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Reliability sensitivity analysis of dropped object on submarine pipelines

Sina Taghizadeh Edmollaii[1], Pedram Edalat[*1] and Mojtaba Dyanati[2]

[1]*Department of Offshore Engineering, Petroleum University of Technology, Mahmoudabad, Iran*
[2]*The University of Akron, USA*

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Abstract. One of the safest and the most economical methods to transfer oil and gas is pipeline system. Prediction and prevention of pipeline failures during its assessed lifecycle has considerable importance. The dropped object is one of the accidental scenarios in the failure of the submarine pipelines. In this paper, using Monte Carlo Sampling, the probability of damage to a submarine pipeline due to a box-shaped dropped object has been calculated in terms of dropped object impact frequency and energy transfer according to the DNV-RP-F107. Finally, Reliability sensitivity analysis considering random variables is carried out to determine the effect intensity of each parameter on damage probability. It is concluded that impact area and drag coefficient have the highest sensitivity and mass and add mass coefficient have the lowest sensitivity on probability of failure.

Keywords: submarine pipeline; dropped object; probabilistic assessment; sensitivity analysis

1. Introduction

Submarine Pipelines failures lead to oil leakage or explosion that results in heavy financial and environmental damages. Failures have occurred over the lifetime of oil and gas submarine pipelines, although they are assumed safer and more economical than the other methods of transporting the petroleum products. Due to industrial experiences of failure in submarine pipelines prior to the assessed lifetime, assessment of pipeline failure in design stage has considerable importance. The most comprehensive database of offshore pipeline failure is available in the report of the UK Health and Safety Executive PARLOC 2001(Kawsar *et al.* 2015). The PARLOC database indicates that about 47% of pipeline failures were caused from external influences in the submarine pipelines including trawling, dropped object, and anchoring (Kawsar *et al.* 2015, Mustafina 2015, DNV-OS-F101, 2012). Typical examples of impacts on a submarine pipeline, such as those caused by dropped objects, is shown in Fig. 1. The accident of dropped objects often occurs and causes great damages to submarine pipeline: denting damage, rupture followed with major accident including oil and gas leakage, fire, and explosion. Damage assessment of pipeline related to the dropped object impact scenario is a complex dynamic mechanism that involves several parameters including stiffness, mass, shape, and velocity of the

∗Corresponding author, Dr., E-mail: Edalat@put.ac.ir

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impacting object; stiffness of the pipeline coating and soil; Diameter and wall thickness of the pipeline; and coating thickness (Mazzola 2000). The previous studies of submarine pipeline impacted by dropped objects are mostly focused on predicting the probability of impact and predict the risk of pipeline damage calculated by energy formula and energy bands according to DNV-RP-F107 (DNV GL, 2017).

In recent years, several researchers have proposed prevalent analysis method in offshore risk-based assessment (Bai and Bai 2005, 2014, Vinnem 2007). Bai and Bai (2014) suggested the probability and consequences of the failure of subsea pipelines from different types of impact and investigated the prediction of risk and acceptance criteria to establish an optimal plan for inspection. Moreover, a theoretical calculation of large plastic deformations in tubes under lateral indentation, bending moment and axial force is performed by Wierzbicki and Suh (1988). A probabilistic methodology is utilized for the estimation of the pipeline impact and rupture frequencies by Mazzola (2000); this information is obtained both for the overall pipeline section exposed to the hazard and for several critical locations along with the pipeline path. The represented algorithm has been developed in a computer program that allows the analysis of a large number of contingent drop points and locations of pipeline target point. This methodology can be used in risk evaluation for platform personnel from dropped objects. Alexander (2007) presented insights garnered in assessing the severity of pipeline damage in the form of dents and gouges. In addition, research associated with impact forces having empirical work is included as part of the presentation, as well as limit analysis techniques using FEM. also, this methodology can be employed to evaluate the intensity of damage and quantify tolerance levels in terms of impact energy. Agamid (2001) investigated collapsible impact energy absorbers and a model of deformation for tubes of different shapes. Palmer *et al.* (2006) fulfilled full-scale experiments by dropping one pipe having concrete coating onto another, measured the dents of the pipes, the damage to the concrete, and its reinforcement to take the impact energy division between different absorption mechanisms into consideration.

Fig. 1 Dropped object impacts on submarine pipelines

Yang *et al*. (2009) carried out experiments and numerical simulations, in which small-scale pipes impacted pipes, finding that the initial impact position had an effect on the impact results. Alsos *et al.* (2012) regarded the global inertia resistance, the denting resistance and impact mass and velocity as the governing parameters for the denting damage of pipelines and proved with tests and numerical simulation. Wang *et al.* (2014) has comprehensively investigated the submarine facilities affected by the dropped object loads and addresses the determination of impact load. The calculation method for the protection structure design is recommended there. Kawsar *et al.* (2015) represent a stochastic and numerical modeling analysis of accidental scenarios to verify the submarine pipelines safety under different conditions. An impact analysis of transverse loading on a submarine pipeline is performed utilizing scenario sampling and FEM to assess safety measures and subside damage by evaluating the effects of impacts in different contingent accidental scenarios. Yu *et al*. (2016) the improved risk-based assessment of FPSO's structural damage influenced by drop objects are performed. ANSYS/LS-DYNA is used to simulate the impact on the deck structure of FPSO and submarine pipelines respectively for several times. To achieve the correlation between the maximum impact force and parameters of falling objects, it is necessary to fit the data gained by simulation, to generate the failure function in Monte Carlo sampling during the subsequent work. Based on the method of DNV's recommendation, the calculation method of collision probability for submarine pipelines will be improved. According to probability statistics, energy method, and failure probability theory the Matlab GUI program can be compiled to simplify the calculation. If the calculated failure probability does not meet the DNV's acceptance criteria, we should find out the larger risk and give it some protective measures. Jing *et al*. (2016) presented the energy transfer law and absorption is one of the most important engineering fundamental problems in view of engineering risk of subsea pipelines impacted by dropped objects, but rarely being studied. Energy transfer between dropped objects and lateral impacted pipes was researched by quasi-static analysis, probability statistical analysis, and FEM simulated analysis to deduce energy transfer law and affecting factors. Impact contact area and time are proved to be the affecting factors of energy transfer by sensitivity analysis of the FEM simulation. Bertin *et al.* (2016) presented deals with a computational model aimed at modeling a mobile crane fall on an aerial pipeline. Results from an experimental study on carbon-steel pipes are used as a conservative threshold for the computational evaluation in order to get worst cases scenarios. Damage influenced by the impact to the pipelines are assessed is taken into consideration different parameters (i.e., pipe, geometry, crane, boundary conditions, etc.). Results indicate that there is no failure of the studied pipelines due to the fall of cranes typically used on LNG production plants during maintenance operations. In order to obtain the probability of failure, the probabilistic damage and loss estimation way is used.

