Mathematical Modelling of Engineering Problems
Vol. 9, No. 6, December, 2022, pp. 1497-1502
Journal homepage: http://iieta.org/journals/mmep

# Assessment of Geo-Environmental Consequences of Oil and Gas Complex Enterprises' Extraction Activities on the Shelf

Marina Zaretskaya

Department of Mathematical Modeling, Kuban State University, Stavropolskaya Street, 149, Krasnodar 350040, Russia

Corresponding Author Email: zarmv@mail.ru

https://doi.org/10.18280/mmep.090608

**Received:** 19 August 2022
**Accepted:** 20 November 2022

***Keywords:***
*oil and gas complex, seismogenic structure, differential factorization method, model of solution, contact stresses*

## ABSTRACT

One of the causes of rising seismic tension in a territory is the production activity of mining enterprises, including those in the oil and gas industry. The paper reports the results of modeling and analysis of the tensions of geological structures, which include the contact areas of the continental and oceanic crust, making a slow horizontal movement. The technogenic impact of the production process of an offshore oil and gas production platform and the pressure of the ocean water column are taken into consideration. The differential factorization method is used to investigate the posed boundary value problems. The study assesses the occurring contact stresses and draws conclusions about their dependence on the distance between the plates, the thickness of the water layer, and the frequency of the external load, modeling the intensity of the production process. The results obtained can be used by oil and gas companies to work out scenarios of the production process in a risk-free mode.

## 1. INTRODUCTION

As traditional onshore oil and gas fields are depleted, the development of hydrocarbon resources on the continental shelf will become progressively more relevant. This is one of the main strategic directions of the development of modern oil and gas companies [1]. It is an indisputable fact that the future of world oil production is on the continental shelf of the World Ocean [2-5].

There are currently thousands of oil and gas production platforms installed around the world. Their presence exerts a dual impact on the environment. On the one hand, industrial activity on the platform causes certain disturbances in the ecosystem and causes a gradual growth of technogenic stresses in the Earth's crust, leading eventually to a discharge in the form of a technogenic earthquake. On the other hand, once the platform's resources are exhausted, it must be decommissioned. This process, too, entails serious economic and engineering problems and disrupts the established ecosystem equilibrium [6].

The present work investigates one of the aforementioned problems - the assessment of the level of technogenic stresses in the area of production activities of an oil production platform. Since the Azov-Black Sea region of Russia belongs to the areas of high seismic hazard, the study focuses on the seismogenic structures responsible for the realization of the seismic potential of the region, the regularities of development of man-made seismicity, and its association with the man-made impact on the upper layers of the lithosphere.

The main consequences of the production activities of offshore oil and gas extraction platforms include changes in the state of the ecosystem, which are often negative, and the gradually escalating seismicity of the region due to the emergence of man-made tensions [7-11]. The first task is resolved by establishing certain environmental parameters, a set of indicators for environmental licensing of offshore oil and gas production, and the introduction of industrial environmental control programs [12-15].

Technogenic earthquakes are often observed during the exploitation of offshore deposits [16-19]. Geodynamic monitoring systems have been created and are active on the platforms of the Yury Korchagin and Vladimir Filanovsky fields in the northern Caspian Sea and the Kravtsovskoye field in the Baltic Sea. Regular monitoring of local seismicity carried out over several years indicates that the presence of earthquake epicenters in the area of oil production on the platform may be of an anthropogenic nature, associated with intensive oil pumping [20].

The design of offshore platforms, especially in regions of high seismicity, must account for the risk of increasing seismicity and its discharge in the form of an earthquake. The territory of Russia is characterized by vast zones of seismic activity (the Far East, the Azov-Black Sea region, and the Caspian Sea coast), where strong earthquakes can be extremely hazardous to the safety and proper operation of offshore platforms. Furthermore, major earthquakes in the region can generate tsunamis, which pose an additional critical threat to offshore oil production. Their risk also needs to be assessed and taken into account in the design of offshore platforms and the development of criteria for their safe operation.

The formulated problem can be addressed in two ways.

