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SIMULATION OF SUBSEA PIPELINE CONDITIONS ON THE ARCTIC CONTINENTAL SHELF UNDER SEISMIC EFFECTS

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Introduction

Amounts of oil and gas in the Artic Regions are one of the biggest uncertainties in the future power distribution. Estimation of the regions located in the north of the Arctic Circle shows that approximately 30% of worldwide non-discovered gas and 13% of non-discovered oil can be mainly found in these areas, principally offshore under 500 meter water layer. Unexplored natural gas is three times richer than oil in the Arctic Regions and primarily concentrated in Russia.

Behavioral analysis of the buried sections of the Trans-Alaska pipeline system allows getting real information about impact of ground movement on the pipeline integrity. For construction of Arctic pipelines theoretical studies of A. Ibeender and A. Palmer were used. Contributions of *Nixon J.F., Morgenstern N., Reesor S.N., Selvadurai A. P., Shinde S. B* helped to describe the performance of the pipeline-ground interaction system. These authors study interaction between the buried pipelines and frozen ground as well pipeline deformations at frost penetration.

It should be noted that development of the effective arctic mineral resources transportation systems ensure adequate balance of several factors such as economic growth, environmental stability, security of power supply, health and safety of humans. In all cases reasonable development of the systems imply compromises for the above factors.

Dynamic behavior and properties of the frozen ground as well as its impact on the seismic stability of the constructions are reviewed in studies performed by Berg *R. L., Guymon G. L., Johnson T. C., Aukenthaler M., Brinkgreve R.B.J., Haxaire A., Hacıefendioɡ K., Kartal M.E., Karaca Z.*

Successful operation of the pipelines is possible taking into account the latest engineering solutions in pipeline design based on deformations. The designers shall bury the pipelines to be constructed in the Arctic regions. Ice events are rare for offshore pipelines; they result in ground displacements in a short period of time and are considered dangerous.

This article describes an approach to examine the pipeline – ground interaction model under seismic impact and at frozen ground. This model shall be applicable in accordance with the materials analysis, which are described in a number of articles detailing examinations using reasonable parameters. Please bear in mind the phenomenon of induced seismicity related to hydrocarbon extractions: such earthquakes occur in several years after the field development started and lead to the worst pipeline conditions.

Materials and methods

Advancement of the offshore pipeline construction made it possible to reduce costs and start deep-sea projects. Pipe laying technology at 650-meter depth was a real breakthrough in the beginning of 1980s. Large-diameter pipelines are economically viable provided that major markets are available and significant confirmed volumes are reserved. Capital expenses are equal to 90% of the pipeline cost. Construction costs of the pipeline

depend on its diameter, operating pressure, length and topographical relief. It is important to bear in mind additional parameters such as climatic conditions, safety precautions, transport communication options since they have impact on the construction costs. High Pressure technology played a significant role in reducing the costs of international major pipe laying projects.

After the hydrocarbon reserves have been discovered in the Artic regions, oil and gas companies faced numerous problems such as ice drift, permafrost thaw, pipe laying methods and leak detection methods. For offshore applications alternative constructions such as pipe-in-pipe system shall be considered.

Solution of the problem related to evaluation of subsea pipeline condition for arctic operations under seismic effects.

This problem represents a practical interest for further improvement of the hydrocarbon transportation routes. Primary objective of the study addresses development issues of the Russian segment of the Arctic Continental Shelf.

Scope of study:

Subsea offshore buried pipeline with the following parameters: diameter, wall thickness and burial depth.

Simulation of the buried subsea “hot” pipeline is under review taking into consideration non-linear properties of the elastic foundation and seismic load. The simulation work is performed on the basis of the materials analysis for the ongoing arctic offshore projects.

Objectives: develop evaluation method of the buried subsea pipeline condition (strength) taking to account non-linear properties of the elastic foundation under seismic loads.

Materials and methods: The approaches are based on mathematic models of structural strength analysis for arctic applications under seismic loads.

Results

Subsea buried pipelines ensure effective and safe transportation of hydrocarbons. This article studies interaction issues between offshore pipelines and surrounding grounds, temperature conditions of pipeline operation, dependence of pipeline behavior on frozen grounds; besides seismic hazards leading to pipeline damage are taken into account.

Results: several approaches have been elaborated for calculation of the subsea buried pipelines on the elastic foundation under seismic loads. The approaches are submitted for review and approval of the Russian Maritime Register of Shipping.

