Definition of Damageability of the Sea Buried Pipeline by Method of Spectral Summation of Tension at Vibrations caused by Technological and Casual Seismic Loadings

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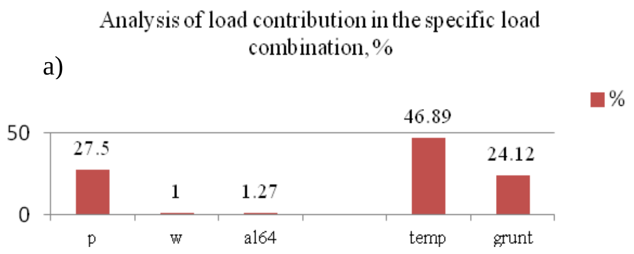
Hazards that lead to severe ecological consequences during laying and operation of subsea pipeline systems are seismic forces. Offshore pipeline system operation must be ensured in case of an earthquake without interruptions for any repairs. Evaluation of the stress-strain stat, fatigue of the buried pipeline is very important with combined technological loads with extreme seismic loads

The aim of this calculation is to analyze safety of these a buried pipeline at random operating and seismic impacts as well as cyclic fluctuations of the transportation parameters. The main objective of the study is to assess the processes of fatigue strength linear sections of offshore pipelines.

Keywords: sea buried pipeline, fatigue, random operating, seismic loadings

I. INTRODUCTION

Designed loads on the sea buried pipeline include internal pressure of the product (natural gas), temperature of the transported product, and weight load of the medium. Certain operating conditions may lead to strength-threatening tension in the subsea pipeline, which is instantaneous us under static and dynamic random exposures. Load analysis of the main combination is shown in Fig. 1 (note: sea buried pipeline is an object of the analysis). The purpose of this study is to evaluate damages of the natural gas pipelines due to fatigue caused by cyclic fluctuations of transportation temperature which contribute to defect growth. The offshore structure are subjected to the cyclic stress produced by waves and tidal motion. The first offshore pipelines were constructed in California in 1900's.Offshore pipelines frequently pass over areas with uneven seafloor. Fatigue can affect pipeline welded joint if dynamic loads act over the free span generating stress cycles. The construction of offshore pipelines has been motivated of exploring underwater oil and gas reserves. This article covers evaluation of the fatigue of the buried subsea pipelines. The fatigue calculations of the sea buried pipelines are made using simplified methodic to evaluate the fatigue of the buried subsea pipelines.



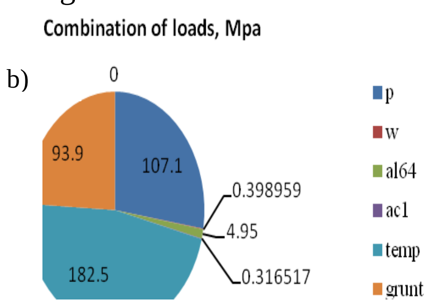


Fig.1. Analysis of sea buried pipeline loads effect on specific combination; where p is a working pressure load, w is a dead weight load, temp–- is temperature impact, al64 is seismic load: a) combination of loads, % a) combination of loads, part of all loads.

II. Mathematic Model

A. Linear Relationship

There is a linear relationship between the input impacts combination and the output process

$$x(t)=w\left[\sum_{i=1}^{k}C_i\xi_i(t)\right]=\sum_{i=1}^{k}C_i w[\xi_i(t)] \quad (1)$$

where C -may be constant or random values.

B. Mathematic model

Mathematic model of the subsea pipeline vibrations under random operating and seismic loads can be described by a linear stochastic operator

$$\left(\frac{EI}{L^2T}\right)^2\frac{\partial^4 w}{\partial x^4}+\left[-\frac{T_0}{T}+\left(\alpha\frac{EA_0}{TL}\theta\right)(1-\gamma)+P\frac{P_0A_0}{T}\gamma\right]\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial t^2}+\left[-\alpha\frac{E\theta_0}{TL}\gamma\theta-P\frac{T_0}{T}\gamma\right]\frac{\partial w}{\partial t}+k_c w=\tilde{F}(t) \quad (2)$$