The first path is the design of offshore oil and gas production platforms capable of withstanding baseline earthquakes and maximum estimated earthquakes without rupturing while retaining their repairability [21, 22]. The shortcoming of this approach is that it does not account for the dynamic nature of seismicity, which changes as the geodynamic process evolves. In addition, this approach does not cover all possible earthquake-related exogenous catastrophic phenomena.

The second approach is related to the development of seismicity monitoring systems, one element of them being a site-specific earthquake forecasting unit.

Real-time earthquake and tsunami forecasting, determining their ultimate shock and destructive characteristics, demands that the parameters of the earthquake source and the causes of their occurrence are known [23]. Forecasting earthquakes, their strength, and potential destructiveness largely depends on determining the geophysical parameters of the origin point, such as depth, orientation, fault line length, the character of crustal movements, and the size and depth of the water basin in the region in question [24-27].

Such structures make a reciprocal slow horizontal movement. This process is accompanied by the gradual subduction of the oceanic plate under the continental plate (plate subduction) [28]. It is clear that a layer of oceanic or sea water has a strong influence on the state of such a mechanical system. Structures of this type are widespread in Krasnodar Krai, the North Caucasus, the Far East, and Russia as a whole.

Therefore, the aim of this study was: to present the results of modeling and analysis of the tensions of geological structures, which include the contact areas of the continental and oceanic crust that belong to the seismogenic structures responsible for the realization of the seismic potential of the region.

## 2. METHODS

In Figure 1, we present a model of a complex multi-type seismogenic structure in the area of contact between the continental and oceanic crust, considering two types of impact: anthropogenic and the pressure of the oceanic water column.

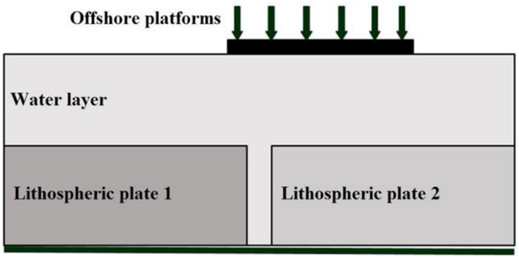

**Figure 1.** Model of a complex seismogenic structure in the contact area of the continental and oceanic lithospheric plates

The study focuses on the wave fields in the area of contact between the oceanic and continental plates, which are modeled by two semi-restricted plates on an elastic base. The plates are pressurized by a layer of water. The technogenic impact of the operation of an offshore oil and gas production platform is modeled by a distributed harmonic load.

The author performed calculations for a model block structure with dimensionless geometric and physical-mechanical characteristics. The distance between the blocks and the frequency of the external load are chosen as the variable parameters.

The calculations are performed in three stages.

At the first stage, contact stresses between the blocks and the base in the absence of a water layer are assessed.

At the second stage, similar calculations are performed after introducing into the mechanical system the layer of water.

At the third stage, contact stresses are assessed under the same mechanical conditions but for a higher frequency of external loading.

To perform calculations at all stages, a program developed by us in the FORTRAN 90 programming language (Compaq Visual Fortran 6.5 environment) was used.

Let us write out the problem statements for the blocks of the considered structure.

Solid lithospheric blocks are modeled by Kirchhoff plates. The equation of motion is given in vectors of displacement amplitudes of the median surface and for the static case has the form (Eq. (1)):

$$\begin{gathered} R_n(\partial x_1, \partial x_2)u_{3n} + \varepsilon_{53n}(t_{3n} - g_{3n}) \\ = \left(\frac{\partial^4}{\partial x_1^4} + 2\frac{\partial^2}{\partial x_1^2}\frac{\partial^2}{\partial x_2^2} + \frac{\partial^4}{\partial x_2^4} - \varepsilon_{43n}\right)u_{3n} \\ +\varepsilon_{53n}(t_{3n} - g_{3n}) = 0 \end{gathered} \tag{1}$$