The probabilistic damage and loss estimation usually involves more complex procedures. When any hazard is considered, probabilistic damage and loss estimation consists of four general steps (Baker and Cornell 2008, Dyanati *et al*. 2015): (1) determining hazard occurrence and intensities (hazard analysis), (2) evaluating the responses of the pipeline (structural analysis), (3) determining damage states (damage analysis), and (4) determining losses due to the damage (loss analysis). Each step involves both inherent randomness and model (epistemic) uncertainty that should be accounted for appropriately. In structural analysis, responses of the pipeline to any hazards contain inherent uncertainty, as well as material property and geometric uncertainties. The probabilistic nature of the pipeline responses to any hazard in loss estimation formulations is usually considered by developing probabilistic engineering demand parameter (EDP) models or using Monte Carlo Simulations considering various levels of the intensity measures for each hazard and other sources of uncertainties such as structural properties (Dyanati *et al*. 2015). In the damage analysis and loss analysis, damage states are usually described qualitatively and then defined by considering limit states on the EDPs (i.e., EDP capacities). Corresponding losses for each damage state are evaluated based on the description of the damage state. The difference between these approaches lies in the levels of the damage definition (limit states) and the corresponding loss evaluation. Probabilistic methods can be used for assessing the current and future ability of pipelines to support operational demand without jeopardizing, safety and reliability. Based on the outcome of the assessment, the pipeline fitness for service as well as the remaining life can be determined. The Monte Carlo Simulation method used to evaluate the probabilistic characteristics of the random variables and then determine the probability of failure, either by sample statistics or by counting methods (Haldar and Mahadevan 2000). Xiang *et al*. (2016) considered ocean currents in the dropped cylindrical object by expanding a three-dimensional (3D) theory of dynamic motion. They simulated the different directions of dropped cylinders falling through uniform currents and introduced the direction of current as the main factor effects on trajectories and landing points of dropped cylinders. As a result, risk free zones for offshore lifting operations was determined by applying the Monte Carlo simulation with considering orientation angle, translational velocity, and rotational velocity as random parameters. Taghizadeh and Edalat (2017) implemented the probability-based damage analysis of existing submarine pipeline located in near a platform under the influence of the dropped object. The probability of failure of the pipeline was evaluated using energy transfer analysis and Monte Carlo simulation method.

In this study, the probability of pipeline failure is calculated in relation to impact frequency including drop frequency per lift and probability of hit a pipeline. The probability of failure for different levels of damage, impact probability on submarine pipeline, failure probability theory, and energy method are calculated. In previous works, object properties such as mass and volume were not solely considered. All the influencing parameters mass, volume, projected area, and drag coefficients are regarded as random variables. In addition, Reliability sensitivity analysis with MCS analysis had been done on the random variables, the analysis shows the magnitude of variation of the damage probability for a one-percent increase in each random variables seperately. As a case study, 32” submarine pipeline in a gas field located in the Persian Gulf is considered.

2. Pipeline damage levels and consequences by dropped object

A dropped object as an accidental potential failure in submarine pipeline most of the time is caused by the failure of crane operation. There are three stages that a dropped object experiences before the impact on the pipeline: falling through the air, impacting on the sea surface, and falling under the water. Based on DNV-RP-F107 (DNV GL, 2017), failure caused by the dropped object is divided into three types of damage and release as shown in Fig. 2. The damage categories are used for economic evaluations, whereas there are different release categories, in addition, to use for estimating the risk of human safety and pollution leakage to the environment.

Most impacts are expected to result in a relatively smooth dent shape. The dent - absorbed energy for steel pipelines is given in Eq. (1), which is known as the energy absorption in the inner tube (DNV GL, 2010)

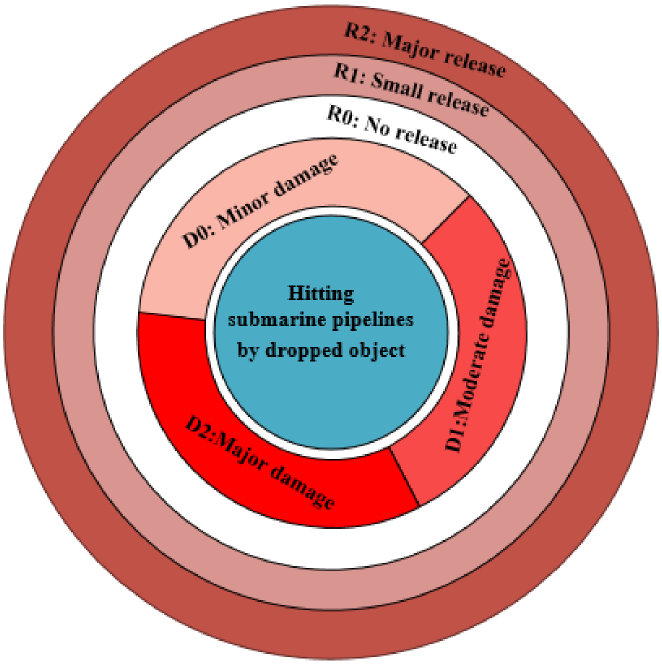

Fig. 2 Damage classification to submarine pipelines by the dropped object

$$E_s = 16.\left[\frac{2\pi}{9}\right]^{\frac{1}{2}}.M_p\left[\frac{D}{t}\right]^{\frac{1}{2}}.D.\left[\frac{\delta}{D}\right]^{\frac{3}{2}} \tag{1}$$

Where E_s = Dent- absorbed energy for steel pipelines, D = Diameter of the pipeline, t = Wall thickness, δ = Pipe deformation (dent depth), and M_p is plastic moment capacity of the pipe wall, Eq. (2)

$$M_p = 0.25 f_y t^2 \tag{2}$$

The additional failure of the wall rupture of line pipe, which leads to leakage, can occur for higher velocity of impacts or locally small projected area and the sharp edge of impact object. The possibility of leakage and total rupture is included as a progressive conditional probability, where probability increases with increasing impact energy. Table 1 in appendix gives the proposed damage classification used for bare steel pipes (DNV GL, 2017).

3. Energy transfer analysis

The denting damage of pipe is formed by energy transfer from the dropped object to the impacted pipe during the impact. Energy transfer ratio is the basic-factor affecting the level of pipe damage. The impact energy depends on mass and velocity of the dropped object. The kinetic energy (E_E) -effective in an impact- includes the terminal energy (E_T) and the energy of added hydrodynamic mass (E_A). The added mass energy may become significant for large volume objects as containers. The effective impact energy becomes Eq. (3)

$$E_E = E_T + E_A = \frac{1}{2}(m + m_a)v_T^2 = \frac{g}{C_D A}\left(\frac{m^2}{\rho_{water}} - V.m + C_a V(m - V\rho_{water})\right) \tag{3}$$

The terminal velocity (v_T) and added mass of water (m_a) are obtained from Eqs. (4) and (5) respectively

$$v_T^2 = 2\frac{(m - V.\rho_{water}).g}{\rho_{water}.C_D.A} \tag{4}$$

$$m_a = \rho_{water} C_a V \tag{5}$$

Where m= Mass of object, V = Volume of object, ρ_{water} = Seawater density, A = Projected area, C_D = Drag coefficient and C_a = Add mass coefficient.