Выводы: the results are obtained empirically using buried subsea pipeline safety assessment method under seismic loads.

Keywords: Arctic region, buried subsea pipelines, thermal and hydro-mechanical effects, permafrost, seismic loads, non-linear elastic foundation, amplitude-frequency response.

Buried subsea pipeline safety assessment taking into account non-linear elastic foundation under seismic loading is of great current theoretical and practical interest.

1. Introduction

Share of natural gas in the global energy demand will increase from 23% in 2000 up to 28% in 2030. Gas transportation costs will double market cost of the gas. It takes much time to implement gas projects. Duration of gas line construction until the start of commissioning can take even 10 years which raises up financial risks[1].Un-explored potential quantities of the hydrocarbons are estimated to be 91% in the Russian Arctic segment (as reported by the Ministry of Natural Resources and Environment of the Russian Federation[2]and as estimated by Ernst&Young[3] experts). The most distinguished oil and gas fields are Shtokmanovskoe field and Leningradskoe field in the Arctic shelf (Barents Sea and Kara Sea).

[1]UNITED NATIONS ECONOMIC COMMISSION FOR EUROPE COMMITTEE ON SUSTAINABLE ENERGY,2012,
Working Party on Gas, STUDY, The Impact of Liberalization of Natural Gas Markets in the UNECE region, 71p., 2012

[2]Power Bulletin No.58, March 2018, Tariff Policy in Fuel and Energy Sector, Analytical Center under the Government of the Russian Federation, p.29.