The contact interaction of a liquid medium and elastic lithospheric plates is determined by the equality of the vertical components of the velocities of the points of the liquid and the elastic medium in the contact zone. For the liquid layer, a differential equation is derived with respect to the velocity potential, which, taking into account the contact conditions at the junction with the lithospheric plates, takes the form (Eq. (2)):

$$\begin{gathered} \Delta^3\varphi_n + (\varepsilon_{53n}\rho g - \varepsilon_{43n})\Delta\varphi_n + \varepsilon_{53n}\rho\frac{\omega H_1^2}{h_n}\varphi_n \\ -i\varepsilon_{53n}\frac{\omega H_1^2}{h_n}(g_{3n} - w_n) = 0 \end{gathered} \tag{2}$$

For the deformed base, the model of which can be an elastic half-space, an elastic layer, or a batch of layers, the relationship between displacements and stresses on the surface is given by the relations (Eq. (3)):

$$\begin{aligned} &u(x_1, x_2) \\ &= \varepsilon_6^{-1}\frac{1}{4\pi^2}\int_{-\infty}^{\infty}\int K(\alpha_1, \alpha_2)G(\alpha_1, \alpha_2)e^{-i\langle\alpha,x\rangle}d\alpha_1 d\alpha_2 \end{aligned} \tag{3}$$

An elastic half-space, or a pack of layers, can be considered as a base.

Let us introduce the following notation: $n=l, r$ is an index corresponding left or right lithosphere plate; $u_{3n}$ is a mid-surface deflection; $g_n = \{g_{n1}, g_{n2}, g_{n3}\}$ is a contact stress vector; $t_n = \{t_{n1}, t_{n2}, t_{n3}\}$ is an external pressure vector; $h_n$ is a thickness of a plate; $H$ is a characteristic base size; $H_1$ is a characteristic size of liquid layer; $\mu_n, \mu$ are material shear modulus of the left or right lithospheric plate and a base; $\nu_n$, $\nu$ are Poisson's ratios of materials of the left or right lithospheric plate and a base; $\rho_n, \rho$ are block and liquid material density; $F_2(\alpha_1, \alpha_2)$ is direct two-dimensional Fourier transform operator; $\alpha_1$, $\alpha_2$ are Fourier transform parameters; $K(\alpha_1,\alpha_2)$ - is a matrix-function of the base, called the symbol of the system of integral equations, its elements contain information about the structure and properties of the base material (Eqns. (4)-(6));

$$G(\alpha_1, \alpha_2) = F_2(\alpha_1, \alpha_2)g \tag{4}$$

$$\langle\alpha, x\rangle = \alpha_1 x_1 + \alpha_2 x_2 \tag{5}$$

$$
\begin{aligned}
\varepsilon_{43n} &= \omega^2\rho_n \frac{12H^4(1-v_n^2)}{E_n h_n^2} \\
\varepsilon_{53n} &= \frac{12H^4(1-v_n^2)}{E_n h_n^3} \\
\varepsilon_6^{-1} &= \frac{(1-v)H}{\mu}
\end{aligned} \tag{6}
$$

The boundary conditions of the problem are written in accordance with the conditions of the interaction of the structure's elements.

To solve the problems in each block, we apply to the system of differential equations the differential factorization method, the algorithm of which is described, for example, in the works of Babeshko and colleagues [29, 30]. Following the algorithm, applying the two-dimensional Fourier transform to the system of differential equations in each block, we obtain systems of functional equations. The further procedure includes differential factorization of matrix functions with elements from several complex variables, the implementation of automorphism, which consists in calculating Leray residue forms or incomplete functional Wiener-Hopf equations, constructing pseudo-differential equations, extracting integral equations from them, the form of which is determined by specific boundary conditions of the boundary problem, solving integral equations, and obtaining an integral representation of the boundary problem in each block.

The construction of a solution for the block structure as a whole involves applying the homeomorphisms necessary to conjugate the block elements, which is achieved by introducing factor-topological spaces [30], where the boundary conditions of the conjugation of deformed bodies dictated by the requirements of mechanics are taken as equivalence relations. As a result, the Wiener-Hopf equations are derived for block structures. The form of the equations varies for different distances between the ends of the lithospheric plates. The conversion of the obtained equations makes it possible to estimate the arising contact stresses and to draw conclusions about their dependence on the distance between the plates.

Let us write out the defining relations at each step of the differential factorization method algorithm.

