for the estimation of reliability sensitivities, it should be noted that standard Monte Carlo cannot be applied since limit-state parameters include surface integral which is over the limit state surface. An approximation of surface integral in terms of a domain integral should be derived. It should be regarded that estimation of the proposed approximation requires the derivative of the limit state function in terms of the parameters at each sample. The probability problem of Eq. (1) can be written as Eq. (5) [19]

$$P_f(\theta) = \int_{D(x)} I(x) fx(\mathrm{x})dx \tag{5}$$

Where $D(x) = \mathbb{R}^n$ and $I(x)$ the indicator function of failure domain. Standard Monte Carlo estimates $P_f(\theta)$

by generating n_s samples $\{x_k, k = 1,...,n_s\}$ of x and taking the sample mean of $I(\mathrm{x})$ [19].i.e.

$$P_f(\theta) \approx \frac{1}{n_s}\sum_{k=1}^{n_s} I(x_k) \tag{6}$$

The indicator function can be expressed by the following equation [20]

$$I(x) = \lim_{x \to 0} \phi\left(-\frac{g(x,\theta)}{\sigma}\right) \tag{7}$$

Where ϕ is the standard normal CDF, Θ is the parameter to which sensitivity analysis is performed, and g is the limit state function. Opting σ small enough, we can estimate $I(x)$ by Eq. (8) as follows [19]

$$I(x) \approx \phi\left(-\frac{g(x,\theta)}{\sigma}\right) \tag{8}$$

Inserting Eq. (8) into Eq. (5), an approximation of the probability of failure denoted by $\tilde{P}_f(\theta,\sigma)$ is obtained and expressed as follows [19]

$$\tilde{P}_f(\theta,\sigma) = \int_{D(x)} \phi\left(-\frac{g(x,\theta)}{\sigma}\right) fx(\mathrm{x})dx \tag{9}$$

Taking the derivative Eq. (9) with respect to θ, we get

$$\frac{\partial \tilde{P}_f(\theta,\sigma)}{\partial\theta} = -\int_{D(x)} \frac{1}{\sigma}\varphi\left(\frac{g(x,\theta)}{\sigma}\right)\frac{\partial g(x,\theta)}{\partial\theta} fx(\mathrm{x})dx \tag{10}$$

Eq. (10) is domain integral. Therefore, it can be estimated by using Monte Carlo samples $\{x_k, k = 1,...,n_s\}$, as Eq. (11)[19].

$$\frac{\partial \tilde{P}_f(\theta,\sigma)}{\partial\theta} \approx \frac{1}{n_s}\sum_{k=1}^{n_s}\left[-\frac{1}{\sigma}\varphi\left(\frac{g(x_k,\theta)}{\sigma}\right)\frac{\partial g(x_k,\theta)}{\partial\theta}\right] \tag{11}$$

3. Probability of bursting failure mode and sensitivity analysis in submarine pipeline

Bursting is one of the most probable and common failure modes in pipeline. Leakage, interruption in production and high repair expenditures are the main consequences of the failure mode. Like other failures, bursting is affected by two main uncertainties including hazard and structural resistance which are considered in design stage by applying related partial safety factors and allowed tolerances. Hazard has natural basis which are not controllable, while the structural resistance uncertainty should be reduced by improving construction quality.

According to aforementioned six steps methodology, a submarine pipeline is considered in this study. The construction quality of the pipeline is reflected in the fabrication tolerance variable. Other factors such as the uncertainty in wall thickness, diameter and Specified Minimum Yield Stress (SMYS) are also included in this analysis. The limit state function is constructed based on the design criteria for bursting, thus the pressure containment (bursting) shall fulfill the following criteria [17]:

$$P_{li} - P_e \le \frac{P_b}{\gamma_m \cdot \gamma_{sc}} \tag{12}$$

Where

$$P_b = \frac{2t}{D-t}\cdot f_{cb}\cdot\frac{2}{\sqrt{3}} \tag{13}$$

$$P_{li} = \gamma_{inc}\cdot p_d + \rho_{cont}\cdot g(h_{ref} - h_l) \tag{14}$$

$$f_{cb} = Min\left(f_y, \frac{f_u}{1.15}\right) \tag{15}$$

$$f_y = \alpha_u(\mathrm{SMYS} - \Delta SMYS) \tag{16}$$

$$f_u = \alpha_u(\mathrm{SMTS} - \Delta SMTS) \tag{17}$$

In accordance with DNV-OS-F101 [17], the parameters (Eq. 13-17) are substituted in Eq. (12) and the limit state function for the bursting criteria is obtained as Eq. (18). It should be noted that in order to consider structural uncertainties and to perform stochastic analysis, the effect of material resistance and material strength factor are neglected by equaling γ_m and α_u respectively to unity.

$$g(t,D,SMYS) = \frac{2.20\cdot t\cdot SMYS}{\gamma_{sc}(D-t)} - P_{li} + P_e \tag{18}$$

To perform sensitivity analysis, the following equations (Eq. 19 to 21) are inserted to Eq. (11) and calculations are done using Matlab code developed by the authors

$$\frac{\partial g(t,D,SMYS)}{\partial t} = \frac{2.20\cdot SMYS}{\gamma_{sc}}\left(\frac{1}{D-t} + \frac{t}{(D-t)^2}\right) \tag{19}$$

$$\frac{\partial g(t,D,SMYS)}{\partial D} = \frac{2.20}{\gamma_{sc}}\left(\frac{-t\cdot SMYS}{(D-t)^2}\right) \tag{20}$$

$$\frac{\partial g(t,D,SMYS)}{\partial(SMYS)} = \frac{2.20}{\gamma_{sc}}\left(\frac{t}{D-t}\right) \tag{21}$$

4. Case Study

In this study, the effect of three different accuracies and qualities in construction are investigated on probability of bursting failure mode. Variation in the random design parameters is in rule defined fabrication tolerances (FT) ranges.

A 609.6 mm diameter lean gas pipeline located in 175m water depth is considered as case study. The line pipe is DNV SAW450. The lean gas has a density of 265 kg/m^3, design pressure of 12 MPa with a reference elevation of +25 m and operates at a temperature of 45°C with a tie-in of 0°C. The pipeline operational and environmental data are presented in Table (1). The pipeline partial factor and design parameters are considered as Table (2) to calculate design value of pipeline wall thickness. As already mentioned, material related partial safety factors are to be taken unity for POF and sensitivity analysis.

Table 1. Pipeline operational and environmental data

Characteristic	Value
h_{ref}	25 [*m*]
h_l	-175[*m*]
ρ_{cont}	265[$kg.m^{-3}$]
ρ_w	1025[$kg.m^{-3}$]
P_d	12 [*MPa*]
E	205 [*GPa*]
ν	0.3[-]
t_{corr}	0 [*mm*]
T_{ti}	0 [°*C*]
T_o	45 [°*C*]

Table 2. Pipeline partial factors and design parameters

Characteristic	Value
α_u	0.96 [-]
γ_m	1.15 [-]
γ_{inc}	1.1 [-]
γ_{sc}	1.138 [-]

According to bursting criteria and regarding fabrication and corrosion allowance, Eqs (13 to 17), minimum wall thickness requirement for pressure containment is evaluated as t_{min}=10.85 mm to use as wall thickness mean value to perform reliability analysis and to obtain probability of failure. The pipeline random variable data using DNV suggested tolerances to fulfil reliability analysis is presented in Table (3).

Table 3. Pipeline random variables data [17] [21]

Characteristic	value
Diameter	
μ	609.6[*mm*]
FT	3.2[*mm*]
Distribution	Normal
Wall thickness	
μ	10.85[*mm*]
FT	1[*mm*]
Distribution	Normal
SMYS	
μ	450[$kg.m^{-3}$]
FT	4.74[$kg.m^{-3}$]
Distribution	Lognormal

5. Result and discussion

A Matlab code has been developed to run Monte Carlo Simulation to generate simulated values of random variables, and these values are used to calculate the limit state function. In this research, 10^8 samples were used to run the simulation for the sake of maximum convergence in results. The initial step in the analysis was to examine how DNV-approved tolerances will affect the pipeline strength against bursting failure. According to Table 4, it is obvious that fabrication procedure on the DNV standard approved range also can bring us at least 0.00007% probability of failure considering ±2, ±2.5 and ±3σ, for the tolerances in probability distribution function. These standard deviation values stand for the quality of several subsea pipeline fabricators which can affect project safety and contingent consequence costs. As shown in Table 5, sensitivity of POF to each random variable of limit state function is estimated in terms of variability of POF with respect to 1% variation in each random variable. Note that negative sign means that increasing in that particular random variable will result to decreasing in POF estimation.