The impact energy is mainly absorbed by structural energy capacity including concrete coating (E_c) as Eq. (6), polymer coating (E_p) according to Table 2 in appendix, and inner tube (E_s) as Eq. (1).

$$E_c = Y.B.\frac{4}{3}.\sqrt{D.x_0^2} \tag{6}$$

Where Y= Crushing strength, x_0= Penetration depth and B= Width of the falling object.

4. Probabilistic assessment

Probability assessment of submarine pipeline failure due to a dropped object contains two main steps: (1) calculation the impact frequency, $F_{hit,sl,r}$ and (2) determination of the probability of damage using energy transfer analysis and Monte Carlo Simulation method, $P_{f,\text{ damage}}$. The proposed methodology is presented in Fig. 3.

4.1 Impact frequency

Impact frequency is the probability of an object falling and hitting the submarine pipeline, which depends on the drop frequency per lift, number of lifts per year, and conditional hitting probability. The effective parameters in the impact frequency calculation are defined schematically in Fig. 4. The respective probable area is divided into numbers of circles with different radius and the object excursions on the seabed are assumed to be normally distributed with angular deviations given in Table 3 in appendix. The location where a dropped object hits the seabed can be considered a normal distribution as Eq. (7) (DNV GL, 2017).

$$p(x) = \frac{1}{\sqrt{2\pi}\delta}e^{-\frac{1}{2}(\frac{x}{\delta})^2} \tag{7}$$

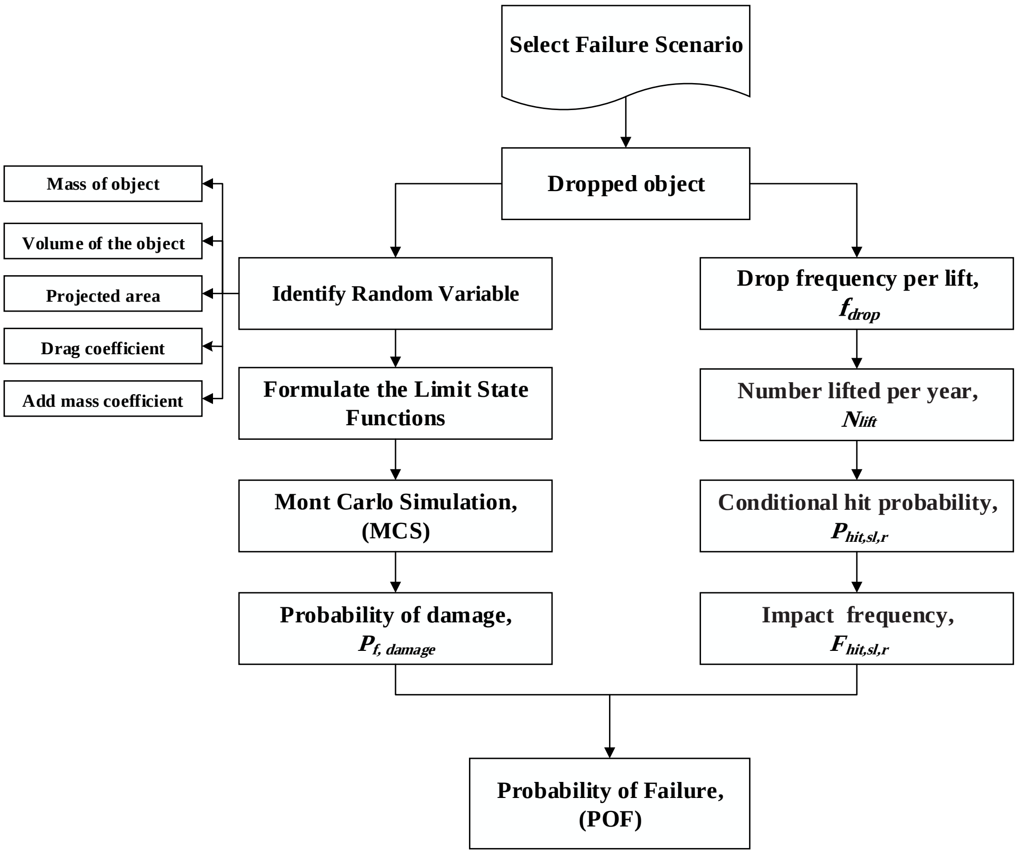

Fig. 3 Proposed methodology of submarine pipeline failure probability assessment of due to dropped object

Wherein $p(x)$ = Probability of a sinking object hitting the sea bottom at a distance x from the vertical line through the drop point, x = Horizontal distance at the sea bottom (meters) and δ = Lateral deviation in the water of the object.

The probability that a dropped object hits the seabed within a distance r from the vertical line through the drop point is calculated from Eq. (8).

$$P(x \le r) = 2\int_0^r p(x)dx = 2\int_0^r \frac{1}{\sqrt{2\pi}\delta} e^{-\frac{1}{2}(\frac{x}{\delta})^2} dx \tag{8}$$

The probability of hit within two circles around the drop point ($P_{hit,r}$) with inner radius r_i and outer radius, r_o, can be found by Eq. (9) which is shown Fig. 5.

$$P_{hit,r} = P(r_i < x \le r_o) = P(x \le r_o) - P(x < r_i) \tag{9}$$

Within a certain ring, the probability of hit to a pipeline or umbilical with an object ($P_{hit,sl,r}$) can be described as the exposed area which gives a hit within a ring divided on the total area of the ring, multiplied with the probability of hit within the ring, see Eq. (10).

$$P_{hit,sl,r} = P_{hit,r} \frac{L_{sl}(B+D)}{A_r} \tag{10}$$

The impact frequency estimated with Eq. (11). The drop frequency per lift (f_{drop}) is given in Table 4 in appendix.