After dividing the variables we have two independent differential equations. The first equation determines free vibrations of the system [1]. The second is equation of pipeline vibrations in generalized coordinates under seismic load and operating parameters of the transported product;

$$\frac{\partial^2 w}{\partial t^2}+\left[\frac{\left(-\alpha\frac{E\theta_0}{TL}\gamma\theta-p\frac{T_0}{T}\gamma\right)L^2T}{EIm}\right]\frac{\partial w}{\partial t}+\frac{\left(\omega_i^2+k_c\right)L^2T}{mEI}w=\frac{\tilde{F}(t)}{m}\cdot\frac{L^2T}{EI} \quad (3)$$

C. Spectral Summation

Let us analyze the pipeline operating loads (internal pressure, temperature effect) as random processes. Here we should determine spectral density of all random processes from operating and seismic loads:

$$S_\sigma(\omega)=S_u(\omega)+S_t(\omega)+2\xi_{ut}^0(\omega) \quad (4)$$

where $S_u(\omega)$ is response spectrum under seismic load, $S_t(\omega)$ is vibration spectrum of temperature effects. The third summand in the equation (4) can be treated as an interference element, which makes additional contribution due to correlation. Let us write the equations of pipeline vibrations when exposed to a sum of loads a used by a random seismic load and variation of the parameters of the transported.

$$\ddot{T}_i(t)+b\cdot\frac{\partial w}{\partial t}+\frac{\left(\omega_i^2+k_c\right)}{m}\cdot\frac{L^2T}{EI}=\frac{\ddot{u}(t)}{m_s+m_{np}} \quad (5)$$

Where is pipeline weight per1 running meter. α is a coefficient.

$$b = \left[\frac{-\alpha \frac{E\theta}{TL}\gamma\theta - P\frac{T_0}{T}\gamma}{m} \cdot \frac{L^2 T}{EI} \right] \quad (6)$$

By solving the equation (5), let us determine the roots of the standard equation:

$$\lambda_1 = -\frac{[b]}{2} - \sqrt{-\left(\frac{[-b]^2}{2} - \left(\frac{\omega_i^2 + k_c}{m}\right)\right)}$$

(6a)

$$\lambda_2 = -\frac{[b]}{2} + \sqrt{\left(\frac{[b]^2}{2} - \left(\frac{\omega_i^2 + k_c}{m}\right)\right)}$$

(6b)

D. Calculate Transfer Function of the Equation

Let us calculate transfer function of the equation (5), assuming that y= Φ(λ) $e^{\lambda t}$ and solving the resultant equation.

Transfer function is described by the equation ambiguities in denominators. Punctuate equations when they are part of a sentence, as in

$$\Phi(\lambda) = \frac{\frac{-\ddot{u}(t) - k_c}{EI}}{\lambda^2 + \omega_i^2 k_c + [b]} S_t(\omega) \quad (7)$$

Joint spectral density of random functions $\ddot{u}$(t) and $S_t(\omega)$ can be calculated on the basis of the following assumption:

$$s_{\ddot{u}t}(\omega) = \Phi(i\omega) s_x(\omega) = \begin{cases} -is_x(\omega)(\omega > 0), \\ is_x(\omega)(\omega < 0). \end{cases} \quad (8)$$

Considering the transfer function(7), the joint spectral density can be defined as

$$s_{ut}(\omega) = \Phi(i\omega) s_t(\omega) = \left(-(\ddot{u}_{10})\right)(t) - k_c \;\;) / \left(\lambda^2 + k_c \omega_i^2 + \left[-\alpha \cdot (E\theta / TL) \cdot \gamma \cdot \theta - p \cdot (T_0 / T) \cdot \gamma\right]\right)(S_t(\omega)) \quad (9)$$

where $S_t(\omega)$ is spectral density of temperature fluctuations of the product.

Stress-strain state of the pipeline shell can be evaluated using a finite element method. Internal stresses are associated with the loads on the pipeline wall shown Fig.2).

