Universitetet i Stavanger

FACULTY OF SCIENCE AND TECHNOLOGY

MASTER'S THESIS

Study programme/specialisation: Marine and Offshore Technology	Spring semester, 2019 Open
Author: Kirill Obriashchenko Student number: 247461	(signature of author)
Supervisors: Ove Tobias Gudmestad (UiS), Yuri Apollonevich Sazonov (Gubkin University)	
Title of master's thesis: FEASIBILITY STUDY OF THE AYASHKINSKOYE LICENSE BLOCK (SAKHALIN OFFSHORE) DEVELOPMENT	
Credits: 30 ECTS	
Keywords: Offshore Field Development, Sakhalin Island, Sea of Okhotsk, Ayashkinskoye license block, Neptun, Triton, Gravity Based Structure, Subsea Production System, FEL analysis, CBA-analysis, feasibility study, ANSYS, GRP, Subsea protection, Dropped objects, Impact loads.	Number of pages: 92 + supplemental material/other: 10 Stavanger, June 15, 2019

Abstract

Keywords: Offshore Field Development, Sakhalin Island, Sea of Okhotsk, Ayashkinskoye license block, Neptun, Triton, Gravity Based Structure, Subsea Production System, FEL analysis, CBA-analysis, feasibility study, ANSYS, GRP, Subsea protection, Dropped objects, Impact loads.

Problem statement and objective

Despite several successful existing offshore Russian projects such as Prirazlomnoye, Arkutun-Dagi, Piltun-Astokhskoye, Chayvo and Kirinskoye, Russian continental shelf remains to be a unique perspective for future exploration and development activities. In terms of recoverable reserves, Sakhalin offshore takes the second position in the chart of Russian Offshore Oil&Gas reserves. There are nine existing projects on the Russian shelf near the Sakhalin island. However, only three from the nine projects have reached the status of being developed. Hydrocarbon production on the island is carried out mainly under the Sakhalin-1, Sakhalin-2 and Sakhalin -3 projects. The Sakhalin -3 project appeals itself as one of the further developments since it has not been fully explored yet. The only successful project, put in operation, is Kirinskoye field.

Nevertheless, there are other potentially perspective structures on the sites of Sakhalin-3. Among these is Ayashkinskoye license block which comprises several fields. The most perspective is Ayashkinskoye and Bautinskoye fields which have already been explored and received names Neptun and Triton respectively.

The objective of the Master's thesis is to come up with the possible solution of development of Ayashkinskoye license block. It is of great importance to narrow the criteria of choice to ensure the successful analysis to be performed as soon as all data would be available.

The superior design of the development was based on:

- analysing the environmental conditions and present challenges of North-East Sakhalin Offshore;
- investigating all existed offshore development projects in that region;
- analysing the status of exploration development of Ayashkinskoye license block;
- Inspecting relevant development technologies, suitable for this license area;
- Calculation ice loads on columns of GBS platform;
- Modelling cases of impact loads from dropped objects.

Scope of work

First four chapters give the comprehensive report on present environmental conditions and associated challenges of Sakhalin Offshore. In the third chapter, the summary is provided on the existed field developments in that region. The fourth chapter is dedicated to the description of Ayashkinskoye license block. In chapter five, the potential field development scenario, based on FEL-analysis, is described. The study is aimed to cover the first three stages of such analysis due to the absence of data. The rough CBA- analysis, workflow chart and principal field layout are developed. The logical field development choice is performed. Possible loads on structures are calculated. The sixth chapter deals impact loads on protection subsea pipeline GRP covers. Six cases modelled in ANSYS workbench simulation software are presented. The seventh chapter shows several relevant technologies for the prevention of oil spill in the sensitive regions of Sakhalin offshore.

Acknowledgements

I would like to express my deep attitude to both Universities: Gubkin and Stavanger University, respectively. I believe that only international cooperation in education and science would lead our society to a sustainable and safe future.

A very special thanks need to be given to my supervisor, Professor Ove-Tobias Gudmestad, whose continuous help during these two years of studying deepened my knowledge in the related sphere. I appreciate his precious help and wise advises in writing this Master Thesis, which would not have been done without his lectures and helpful tips. I appreciate his concerns about our studying in Norway too.

I am also very grateful to my supervisor from Gubkin University Professor Yuri Ap. Sazonov for his help and support and fresh point of view on some issues which have been touched in the scope of this work.

I would like to highlight the significant contribution of the scientific supervisor of the Programme professor Anatoly B. Zolotukhin. His efforts to create such unique joint Programme and give a chance to students to broaden their knowledge, gain new experience and to understand this unique and fragile world are highly appreciated, I believe, by all alumni of this outstanding Programme.