$$F_{hit,sl,r} = N_{lift} . f_{drop} . P_{hit,sl,r} \tag{11}$$

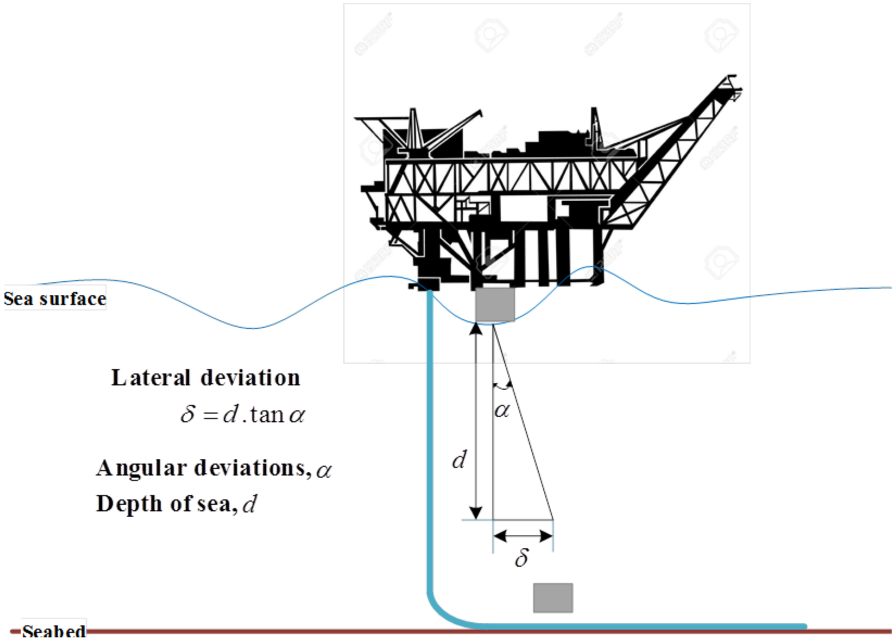

Fig. 4 Underwater analytical impact scenario

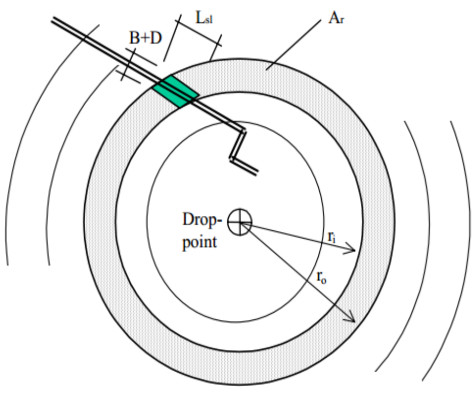

Fig. 5 Probability of hit within a ring, defined by inner radius, r_i, and outer radius, r_o, from the drop point (DNV GL, 2017)

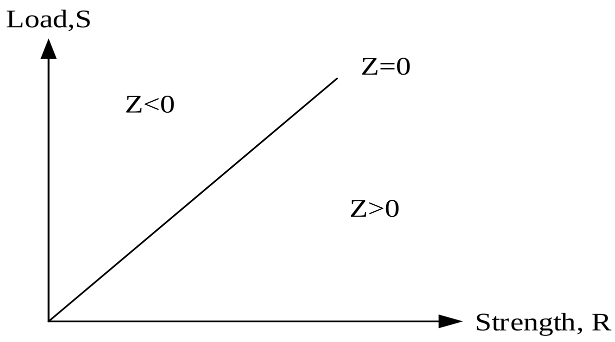

Fig. 6 Failure space as a function of basic variables

4.2 Probability of failure

The definition of reliability function can be based on limit state function. Limit state function can be defined as follows

$$Z = R - S \tag{12}$$

In which R and S are random variables or probability density function. Fig. 6 shows the relationship between two parameters ad RS-plane.

The limit state is described by $Z = 0$. Failures take place when the failure surface falls in the region of $Z < 0$ while $Z > 0$ is a survival region. The probability of failure is then given by Eq. (13)

$$P_f = \Pr(z \le 0) = \Pr(R \le S) \tag{13}$$

The Monte Carlo simulation (MCS) is known as an effective method to calculate the probability of failure. As Eq. (14), with the implementation of MCS method, the sum of the number of simulation trials that volatile the LSF (N_f) is computed, i.e. when the LSF becomes less than zero and this sum is divided by the number of simulation trials (N) to obtain the probability of failure (Van Gelder 2000).

$$POF = \frac{N_f}{N} \tag{14}$$

According to Eq. (3), random variables are mass, volume, collision area of the dropped object, drag coefficient, and add mass coefficient. The crane has a limited capacity and the object has a random mass and a random volume. It is assumed that the mass of the object has a uniform distribution between the predefined operational capacity of crane equal to 1 through 10 tones. Because an object with a certain mass should have an actual volume, a normally distributed volume according to the mass has been considered for the object. Collision area between dropped object and pipeline depends on several conditions and the exact value of the impact area can’t be predicted. In practical cases, the minimum value of the impact area is used. Yu *et al*. (2016) have proposed mass related upper and lower bounds for the minimum impact area, therefore bounded normal probability distribution is an appropriate assumption to modeling impact area as a random variable. The bounded normal distribution is also applicable for drag coefficient and added-mass coefficient based on DNV, which proposes maximum and minimum. Random variables, considered for probabilistic assessment, are described in Table 5 with relevant mean value and standard deviation. Distribution types which are mentioned in Table 1.

Neglecting the deformation of the dropped object and considering that all the energy is absorbed by the pipeline, the limit state function is obtained as Eq. (15).

$$\begin{aligned} Z(m, V, A, C_d, C_a) &= (E_C + E_P + E_s) - E_E \\ &= (E_C + E_P + E_s) - \frac{g}{C_D A}\left(\frac{m^2}{\rho_{water}} - V.m + C_a V(m - V\rho_{water})\right) \end{aligned} \tag{15}$$

According to the limit state Eq. (15), using Monte Carlo Simulation to gain the conditional hit probability versus dent depth, and then getting the hit frequency versus dent depth. Finally, the probability of failure is determined from Eq. (16).

$$POF = F_{hit,sl,r} . P_{f,damage} \tag{16}$$

4.3 Probability sensitivity analysis with MCS

In this method, an approximation of the probability of failure denoted by $\tilde{P}_f(\theta, \sigma)$ is considered and expressed as Eq. (17). (Papaioannou *et al.* 2010)

$$\tilde{P}_f(\theta, \sigma) = \int_{D(x)} \phi\left(-\frac{Z(x, \theta)}{\sigma}\right) fx(\mathrm{x}) dx \tag{17}$$

Where X is an n-dimensional vector of random variables described by the joint PDF $f_x(X)$, $D(X) = R^n$ and ϕ is the standard normal CDF, θ is the parameter to which sensitivity analysis is performed, and Z is the limit state function. The accuracy of estimation in Eq. (17) depends on choosing a small enough σ. (Spanier and Oldham 1987)
Taking the derivative Eq. (23) with respect to θ, we get

$$\frac{\partial \tilde{P}_f(\theta, \sigma)}{\partial \theta} = -\int_{D(x)} \frac{1}{\sigma} \varphi\left(\frac{Z(x, \theta)}{\sigma}\right) \frac{\partial Z(x, \theta)}{\partial \theta} fx(\mathrm{x}) dx \tag{18}$$

Table 1 Random variables of parameters with their relevant mean and standard deviation

Parameter	Distribution Type	Mean	Standard deviation
Mass (m)	Uniform		
Volume (V)	Normal	0.00081m	0.00023m
Projected Area (A)	Bounded Normal	1	0.2
Drag coefficient (Cd)	Bounded Normal	1.05	0.2
Add mass coefficient (Ca)	Bounded Normal	1.25	0.2

Eq. (18) is domain integral. Therefore, it can be estimated by using Monte Carlo samples $\{x_k, k=1,\ldots, n_s\}$, as Eq. (19) to obtain sensitivity analysis of the probability of failure with respect to θ.

$$\frac{\partial \tilde{P}_f(\theta,\sigma)}{\partial \theta} \approx \frac{1}{n_s}\sum_{k=1}^{n_s}[-\frac{1}{\sigma}\varphi(\frac{Z(x_k,\theta)}{\sigma})\frac{\partial Z(x_k,\theta)}{\partial \theta}] \tag{19}$$

5. Case study

In this research, the probability of failure of the 32” pipeline, existing in Persian Gulf, due to the dropped object accident has been investigated. The details of pipeline and platform parameters are presented in Table 2. The dropped body is assumed as box-shaped with a maximum weight of 10 tonnes. In addition, numbers of lifts per year are considered 250, according to Table 5 in appendix. The generic drop frequency for crane activities can be determined according to Table 4 in appendix. For this example, all lifts are below 20 tones and the frequency of dropped load into the sea is then to 1.2×10^{-5} per lift. According to DNV-OS-F101, the acceptance criteria for the annual failure frequency shall be less than 10^{-5}. The field layout with the pipeline approach and crane location is given in Fig. 6. Based on the crane location, the vessel approach area and the land area on the platform a most likely drop point is chosen. As shown in Fig. 7 from the drop point concentric rings of increasing 10 meters radius are drawn up.

