Chapter

Defects Assessment in Subsea Pipelines by Risk Criteria

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Abstract

Subsea inter-field pipelines are an important element of offshore oil and gas infrastructure. Leakage or fracture of these pipelines is associated with the risk of large economic and environmental losses. One of the main sources of pipeline fracture is pipe defects. The presented section discusses the methodological aspects of assessing the hazard of defects of subsea inter-field pipelines by risk criteria of accidents. A conceptual approach of defects hazard assessing by risk criteria has been formulated, based on analysis the requirement of modern standards. The risk is defined as the probability of negative consequences, the scale of which is determined by the hazard class of pipeline accidents. The probability and scale of accidents are linked by a risk matrix. A method for a three-level assessment of the suitability of a pipeline for operation after in-line inspection has been developed. The method allows assessing the hazard of the most typical defects in subsea pipelines, such as metal loss, metal delamination, cracks and crack-like defects. The allowable defect sizes are determined for the given risk criteria using partial safety factors. The novelty of the methodology lies in the substantiation of safety factors according to risk criteria corresponding to a given class of damage and loss. A scheme for making decisions on the admissibility of defects by risk criteria has been developed. An example of hazard assessment of defects in subsea pipelines is presented.

Keywords: subsea inter-field pipelines, defect, fracture, criterion, risk, calculation

1. Introduction

Subsea inter-field pipelines are an important element of the offshore oil and gas condensate field infrastructure. Leakage or breakdown of these pipelines is associated with the risk of large economic and environmental damage. To ensure the safe operation of pipelines, systematic non-destructive testing is carried out using in-line diagnostics. Production, construction and operational defects of pipes are often by found the diagnostics. The presence of defects in the pipes requires solving the problem of classification and risk assessment of defects. In the classical setting, this problem is solved on the basis of the norms allowable defect sizes [1, 2]. The unacceptable defects are subject to mandatory repair or elimination. This approach is irrationality and has been repeatedly discussed and criticized from various points of view [3–5]. Classifications of defects on the basis of calculation their hazard, taking into account the peculiarities of the operating conditions are more reasonable. At the moment such calculation base on using a number of methods [6–10]. However, these methods also have a number of disadvantages. The most significant disadvantage is that they are based on a deterministic concept of ensuring strength, with deterministic defects sizes, loads values and characteristics of mechanical properties of pipe metal. In real conditions, random variations and statistical scattering of calculated variables always occur, which violate the uniqueness of the estimates of the hazard of defects. Taking this into account, the methods assessment of defects hazard based on the normative approach and deterministic strength calculations can be considered justified during the construction or reconstruction of pipelines. But they are irrational at the stage of pipeline operation, when deviations from design solutions, specified technological modes, environmental conditions and other factors affecting the performance arise. In such conditions, some of the permissible defects can be dangerous, and vice versa, pipelines with defects that are unacceptable according to the norms can be (and often turn out to be) workable.

Probabilistic risk analysis methods develop to assess the operability of structures with defects [11]. In these methods, the defect hazard is determined by the level of risk of pipeline destruction. This ensures, on the one hand, taking into account the probabilities of violation of the strength conditions in the presence of defect, on the other hand, taking into account the severity of the consequences of accidents. This article discusses the methodological aspects of assessing the defects hazard in subsea inter-field pipelines according by the criteria of the risks of destruction. Risk is understood as the probability of losses from leakage or pipeline failure, caused by the considered defects. This formulation of the problem differs significantly from the above-mentioned traditional approaches to assessing the defects hazard, based on strength calculations.

2. Accident analysis of subsea pipelines

The safety of operation subsea pipelines is ensured by using modern methods of design, manufacture, operation and maintenance, regulated by the rules and regulations. Nevertheless, the practice of operating pipelines is accompanied by cases of fracture with negative consequences. Currently, a large amount of statistical data has been accumulated on accidents of onshore and subsea pipelines. Statistical data on emergency conditions for subsea pipelines qualitatively and quantitatively differ from statistics on emergency and underground pipelines due to differences in operating conditions and modes. Therefore, the statistical data for surface and underground pipelines can only be taken into account for qualitative comparisons.

Accident rate statistics for subsea pipelines are mainly presented for the water areas and continental shelf of the North Sea (PARLOC database) and the Gulf of Mexico (DOT database) [12]. These data cover the period from 1984 to the present, with operating experience over 480 thousand km $\times$ year (PARLOC base) and over 650 thousand km $\times$ year (DOT base). According to PARLOC data the average failure rate is 8.79×10^{-5} 1/km $\times$ year, and according to DOT data is 3.51×10^{-4} 1/km $\times$ year. For comparison, according to the UKOPA database (Great Britain), which includes statistics on underground pipelines, with experience over 700 thousand km $\times$ year, the average failure rate is 4.86×10^{-5} 1/km $\times$ year. According to the EGIG database (European Union), which also includes data on the accident rate of underground pipelines, with experience over 3150 thousand km $\times$ year, the average failure rate is 3.70×10^{-4} 1/km $\times$ year. According to statistics, the main reasons for failure of subsea pipelines are:

- mechanical damage (hooking with anchors and trawls, falling heavy objects);
- corrosion and aging processes;

- construction and pipe metal defects;

- natural impacts (landslides, earthquakes, underwater currents, etc.).

At the same time, the average failure rate due to corrosion is in the range (1.16×10^{-6}–4.21×10^{-4}) 1/km × year (PARLOC data) and in the range (1.01×10^{-5}–7.10×10^{-5}) 1/km × year (DOT data). The average failure rate due to external influences is in the ranges: DOT is (5.52×10^{-6}–1.3×10–^{4}) 1/km × year; PARLOC is (1.53×10^{-5}–9.46×10^{-5}) 1/km × year.