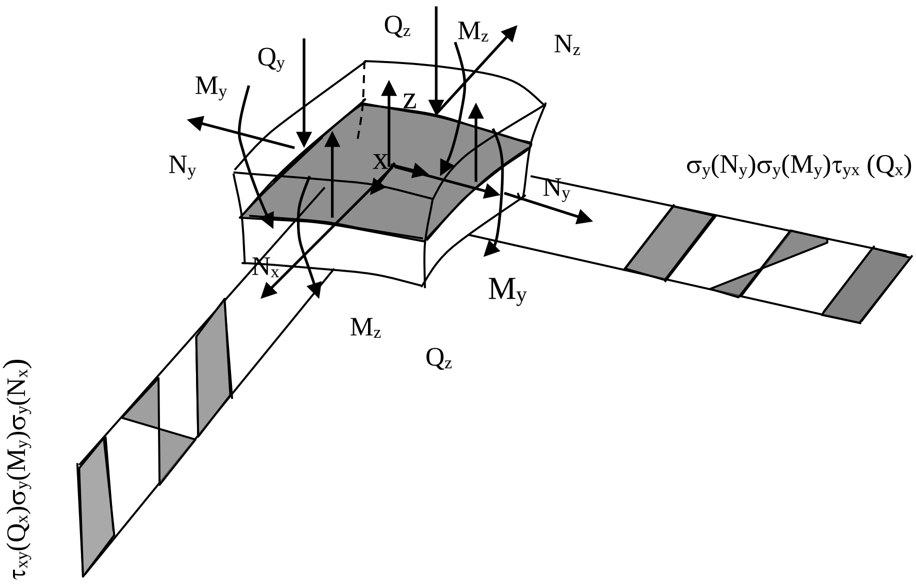


Fig. 2. Loads and stresses in the section of the pipeline shell: where N are longitudinal stresses in the pipeline wall, M,Q - bending moments and shearing stresses are distributed along the pipeline wall symmetric with respect to mid-surface of the shell.

Let us analyze random stationary external impact on the wall of the offshore pipeline. A relation linking tensor of the random strain with equivalent stress is called von Mises equation[2,4].

$$\sigma^2_{экв}(t) = \frac{1}{2}\left[\left(\sigma_x - \sigma_y\right)^2 + \left(\sigma_y - \sigma_z\right)^2 + \left(\sigma_z - \sigma_x\right)^2 + \sigma\left(\tau^2_{xy} + \tau^2_{yx} + \tau^2_{zx}\right)\right] \tag{10}$$

We can evaluate probabilistic characteristics of there and nonequivalent stressed state in time and spectral ranges. Let us have matrix representation of an expression for $\sigma^2_{экв}$(t): ambiguities in denominators.

$$\bar{\sigma}(t) = \begin{pmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_{xy} \\ \tau_{yz} \\ \tau_{zz} \end{pmatrix} \tag{11}$$

Stressed state in a point $\sigma_{экв}$ of the pipeline is a multidimensional random process with the six time-varying components. Equivalent stresses are considered to be strength criteria of the pipeline design as per von Mises criterion [4]. The equivalent stress $\sigma^{(r)}_{экв}$(t) in the point *n* of the pipeline under review determines fatigue life of the pipeline.

In practice, the pipelines operated in seismic areas are often exposed to random loads, insofar as the external impact parameters are stochastic here. The distributed static load leading to a dangerous stressed state in the pipeline wall is restricted by the maximum allowable load.

Let us describe a sea buried pipeline as a linear system. We assume that vector *Z*(t) is a normal random stationary vector function supposing that the external loads acting on the offshore subsea pipeline are similar. The equivalent stresses $\sigma_{эквj}$(t) can used by random generalized displacement $\bar{Z}$ (t) are stochastic processes.

The above stresses acting in the pipeline section can be regarded as a stationary normal process with spectral density approximated by the following equation(Kanai-Tajimi spectrum);

$$G(\omega) = G_0 \frac{1 + 4\zeta_m^2 (\omega/\omega_m)^2}{\left[1 - (\omega/\omega_m)^2\right]^2 + 4\zeta_m^2 (\omega/\omega_m)^2}$$

(12)

where G_0 is a rate of stress variation in the pipeline

If frequencies of a construction as a linear dynamic system are known, in other words transfer functions from impacts to the power factors under analysis, the components of the spectral loading matrix can be represented as follows:

$$S_1(\Omega) = S_{вх}(\Omega)\left|T_1(i\Omega)\right|^2$$

(13)

where $T_1(i\Omega)$, are complex conjugated frequencies; $S_1(\Omega), S_{12}(i\Omega)$ are spectral densities and mutual spectral densities of the bending and shearing stresses;Ω=w/V[rad/min] is spatial frequency [5]

The distribution of the extreme random process can be determined according to [5]. β parameter can be interpreted as average extreme of the process to average zero crossing ratio.