Table4 and Table 5 indicates that the wall thickness of pipeline is the dominant random variable among other variables that affects the POF of bursting of pipeline comparing to SMYS and diameter. Therefore, consistent and accurate wall thickness of pipeline should be assured in pipeline construction projects to decrease the POF of pipeline and prevent corresponding consequences.

Table 4. Pipeline POF sensitivity

σ	POF(%)	POF sensitivity to (t) (%)	POF sensitivity to (D) (%)	POF sensitivity to (SMYS) (%)
FT/2	5.9e-2	-3.35e-3	7.66e-05	-6.17e-05
FT/2.5	2.6e-3	-1.77e-4	5.41e-06	-3.55e-06
FT/3	7e-5	-5.21e-06	2.21e-07	-1.08e-07

Table 5. Pipeline POF increase rate

σ	POF (%)	POF increase rate due to t (%)	POF increase rate due to D (%)	POF increase rate due to SMYS(%)
FT/2	5.9e-2	-59.1	43.14	-45.13
FT/2.5	2.6e-3	-70.97	54.95	-59.15
FT/3	7e-5	-86.92	67.5	-74.61

6. Summary and conclusion

Construction quality plays an important role in the integrity of submarine oil and gas pipelines during their lifetime. Quality of material and quality of construction contractors are two major contributors to the durability of the pipelines. While material uncertainties have been included in risk based assessment of pipelines, impact of subcontractor quality has not been investigated.

This study investigated the impact of structural uncertainties resulted from construction quality on the probability of bursting of pipelines. The limits states were constructed from design formulations of DNV [17]. Monte Carlo Simulation method is used to calculate probability of failure from limit states function. Construction quality was modeled as the standard deviation of random variables related to structural properties of pipeline (i.e., better quality equals to lower variations in structural parameters). A sensitivity analysis was also included to find the highest contributor to POF of pipeline among considered random variables.
Results indicate that the accuracy in the construction parameters including wall thickness, material properties, and line pipe diameter, significantly affect the probability of failure. With improving construction quality, by decreasing 1/2 to 1/3 in standard deviation of random variable, leads a reduction of more than 99 percent of POF.
Sensitivity analysis shows that wall thickness has the greatest effect on the POF. SMYS and diameter are respectively in second and third degree of importance.

7. List of symbols

CDF	Cumulative density function
D	Outside diameter
DNV	Det norske veritas
E	Elastic modulus
FAB	Fabrication process
FT	Fabrication Tolerance
f_{cb}	Characteristic yield resistance
f_u	Ultimate strength
f_y	Yield strength
GPa	Giga Pascal
h	Maximum water depth[m]
h_{ref}	Design pressure reference level[m]
$I(x)$	Indicator function
LSF	Limit State Function
MPa	Mega Pascal
n_s	Number of samples
P_b	Pressure containment resistance
P_d	Design pressure
Pe	External pressure
P_{li}	Local incidental pressure
PoF	Probability of failure
SAW	Submerged arc-welding
α_u	Material strength factor
β	Reliability index
Φ	Normal probability density function
γ_{inc}	System incidental/ design pressure factor
γ_m	Material resistance factor
γ_{sc}	Safety class resistance factor
$\Delta SMTS$	Material derating
$\Delta SMYS$	Material derating
μ	Mean value
μ_z	Mean of LSF
Θ	Parameters of LSF
ν	Poisson ratio
ρ_{cont}	Product contents density
ρ_w	Water density
σ	Standard deviation
σ_z	Standard deviation of LSF

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