According to the data [13] for the period 1970–2009 years 6183 accidents of subsea pipelines occurred in the world. The main number of accidents was recorded in the North Sea (3505) and the Gulf of Mexico (1658). In the Mediterranean Sea, the number of accidents was 45, in the Black and Caspian Seas – 29 accidents. At the same time, up to 41% of accidents occur due to external reasons, and up to 47% of accidents due to pipe defects. According to [14], 95 accidents occurred on the continental shelf of Great Britain in 2012–2013 years, of which 49 accidents occurred due to mechanical reasons (defects, fatigue, corrosion, erosion).

Of particular interest are assessments of damage from pipeline accidents. Unfortunately, such data are rarely published. In the above-mentioned work [12], it is noted that the total damage from 125 accidents of subsea pipelines in 2012 year amounted to $138,757 million, which gives an average damage per accident of about $1,11 million. According to [15], the total direct economic losses from accidents on US gas pipelines for the period 1986–2012 years amounted to $558,778 million. According to [16], the average damage from accidents at gas and oil pipelines is $\$10^4$–$\$10^7$, excluding the cost of gas losses. The actual gas losses reach 10^4 m^3.

As follows from the data presented, the frequency ranges of accidents for various water areas, pipelines and their operating conditions are within the range of (10^{-6}–10^{-3}) 1/km × year. Therefore, these values can be considered as the initial ones for substantiating the criteria for assessing the hazard of defects. Taking into account these frequencies and the amounts of damages presented above, the range of risks can be $\$10^1$–$\$10^4$ per accident. It should be noted that these values only include direct damages. Taking into account consequential damages, the risks can be significantly higher. It should also be emphasized that recently, risk assessments have taken into account not only the cost of restoring objects after accidents, but also the time of their restoration.

3. Brief of the problem of defects hazard assessing

The problem of assessing the safety of pipelines arose at the turn of the 50s - 60s due to the aging of pipeline systems in the United States. Later it became relevant for pipeline systems in other countries. The initial approaches to its solution were based on the methods of fracture mechanics, since the most large-scale accidents were caused by the development of cracks. For a number of reasons (the need for special tests, imperfection of models, the use of steels with increased crack resistance in pipes, etc.) they have not found wide practical application.

The pipeline transport development in the 1970s adduce three significant changes: pipeline systems swept the all world; the problem of ensuring the safety of pipeline systems, taking into account their aging, has become global; methods of in-line inspections (ILI) are become widely used. The ILI showed the presence of various types of defects in the pipes that reduce the efficiency of pipelines. Takin this in to account the defects hazard assessment began to occupy a special place in the security problem. To solve this problem, the methods ASME B31, APT1160, RSTRENG, DNV and others focused on the analysis of the most common defects in the form of corrosion damage [17] were developed. Parallel to this, the methods of breaking mechanics have developed and improved, which are reflected in the standards BS7910, API RP579, SINTAP.

Further research and development, sponsored by major international oil and gas companies (BP, DNV, Shell, Statoil, Total, and others), lead to the development of the Pipeline Defect Assessment Manual (PDAM). PDAM is based on a comprehensive critical review of available methods and full-scale pipe test results [18]. The scope of PDAM includes steel pipelines manufactured to API 5 L or equivalent national and international standards. The methods given in PDAM are applicable to defects in surface, underground and subsea pipelines. In these methods the following types of defects are considered: corrosion damage, scoring and marks, dents and corrugations, welding defects, delamination and cracking of the metal. These methods take into account the interactions of defects. The methods take into account the main and additional loads. At the same time, it should be noted that many PDAM methods are empirical, with a limited scope.

A significant drawback of PDAM methods is the use of a deterministic approach to defect hazard assessing. The dimensions of defects, loads and characteristics of the mechanical properties of steels are considered as deterministic, unambiguously given values. The partial safety factors used in the calculation methods are based on empirical data and are not directly related to the inevitable random variations of these parameters. Due to these circumstances PDAM methods are not combined with the developed concepts of Risk based performance management and Risk based Inspection (RBI).

Comparative analysis of methods for hazard assessment of pipeline defects allows us to draw the following conclusions:

1. For the bulk defects in the form of metal loss (corrosion) and dents the main parameters are the relative depth h/t and the relative length $l^2/(Dt)$. The defect size of around the circumference of the pipe is usually not taken into account. For the flat defects (crack, delamination) the main parameters are length and depth of the defect.

2. The calculated ratios used for the limiting sizes of defects differ in terms of the shape of approximation of the area A of defect cross-sections: rectangular ($A = hl$), parabolic ($A = 2h/3l$), combined ($A = 0.85hl$). It is not possible to single out a more accurate approximation on the available results of field tests of pipes with defects. Taking into account random variations in the shape and size of real defects, any approximation with an undefined error can be used.

3. Defect hazard assessments are carried out for given limit states function of pipes, defined as $\mathcal{L} = \Phi(P, Q, C_f, D, t, h, l)$, where Φ is a function of a given form, P is operation pressure; Q is external loads; C_f is the strength criterion of a pipe with a defect; D, t are pipe diameter and wall thickness; h, l are depth and length of defect [19].

In conclusion, it should be noted that pipeline defects are random, unique and complex in shape and their sizes are depend on the operating conditions and the properties of the external environment. The characteristics of defects cannot always be described by the current norms and calculation methods.