Considering that

$$p(v) = \frac{1}{\sqrt{2\pi}\beta\omega_e^2\sigma_v} \exp\left(-\frac{v^2}{2\beta^2\omega_v^2}\right)$$

(14)

we can get the following:

$$p_{макс}(v_*) = \frac{1}{\sqrt{2\pi}\beta\sigma_v}\left\{\sqrt{\beta^2 - 1}\exp + \sqrt{2\pi}\frac{v_*}{\sigma_v}\exp\left(-\frac{v_*^2}{2\sigma_v^2}\right)\Phi\left(\frac{v_*}{\sqrt{\beta^2 - 1}\sigma_v}\right)\right\}$$

(14b)

where ω_e, σ_v, v are characteristic of seismic vibrations.

Changes of stresses in the element can be described by G_0 intensity when a seismic wave passes through. Intensity variation coefficient of stresses in the pipeline can be regarded as a factor that has impact on the pipeline strength. Element performance function with consideration of any damage can be represented in the following way:

$$S(G_0) = \frac{1}{G_0^2 + 1} S_R$$

(15)

Safety factor of the subsea pipeline with consideration of any damage is equal to

$$\beta_S = \frac{\bar{S}(G_0)}{\sqrt{\sigma_S^2 \cdot \left(\frac{1}{G_0{}^2 + 1}\right)^2}}$$

(16)

where σ_s is standard strength factor of the pipeline.

Cyclic variations of the transported product parameters can be recorded using linear addition hypothesis or Miner's rule [2]. This method has been developed to determine total damager ate Π over a period of time T caused by all loading cycles on the pipeline [5]:

$$\Pi = \sum_{k=0}^{N_m-1} \sum_{j=0}^{N_a-1} \frac{P_{kj}}{N_{pkj}} \qquad (17)$$

Where N_m is a number of intervals composing the measurement range σ_m,;N_a is a number of intervals composing the measurement range σ_a, σ_a is amplitude of stresses; P_{ki} is repeat ability of full cycles that are in k range for$\sigma_a$and j range for σ_m; k=0.1,…, (N_a-1); j=0.1,…, (N_m-1); $k\Delta\sigma_a<\sigma_a\leq(k+1)\ \Delta\sigma_a$; $(\sigma_m)_{min}+j\Delta\sigma_m<\sigma_m\leq(\sigma_m)_{min}+(j+1)\ \Delta\sigma_m$.$\sigma_m$ is a constant component of the cycle, where $(\sigma_m)_{min}$ is a minimum value σ_m ;$\Delta\sigma_m$ is a step for σ_m; $\Delta\sigma_a$ is a step for σ_a.

Flow chart of formula (17) implementation is shown in Fig.3.