The functional equations obtained by immersing the boundary value problem into the topological structure induced by the Euclidean metric take the form (Eqns. (7)-(9)):

$$
N_n(a_1,a_2)\phi_n(a_1,a_2) = \int_{\partial\Omega} \omega_n(a_1,a_2) + S_n(a_1,a_2) \tag{7}
$$

$$
\begin{gathered}
N_n(\alpha_1,\alpha_2) = (\alpha_1^2+\alpha_2^2)^3 \\
+(\alpha_1^2+\alpha_2^2)(\varepsilon_{53n}\rho g - \varepsilon_{43n}) - \varepsilon_{53n}R_n
\end{gathered} \tag{8}
$$

$$
\begin{gathered}
S_n(\alpha_1,\alpha_2) = F_2(\alpha_1,\alpha_2)\varphi_n \\
R_n = \rho\frac{\omega^2 H_1^2}{h_n}
\end{gathered} \tag{9}
$$

Requiring that automorphism is fulfilled, we obtain pseudo-differential equations that degenerate into algebraic ones (Eq. (10)):

$$
\begin{gathered}
-e^{-ia-\theta}\big[B_{1n}(\alpha_1,\alpha_{2j-})Q_n(\alpha_1,-\theta) + B_{2n}(\alpha_1,\alpha_{2j-})M_n(\alpha_1,-\theta) + B_{3n}(\alpha_1,\alpha_{2j-})U_{3n\partial x_2}(\alpha_1,-\theta) \\
+ B_{4n}(\alpha_1,\alpha_{2j-})U_{3n}(\alpha_1,-\theta) + B_{5n}(\alpha_1,\alpha_{2j-})P(\alpha_1,-\theta) + B_{6n}(\alpha_1,\alpha_{2j-})V_{x_2}(\alpha_1,-\theta)\big] \\
+S_n(\alpha_1,\alpha_{2j-}) = 0, \qquad j = 1,2,3
\end{gathered} \tag{10}
$$

To solve the problem for the block structure as a whole, it is necessary to apply the homeomorphisms needed to conjugate the block elements [31].

When formulating equivalence relations, we take into account that the space between the ends of the lithospheric plates is also filled with water. However, since the density of water is much less than the matter density of the lithospheric plates, the influence of this minor volume of water on the base can be neglected.

Wiener-Hopf equations for determining contact stresses are as follows (Eq. (11)):

$$
\begin{gathered}
M_{rl}(\alpha_1,\alpha_2)G^+(\alpha_1,\alpha_2) \\
= G^-(\alpha_1,\alpha_2) + T_{rl}(\alpha_1,\alpha_2) + U_{3w}
\end{gathered} \tag{11}
$$

The following notations are introduced (Eqns. (12)-(19)):

$$
M_{rl}(\alpha_1,\alpha_2) = M_r(\alpha_1,\alpha_2)\cdot M_l^{-1}(\alpha_1,\alpha_2) \tag{12}
$$

$$
T_{rl}(\alpha_1,\alpha_2) = [T_l(\alpha_1,\alpha_2) - T_r(\alpha_1,\alpha_2)]M_l(\alpha_1,\alpha_2) \tag{13}
$$

$$
M_r(\alpha_1,\alpha_2) = [N_r^{-1}(\alpha_1,\alpha_2)\varepsilon_{53r}iR_r + \varepsilon_6^{-1}K(\alpha_1,\alpha_2)] \tag{14}
$$

$$
\begin{aligned}
M_l(\alpha_1,\alpha_2) = -[N_l^{-1}&(\alpha_1,\alpha_2)\varepsilon_{53l}iR_l \\
&+ \varepsilon_6^{-1}K(\alpha_1,\alpha_2)]
\end{aligned} \tag{15}
$$

$$
\begin{gathered}
T_r(\alpha_1,\alpha_2) = N_r^{-1}(\alpha_1,\alpha_2)\omega_r(\alpha_1,\alpha_2) \\
-N_r^{-1}(\alpha_1,\alpha_2)\varepsilon_{53r}iR_rW_r
\end{gathered} \tag{16}
$$