4. The concept assessing for hazard of defects by risk criteria

The above analysis shows that pipeline will invariably contain defects at some stage during its life. These defects will require a "fitness-for-purpose" assessment to determine whether or not to repair the pipeline. The full-scale tests of pipelines with defects and limit state functions method are used for such assessment. The limit state function method allows determining the limit size of defect upon reaching which the pipeline will fail. The limit state function $\mathcal{L}$ for pipe with defect can be write as:

$$\mathcal{L}\{P, Q, \sigma_f, D, t, l\} = l_r(P, Q, \sigma_f, D, t, l) - l_i = 0 \quad (1)$$

where P is operation pressure; Q is external loads; σ_f is fracture stress; D is outside diameter of pipe; t is wall thickness of pipe; l_r is allowable defect size; l_i is defect size in pipeline.

The defects sizes l_i are established during ILI. The allowable defects sizes l_r are determined by calculation methods by the specified criteria for the strength and durability of structures, taking in to account the operating conditions and the character of the mechanisms of deformation and destruction [6–10]. It should be emphasized that in these methods the sizes of defects l_i and l_r are assumed to be deterministic values.

In reality, the defects have inevitable random dispersion of sizes. For detected defects, these are caused by the random nature of the defects, as well as by statistical errors and the probabilistic nature of the operational characteristics (sensitivity and detectability) of non-destructive testing methods [16]. The dispersion of the calculate sizes of defects determined by statistical scattering loads, operating conditions and scattering of mechanical properties. A certain contribution to the possible dispersion of defect sizes is made by idealization of the shapes and schemes of defects. Taking this into account, instead of single-valued sizes in the calculations, it is necessary to use the probability densities distribution functions of defect sizes $f(l_i)$ and $f(l_r)$.

Using the functions $f(l_i)$ and $f(l_r)$ gives reason to believe that there are always nonzero probabilities P presence of defects with sizes l_i larger than l_r (**Figure 1**):

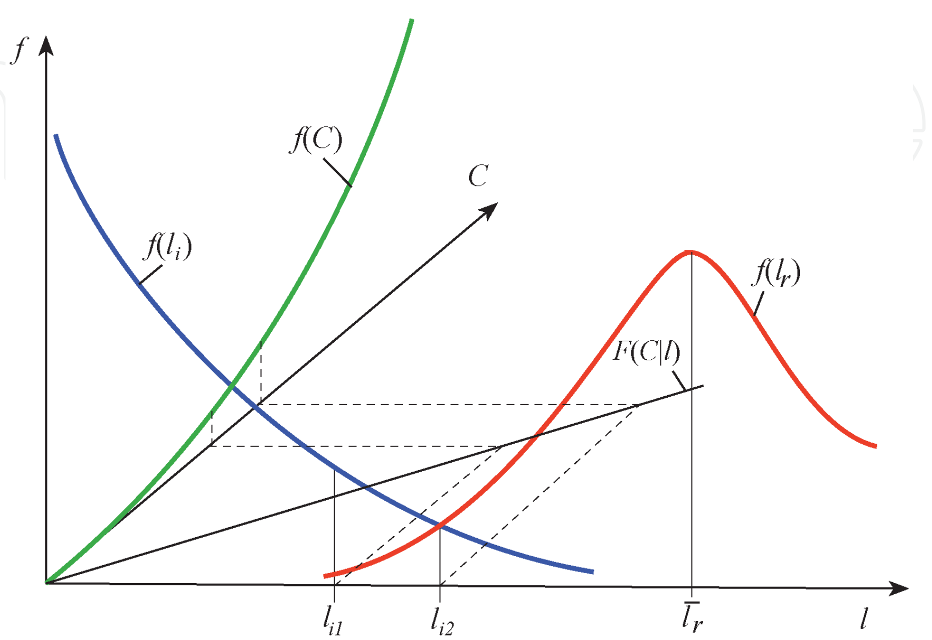

Figure 1.
Probabilistic scheme of the defects hazard analysis.

$$P(l_i > l_r) = \int_0^{\infty}\int_{l_r}^{\infty} f(l_i) f(l_r) dl_r dl_i \tag{2}$$

Exceeding the sizes l_r leads to some losses $C = F(l)$ due to the need to carry out repair operations or leakage and structural failure. Moreover, the larger the defect, the more significant losses can be. It should be emphasized that the losses are also random in magnitude, since it depends on the many technical and socio-economic factors.

Joint analysis of the probabilistic nature of defects, their hazard and possible losses leads to the concept of the admissibility of defects according to risk criteria [11, 18]. The essence of this concept is that the criterion condition for the admissibility of defects is represented in the form:

$$P(l_i > l_r) \times C(l) \le [R], \tag{3}$$

where $[R]$ is the acceptable risk.

Assuming the defect size l_i as a fixed random variable from (3) we can obtain the following condition for the admissibility of a defect:

$$l_i \le l_{[R]} \tag{4}$$

where $l_{[R]}$ is the size defect at which the risk R is acceptable.

Due to the unresolved problem of assessment and statistical analysis of losses, currently, sufficiently substantiated proposals for determining the allowable risk have not been developed. As a rule, losses are categorized into some qualitative classes: negligible, acceptable, unacceptable, etc. [19, 20]. Each class of losses is associated with a certain acceptable level of its probabilities $[R_f]$. Taking this into account, instead of (3), one can go to a simpler form of assessing the admissibility of defects by risk criteria, which does not require a direct assessment of damages, namely:

$$P(l_i > l_r) = \int_0^{l_i} f(l_r) dl_r \le [R_f] \tag{5}$$

On this basis, similarly to (5), the following condition for the admissibility of defects can be written:

$$l_i \le l_{[R_f]} \tag{6}$$

where $l_{[Rf]}$ is the size of the defect at which the probability of losses belongs to a given class.