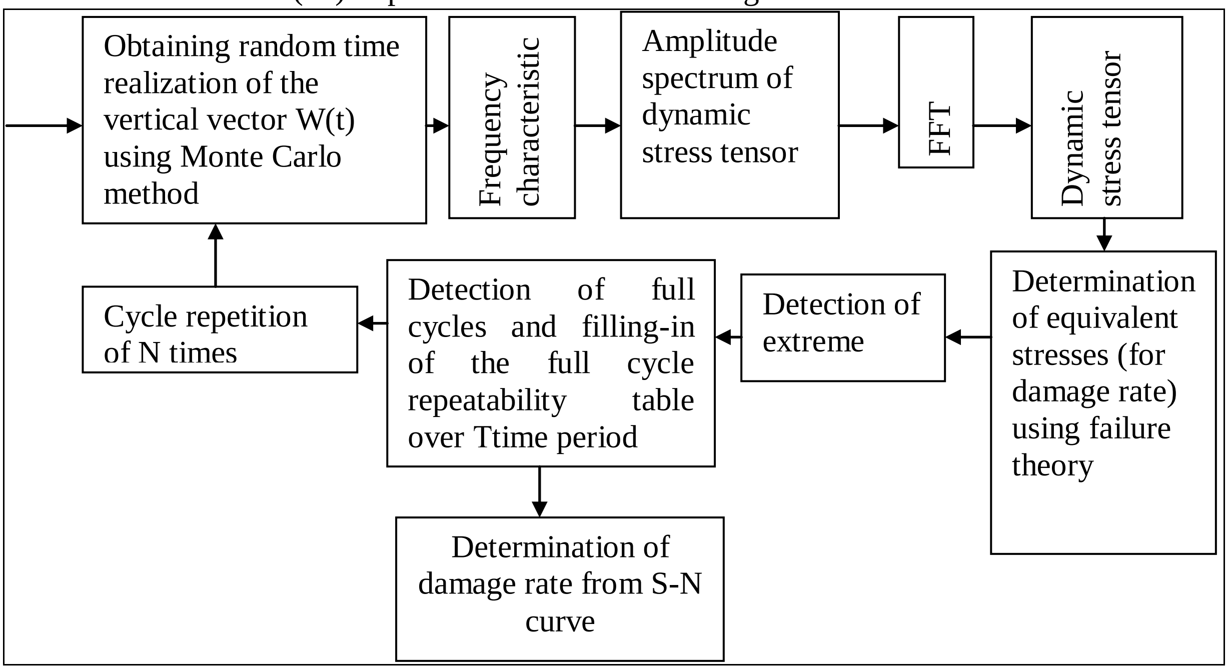


Fig. 3. Flow chart of total damage rate determination of the pipeline design.

For determination of internal stresses that appear in the walls of the offshore subsea pipeline under design loads a finite element model of the pipeline has been developed using solid finite elements. The internal stresses are calculated using finite element method and ANSYS software.

More searches of the fatigue parameters of the buried offshore subsea pipelines were made. We can determine total damage rate of the pipelines using technique from Fig. 3. Combination of the subsea pipeline loads present on figure 4 (shown as a percentage in the diagram). This method is not fully applicable to the operating mode of the buried offshore subsea pipelines (see Fig.1).

The fatigue calculations of the sea buried pipelines are made using simplified formulas to evaluate the fatigue rate of the underground pipelines. This method is not fully applicable to the operating mode of the buried offshore subsea pipelines (see Fig.1).

E. Fatigue Parameters

Calculations previously made for the non-buried pipeline as shown in [6] demonstrated that the total damage rate, service life T=38.4years [6]. Simplified method of fatigue strength the valuation using Weibull distribution for simulation of the long-term fatigue stress distribution is described in the guidelines [2]

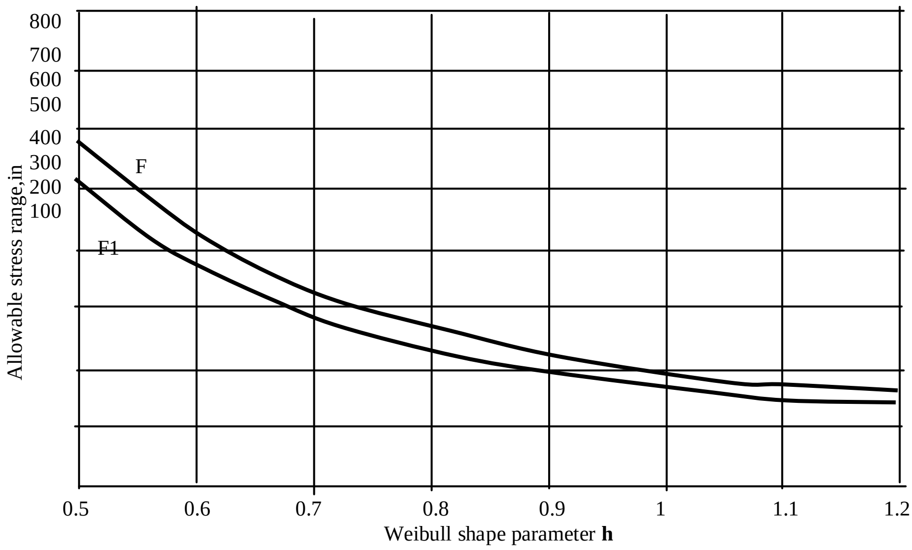


Figure.5 Allowable extreme stress range during 10^8 cycles for components in seawater with cathodic protection [21].