[3]British Audit and Consulting Company

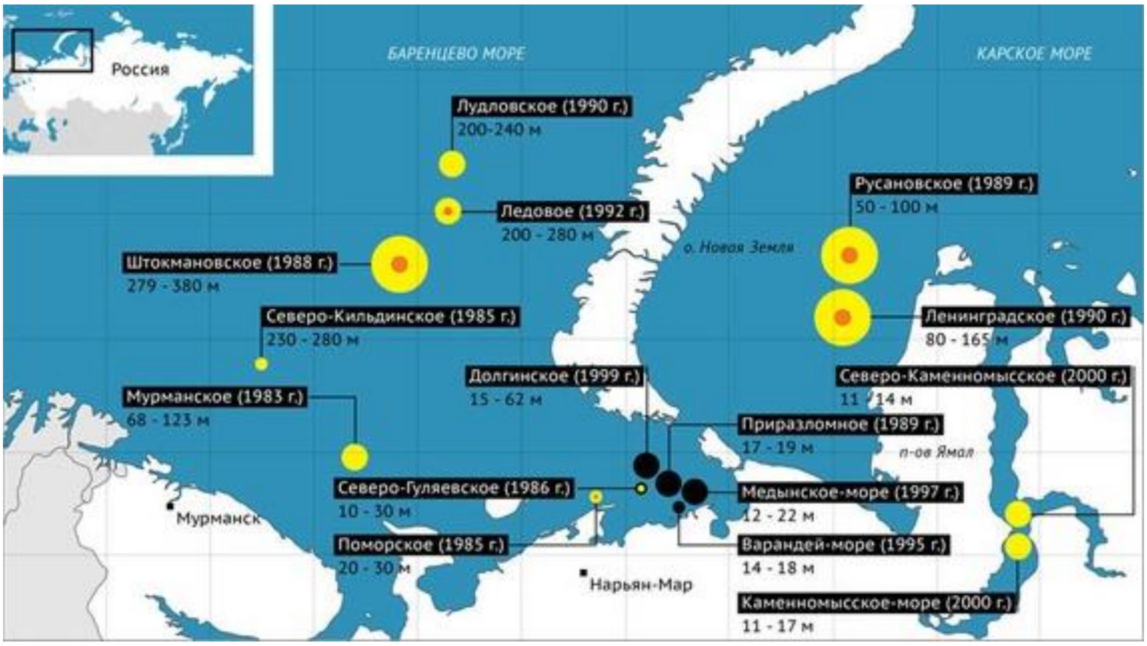

Fig. 1. Map of the Arctic zone of the Russian Federation

Scale 1:3900000

Conformal azimuthal projection

0 500 km

0 500miles

Classification of the fields

unique- more than 300 mln. tons of oil or 500 billion m^3 of gas

large - from 3 to 30 mln. tons of oil or up to 500 billion m^3 of gas

average- from 30 mln. tons of oil or 3 to 30 billion m^3 of gas

Prudhoe Bay field(1990) name, year of discovery

200-240 m Sea depth

Oil field

Oil and gas condensate field

Gas condensate field

Gas field

Fig. 1. Map of the Arctic zone of the Russian Federation[4]***(RFAZ).***

Arctic pipelines are the pipelines laid to the 60^{th} parallel North. The first arctic pipeline was constructed in 1978 during Drake Point field development. The pipeline was constructed under the ice and was a part of Endicott project. As stated in [1] “The pipeline was assembled onshore and pulled through the subsea trench using a hoist installed on the ice. Special plough was used to make an underwater trench”.

Immediately after having discovered recoverable reserves in the Arctic regions the operators faced numerous challenges such as selection of the transportation methods of the produced hydrocarbons to the market. Thanks to improvement of the subsea pipeline construction technologies the costs decreased thus allowing realization of various projects which seemed impossible before. They played an important role in the development of the gas reserves of the North Sea in 1970-80s and in the Gulf of Mexico.

During extensive explorations of Alaska territories a subsea arctic oil pipeline was constructed in 1960 for Endicott field development. The Trans-Alaska Pipeline was built between 1974 and 1977, after the 1973 oil crisis thus making the exploration of the Prudhoe Bay oil field economically feasible. Due to seismic hazards the pipeline was laid on the above-ground steel tube supports.

[4] Legal Definition of the Arctic Zone of the Russian Federation: This zone includes: “…exclusive economic zone and continental shelf of the Russian Federation, within which Russia has sovereign rights and jurisdiction in accordance with international law”.

External dynamic seismic effect is determined by the ground movement accelerogram. Soil-pipeline interaction under arctic conditions can be described by thermal and hydro-mechanical process. Ground parameters depend on its loading rate.

The designers of the arctic pipeline systems came up with a wide range of unique conditions. Buried pipeline-soil interaction is accompanied by various effects[5]: workload action, deformations caused by internal pressure and temperature of the transported fluids, engineering and geological loads, frost heave, thawing, soil swell and external seismic loads.

Problem overview

Studies of the pipeline-soil interaction (interaction between the pipeline and the surrounding soils) are quite extensive; they are reviewed in the papers of A. Ibeender, O.B. Andersland [3], Yu. Zaretskiy [3], V. Ladanyi [4], A. Pickell [5], A.P.S Selvadurai [7] and other authors.

During the pipeline-soil interaction soil parameter to time dependence shall be taken into consideration. Thermal and hydro-mechanical effects determine interaction between the pipeline and the surrounding soils, as well as pipeline-soil response. Comprehensive analysis of the pipeline-soil interaction issues is a complicated task. At this point a variety of analytical and computational procedures with varied complexity have been tested in the literature, ranging from simplified models with one-dimensional discrete spring elements (refer to Nixon [6]; and Selvadurai [7]), to more sophisticated models that accommodate three-dimensional continuum response of the soils [7,8].

In recent years there has been a great interest in the utilization of the trunk lines to transport natural gas from the northern regions (Russian Arctic regions) [6] to the gas consumers in the South of the country [7][1].

One of the options is to transport refrigerated gas at sub-freezing temperature. The purpose to use a refrigerated gas pipeline is to avoid thawing of the ice-rich soils which can cause ecological destruction of the permafrost areas. The presence of a chilled gas pipeline in a frost-susceptible zone can also result in the gradual development of a zone of frozen soil around the pipeline. This fact is highlighted in the papers by Grechishchev, B. Moiseev and others.

High ice soil behavior simulation approaches have been analyzed. Behavior of the time-dependent frozen soils can be described through creep models and viscoelastoplastic models. Frozen soils are characterized by a combination of ice and non-frozen water. Creep rate of frozen soils was studied of V. Ladanyi [5], Yu. Vyalov [4], O.B. Andersland [3], A. Pkhuket [6]. Primary and secondary creep rates were taken into account during the experiments.

Yu.Vyalov [4] and Zaretskiy applied a viscoelastoplastic model for simulation of the frozen soil creep rates based on soil failure criteria. Specific type of model is selected from the analysis of the experiment results. The models accounting for the primary and secondary creep rates are applicable to describe slow generation of the complicated discontinuous processes, they realize discontinuous heaving situations.

