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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Abstract— Based on the finite element analysis a method to determine damages and fatigue zones of a pipeline has been suggested.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. Offshore pipeline system operation must be ensured in case of an earthquake without interruptions for any repairs. This is very important in view of the widely varying extreme loads, combined pressure and temperature effects as well as extreme environmental impacts, and inspires to solving a number of tasks related to the evaluation of the stress-strain state of the pipeline. The aim of this calculation is to analyze safety of these a buried pipeline at random operating and environmental impacts as well as cyclic fluctuations of the transportation parametersDo not cite references in the abstract. Do Don't use all caps for research paper title.

Index Terms— sea buried pipeline, fatigue, cyclic fluctuations, random operating, seismic loadings.

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1 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).

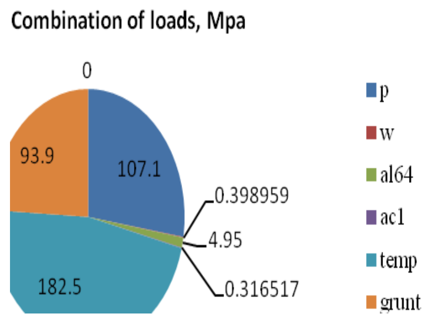

Fig.1. Analysis of sea buried pipeline loads effect on specific combinaion; where p is a working pressure load, w is a dead weight load, temp-- temp-- is temperature impact, al64 is seismic load.

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.

2 .1 Mathematic model.

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

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

where C -may be constant or random values.

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

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

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

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;

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

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.

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

Where is pipeline weight per1 running meter.

$$b=\left[\frac{-\alpha\frac{E\theta}{TL}\gamma\theta-P\frac{T_0}{T}\gamma}{m}\cdot\frac{L^2T}{EI}\right]$$, α is a coefficient.

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

$$\lambda_1=-\frac{[b]}{2}-\sqrt{-\left(\frac{[-b]^2}{2}-\left(\frac{\omega_i^2+k_c}{m}\right)\right)}\quad(6a)$$

$$\lambda_2=-\frac{[b]}{2}+\sqrt{\left(\frac{[b]^2}{2}-\left(\frac{\omega_i^2+k_c}{m}\right)\right)}\quad(6b)$$

2.2 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

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

Joint spectral density of random functions $\ddot{u}$(t) and S_t(ω) can be computed with the following assumption:
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$$s_{ut}(\omega)=\Phi(i\omega)s_x(\omega)=\begin{cases}-is_x(\omega)(\omega>0),\\ is_x(\omega)(\omega<0).\end{cases}\quad(8)$$

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

$$s_{ut}(\omega)=\Phi(i\omega)s_t(\omega)=(-(u_{10}))(t)-k_c\ )/(\lambda^2+k_c\omega_i^2+[-\alpha\cdot(E\theta/TL)\cdot\gamma\cdot\theta-p\cdot(T_0/T)\cdot\gamma])(S_t(\omega))$$

, (9)

where S_t(ω) 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).

