Hazardous natural processes and risks at offshore fields development with the use of subsea production of hydrocarbons

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Abstract

Introduction. The article considers the main risks (technological, geological, societal and environmental) of offshore fields development, facilities construction and exploitation with the use of subsea production of hydrocarbons.

Research aim is to analyze the main risks of offshore oil and gas projects implementation, which are associated with harsh natural and climatic conditions of the Sakhalin Island shelf, their impact on subsea facilities and to develop the remedial measures for the risks.

Methodology. Risk analysis made it possible to identify the main risk factors in offshore projects development and determine remedial measures that are high-priority in offshore field exploitation at the stage of design and, most importantly, at the stage of project implementation.

Analysis and discussion. Based on actual data of large oil and gas fields development, an in-depth analysis of the main risks associated with the climatic conditions on the Sakhalin shelf has shown that the region's main geological risks are: seismicity, surface gas, seabed gouging by ice and soil liquefaction. Therefore, it is necessary to use modern environmentally sound technologies of subsea oil and gas production, which are based on successfully implemented projects abroad and the experience of shelf fields development in Russian.

Conclusion. Effective development of oil and gas fields on the Sakhalin shelf is possible only if in the course of project implementation the geological, technological, societal and environmental risks are taken into account and controlled based on the developed remedial measures.

Key words: shelf; risks; seismic activity; gas anomaly; soil liquefaction; gouging by ice.

Introduction. Russian oil and gas industry has faced a daunting and vital task of exploiting oil and gas resources on the continental shelf.

Nowadays, the shelf is a crucial segment in global hydrocarbon production and a compensation tool in the conditions of the outlined stabilization of oil and gas production on land and its further decline. However, offshore oil and gas projects are implemented in complex geological and natural and climatic conditions requiring individual approach to a wide range of issues from flow chart selection to field facilities installation [1].

Oil and gas entities are high-risk facilities associated with many complex tasks. Main risks (technological, geological, societal, and ecological) occur not only in the course of development, but also during facilities construction, production, transportation, exploitation of offshore fields. They may cause major emergencies and catastrophes exerting irreversible effect on people and environment. Due to particular circumstances (severe climate, poor transport infrastructure, sea depth, long-term ice cover, distance from the shore, and lack of technologies) the implementation of offshore oil and gas

projects is highly risky; these circumstances require individual approach and effective measures on risk management at the stage of design and especially at the stage of the project implementation.

Research aim is to analyze the main risks of offshore oil and gas projects implementation, which are associated with harsh natural and climatic conditions of the Sakhalin Island shelf, their impact on subsea facilities and to develop the remedial measures for the risks.

Analysis and discussion. Global offshore oil and gas production has gained wide proven experience of applying subsea production systems to develop offshore fields. Subsea technologies ensure independence of hydrocarbon products production from adverse natural and climatic conditions, and in some instances allow to abandon floating production units, which, among other advantages, considerably decreases the cost of development [2].

In more than 140 offshore fields worldwide subsea production technologies are applied. The geography of subsea production is vast: shelves of the North and Mediterranean seas, India, Southwest Asia, Australia, West Africa, North and South America.

In Russia, first subsea system has been installed on the Sakhalin shelf when constructing facilities for the Kirinsky gas condensate field. Same technologies are planned to be applied in the fields nearby, such as South-Kirinsky, Mynginskoe and South-Lunskoe fields.

The analysis of the main risks connected with severe climatic conditions of Sakhalin Island and their effect on the subsea field facilities is of significant interest and practical utility.

Geological risks. Severe natural and climatic conditions, geological uncertainty (reserves, formation parameters, and formation fluid properties) and anomalies associated with probable presence of shallow gas, loose soil in the upper part of the section, tectonic dislocations, etc. predetermine the development of geological risks.

Let us consider the following basic geological risks:

- seismicity of the area;
- gas anomalies (shallow gas);
- seabed gouging by ice;
- soil liquefaction.

Seismicity of the area. The sea of Okhotsk is within the zone of increased seismic activity which significantly impacts the tectonic structure of oil and gas condensate fields, Odoptinskoe, Chaivinskoe, Piltun-Astokhskoe, Lunskoe, Kirinsky, etc. General level of seismic hazard for the territory of Sakhalin Island is regulated by the map of general seismic zoning of the territory of the Russian Federation (GSZ-97). It is a set of three maps constructed for various seismic gaps: once in 500, 1000, and 5000 years. GSZ-97 map is based on probabilistic seismic hazard analysis (fig. 1).