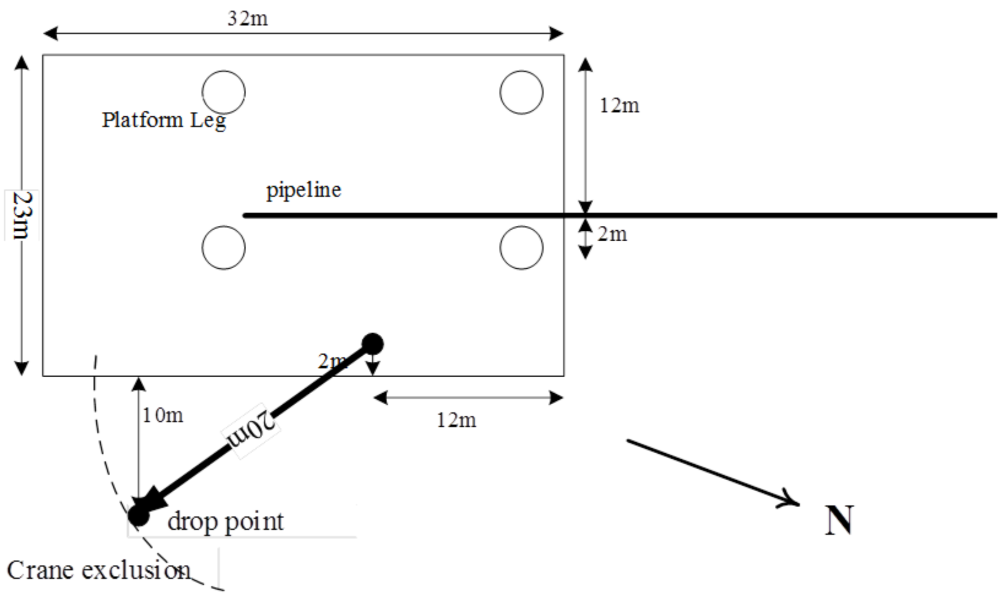

Fig. 6 The field layout with the pipeline approach and crane location

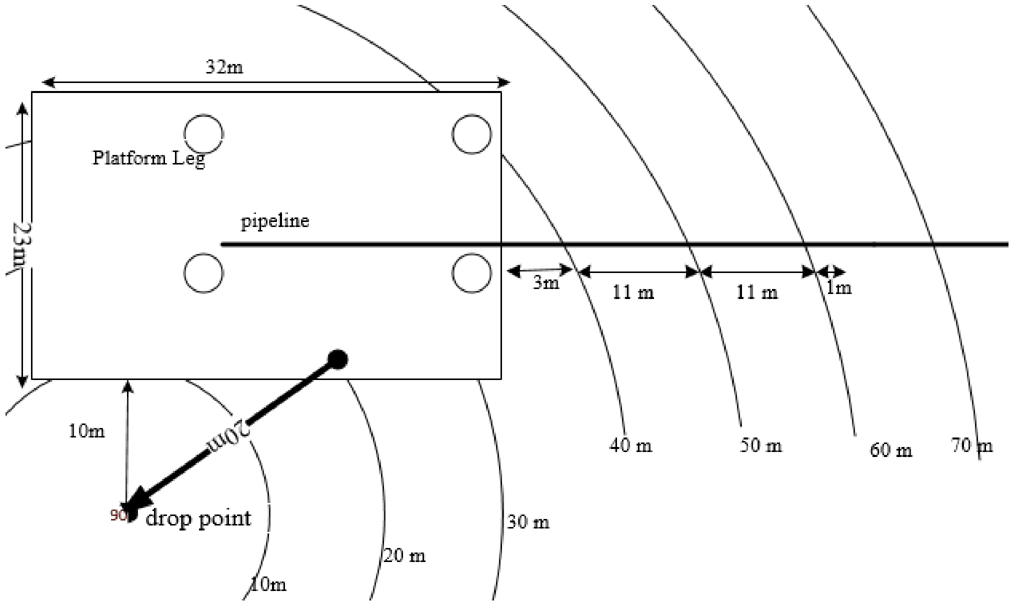

Fig. 7 Field Layout with the indication of a 10-meter interval of operational radius related to the object excursion and hit probability calculation

Table 2 Submarine Pipeline and platform data

Parameter	Value	unit
Outer diameter	812.8	[*mm*]
Wall thickness	20.6	[*mm*]
Steel quality	SAWL450 I SF(X-65)	
Specified minimum yield stress	450	[N/mm^2]
Specified minimum tensile strength	535	[N/mm^2]
Coating type	Concrete	
Coating thickness	50	[*mm*]
Coating density	3040	[kg/m^3]
Coating type	Polymer	
Coating thickness	6	[*mm*]
Coating density	1400	[kg/m^3]
Water depth	65	[m]
Platform dimension	23×32	[m×m]
Maximum crane capacity	10	[tones]
Acceptance annual frequency (Safety class: high)	10^{-5}	

6. Results and discussions

6.1 Calculation of impact frequency

The pipeline diameter equal to 0.813 meters including coating and the object size is assumed 12-meters long for the slender objects and 5-meters long for the box-shaped according to the dropped object characteristics. The conditional probabilities for objects from each of the object categories to fall within these rings are calculated. The impact probability depends on the excursion of the objects as calculated in Table 3 and the length of the pipeline within each ring and the pipeline diameter and object size.

The resulting conditional probability of hitting the pipeline according to Eq. (10) is given in Table 4. The length of the exposed pipeline is three meters as given in Fig. 9 and the breadth of the object is conservatively taken as the whole length of a pipe string, i.e., 12 meters. The conditional probability of hitting the pipeline then becomes.

The resulting final hit frequency according to Eq. (11) is shown in Table 5 with the drop frequency of to 1.2×10^{-5} per lift. The annual hit frequency is found to be to 1.85×10^{-5}. The annual hit frequency for box-shaped is calculated to 4.64×10^{-7}. The annual hit frequency for flat shaped is 1.803×10^{-5}.