Selvadurai [7] articles provide details about cryogenic effects dependent on the moisture movement and soil heat conduction, and takes into consideration pipeline-soil interaction. Three-dimensional computational model has been used to examine the progress of the frost heave inside the freeze-resistant soils. Stress-strain behavior and time dependency of the frozen soils is taken into account. Numeric modeling is used to study the interaction between the frozen soils and the pipeline.

Considerable experimental and theoretic examinations of the frozen soils have been carried out over the last two decades.

The scope of the present article is limited to the thermotechnical calculation procedure and modeling of the "hot[8]" pipeline impact on the frozen soil.

MATERIALS AND METHODS

Only subsea buried pipelines ensure effective and safe transportation of hydrocarbons. Let us review the modeling of the "hot" pipeline. Three-dimensional thermal field around the pipeline can be described by means of the following non-linear heat conductivity equation[9];

$$C(x,y,T)\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\lambda(x,y,T)\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda(x,y,T)\frac{\partial T}{\partial y}\right), \quad (1)$$

which can be solved using numeric methods. In this equation $C(x,y,T)$ is specific heat capacity of soil, x and y are horizontal and vertical coordinates, T is temperature distribution function, t is time, $\lambda(x,y,T)$ is thermal conductivity coefficient of soil.

While modeling the behavior of the buried pipeline let us consider the following cases:

- 1. Pipeline is modeled as a beam on elastic foundation (flexible beam), non-linear coupling is used to calculate soil resistance to pipeline deformations;

[5]Alaska Stand Alone Gas Pipeline /ASAP Design Methodology to Address Frost Heave Design Methodology to Address Frost Heave Potential, 2011. 108 p.

[6]Resolution No. 1064 dated August 31, 2017 of the National Program "Social and Economic Development of the Arctic Zone of the Russian Federation", updated list of sub-programs, main objectives, Key Performance Indicators, expanded list of participants. Deadline of the National Program implementation is extended to 2025. Implementation of this National Program will make it possible to improve social and economic development of the Arctic zone and ensure national security in the Arctic region. PDF Document. Resolution No. 1064 dated August 31, 2017.

[7] Gazprom Program "Development of the hydrocarbon reserves in the continental shelf of the Russian Federation until 2030"

[8]"hot" means a pipeline which conveys positive temperature fluid

[9] FROST 3D UNIVERSAL software application for thermal technical calculations [electronic media]. URL: http://www.simmakers.ru/frost-3d. 2014.

-2. Pipeline is modeled as a long cylindrical shell where connectivity between the shell and the surrounding soil is established at nodes located at the soil-pipeline interface.

Since the shell structure is long, the pipeline ends are rigidly fixed.

- During the first calculation stage let us review the first case when the pipeline is modeled as a beam element represented as Raleigh beam on the non-linear elastic foundation [9], (Fig. 2). Let us adopt the following assumptions: 1. The material of the beam has linear properties; 2. The beam is rigidly fixed at the ends; 3. Damping (ζ) and rigidity (k_f) of the foundation are non-linear.

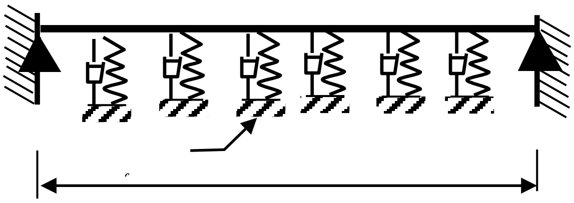

Fig. 2. Raleigh beam on the non-linear elastic foundation.

In this case homogeneous pipeline bending equation is represented as follows:

$$u_{tt} + u_{xxxx} - u_{xxtt} + \omega_*^2 u + \omega_{**}^2 u^3 = 0, \qquad (2)$$

where $\omega_{**} = u_0\sqrt{\frac{h_1}{E}}\sqrt{\frac{I}{F}}$, and u_0 is amplitude of flexural wave; u is transverse displacement; $\omega_* = \sqrt{h/\rho F}$, *E* and *I*-module of elasticity of the pipe material and moment of inertia respectively, *h* is modulus of foundation, ρ is density of pipeline material.

Asymptotic method is used to solve this equation.