$$
\begin{gathered}
T_l(\alpha_1,\alpha_2) = N_l^{-1}(\alpha_1,\alpha_2)\omega_l(\alpha_1,\alpha_2) \\
-N_l^{-1}(\alpha_1,\alpha_2)\varepsilon_{53l}iR_lW_l
\end{gathered} \tag{17}
$$

$$
\begin{gathered}
G^+(\alpha_1,\alpha_2) = G_{3r}(\alpha_1,\alpha_2) \\
G^-(\alpha_1,\alpha_2) = G_{3l}(\alpha_1,\alpha_2)
\end{gathered} \tag{18}
$$

$$
\begin{gathered}
R_r = \rho\frac{\omega^2 H_1^2}{h_r} \\
R_l = \rho\frac{\omega^2 H_1^2}{h_l}
\end{gathered} \tag{19}
$$

Conversion of the obtained equations allows us to estimate the arising contact stresses and draw conclusions about their dependence on the distance between the plates.

The advantages of the differential factorization method include the fact that the analysis of the boundary value problem is carried out analytically. Numerical calculations are performed at the last stage when it is necessary to invert the integral representation of the solution and calculate the double integral of the inverse Fourier transform. The accuracy of the calculation is determined by the specified accuracy of the calculation of the integral and is regulated by the task manager.

Previously, the method was successfully applied to assess the tension in the continental fault-block structure [32], some of the causes of tsunamis [23], the tension arising from subduction processes, due to which earthquakes can occur [24], and the causes of climate change. The content of the method and individual results were reported at the Congress on

Climate Change and Global Warming (24-25 April 2019, Vancouver, Canada) and World Summit on Climate Change and Global Warming (26-27 November 2018, Tokyo, Japan) and aroused scientific interest.

To perform calculations, a program developed by us in the FORTRAN 90 programming language (Compaq Visual Fortran 6.5 environment) was used.

The calculations were carried out for a model block structure.

For the material of both lithospheric plates, the values taken are Young's modulus MPa, Poisson's ratio, and density $kg/m^3$.

For the base material, Young's modulus MPa, Poisson's ratio, and density $kg/m^3$.

Next, the non-dimensionalization of geometric and physical-mechanical characteristics was performed.

As a variable parameter, the distance between the blocks and the frequency of the external load were chosen.

## 3. RESULTS AND DISCUSSION

The calculations do not consider the critical frequencies at which the wavenumber of longitudinal vibrations of the elastic base coincides with the wavenumber of natural vibrations of the liquid. In this case, there is a sharp, almost exponential growth of the amplitude of contact stresses for the base in the form of a half-space [33].

Based on the results of the first stage of assessing the contact stresses between the blocks and the base in the absence of a water layer, a general trend was revealed: we can observe an increase in tension as the distance between the blocks decreases [11, 32]. This mechanical system simulates a continental fault-block structure. The fixed initial value of the distance between the blocks of lithospheric plates is taken as equal to one.

At the second stage, calculations were carried out for three water layer depths: 10, 15, and 20. The values of distances between the ends of lithospheric plates are reduced from 1 to 0.1 with a step of 0.1. The last value of the distance is taken as 0.05 (Figure 2).

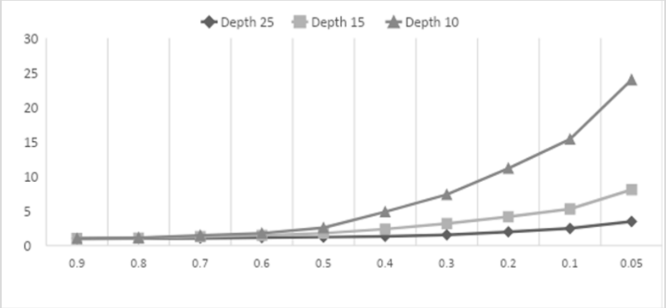

**Figure 2.** Dependence of contact stresses on the width of the fault in the presence of a water layer

The ordinate axis demonstrates the growth of contact stresses for different depths of the water layer. The results obtained allow drawing the following conclusions. In general, the intensity of the growth of contact stresses decreases in the presence of a water layer: The thicker the water layer, the lower the values of contact stresses at equal values of the distance between the plates.