Table 3 Conditional probability of hit for each of the objects to fall within 10-meter intervals on the seabed

Object				The probability of hit per seabed area [m^2], $P_{hit,r}$						
no	Des.	Angular (deg)	Lateral dis(m)	0 - 10	10 - 20	20 - 30	30 - 40	40 - 50	50 - 60	60 - 70
1	Flat/long shaped	15	17.42	0.001382	0.000334	1.06 E-4	2.89 E-5	6.2 E -6	1.0 E -6	1.26 E-7
2		9	10.3	0.00212	0.000296	3.0 E-5	1.5 E-6	3.6 E-8	3.4 E-10	9.8 E-13
3		5	5.69	0.00293	8.32 E-5	2.8 E-7	6.1 E-11	7.3 E-16	4.4 E-22	0
4	Box/round shaped	10	11.46	0.00196	0.000321	4.59 E-5	3.81 E-6	1.66 E-7	3.67 E-9	6.01 E-11
5		5	5.69	0.00293	8.32 E-5	2.8 E-7	6.1 E-11	7.3 E-16	4.4 E-22	0
6		3	3.40	0.00317	3.47 E-6	2.58 E-12	5.04E-22	0	0	0

Table 4 Conditional probability for each of the objects to hit the pipeline within 10-meter intervals on the seabed

Object				Conditional probability , $P_{hit,sl,r}$								
no	Des.	Weight [tones]	Berth[m]	0 - 10	10 - 20	20 - 30	30 - 40	40 - 50	50 - 60	60 - 70	Sum
1	Flat/long shaped	< 2	12	0	0	0	1.11E-03	8.74E-04	0.000141	1.61E-06	2.11E-03
2		2 – 8	12	0	0	0	5.77E-05	5.07E-06	4.89E-08	1.25E-11	6.28E-05
3		> 8	12	0	0	0	2.34E-09	1.03E-13	6.2E-20	0	2.34E-09
4	Box/round shaped	< 2	5	0	0	0	6.64E-05	1.06E-05	2.35E-07	7.70E-10	7.73E-05
5		2 – 8	5	0	0	0	1.06E-09	4.67E-14	2.81E-20	0	1.06E-09
6		> 8	5	0	0	0	8.79E-21	0	0	0	8.79E-21

Table 5 Resulting hit frequency

no	Description	Weight (tons)	Number lifted per year, N_{lift}	Drop frequency per lift, f_{drop}	Conditional hit probability, $P_{hit,sl,r}$	Hit frequency, $F_{hit,sl,r}$
1	Flat/long shaped	< 2	700	1.20E-05	2.11E-03	1.80E-05
2		2 – 8	50	1.20E-05	6.28E-05	3.77E-08
3		> 8	5	1.20E-05	2.34E-09	1.41E-13
4	Box/round shaped	< 2	500	1.20E-05	7.73E-05	4.64E-07
5		2 – 8	2500	1.20E-05	1.06E-09	3.19E-11
6		> 8	250	1.20E-05	8.79E-21	~ 0

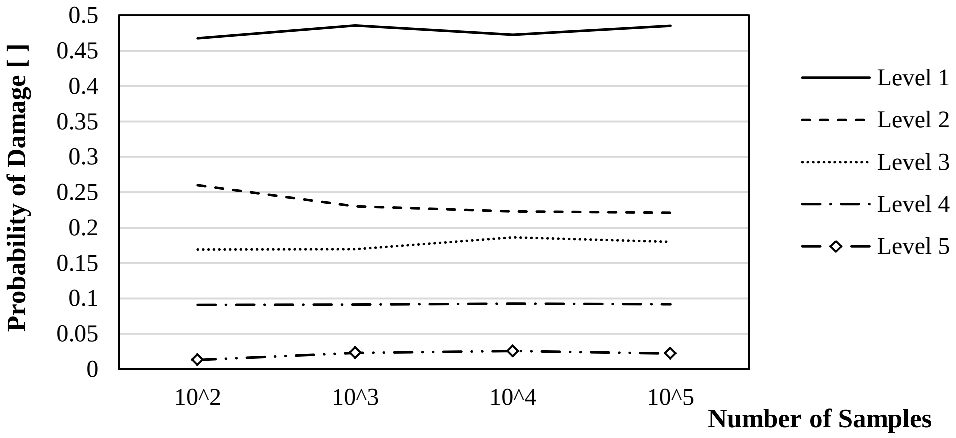

Fig. 8 Minimum number of samples for MCS convergence

6.2 Calculation of failure probability

The damage probability of pipeline is determined for a box-shaped object with a weight lower than 10 ton using Monte Carlo codes developed in MATLAB and according to the limit state Eq. (15). Wherein, the probability of failure is calculated based on Eq. (16). In this research, 10^5 samples were used to run the simulation for the sake of convergence in results. The trend of convergence for different damage level is illustrated in Fig. 8.

Pipeline capacity for 5% dent and coatings resistance are determined by using Eqs. (1) and (6) as follows. Here the breadth, B, and height, h, of the impacting object are assumed to be 30 mm and 300 mm respectively. Finally, the determined probability of failure has been proposed in Table 6 based on damage intensity.

Failure and leakage frequency are calculated on damage classification for any level of damage and release according to Table 1 in appendix. Total failure frequency calculated by energy method for box-shaped objects is 4.54×10^{-7}, and the leakage frequency is 2.64×10^{-7}. It can be seen that the annual frequency of failure is 4.54×10^{-7}, which is within the acceptance criteria of 10^{-5}. It could be concluded that dropping box-shaped objects with a weight under 10 tones is not dangerous for the understudy pipeline. In other words, this level of protection is safe for the pipeline. Fig. 9 and Table 7 shows that the probability of damage in different levels changes by the value of masses, which increases the likelihood of major damage as the mass increases and consequently the risk of rupture increases. Fig. 10 shows the trend of changes in the probability of damage in various levels of damage by increasing the mass in percentage terms. As the mass increases up to 10 tons, damage level increases considerably and for the mass equal to 10 tones the contribution of level 1 decreases more than 90 percent. The likelihood of level 5 damage (rupture) for masses of more than 6 tons starts. In addition, up to a mass of 10 tons, it will increase by 22 percent and reach its maximum.