Vibration mode is represented in the following manner:

$$w = \sum_{i=1}^{\infty} A_i sin(\Omega_i t) sin\left(\frac{\pi i}{l}\right) + O(\varepsilon), \qquad (3)$$

where $\Omega_i = \frac{\omega_i^{lin}}{\omega_1^{lin}}\omega$, $\omega_i^{lin} = \sqrt{\frac{\pi^4 c^2 i^4}{l^4} + \beta_1}$, $\beta_1 = 9c^4\pi^4/l^4$, $c = \sqrt{EI/\rho S}$,

Here S is square area of the beam, ε is non-dimensional small parameter, ε→0. *i*=1,3. Positive and negative values of ε correspond to rigid and soft restoring forces.

Let us review the behavior of the frozen soil in the pipeline-soil model.

<u>This model can be applied on the basis of several articles which are dedicated to examination of the soil behavior models within reasonable parameters.</u> A wide range of simplified models of the soil is used during non-linear analysis [2,8,14,15]. Hyperbolic models are widely used. The article describes non-linear and time-dependent soil behavior model[10].

Linear iterative soil loading-unloading procedure is built using equation (4) or taking into consideration confining pressure σ_{ref} (5):

$$\tau = \frac{\gamma \cdot G_0}{1+\beta\left(\frac{\gamma}{\gamma_r}\right)^s}, (4) \quad \tau = \frac{2 \cdot G_0 \cdot \left(\frac{\gamma-\gamma_{rev}}{2}\right)}{1+\beta\left(\frac{\gamma-\gamma_{rev}}{2\cdot\gamma_r}\right)^s} + \tau_{rev}, \qquad (5)$$

where γ is specified shear strain, γ_r is initial shear strain, β is non-dimensional coefficient, G_0 is maximum shear modulus, S is non-dimensional exponent.

Maximum soil stress γ_r can be determined from the following equation:

$$\gamma_r = a\left(\frac{\sigma'_v}{\sigma_{ref}}\right)^b, \qquad (6)$$

where *a* and *b* are parameters of the curve, σ'_v is vertical effective stress in the center of soil layer, σ_{ref}- is overburden (total, confining) stress assumed to be equal to 0.18 MPa.

Decrease in soil strain damping while confining pressure [19] is increased is determined from the following equation:

$$\zeta = \frac{c}{(\sigma'_v)^d}, \qquad (7)$$

where c and d are curve fitting parameters.

It should be noted that the majority of the suggested soil models demonstrate almost zero damping under low stresses as opposed to the laboratory and field measurement results.

[10]Bardet J. P.: Computer Program NERA 2001 (Nonlinear Earthquake site Response Analyses of Layered Soil Deposits), University of Southern Carolina,

Equation (8) reflects relation between the effective shear strain and maximum shear strain (R_γ) with earthquake magnitude M;

$$R_\gamma = \frac{M-1}{10}. \qquad (8)$$

Non-linear analysis of soil response is basically required for modeling of the soil movement. The accuracy of results depends on how practicing engineer is able to understand requirements to the soil response analysis.

By calculating seismic impact for the pipeline-soil model we can determine the most dangerous condition of the structure. Spectral method is used for modeling of the seismic effects. One of the most important factors in defining the seismic impact is a type of spectral function of power density. Spectral function of power density [2,10,16,20] depends on stochastic model of the earthquake.

Spectral function of the seismic impact density can be determined from the structural motion equation:

$$S_{ij}(\omega) = S_{\ddot{u}_g}(\omega) \sum_{r=1}^{N} \sum_{s=1}^{N} \psi_{ir}\psi_{js} H_{ir}(\omega) H_{js}^*(\omega) \qquad (9)$$

where $S_{\ddot{u}_g}$ is a function of spectral power density of soil movement, ω is frequency, *H*(*ω*) is a function of frequency response, *N* is as number of modes during response, Ψ_{ir} is a contribution of r-*th* mode in the movement $u_j(t)$, mark * means complex conjugation of the spectral function of the output process power density.