Expressions (4) and (6), in fact, are a semi-probabilistic solution to problems (3) and (5), since they relate fixed random variables, one of which has a given probabilistic support.

5. Method for determining the allowable sizes of pipe defects by risk criteria

In this section the probabilistic methodology is use for develop a semi-probabilistic method for assessing the admissible sizes of defects in subsea inter-field pipelines based on risk criteria. The basis of this method are requirements of standards [7, 9]. The risk is defined as the probability R_f negative consequences of pipeline accident, the scale of which is determined by the hazard class. The proposed hazard classes (risk matrix) for inter-field subsea pipelines are presented in **Table 1**. Quantitative economic and environmental damage assessments are not considered here.

The suitability of the pipeline for operation is determined by three-level assessment of the allowable size of defects by risk criteria (**Figure 2**). The first, basic level, determines the allowable defect sizes by the strength characteristics of metal for pipelines exposed to the main loads - internal overpressure and hydrostatic external pressure. The second, extended level, determines the allowable defect sizes by the strength characteristics for metal, taking into account the effect on pipelines of additional longitudinal and bending loads. The third, special level, determines the allowable sizes of cracks, crack-like defects and delamination by the characteristics of crack resistance of the metal.

The calculations use information about: pipe sizes, location of the pipeline on the seabed, loads and impacts; the size, location and types of defects; mechanical properties, industry standard requirements, and pipe specifications.

The hazard of pipe defects depends on their shape and size. The sizes of defects are determined by their spatial coordinates $l = \{l_x, l_y, l_z\}$ (**Figure 3**). By shape the defects can be classified into volumetric and flat. For the volumetric defects the size $l_x \geq l_y \geq l_z$, for the flat defects the size $l_x \geq l_y >> l_z$. The defect hazard calculations usually use relative defect sizes $\tilde{l}_x = \frac{l_x}{\sqrt{Dt}}, \tilde{l}_z = \frac{l_z}{t}$. These relative dimensions are used in this technique taking into account the classification of defects shape.

The limit state function $\mathcal{L}$ for pipe volumetric defects may be write as:

for hoop stress

$$\mathcal{L}\left(P, D, t, \sigma_f, \tilde{l}_x, \tilde{l}_x\right) = \sigma_f \frac{2t}{D} RF\left(\tilde{l}_x, \tilde{l}_x\right) - P = 0 \tag{7}$$

for equivalent stress

$$\mathcal{L}\left(P, D, t, \sigma_f, \tilde{l}_x, \tilde{l}_x\right) = \sigma_f - \sigma_e RF\left(\tilde{l}_x, \tilde{l}_x\right) = 0 \tag{8}$$

Hazard classes	**Low**	**Middle**	**High**	**Very high**
Failure classes	Neglected	Uncritical	Critical	Catastrophic
Level of loss	Negligible environmen-tal and econo-mic impact. Pipeline repa-ir can be post-poned until the planned shutdown.	Short-term local disturbance of the state of the ecological envi-ronment and/or insignificant material losses. Unscheduled pipeline shut-down and repair.	Short-term da-mage to the environment and/or signify-cant economic damage. Unscheduled pipeline shut-down and repair.	Large-scale long-term environmental damage and large economic damage. Long shutdown and pipeline repair.
$[R_f]$	10^{-2}	10^{-3}	10^{-4}	10^{-5}

Table 1.
Hazard classes of fracture for subsea inter-field pipeline.