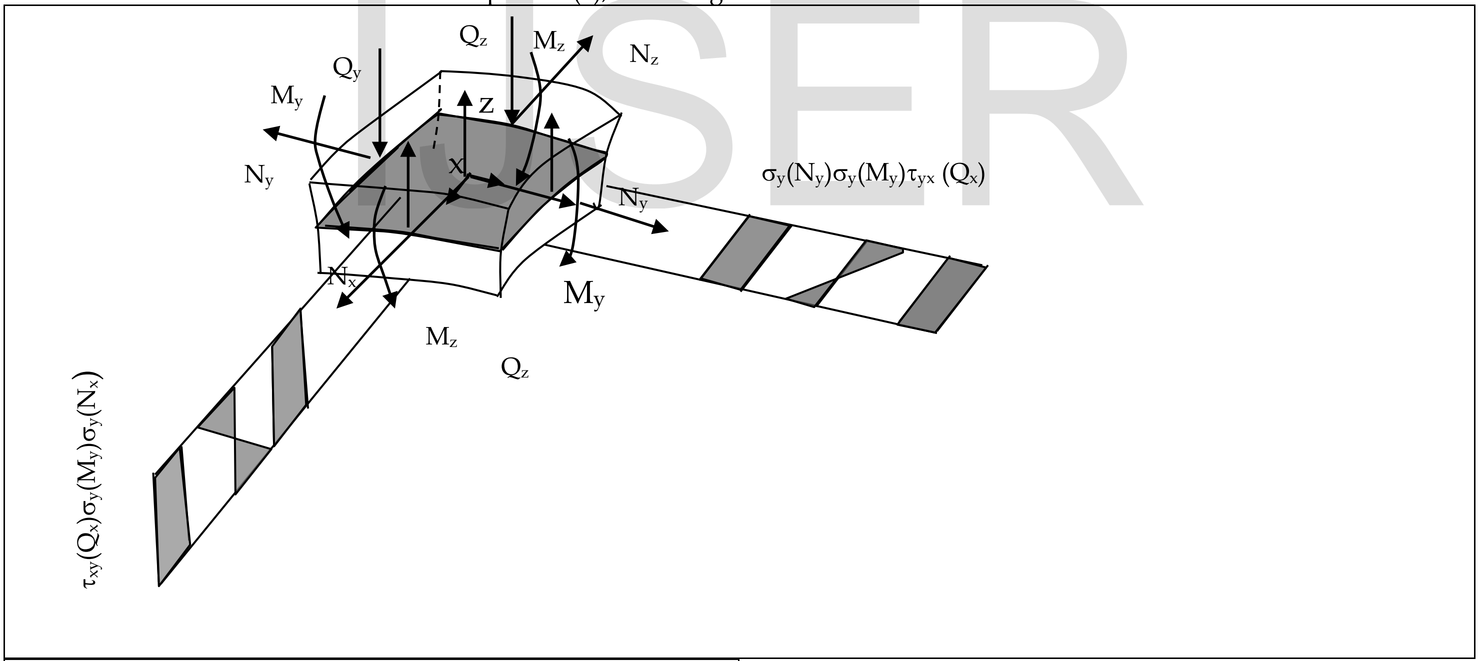

Fig. 2. Loads and stresses in the section of the pipeline shell: where N are longitudinal stresses in the pipeline wall, M,Q - bending moments and shearing stresses are distributed along the pipeline wall symmetric with respect to mid-surface of the shell.

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

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

We can evaluate probabilistic characteristics of there and nonequivalent stressed state in time and spectral ranges.

2.3 Matrix representation of stress on pipeline.

3 SECTIONS

Let us have matrix representation of an expression for $\sigma^2_{экв}$(t):

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

Then , where according to [5]

$$\mathbf{M}=\frac{1}{2}\begin{pmatrix}2 & -1 & -1 & 0 & 0 & 0\\ -1 & 2 & -1 & 0 & 0 & 0\\ -1 & -1 & 2 & 0 & 0 & 0\\ 0 & 0 & 0 & 6 & 0 & 0\\ 0 & 0 & 0 & 0 & 6 & 0\\ 0 & 0 & 0 & 0 & 0 & 6\end{pmatrix}^{*} \qquad (12)$$

At tri axial compression or tension $\sigma_{\text{экв}} = 0$, |M|=0.

Stressed state in a point $\sigma_{\text{экв}}$ 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 $\sigma^{(r)}_{\text{экв}}(t)$ 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. Seismic damage is other than local damage, as an increase in the pipe curvature is observed along the fixed sections.

This study focuses on designed pipeline risk assessment by virtue of the theory of runs.

Average number of runs *U(Q₀)* within level *Q₀* is calculated by formula: $\overline{U}(Q_0)=\frac{1}{2\pi}\sqrt{\frac{D_{\dot F}}{D_F}}\,e^{-\frac{(Q-m_F)^2}{2D_F}}$, (13)

Failures may be treated as independent accidental events and estimated using a rare-event probability equation.

The conditional probability of the structural strain φ(t) exceeding the level *a* within the duration of an earthquake $0 \le \tau \le t$ at least once is equal to:

$$P(\varphi > a|t)=1-exp\left(-\int_0^t U(a|\tau)d\tau\right) \quad (14)$$

The probability of the load F(t) to exceed the value Q_0 within the duration T at least once is equal to:

$$H_t=1-exp\left[-\int_0^T \overline{U}(Q_0)dt\right]. \qquad (15)$$

The required safety level of a structure $P(\varphi > a^*|t)$ which supports the design seismic risk value P^* over the rated life T_0 is calculated by formula:

$$P\left(\varphi > a^*\middle|t\right)=\frac{P^*}{1-exp(-\Lambda T_0)}, \qquad (16)$$

where Λ is the earthquake event frequency.

Reasonable structure reliability level is established on the basis of performance and reliability analysis carried out for existing structures; contingency analysis (for accidents occurred and simulated); and also on the basis of material resource efficiency considerations and safety requirements.