According to GSZ-97 maps, the coastal region of northeast Sakhalin and the adjacent part of the continental shelf are characterized by magnitude-9 earthquake activity.

Open border of the sea of Okhotsk goes along the Kuril Islands not far from a major tsunami origination zone in the Pacific, which is the Kuril-Kamchatka Trench. The Kurils are a most seismically active region of the world. Tsunami is of serious hazard to onshore infrastructure. Tsunami is hazardous to subsea pipeline only in the landfall area. In the remaining part the effect may manifest in the form of alternating streams and sea-level variation within the range of tsunami frequencies.

Gas anomalies (shallow gas). Apart from increased seismic activity, Eastern Arctic seas of the RF including the Sea of Okhotsk are characterized by the presence of multiple tectonic dislocations. In the course of development in oil and gas condensate

fields of Kirinsky, South-Kirinsky, and Lunscoe, gas accumulation manifestations have been recorded in the upper part of the open cut in the form of “gas jets and gas blisters”.

In the course of exploration and production drilling in wells, shallow gas inflow has been received which significantly complicated the process of well construction. These facts determine conceptual solutions on field reserves development and complicate the implementation, regulation and control of the process of exploitation [3, 4].

Fig. 1. Seismic activity of Sakhalin island
a – once in 500 years; *b* – once in 1000 years; *c* – once in 5000 years
Рис. 1. Сейсмическая активность о. Сахалин:
a – 1 раз в 500 лет; *b* – 1 раз в 1000 лет; *c* – 1 раз в 5000 лет

The Kirinsky field. According to the data from the high-resolution seismic prospection, over the arch of the Kirinsky oil and gas condensate field, four anomalous zones connected with gas have been discovered: “gas pipe” characterized by total attenuation of the seismic signal (absence of reflecting boundaries); three zones of increased amplitudes (“gas blisters”) at the depths of 113–125 m (zone 1), 151–158 m (zone 2) and 206–220 m (zone 3).

Shallow gas accumulations in Kirinsky GCF are confined to quaternary sediments and sands of the Pliocene (N2). Fault zones are probably the ways of vertical migrations of gas from the underlying commercial pools of hydrocarbons.

According to the results of high-resolution seismic prospection and actual data in drilled wellbores, a generalized map of geological perils has been constructed in the area of the Kirinsky field. In order to reduce the risk of gas manifestations, a decision has been made to transfer the initial design drilling spots and locate the wellheads beyond the hazardous zones [5].

The Lunscoe field. In the course of the engineering-geologic survey, gas manifestations within the Lunscoe field have been studied in details. Lunsky structure represents a large brachyanticline intersected by the network of diagonal wrench-fault displacements contributing to field degasation. Here, like in the neighboring areas of the Kirinsky and South-Kirinsky fields in the upper part of the sedimentary cover, the zones of gas saturation have been discovered.

The “gas pipe” is recorded near the surface of the seabed and is about 260 m wide. Such advanced gas anomaly is most likely due to major disturbance of the Lunsky structure, thick productive strata and mean depth of occurrence.

The Neptun field. In the course of prospecting and exploratory drilling at Ayashsky license block on the shelf of the sea of Okhotsk, OOO Gazpromneft-Sakhalin faced the problems of shallow gas in the upper part of the open cut (depth up to 500 m) and loose

soil. According to the results of seismic analysis, local zones of speed reduction have been recorded and interpreted as possible zones of abnormally high formation pressure.

The technology of riserless drilling was used to reduce risks in this area. The technology has made it possible to sink first hundreds of meters with minor risks.

The problem of shallow gas is not unique for Sakhalin. It also exists in the Gulf of Ob, the Kara Sea, and the Pechora Sea, i. e. wherever potentially high content of gas is present. Gas-saturated sediments and isolated gas lenses are also frequently recorded when drilling in various parts of the world's oceans indicating their widespread and almost universal occurrence [6]. Shallow deposits of free gas may be developed due to the subvertical migration of gas from a major field [7]. Sufficiently thick impenetrable layers of clay playing a role of deterrent for further rise of gas may localize gas deposits at various hypsometric levels near the bottom surface.

In this regard, when drilling wells in the conditions of potentially gaseous upper part of the section, greater attention should be paid to planning process operations on uncovering the potentially gaseous section, personnel training and facilities preparation to prevent and eliminate emissions [8, 9].

Seabed gouging by ice. A characteristic feature of offshore oil and gas fields development, mining and exploitation is the need in making decisions on facilities construction and production transportation in the conditions of long-term or constant presence of drifting ice cover and seabed gouging (exaration) by ice.