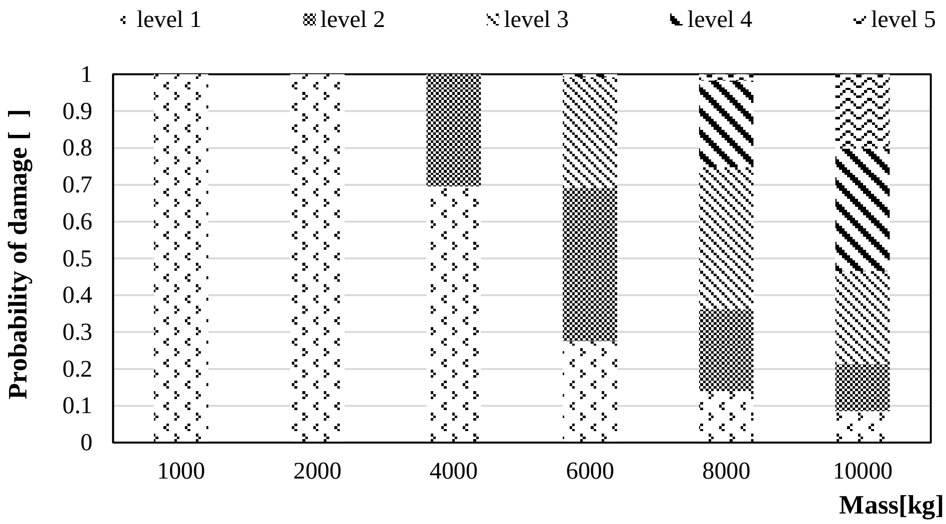

Fig. 9 The probability of damage in different levels in different masses

Table 6 Failure frequency versus damage category

Different levels of damage	Dent / Diameter δ / D (%)	Impact energy		Damage probability With MCS, $P_{f,damage}$	Conditional probability of failure, POF					
		Steel pipe only	Total(Coating included)		D1	D2	D3	R0	R1	R2
Level 1	< 5	<30	<70	0.48528	2.25E-07	0	0	1.44E-07	0	0
Level 2	5 - 10	30 - 117	70 - 157	0.221186	1.03E-08	8.21E-08	0	9.23E-08	1.03E-08	0
Level 3	10 - 15	117- 264	157 - 304	0.179705	0	6.25E-08	2.08E-08	6.25E-08	1.67E-08	4.17E-09
Level 4	15 - 20	264- 470	304 - 510	0.091765	0	1.06E-08	3.19E-08	1.06E-08	2.13E-07	1.06E-08
Level 5	> 20	> 470	> 510	0.022064	0	1.02E-09	9.21E-09	1.02E-09	2.05E-09	7.16E-09
		Total		1	2.35E-07	1.56E-07	6.20E-08	3.11E-07	2.42E-07	2.20E-08

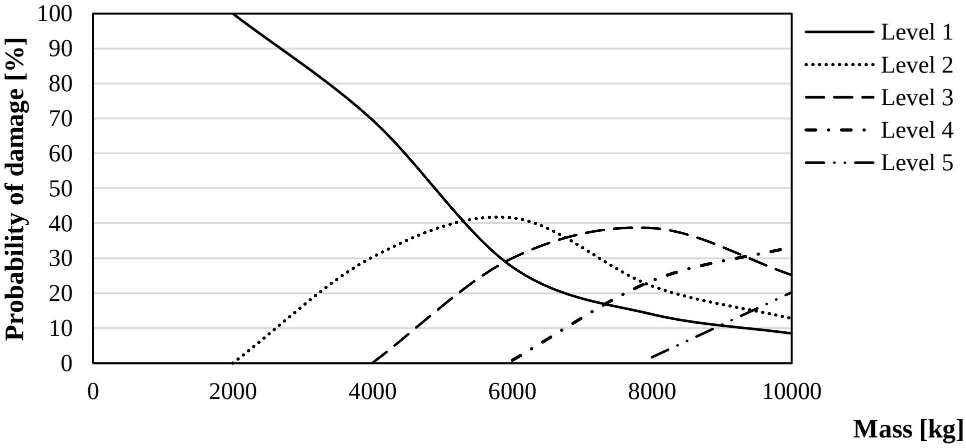

Fig. 10 The trend of change of the probability of damage with change of masses in different levels

Table 7 The value of probability of damage in different levels in different masses

Different levels of damage	probability of damage					
	1000 [kg]	2000 [kg]	4000 [kg]	6000 [kg]	8000 [kg]	10000 [kg]
Level 1	1	1	0.69572482	0.27558416	0.14008338	0.0851022
Level 2	0	0	0.30340056	0.41591438	0.22102627	0.12796122
Level 3	0	0	0.00087462	0.30015438	0.38645183	0.25235849
Level 4	0	0	0	0.00834707	0.23544759	0.33212788
Level 5	0	0	0	0	0.01699093	0.20245021

6.3 Result of sensitivity analysis

The results of reliability sensitivity analysis with MCS for the probability of damage related to the random variables of a dropped object are calculated. The trend of change in random variables' sensitivity has been shown in Fig. 11. When the probability of damage is zero or one, the sensitivity is zero. As it can be seen, impact area and drag coefficient have the highest sensitivity and mass and add mass coefficient have the lowest sensitivity. For more details, the relating values of the sensitivity analysis versus random variables has been presented in Tables 6 to 9 in appendix. Damage levels 4 and 5 have the lowest sensitivity to the all random variables. In addition, the magnitude of variation of the damage probability for one-percent increase in the random variables is calculated has been proposed in Tables 10 to 13 in appendix and is shown in Fig. 12. As it indicates impact area and drag coefficient reduce the probability of damage while mass and add mass coefficient increases it. Although mass has the lowest sensitivity, it increases the probability of damage more than other variables. However, all random variables in damage level 5 have the lowest sensitivity; they cause the highest increase or reduction in the probability of damage. The increase of each random variable usually leads to the increase of changing of the probability of damage.