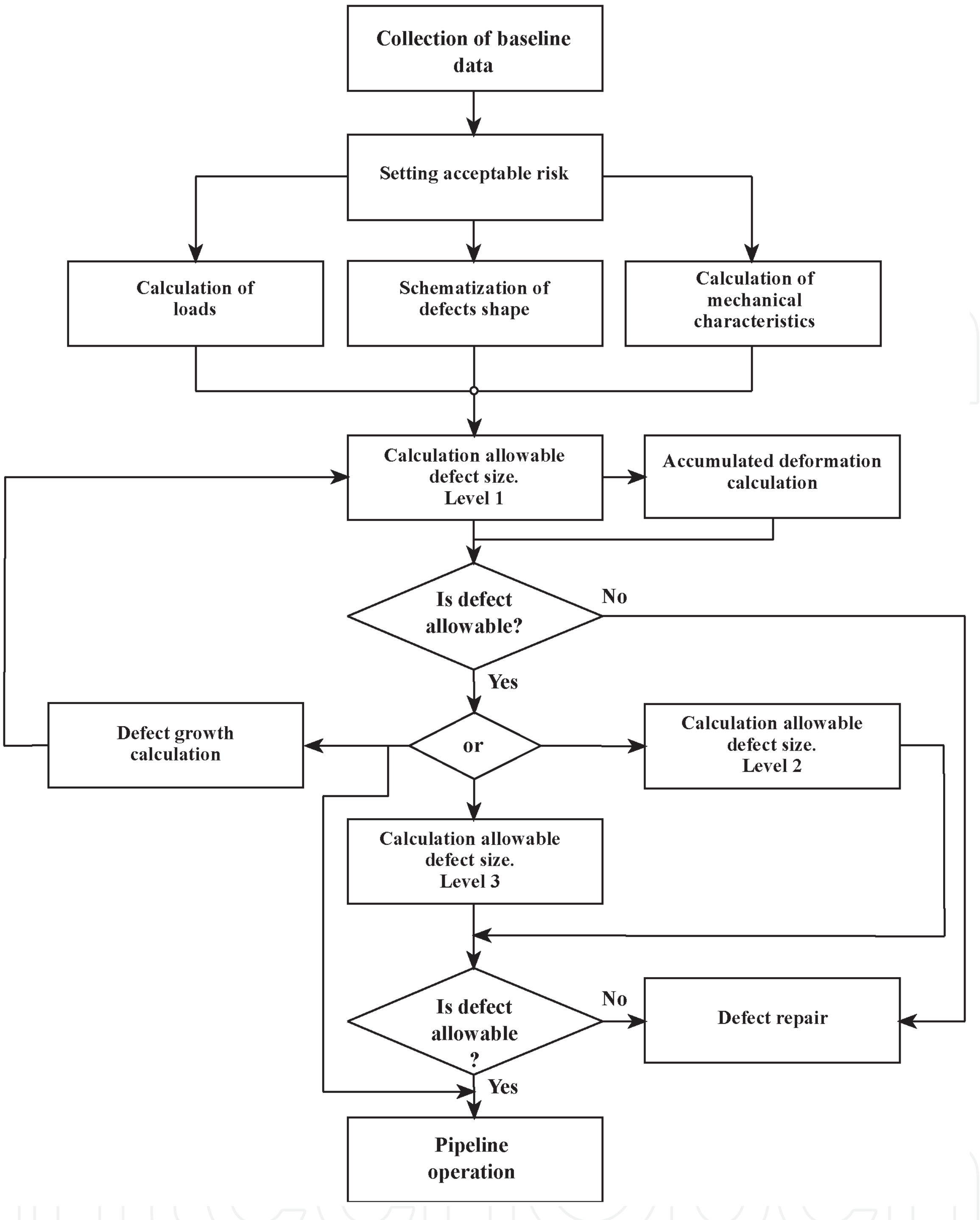

Figure 2.
Scheme for calculating the allowable size of defects.

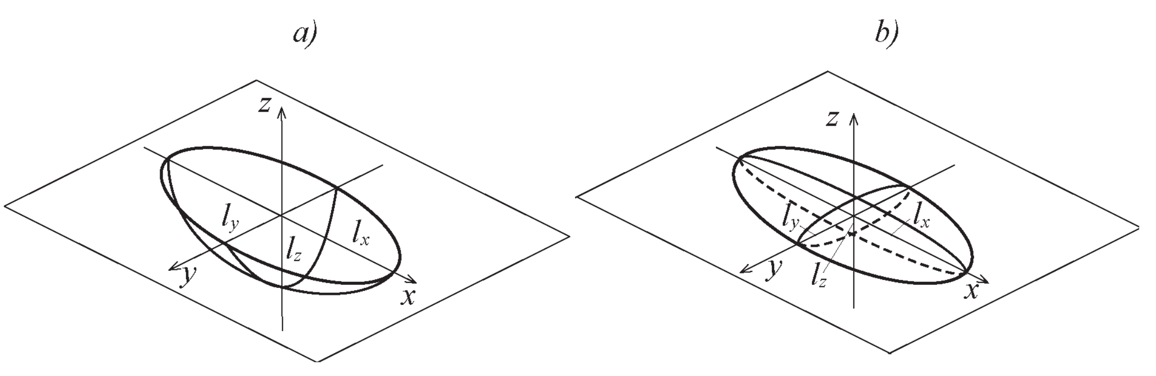

Figure 3.
Idealization of volumetric (a) and flat (b) defects shape.

where $\sigma_f = \min\left\{\frac{R_e}{\gamma_e}; \frac{R_m}{\gamma_m}\right\}$ is fracture stress; $\sigma_e = \sqrt{\sigma_h^2 + \sigma_l^2 - \sigma_h\sigma_l + 3\tau_{hl}^2}$ is equivalent stress; σ_h is hoop stress; σ_l is longitudinal stress; τ_{hl} is tangential shear stress; $RF\left(\tilde{l}_z, \tilde{l}_x\right) = \frac{1-\tilde{l}_z}{1-\tilde{l}_z/M\left(\tilde{l}_x\right)}$ is risk-factor of defect; $M\left(\tilde{l}_x\right)$ is Folies factor; γ_e, γ_m are partial safety factor.

If the components of limit state functions have a Gaussian distribution, then from the solutions of Eqs. (7) and (8) it is possible to determine the allowable sizes $\tilde{l}_z$ for given sizes $\tilde{l}_x$ with use partial safety factors:

for hoop stress

$$\tilde{l}_z \leq \frac{1}{\gamma_d} \frac{\sigma_f - 0.75\frac{\gamma_R PD}{t}}{1.1\sigma_f - \frac{\gamma_R PD}{2t}\frac{1}{M}} \tag{9}$$

for equivalent stress

$$\tilde{l}_z \leq \frac{1}{\gamma_d} \frac{\sigma_f\gamma_S - \sigma_e\gamma_\sigma}{1.1\sigma_f\gamma_S - \frac{\sigma_e\gamma_\sigma}{M}} \tag{10}$$

where γ_d, γ_R, γ_s, γ_σ are safety factors determined by the admissible of risk fracture $[R_f]$.

The safety factor γ_R is determined taking into account the admissible level of fracture probability $[R_f]$:

$$\gamma_R = \frac{1 - u_p\sqrt{V_f^2 + V_p^2 - \left(u_p V_f V_p\right)^2}}{1 - \left(u_p v_f\right)^2} \tag{11}$$

where u_p is the quantile corresponding to the probability $[R_f]$; V_f is the coefficient of variation of the fracture pressure; V_p is coefficient of variation of operation pressure.