According to the technique[11], Weibull distribution parameters h are determined using linear interpolation of the stress range for values (0.90÷1.0) from the **Table 1** for the curves S-N[21] We can calculate diction factor of the allowable stresses from the curve F1[21], it's present on **fig.5.**. Considering corrosion protection of the pipeline from the Table 2[14] we obtain a reducing factor of 0.19. In this case the stress reduction will be within 82.501 MPa for σ_e=485.3.

Table 1. Allowable extreme stress range during 10^8 cycles for components in seawater with catholic's protection [21]

S-N	*Weibull shape parameter h*							
curves	0.50	0.60	0.70	0.80	0.90	1.00	1.10	1.20
F1	**523.3**	**376.7**	**289.9**	**233.9**	**196.4**	**169.6**	**149.6**	**134.3**

Table 2 Reduction factor on stress to correspond with utilization factor η □for C - W3 curves .[14]

Fatigue damage Utilization η	*Weibull shape parameter h*							
	0.50	*0.60*	*0.70*	*0.80*	*0.90*	*1.00*	*1.10*	*1.20*
0.10	0.497	0.511	0.526	0.540	0.552	0.563	0.573	0.582
0.20	0.609	0.620	0.632	0.642	0.652	0.661	0.670	0.677
0.22	0.627	0.638	0.648	0.659	0.668	0.677	0.685	0.692
0.27	0.661	0.676	0.686	0.695	0.703	0.711	0.719	0.725
0.30	0.688	0.697	0.706	0.715	0.723	0.730	0.737	0.743
0.33	0.708	0.717	0.725	0.733	0.741	0.748	0.754	0.760
0.40	0.751	0.758	0.765	0.772	0.779	0.785	0.790	0.795
0.50	0.805	0.810	0.816	0.821	0.826	0.831	0.835	0.839
0.60	0.852	0.856	0.860	0.864	0.868	0.871	0.875	0.878
0.67	0.882	0.885	0.888	0.891	0.894	0.897	0.900	0.902
0.70	0.894	0.897	0.900	0.902	0.905	0.908	0.910	0.912
0.80	0.932	0.934	0.936	0.938	0.939	0.941	0.942	0.944
1.00	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

Let us analyze the sea buried pipeline laid on the bottom of the Caspian Sea. The pipeline is buried and its designed service life is 30 years. Taking into account the allowable stresses [14] σ_e=485.3 MPa, stress reduction will be as follows:

(485.3-(82.501)=402.799MPa

Fatigue damages reduce the allowable stresses by 17%.

F. *Additional Distinguishing Marks*

Additional distinguishing marks to be added to the character of classification of steel subsea pipelines present in Table 3[14]Appendix . Seismically active regions and ice - resistant and pipes L3, G3[14].

The stress value of 402.799 MPa is obtained from the Table 3[Appendix] of the standards [14] using n_e(G3) coefficient of 1.33 and considering k_σ coefficient of 0.864 from the Table 4 [14] Appendix.For the pipeline having diameter of 406.4mm and wall thickness of 14.5 mm the allowable stress range is 261.66 MPa.

Result

The allowable stress for the pipeline is 255.6 MPa [14].

III. Conclusion

The result obtained does not exceed the allowable level but we still have 2.3% to reach the allowable stress level. Requirements of standards [4,9] are used in the calculation. To evaluate fatigue of the buried subsea pipeline, it is required to carry out fatigue tests of the pipelines in order not to rely on standard coefficients in the calculations when evaluating strength of the pipelines during the design stage and not to contemplate about probable margin of the allowable stresses.

Appendix

Table 3

Strength factor k_c for pipeline pure buckling calculation

Pipeline class	k_c
L , LI	1.5
L2	1.65
L3	1.8
G , G l	1.4
G2	1.5
G3	1.65

Table 4

Strength factors in terms of total stresses k_σ

Pipeline class	k_σ	
	For normal operational conditions	For short - term loads during construction and hydraulic tests
L , L1	0.8	0.95
L2	0.727	0.864
L3	0.696	0.826
G , Gl	0.8	0.95

G2	0.762	0.905
G3	0.727	0.864

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- Research of Theory of Catastrophe of pipeline constructions ,
- Reliability of structural systems and Retaining structures,
- Estimation of reliability offshore pipelines at action of random seismic loads,

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