Offshore fields development with the use of subsea pipelines is complicated by the "ice" factor. In particular, when transporting hydrocarbons from the subsea deposits to the shore or to the platform, it is crucial to take into account such hazardous phenomenon as ice gouging (ice exaration) when subsea parts of ice-hummocks and grounded ice-hammocks (stamukhas) impact the seabed and may break subsea production facilities causing irrecoverable damage to people and environment [10]. Because of the seabed gouging by ice there is a hazard of damaging subsea pipelines and subsea production facilities located at the depth of more than 25–30 m.

Special attention is mainly called by the coastal parts.

Ice cover and seabed gouging by ice create significant engineering challenges for subsea pipelines design, construction and maintenance. The determination of the optimal depth of pipeline location is a key factor in hydrocarbon transportation systems design.

Main methods of protection against seabed gouging may be protective trenches, caissons, berms, and islands.

Soil liquefaction. Liquefaction develops in loose and mean-density sandy saturated soil during seismic shocks. Soil loses shear resistance during liquefaction which in its turn results in side sweep of liquefied soil and the strata above it.

This effect may represent a risk factor for safe operation of subsea mining facilities, including subsea pipelines intersecting large area. For buried pipelines liquefaction may cause extra buoyant force. If vertical resistance is insufficient, pipes come to the surface. Support structures may also be affected during soil liquefaction [11].

Taking into account high cost of soil replacement in the areas of subsea equipment arrangement, the stability of manifold, baseplates, tee fittings, end termination of pipelines under the sea must be maintained by design.

Basic but not the only process solutions in constructing facilities of a subsea production complex may be setting the routes of pipelines in broken stone and annual monitoring the technical condition of the underwater production unit (fig. 2).

In the course of the offshore field development, along with geological risks, a number of risks should be taken into account which impact field development, including societal risk (risk of mortality due to accidents and emergencies), ecological

(environmental damage) and technological risks [12]. The indicated risks analysis makes it possible to develop an integrated approach to identification, assessment, management and monitoring of the offshore fields ensuring maximum efficiency of risks management in the course of the project implementation.

Societal risk. The societal risk characteristic of offshore fields with entirely subsea facilities differs from the societal risk present in offshore fields equipped with platforms (Lunskoe, Piltun-Astokhscoe, Arkutun-Daginskoe, etc.). If the facilities are entirely subsea, people are within the zone of possible damage in case of emergency at process facilities only within particular periods of deepwater operations (drilling, construction, maintenance and repair), all the rest of the time there is no mortality risk from emergency in this facilities. At the same time, construction and maintenance of subsea facilities requires wellhead platforms and a large number of vessels in the field, which is associated with increased risk.

Fig. 2. The sequence of dumping stone on the trench-mounted pipeline

Рис. 2. Последовательность отсыпки камня на трубопровод, смонтированный в траншее

Environmental risks. Environmental risks may happen at any stage of the project, from exploration to products shipment to consumers. Development and exploitation of the offshore fields and complex natural and climatic conditions significantly increases the risk of ecological emergencies and catastrophes disturbing ecological balance long afterward.

Main factors of environmental risks may be adverse seismic and natural factors, malfunction of equipment, design and construction errors, unqualified personnel, and unsafe professional behavior.

Technological risks. Increased accident rate, poor professional experience at subsea fields, engineering and technical complication, technological sanction restrictions are the components of the technological risk. There are technological risks at every stage of offshore oil and gas field development, from exploitation to distribution.

Risks of offshore fields development. Risks analysis has made it possible not only to reveal main risks of shelf projects, but also to develop basic remedial measures at the stage of design and implementation of a project (table 1). Likert scale ranging from 1 (rare, low) to 5 (frequent, high) has been used for high-quality assessment of risks by cross-sectional indicators of frequency and occurrence probability.

Insurance against technological risks, implementing best worldwide practices and shareholding promote to reducing technological risks when implementing the project, significantly increasing the validity of making investment decision and allowing to divide risks between the partners.

To reduce geological, societal, and ecological risks, the following measures may be taken as basic: planning actions on opening the potentially gas-containing open cut, applying the technology of riserless drilling, creating the legal framework, improving business processes, elaborating the plans of oil spill response, joint exercise, etc.; the indicated actions make it possible to improve industrial and environmental security of the project.