The u_p quantile is set taking into account the accepted safety class of the pipeline according to **Table 2**.

The coefficients of variation of fracture pressure and operation pressures V_f and V_p are determined by statistical methods based on data for statistical scattering of the operation pressure, pipe metal mechanical characteristics, diameter D and wall thickness t of pipes.

The partial safety factor for the defect size γ_d is determined taking into account requirements [7] base on the value standard deviations $S_h/_t$ of the defect size (**Table 3**). The partial safety factors γ_s and γ_σ are set according to **Tables 4** and **5**.

The hazard of defect is determined by the design point position, given by the actual coordinates $\tilde{l}_z$ and $\tilde{l}_x$on the design diagram (**Figure 4**).

Hazard classes	Probability of fracture	u_p
I - Low	$\leq 10^{-2}$	2.33
II - Meddle	$\leq 10^{-3}$	3.1
III - High	$\leq 10^{-4}$	3.72
IV – Very high	$\leq 10^{-5}$	4.27

Table 2.
Values of quantiles u_p.

Hazard classes	Partial safety factor γ_d	
I - Low	$\gamma_d = 1.0 + 3.0S_{h/t}$	
II - Meddle	$\gamma_d = 1.0 + 4.0S_{h/t}$	$S_{h/t} < 0.04$
	$\gamma_d = 1.0 + 5.5S_{h/t} - 37.5S_{h/t}^2$	$0.04 \le S_{h/t} \le 0.08$
	$\gamma_d = 1.2$	$0.08 \le S_{h/t} \le 0.16$
III - High	$\gamma_d = 1.0 + 4.6S_{h/t} - 13.9S_{h/t}^2$	
IV – Very high	$\gamma_d = 1.0 + 4.3S_{h/t} - 4.1S_{h/t}^2$	

Table 3.
Values of safety factor γ_d.

Hazard classes	Low	Middle	High	Very high
γ_S	0.76	0.72	0.63	0.6

Table 4.
Values of safety factor γ_S.

Hazard classes	Low	Middle	High	Very high
γ_σ	1.12	1.4	1.5	1.6

Table 5.
Values of safety factor γ_σ.

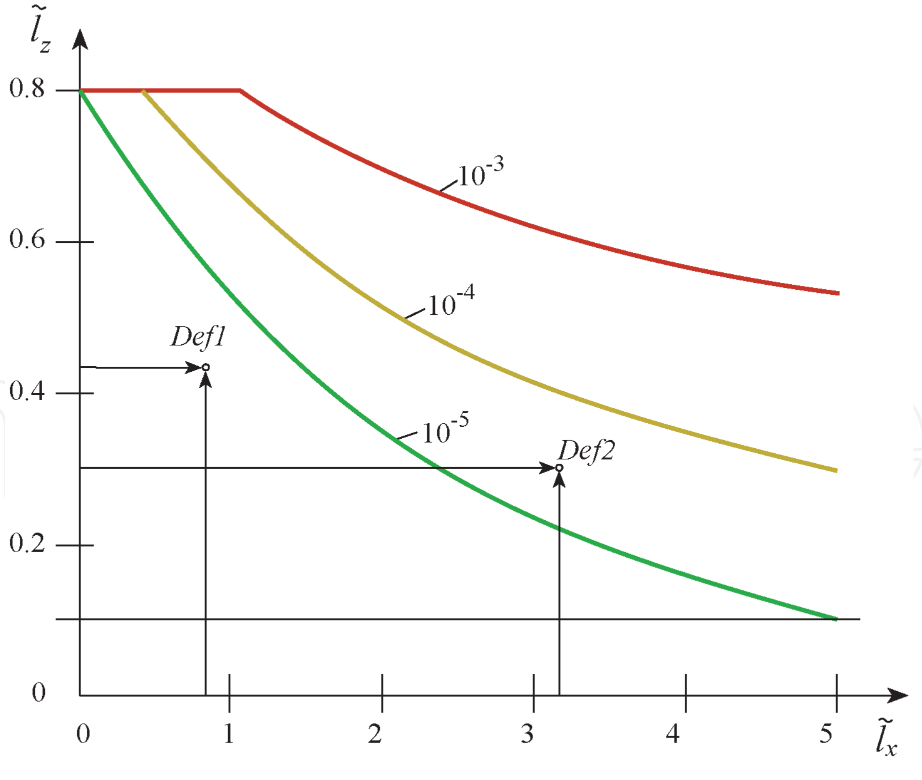

Figure 4.
Diagram for determining the allowable size of defects.

The assessment of the allowable sizes of flat defects (cracks and crack-like defects, delamination) in pipes is based on a Failure Assessment Diagram (FAD). The FAD concept combines the approaches of fracture mechanics to the analysis of brittle and quasi-brittle fractures, with the approaches of limiting analysis, which determines the conditions of ductile fracture of structural elements with crack-like defects. The fracture diagram is given by the following Equations [9, 10]:

$$f(L_r) = \begin{cases} \left(1 + 0.5L_r^2\right)^{-1/2} \times \left[0.3 + 0.7\exp\{-\mu L_r^6\right], & L_r < 1 \\ f(L_r = 1)L_r^{(n-1)/n} & 1 \le L_r \le L_r^{max} \end{cases} \tag{12}$$

Parameter L_r^{max} is calculated by the formula:

$$L_r^{max} = 0.5\left(1 + \frac{R_y}{R_m}\right) \tag{13}$$

Parameter μ is calculated as:

$$\mu = min\left\{\frac{0.001E}{R_e}; 0.6\right\} \tag{14}$$

Parameter n is calculated by the formula:

$$n = 0.3\left(1 - \frac{R_m}{R_y}\right) \tag{15}$$

The risk of fracture is taken into account by introducing safety factors for crack resistance and load:

$$K_r = \frac{f(L_r)}{\gamma_K}, L_r = \frac{L_r^{max}}{\gamma_L} \tag{16}$$

The values of safety factors γ_K and γ_L are taken according to **Tables 6** and 7.