Standard behavior of the structural response can be calculated from the following equation:

$$F_{R_\tau}(r) = [1 - exp(-s^2/2)] exp\left[-\upsilon\tau \frac{1 - exp\left(-\sqrt{\pi/2}\right)\delta_e s}{exp(s^2/2) - 1}\right] r>0, \qquad (10)$$

where $\lambda_{m,ij} = \frac{1}{2\pi}\int_0^\infty \omega^m S_{ij}(\omega) d\omega$,

Here $s = \frac{r}{\sqrt{\lambda_0}}$, $\upsilon = \frac{1}{\pi}\sqrt{\lambda_2/\lambda_0}$; $\delta_e = \delta^{1.2}$; $\delta = \sqrt{1 - \frac{\lambda_1^2}{\lambda_0\lambda_2}}$, $\lambda_{m,rs}$ is a cross spectral moment of coordinate per forms, m=0,1,2.

The model of subsea pipeline materials

For execution of the projects in Arctic shelf regions it is recommended to use cold resistant materials with low cold brittle properties. These materials shall withstand general longitudinal strains induced by the combined axial force and bend. High strength steels match these requirements. Ramberg Osgood equation[11] is used to calculate strain and strength of the subsea pipelines:

$$\varepsilon = \frac{\sigma}{E}\left[1 + A\left(\frac{\sigma}{\sigma_y}\right)^{n-1}\right], \qquad (11)$$

$$A = 0.005\left(\frac{E}{\sigma_y}\right) - 1, n = \frac{log\left[\frac{\left(\varepsilon_i - \frac{\sigma_i}{E}\right)}{\left(0.005 - \frac{\sigma_y}{E}\right)}\right]}{log\left(\frac{\sigma_t}{\sigma_y}\right)}, \qquad (12)$$

where: σ,ε are points of Ramberg Osgood equation; E is Young's modulus;σ_y is yield strength (if tensile strength is 0.5%);σ_t-is tensile point strain.

SUMMARY

Let us review the example of the buried arctic pipeline calculation.

This example describes non-linear behavior of the frozen soil and seismic load action.

Calculation models of the buried arctic pipelines are determined using finite element method. Example of the equivalent linear iteration procedure of soil movement is shown in Figure 3.

[11]SP 108-34-97. Construction of Underwater Crossings; GOST R 54382-2011. Petroleum and Gas Industry. Submarine Pipeline Systems. General Specifications. M.: Federal Agency on Technical Regulating and Metrology. p.447.

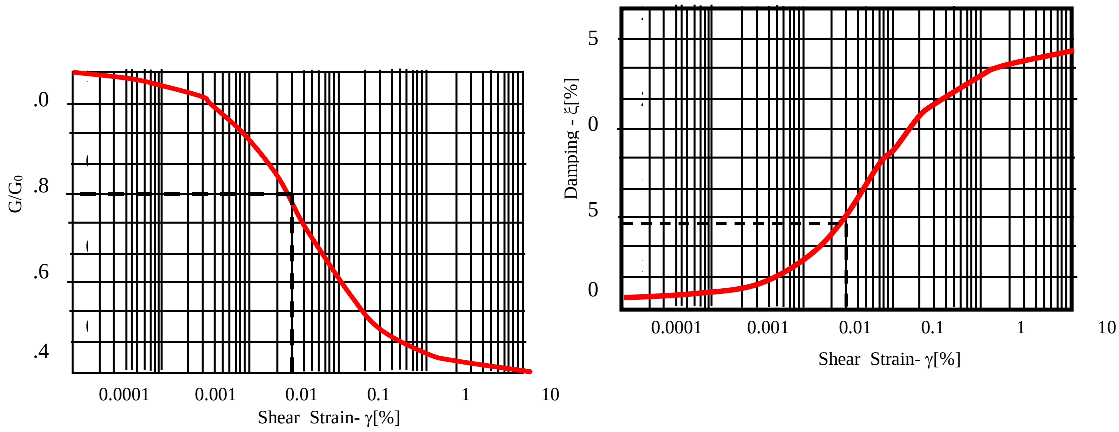

Рис. 3 Iterative procedure of soil movement [12].

Spectral function of soil acceleration power density developed by Kanai and Tajimi, and modified by Penzien [10] is given in the following equation: (19)

$$S_{\ddot{u}_g}(\omega) = S_0 \frac{\omega_g^4 + 4\zeta_g^2\omega_g^2\omega^2\omega^4}{(\omega_g^2-\omega^2)^2 + 4\zeta_g^2\omega_g^2\omega^2(\omega_f^2-\omega^2)^2 + 4\zeta_f^2\omega_f^2\omega^2}, \quad (13)$$

where ω_g is ground motion frequency, ξ_g is ground attenuation factor, ω_f,$\xi_f$is frequency and damping of pipeline, $S_0$is acceleration spectrum pf primary rock.