Table 1. Summary table of main risks
Таблица 1. Сводная таблица основных рисков

Main risks	Risk analysis		Remedial measures		Risk assessment (grade)
	Risk factors	Risk assessment (grade)	Actions	Risk assessment (grade)	
Technological	Lack of technology	5	Making an insurance against technological risks	3	3
	Complex natural and climatic conditions		Investing in technological development		
	Equipment failure		Implementing best worldwide practices		
Geological	Work in unknown conditions	5	Finding a technology partners	2	2
	Outdated infrastructure		Поиск технологического партнера (shareholding)		
	Lack of profession experience, etc.				
Societal	Seismicity of the area	4	Planning actions on opening the potentially gas-containing open cut	2	2
	Gaseous anomaly		Applying the technology of riserless drilling		
	Seabed gouging by ice		Designing subsea drilling and subsea pipelines with the account of the seismic hazard		
Environmental	Soil liquefaction	4	Applying structured approach	2	2
	Geodynamic processes		Predicting future development		
	Tightening the tax system		Creating the legal framework		
	Constraining political factors	4	Improving business processes	2	2
	Geopolitical events		Professional development of the personnel		
	Staffing shortage		Introducing updates in legislation with regard to taking measures on improving safety measures and tightening the requirements in the field of observing the standards of environmental legislation		
	Sanctions	4	elaborating the plans of oil spill response and joint exercise	2	2
	High water and leakage		Liability insurance		
	Accidents				
	Ecological disasters	4		2	2

In spite of hydrocarbons price volatility, increased rivalry and the intricacy of offshore oil and gas projects realization, the shelf segment of hydrocarbons production keeps its share in the global balance by means of the risk-oriented programs implemented by the companies aimed at high energy, economic and ecological efficiency.

Summary. Offshore oil and gas projects in arctic and subarctic zones are implemented in the conditions of high geological, technological, societal and ecological risks. In this regard, it is essential to apply modern safe technologies of subsea production of oil and gas based on the successfully implemented foreign projects.

Advanced analysis of the examined risks based on large oil and gas field exploitation, connected with the climatic conditions of Sakhalin island, has revealed that the main geological risks in the region are earthquake activity, shallow gas, seabed gouging by ice and soil liquefaction.

In the course of the exploration and production drilling in the fields of the Sea of Okhotsk, occurrence of gas accumulation has been recorded in the upper part of the section. Research results determined that shallow gas accumulation and related risks are widespread up to the depth of 550 m and more.

There is a hazard of damaging the subsea production facilities and subsea pipelines at the depth of less than 25–30 m due to the seabed gouging by ice in the offshore strip. This phenomenon is a particular factor of risk for secure operation of subsea production facilities including long subsea pipelines.

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Опасные природные процессы и риски при освоении морских месторождений с применением подводной системы добычи углеводородов**Дзюбло А. Д.¹, Савинова М. С.¹**¹ Российский государственный университет нефти и газа (НИУ) им. И. М. Губкина, Москва, Россия.**Реферат**

Введение. В статье рассмотрены основные риски (технологические, геологические, социальные и экологические), которые возникают при освоении, обустройстве и эксплуатации морских месторождений с применением подводной системы добычи углеводородов.

Целью исследования является анализ основных рисков при реализации морских нефтегазовых проектов, связанных с суровыми природно-климатическими условиями шельфа о. Сахалин, влияние их на объекты подводного обустройства морских месторождений и разработка мероприятий, компенсирующих выявленные риски.

Методика. Анализ рисков позволил выявить основные риск-факторы при разработке шельфовых проектов и предложить компенсирующие мероприятия, которые являются первоочередными при освоении морского месторождения на стадии проектирования и, главное, на стадии реализации проекта.

Анализ и обсуждение. Углубленный анализ основных рисков, основанный на фактических данных освоения крупных нефтегазовых месторождений, связанных с климатическими условиями шельфа о. Сахалин, показал, что основными геологическими рисками в регионе являются сейсмичность, приповерхностный газ, ледовое выпавивание морского дна и разжижение грунтов. В силу этого необходимо применение безопасных современных технологий подводной добычи нефти и газа на основе успешно реализованных проектов зарубежных стран и опыта освоения шельфа России.

Выводы. Эффективное освоение нефтегазовых месторождений на шельфе о. Сахалин возможно при условии учета и управления в ходе реализации проекта геологическими, технологическими, социальными и экологическими рисками на основе разработанных компенсирующих мероприятий.

Ключевые слова: шельф; риски; сейсмичность; газовые аномалии; разжижение грунта; ледовое выпавивание.

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