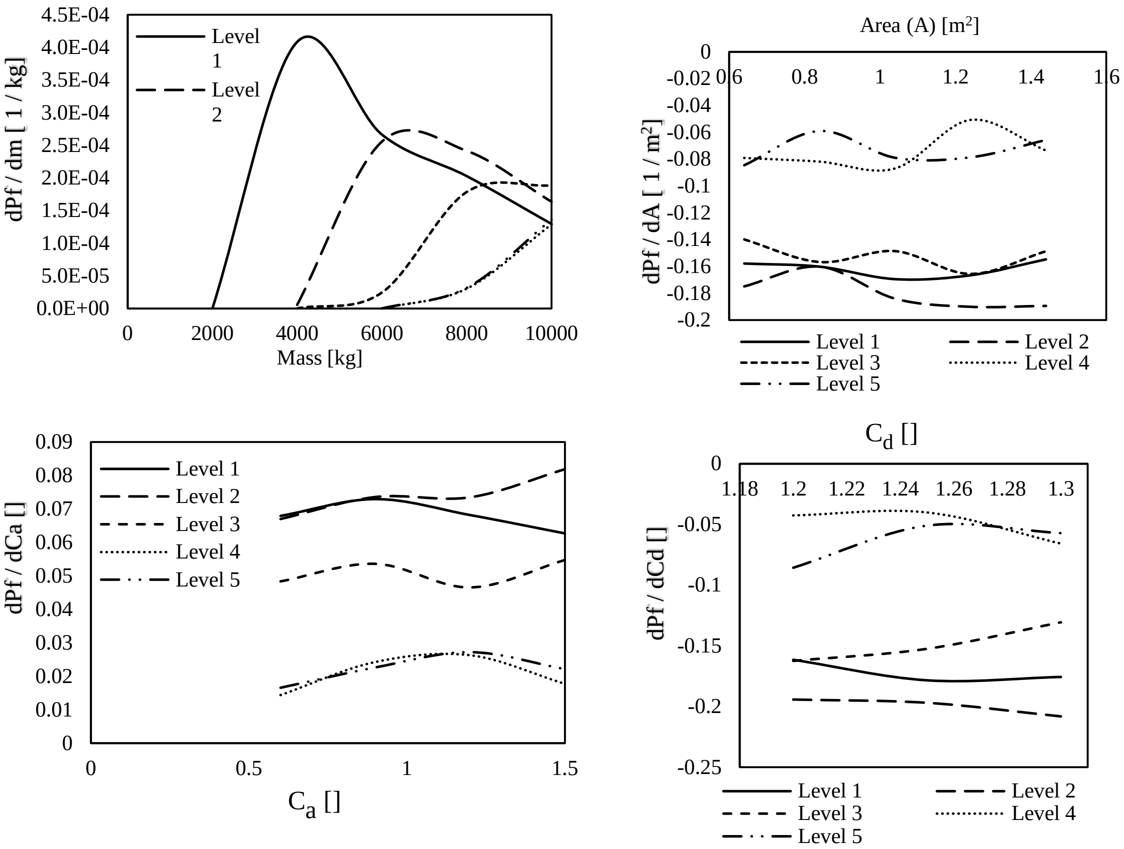

Fig. 11 The trend of sensitivity of POF related to random variables

7. Conclusions

In this paper, a probabilistic methodology to establish risk estimation strategy in the submarine pipeline industry is presented and applied for a real pipeline. In addition, it introduces guideline of probabilistic damage and loss analysis. In design step, having platform field layout and crane activity, this methodology could be used to design a pipeline with an optimum coating which decreases the costs. By having the sensitivity of probability of failure related to effective and controllable parameters, the risk of pipeline failure due to the dropped object can be reduced and controlled.

In the case study condition, box-shaped objects weighed less than 10 tones cannot damage the pipeline. That means the line pipe structure and coating can suffer the impact energy as rule criterial limitation. In addition, the probability of flat-shaped objects falling is more than box-shaped objects. Using the methodology applied in this paper, one can calculate the probability of failure of pipeline impacted by other objects like flat-shaped ones.

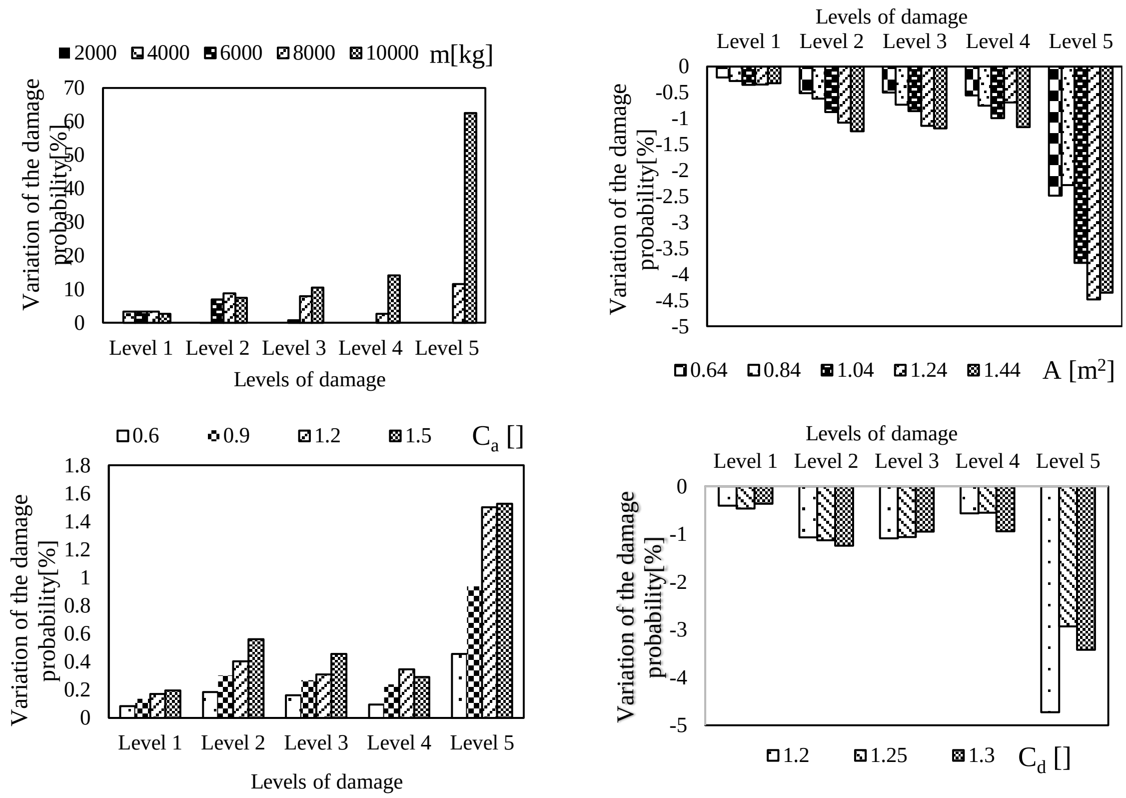

Fig. 12 The magnitude of variation of the damage probability for one-percent increase in random variables

The results of reliability sensitivity analysis with MCS related to the random variables of dropped object shows that impact area and drag coefficient have the highest sensitivity and mass and add mass coefficient have the lowest sensitivity. As it indicates increasing in impact area and drag coefficient reduce the probability of damage while increasing in mass and add mass coefficient increases the probability. The increase of each random variable usually leads to the increase of changing of the probability of damage.

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Mk

Glossary

E_s	Dent - absorbed energy for steel pipelines
D	Diameter of the pipeline
δ	Pipe deformation, dent depth
t	Wall thickness
f_y	Yield stress
m	Mass of the object (kg)
g	Gravitation acceleration (9.81 m/s2)
V	Volume of the object (the volume of the displaced water) (m^3)
ρ_{water}	Density of seawater
C_D	Drag-coefficient of the object
Ca	Add mass-coefficient of the object
A	Projected area of the object in the flow direction (m^2)
V_T	Terminal velocity through the water (m/s).
Y	Crushing strength
x_0	Penetration depth
B	Width of the falling object
$p(x)$	Probability of a sinking object hitting the sea bottom ata distance x from the vertical line through the drop point
x	Horizontal distance at the sea bottom (meters)
δ	Lateral deviation in the water of the object
d	The depth ofsea
a	Angular deviation
L_{sl}	Length of subsea line within the ring(m)
A_r	Area within the ring(m^2)
f_{drop}	Drop frequency per lift
N_{lift}	Number lifted per year,
$P_{hit,r}$	Probability of hit within the ring
$P_{hit,sl,r}$	Conditional hit probability
$F_{hit,sl,r}$	Impact frequency
$P_{f,damage}$	Probability of damage,
P_f	Probability of failure

P_r	Probability of reliability
MCS	Monte Carlo Simulation
Z	The limit state function
R	The strength
S	The load