The load parameter L_r is defined as the ratio of the working pressure P to the plastic flow pressure P_y of the section of a pipe with a crack, $L_r = P/P_y$. The plastic flow pressure P_y is determined taking into account the geometry and orientation of the crack in the pipe. The fracture toughness parameter K_r or J_r is defined as the ratio of the effective stress intensity factor K_{eff} or J-integral J_I to the fracture toughness characteristic of the material K_{mat} or J_{mat}:

$$K_r = K_{eff}/K_{mat}, J_r = J_\text{I}/J_{mat} \tag{17}$$

The effective stress intensity factor K_{eff} is determined taking into account the geometry and orientation of the crack in the pipe using fracture mechanics methods or by finite element method.

Hazard classes	Low	Middle	High	Very high
γ_K	1.41	1.73	2.23	3.16

Table 6.
Values of safety factor γ_K.

Hazard classes	Low	Middle	High	Very high
γ_L	1.5	1.8	2.25	3.0

Table 7.
Values of safety factor γ_L.

Based on results of the calculations a fracture diagram is constructed (**Figure 5**). The danger of defect is determined by the position of the design point, given by the coordinates (K_r, L_r) on the diagram. If the calculated point is inside the diagram, then the considered defect is admissible, with a given level of risk fracture.

The presented approach is applied in practice, taking into account the following provisions. The decision on the identified defects is made on the basis of all available information about their type, size and location, as well as the stability of the working loads and the operating conditions of the pipeline. Defects corresponding to the level of fracture probabilities R_f less than 10^{-5} according to the defect hazard diagrams are considered as allowable under the given operating conditions. Defects located in the zone of probability of destruction $10^{-5} < R_f \le 10^{-4}$ are considered as potentially dangerous and are allowed for operation provided that there is a monitoring system and automatic limitation of internal pressure in the pipeline, and periodic non-destructive testing. Defects located in the zone of destruction probability $10^{-4} < R_f \le 10^{-3}$ are considered dangerous and must be repaired in a planned manner. Defects located in the destruction probability zone $R_f > 10^{-3}$ according to the defect hazard diagrams are considered unacceptable and must be repaired immediately.

More promising is the transition from the described approach to probabilistic approach for determining allowable sizes of defects. Such approach is developed on the basis of taking into account probability density functions of distributions defects sizes $f(l)$. This approach assumes that the probability density $f(l)$ is a mixture of distributions of random variables included in the limiting state equation, and is approximated by the Weibull distribution [11]:

$$f(l) = \frac{\beta}{\theta}\left(\frac{l}{\theta}\right)^{\beta-1} exp\left\{-\left(\frac{l}{\theta}\right)^{\beta}\right\} \tag{18}$$

Substitution of expression (18) into (5) gives the following expression for the admissible size of the defect $\tilde{l}_z$:

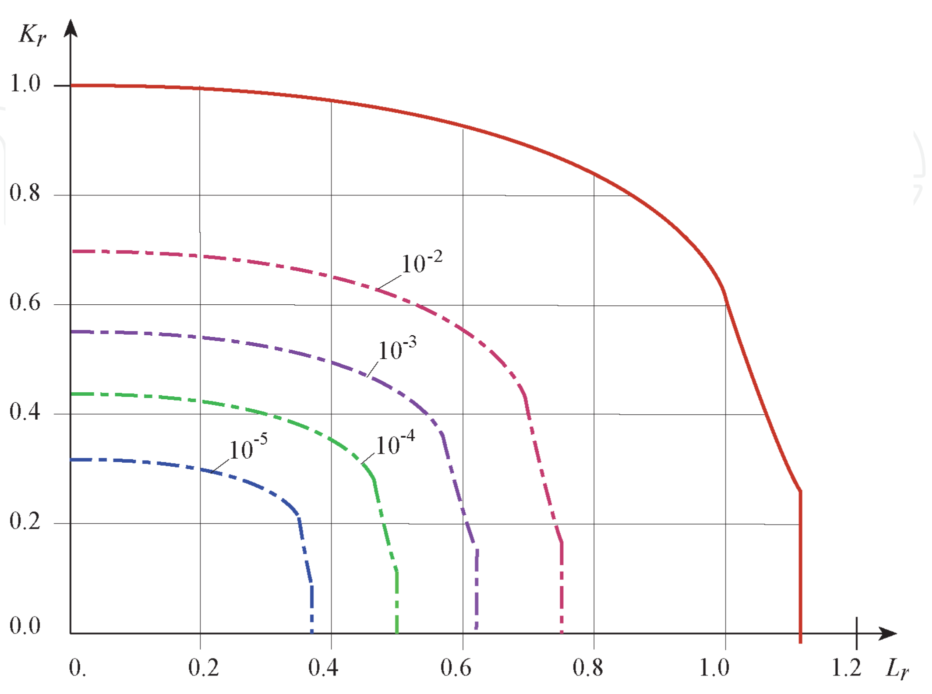

Figure 5.
Failure assessment diagram with risk level.

$$\tilde{l}_z \leq \theta \sqrt[\beta]{-\ln\left(1 - P_f\right)} \tag{19}$$

where P_f is the fracture probability corresponding to the given fracture risk R_f. The parameters β and θ are related to the mean value μ_l and standard deviation S_l:

$$\mu_l = \theta\Gamma\left(1 + \frac{1}{\beta}\right), S_l = \theta\sqrt{\Gamma\left(1 + \frac{2}{\beta}\right) - \Gamma^2\left(1 + \frac{1}{\beta}\right)} \tag{20}$$

where $\Gamma(x)$ is Gamma function.