At the third stage, the contact stresses were evaluated under the same mechanical conditions but for a higher frequency of external loading (Figure 3). This model allows estimating the dynamics of the rise of technogenic stresses depending on the intensity of the production process on the oil and gas production platform.

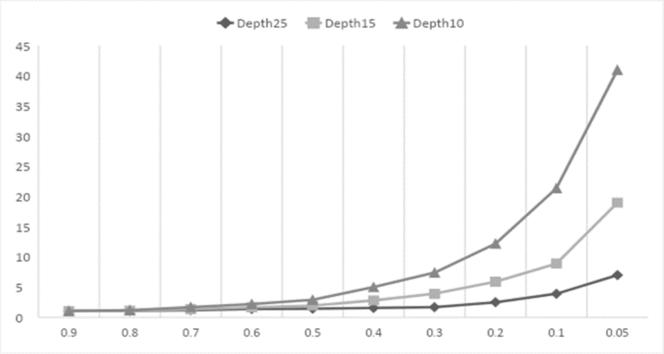

**Figure 3.** Dependence of contact stresses on the frequency of the external load in the presence of a water layer

An increase in the frequency of external anthropogenic impact generates a more intensive growth of contact stresses with a slow horizontal convergence of the lithospheric plate ends. However, all stresses remain finite and no exponential growth is observed even at a distance close to zero.

The constructed mathematical model for estimating contact stresses serving as a measure of technogenic seismicity makes it possible to assess the consequences of production activities of an offshore oil production platform under specific operating conditions. Such scenarios can be worked out before the start of the production process to identify hazardous combinations of geophysical, mechanical, landscape, and production factors.

## 4. CONCLUSION

The developed mathematical model for assessing technogenic tension at this stage has certain limitations.

First of all, the simplest models of slabs and foundations were used for verification.

The further development of the model involves the complication of the configuration of the plates and the gradual approximation to the real geometry. In order to obtain results that can be used by researchers or specialists, it is necessary to use material models that are as close as possible in their mechanical, physical, and chemical properties to real geological rocks.

The results obtained can be used by oil-and-gas complex enterprises engaged in the extraction or processing of hydrocarbons on the shelf. The findings may also be useful to organizations that monitor regional seismicity to assess the seismicity of the territory and to work out scenarios of seismicity growth depending on the level of technogenic impact on the underlying base. The management of technogenic loads makes it possible to preempt the rise of seismicity to a destructive level and allows the production process to be carried out in a risk-free mode.

Further development of the model involves the complication of the configuration of the plates and the gradual approximation to the real geometry. Also, in order to obtain results that can be used by researchers or specialists, it is necessary to choose material models that are as close as possible to real geological rocks in their mechanical, physical, and chemical properties.

**ACKNOWLEDGMENT**

Some of the research results were obtained with the support of the Russian Ministry of Science and Higher Education (Grant No.: FZEN-2020-0022), the Russian Foundation for Basic Research, and the Administration of the Krasnodar Region (Grant No.: 19-41-230002).

## REFERENCES

[1] Escandón-Panchana, P., Morante-Carballo, F., Herrera-Franco, G., Pineda, E., Yagual, J. (2021). Computer application to estimate PVT conditions in oil wells in the Ecuadorian Amazon. Mathematical Modelling of Engineering Problems, 8(5): 727-738. https://doi.org/10.18280/mmep.080507

[2] Carayannis, E.G., Ilinova, A., Cherepovitsyn, A. (2021). The future of energy and the case of the arctic offshore: The role of strategic management. Journal of Marine Science and Engineering, 9(2): 134. http://dx.doi.org/10.3390/jmse9020134

[3] Chanysheva, A., Ilinova, A. (2021). The future of Russian arctic oil and gas projects: Problems of assessing the prospects. Journal of Marine Science and Engineering, 9(5): 528. http://dx.doi.org/10.3390/jmse9050528

[4] Ilinova, A., Solovyova, V., Yudin, S. (2020). Scenario-based forecasting of Russian Arctic energy shelf development. Energy Reports, 6(Suppl. 9): 1349-1355. http://dx.doi.org/10.1016/j.egyr.2020.11.022