Safety calculation is performed for the buried subsea pipeline under seismic loading.

For earthquake calculation average soil exponents have been recorded: soil intensity value S_0 (average) = 0.00593 m^2/c^2, filter parameters (w_g,=10.0 rad/s,ζ_g= 0.4, w_f,= 2.19 rad/s,ζ_f=0.6). The pipeline has the following features: diameter of 406.4 mm, wall thickness of 12mm. Conveyed medium is natural gas.

$S_{\ddot{u}_g}$ =6,049×$10^{-3}$$m^2/c^2$.

Amplitude frequency response calculation[13] shows at what frequencies the pipeline responds during earthquake. Spectral overlap analysis is illustrated in Fig. 4.

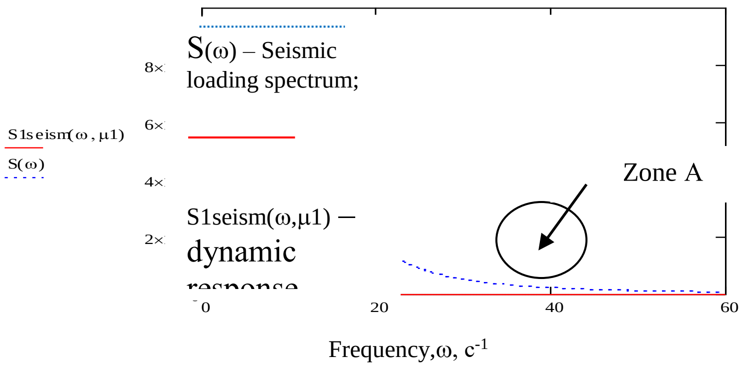

Fig.4 Spectral overlapping of the seismic loading and amplitude frequency response of the pipeline:

Here Zone A demonstrates intersection of the seismic load spectrum line (blue line) and dynamic response characteristic of the pipeline taking into account natural frequency of the structure (red color).

Spectral calculations show that frequencies of seismic loads are greater than natural frequency of the pipeline; the pipeline is not resonating.

This article depicts modeling of the pipeline-soil interaction taking into consideration soil non-linearity

[12]Berg R. L., Guymon G. L., Johnson T. C., Mathematical model to correlate frost heave of pavements with laboratory predictions. Report CRREL (Cold Regions Research and Engineering Laboratory). 1980.pp. 80-10

[13]Rules for Classification and Construction of Subsea Offshore Pipelines [text of regulatory document No. 2-020301-004]: Russian Maritime Register of Shipping – Saint Petersburg: Russian Maritime Register of Shipping, 2017. – p.164.

and seismic loads on the structure. Worst-case scenario of seismic loading on the pipeline has been performed.

Analysis of the worst-case scenario is submitted in a form of suggestions and proposals to be added in the Rules for Classification and Construction of Subsea Offshore Pipelines of the Russian Maritime Register of Shipping[10].

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ВАРИАЦИОННЫЙ ПРИНЦИП ОПТИМАЛЬНОГО ДЕЙСТВИЯ

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VARIATIONAL OPTIMUM ACTION PRINCIPLE

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АННОТАЦИЯ

Представлен раздел дистанционного курса «Метамеханика». Исходя из принципа наименьшего действия, построена вариационная система потенциалов взаимодействия систем и полей, предпочитаемых Природой.

ABSTRACT

The section of the distance course "Metamechanics" is presented. Based on the principle of least action, a variational system of potentials for the interaction of systems and fields preferred by Nature is constructed.

Ключевые слова: метамеханика, потенциал, принцип, действие, оптимальность.

Key words: metamechanics, potential, principle, action, optimality.

1. Введение.

Как известно, наиболее общим методом вывода фундаментальных закономерностей во всех научных областях считается дедуктивный аксиоматический метод, базирующийся на вариационных принципах. Основа всех принципов экстремума представлялась основоположникам науки завидно ясной. Леонард Эйлер писал в 1744 году: «Так как здание всего мира совершенно и возведено премудрым Творцом, то в мире не происходит ничего, в чем не был бы виден смысл какого-нибудь максимума или минимума; поэтому нет никакого сомнения, что все явления мира с таким же успехом можно определить из причин