The mean value μ_l, standard deviation S_l, coefficient of variation V_l of the defect sizes can be determine based on experimental, calculated or literature data related to the subject pipeline.

The risk diagram can be constructed based on calculations for different probabilities P_f similar as shown above. The permissible defect sizes must be below the specified probability.

The presented probabilistic fracture model can be used to assess the risk of accidents based on the methodology of Probabilistic Risk Analysis (PRA). Features of solving this problem for subsea pipelines can be found in the works [21, 22].

6. Estimation of allowable defect sizes

As an example, **Figure 6** shows the results of a calculated assessment of the risk of metal loss defects in an inter-field subsea gas pipeline∅ 406.4 × 17.5 mm by risk criteria. The pipe material is steel X60 (R_y – 415 MPa, R_m – 520 MPa, E = 2.06 × 10^5 MPa, α_t = 1.1 × 10^{-5}). The operation pressure is 16 MPa. Temperature operation difference is ΔT = 50°C. The total number of detected defects is 916 pcs: h/t = from 20 to 39%, – 5 defects, h/t = from 10 to 19% – 82 defects, h/t < 9% – 829 defects. Of these, 16 defects are unacceptable according to the standard [2].

The presented results show, that three defects are located in a hazard area with a risk level higher than 10^{-3} and require immediate elimination. Two defects correspond to a risk level above 10^{-4} and can be corrected in a planned manner.

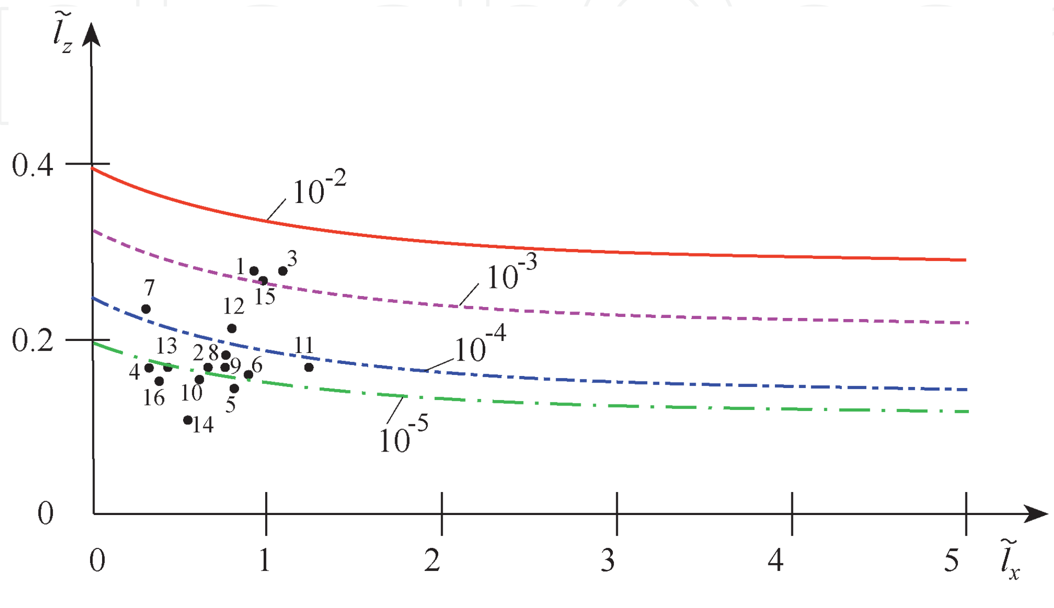

Figure 6.
The defects hazard diagram (with indicate defect numbers).

Five defects are in the risk zone 10^{-5}–10^{-4} and can be repaired as planned at a later date. Defects below the level 10^{-5} can be allowed for operation, provided that periodic non-destructive testing is carried out.

Thus, the proposed method provides a more flexible and more substantiated scheme for assessing the hazard of defects. On the one hand, this assessment takes into account the risk of accidents, thereby ensuring the required level of safety. On the other hand, it allows a more rational use of financial and material resources allocated for diagnostics and repair of subsea pipelines.

7. Conclusion

The paper discusses the possibilities of implementing the risk-based control method for inter-field subsea pipelines. The results obtained allow us to draw the following conclusions. Currently, there are a number of methods for assessing the hazard of pipeline defects based on deterministic approaches. Risk-based inspection provides greater opportunities for prioritizing, planning, justifying and evaluating the results of non-destructive testing. For the practical implementation of the risk-based control method, it is necessary to develop special probabilistic and semi-probabilistic calculation methods for assessing the hazard of pipeline defects taking into account random factors.

The proposed semi-probabilistic methodology is a development of the provisions of the DNVGL-ST-F101, SINTAP and DNV-RP-F116 standards. The novelty of the methodology lies in the justification of the safety factors through the level of failure probabilities corresponding to a given class of damage and loss. This opens up new possibilities for solving the problem of admissibility of defects in inter-field subsea pipelines from the standpoint of the concept of serviceability according to risk criteria.

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