[5] Shapovalova, D., Galimullin, E., Grushevenko, E. (2020). Russian Arctic offshore petroleum governance: The effects of western sanctions and outlook for northern development. Energy Policy, 146. http://dx.doi.org/10.1016/j.enpol.2020.111753

[6] Meyer-Gutbrod, E.L., Love, M.S., Schroeder, D.M., Claisse, J.T., Kui, L., Miller, R.J. (2020). Forecasting the legacy of offshore oil and gas platforms on fish community structure and productivity. Ecological Applications, 30(8). http://dx.doi.org/10.1002/eap.2185

[7] Baranova, V., Mustaqeem, A., Bell, S. (1999). A model for induced seismicity caused by hydrocarbon production in the Western Canada Sedimentary Basin. Canadian Journal of Earth Sciences, 36(1): 47-64. https://doi.org/10.1139/e98-080

[8] Jacobs, T. (2014). Searching for solutions to induced seismicity. Journal of Petroleum Technology, 66(9): 60-72. http://dx.doi.org/10.2118/0914-0060-JPT

[9] Pavlova, A.V., Zaretskaya, M.V., Telyatnikov, I.S., Rubtsov, S.E. (2019). Assessment of the environmental consequences caused by endogenous and anthropogenic hazards for the Azov recreation area. Journal of Environmental Management and Tourism, 10(7): 1445-1457.

[10] Suckale, J. (2009). Induced seismicity in hydrocarbon fields. Advances in Geophysics, 51(C): 55-106. http://dx.doi.org/10.1016/S0065-2687(09)05107-3

[11] Zaretskaya, M. (2020). Analysis and assessment of seismic hazard for the Azov-Black Sea recreation area. Journal of Environmental Management and Tourism, 11(7): 1669-1679.

[12] de Oliveira Bredariol, T. (2020). Developing indicators for environmental licensing the case of the Brazilian offshore oil and gas sector. Impact Assessment and Project Appraisal, 38(5): 427-440. http://dx.doi.org/10.1080/14615517.2020.1804305

[13] Manfra, L., Lamberti, C.V., Ceracchi, S., et al. (2020). Challenges in harmonized environmental impact assessment (EIA), monitoring and decommissioning procedures of offshore platforms in Adriatic-Ionian (ADRION) region. Water, 12(9): 2460. http://dx.doi.org/10.3390/w12092460

[14] Ratner, S., Zaretskaya M. (2020). Evaluating efficiency of Russian regional environmental management systems. Quality - Access to Success, 21(175): 120-125.

[15] Temerdashev, Z.A., Pavlenko, L.F., Korpakova, I.G., Ermakova, Y.S. (2018). Analytical aspects of the determination of the total concentration and differentiation of anthropogenic and biogenic hydrocarbons in aquatic ecosystems. Journal of Analytical Chemistry, 73(12): 1137-1145. https://doi.org/10.1134/S1061934818120092

[16] Bardainne, T., Gaillot, P., Dubos-Sallée, N., Blanco, J., Sénéchal, G. (2006). Characterization of seismic waveforms and classification of seismic events using chirplet atomic decomposition. Example from the Lacq gas field (Western Pyrenees, France). Geophysical Journal International, 166(2): 699-718. http://dx.doi.org/10.1111/j.1365-246X.2006.03023.x

[17] Dahm, T., Cesca, S., Hainzl, S., Braun, T., Krüger, F. (2015). Discrimination between induced, triggered, and natural earthquakes close to hydrocarbon reservoirs: A probabilistic approach based on the modeling of depletion-induced stress changes and seismological source parameters. Journal of Geophysical Research: Solid Earth, 120(4): 2491-2509. http://dx.doi.org/10.1002/2014JB011778

[18] Doglioni, C. (2018). A classification of induced seismicity. Geoscience Frontiers, 9(6): 1903-1909. http://dx.doi.org/10.1016/j.gsf.2017.11.015