Pipelines having diameter to wall thickness ratio of higher than 20 mm are called thin walled, distribution of normal stresses that are perpendicular to the surface is uniform over the entire wall thickness. For isotropic materials stress-strain dependence is represented as follows under plane stress: follows:

$$\begin{pmatrix}\varepsilon_H\\ \varepsilon_L\end{pmatrix}=\frac{1}{E}\begin{bmatrix}1 & -\nu 1\\ -\nu & 1\end{bmatrix}\begin{pmatrix}\sigma_{\mathrm{H}}\\ \sigma_{\mathrm{L}}\end{pmatrix} \qquad (17)$$

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 is present in fig.1.

Pressure and temperature variation cycles associated with changes in natural gas transportation modes were simulated using a technique represented in Fig. 3 [5].

Calculations previously made for the non-buried pipeline as shown in [6] demonstrated that the total damage rate D_i for all wave loads was D=0.026, A=1.574 $\times 10^{14}$, considering that service life T=38.4years [6].

At the stage of designing the subsea pipelines in the Caspian Sea, the decision was taken to bury the pipelines with consideration of seismic hazard.

Based on the calculations it was decided to bury the subsea pipelines in the landfall sections to ensure protection from cycling waves [6].

More searches of the fatigue parameters of the buried offshore subsea pipelines were made. We can determine total damage rate of the pipelines from Fig. 3. Combination of the subsea pipeline loads present on figure1 (shown as a percentage in the diagram).

It is necessary to perform researches to determine pipeline fatigue. This article covers evaluation of the fatigue of the buried subsea pipelines. 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).

Simplified method of fatigue staring the valuation using Weibull distribution for simulation of the long-term fatigue stress distribution is described in the guidelines [2].

Cumulative stress distribution function can be expressed as follows [8,9]:

$$Q(\Delta\sigma) = \exp\left[-\left(\frac{\Delta\sigma}{q}\right)^{h}\right] \qquad (18)$$

Where Q is probability of stress range exceedance Δσ; h are parameters of Weibull distribution; q is Weibull scale parameter, it is determined for the stress range, Δσ:

$$q = \frac{\Delta\sigma_0}{(\ln n_0)^{\frac{1}{h}}} \qquad (19)$$

Where σ_0 is stress range of n_0 cycles.

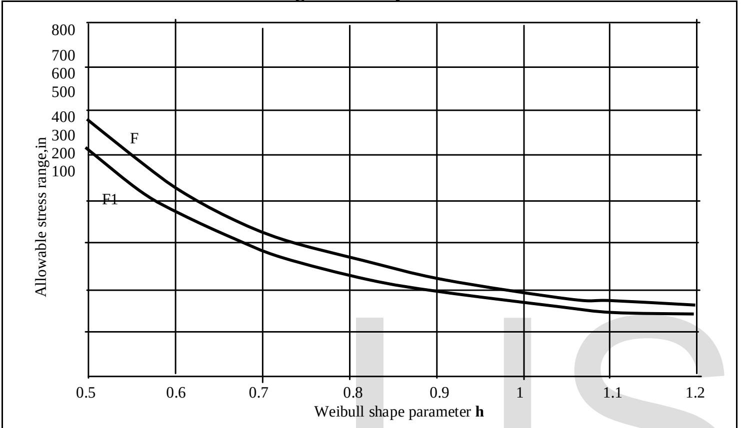

Figure.3 Extreme stress range for components in seawater for 10^8cycles subject to cathodic protection [21]

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 duction factor of the allowable stresses from the curve F1[21], it's present on **fig.3.**. 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. Extreme stress range in seawater subject to cathodic protection from 10^8 cycles [21]

Table 2. Coefficients to stress with utilization factor η for C - W3 curves .[14]

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%.

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

Table 3.

Strength factor k_c for pipeline pure buckling calculation

demonstrated in this document, the numbering for sections upper case Arabic numerals, then upper case Arabic numerals, separated by periods.

The stress value of 402.799 MPa is obtained from the Table 3 of the standards [14] using ne(G3) coefficient of 1.33 and considering k_σ coefficient of 0.864 from the **Table 2[21].** For the pipeline having outer diameter 406.4mm with thickness of wall 14.5mm the allowable stress range is 261.66 MPa.

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

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.

TABLE 1

NOMENCLATURE

Symbol	Quanity
EI	pipeline rigidity
m	pipeline weight
T_0	initial stress in the pipeline
θ	temperature of the transported product
P_0	initial pressure of the product
γ	strain factor of the pipe, assumed equal to 0.2
$\tilde{F}(t)$	random seismic load

4 CONCLUSION

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