[19] Yerkes, R.F., Castle, R.O. (1976). Seismicity and faulting attributable to fluid extraction. Engineering Geology, 10(2-4): 151-167. http://dx.doi.org/10.1016/0013-7952(76)90017-X

[20] Krylov, A., Kovachev, S. (2019). Seismological monitoring for offshore drilling platforms. International Multidisciplinary Scientific GeoConference: SGEM, 19(1.4): 67-72. http://dx.doi.org/10.5593/sgem2019V/1.4/S01.009

[21] Glagovsky, V.B., Kassirova, N.A. (2015). Stress-strain state of the gravity base substructure of the fixed offshore platform at seismic impacts. Geotechnical engineering for infrastructure and development: Proceedings of the XVI European Conference on Soil Mechanics and Geotechnical Engineering, ECSMGE 2015, 7: 3869-3874.

[22] Zanoli, O., Cademartori, M., Parker, E.J., Poggi, P., Zuccarino, L. (2019). Seismic design for the Mediterranean Sea - Engineering basics for project planning. Paper presented at the Offshore Mediterranean Conference and Exhibition 2019, Ravenna, Italy.

[23] Rueda-Bayona, J.G., Guzmán, A., Osorio, A.F. (2022). DOE-ANOVA for identifying the effect of extreme sea-states over the structural dynamic parameters of a floating structure. Mathematical Modelling of Engineering Problems, 9(3): 839-848. https://doi.org/10.18280/mmep.090334

[24] Babeshko, V.A., Babeshko, O.M., Evdokimova, O.V. (2019). Application of the block element method to the problem of predicting the preparation of a tsunami. Doklady Physics, 64(9): 370-375. http://dx.doi.org/10.1134/S1028335819090064

[25] Babeshko, V.A., Evdokimova, O.V., Babeshko, O.M. (2020). On features of starting earthquakes at rigid contacts of lithospheric plates with the base. Acta Mechanica, 231(12): 5205-5212. http://dx.doi.org/10.1007/s00707-020-02816-2

[26] Baeda, A.Y., Carayannis, G.P. (2020). Assessment of tsunami risk to offshore platforms in Indonesia archipelago. IOP Conference Series: Earth and Environmental Science, 419(1): 012011. http://dx.doi.org/10.1088/1755-1315/419/1/012011

[27] Morozov, V.N. Manevitch, A.I., Tatarinov, V.N. (2018). Stress state modeling and geodynamic zoning in seismically active regions. Mining Informational and Analytical Bulletin, 2018(8): 123-132. http://dx.doi.org/10.25018/0236-1493-2018-8-0-123-132

[28] Babeshko, V.A., Babeshko, O.M., Evdokimova, O.V., Evdokimov, V.S., Uafa, S.B. (2020). On bearing resources and on the mechanics of subduction processes. Mechanics of Solids, 55(3): 309-315. http://dx.doi.org/10.3103/S0025654420030036

[29] Babeshko, V.A., Evdokimova, O.V., Babeshko, O.M., Zaretskaya, M.V., Pavlova, A.V. (2009). The differential factorization method for a block structure. Doklady Physics, 54: 25-28. https://doi.org/10.1134/S1028335809010078

[30] Babeshko, V.A., Evdokimova, O.V., Babeshko, O.M., et al. (2015). Convergent properties of block elements. Doklady Physics, 60(11): 515-518. http://dx.doi.org/10.1134/S1028335815110099

[31] Babeshko, V.A., Babeshko, O.M., Evdokimova, O.V. (2011). Automorphism and pseudo-differential equations in the block-element method. Doklady Physics, 56(6): 348-351. http://dx.doi.org/10.1134/S102833581106005X.

[32] Babeshko, V.A., Evdokimova, O.V., Babeshko, O.M., et al. (2018). Origin of starting earthquakes under complete coupling of the lithosphere plates and a base. Doklady Physics, 63(2): 70-75. http://dx.doi.org/10.1134/S1028335818020015

[33] Zaretskaya, M.V. (2021). Study of the tension of a heterogeneous hydroelastic system. IOP Conference Series: Materials Science and Engineering, 1103: 012032. http://dx.doi.org/10.1088/1757-899X/1103/1/012032