I would like to pass a sincere thanks to Professor Muk Chen Ong and PhD student Muhammad Ahmad Tauqeer for their support and coordination throughout the simulation part of this Thesis. In addition to this, I appreciate the University of Stavanger to provide workspace and powerful computer for the simulations. I also would like to thank PhD students Hui Cheng and Marek Jan Janocha for the help in working with ANSYS software and doing this project.

The experience of studying on this Programme would not have been possible without the sponsorship from the company "Gazprom Neft Shelf". I highly appreciate the help provided me to finish my Master's Degree.

Finally, the most important gratefulness goes to my family. Their support during all my education gave me a will to and courage to enter, study and finish my education.

Contents

List of Figures

List of tables

List of abbreviations

AFE – Authorization for Expenditure

BEP – Break Even Price

BPS – Booster Pump Stations

CAPEX – Capital Expenditures

CBA – Cost-Benefit Analysis

CIDS – Concrete Island Drilling System

CNOOC – China National Offshore Oil Corporation

COSL – China Oilfield Services

DPB – Discounted Payback Period

ERD – Extended Reach Drilling

FEL – Front-End-Loading

FPB – Friction Pendulum Bearings

FPSO - Floating Production, Storage and

FSO – Floating Storage and Offtake

Offloading unit

FY – first year (ice)

GBS – Gravity Based Structure

IRR – Internal Rate of Return

ITS – Integrated Template System

JVC – Joint Venture Company

LNG – Liquefied Natural Gas

MN – Meganewton

MODU – Mobile Offshore Drilling Unit

MPa - Megapascal

NPV – Net Present Value

OET – Oil Export Terminal

O&G – Oil and Gas

ONGC – Oil and Natural Gas Corporation

OPEX – Operational Expenses

OPF – Onshore Processing Facility

OSR – Oil Spill Response

PB – Payback Period

PI – Profitability Index

SALM – Single-Anchor Leg Mooring

SFDD – Suspended Flexible Docking Device

SPS – Subsea Production System

TLU – Tanker Loading Unit

USD – United States Dollar

Introduction

Despite several successful existing offshore Russian projects such as Prirazlomnoye, Arkutun-Dagi, Piltun-Astokhskoye, Chayvo and Kirinskoye, Russian continental shelf remains to be a unique perspective for future exploration and development activities. Russian Arctic is believed to be one of the most promising areas for O&G resources; approximately 60% of planned hydrocarbon production is believed to be derived from the Russian shelf by 2035 [1].

The zone of the Russian continental shelf nearly comprises 21% of the total area of all continental shelf areas among the global ocean, which is approximately 31.2 million square kilometres, as it presented in Figure 1. It is believed that 70% of this area seems to be perspective in the scope of the presence of resources, first and foremost, hydrocarbon endowments, such as oil and gas. Moreover, this zone of potential interest is about 4 million square kilometres, which are commensurable to the area of all Russian O&G deposits onshore [5].

According to estimates, recoverable hydrocarbon resources of the Russian shelf contain almost 100 billion tons of fuel equivalent, including 16,7 billion tons of oil and condensate and nearly 78,8 trillion m^3 of gas, which in its turn corresponds to 20-25% of world volume of hydrocarbon resources [6].

The most significant percentage (approx. 65%) of Russian shelf reserves accounts for the western Arctic seas, presented in Figure 1, such as Kara Sea (37.4%), Barents Sea (19.8%) and Pechora Sea (8.1%). The second place belongs to the Sea of Okhotsk (11%), East Siberian Sea (7%), Caspian Sea (4.6%), Chukchee Sea (4.2%), Laptev Sea (3.7%) and the Bering Sea (1.4%) [5].

One of the most useful and most developed sites among those listed above is the Sea of Okhotsk shelf, especially the region of Sakhalin island. It is connected with the fact that despite the superiority of resources of the Russian Arctic regions, the area of the Arctic is firstly aimed at the European market. The attempt of energy export to other markets faces the one, but a quite challenging problem – the presence of the only one ice-free port of Murmansk. Difficulties of large-capacity crude tankers transportation through the Danish Straits also plays an important role

5]. In light of these points, the value of Far East Russian assets plays a crucial role in the future energy policy of the country [7].

Figure 1. Hydrocarbon shelf production in Russia [6]

O&G industry remains to play a crucial role in the economy of the Sakhalin region; it is needless to mention that further developments would determine the economic wealth of that region. There have been identified 82 deposits of hydrocarbons on Sakhalin island and the adjacent shelf, including 64 on land and 18 on the shelf. Also, there nine fields on the shelf which have been already put in production [2].

There are nine existing projects on the Russian shelf near the Sakhalin island. However, only two from the nine projects have reached the status of being developed. Hydrocarbon production on the island is carried out mainly under the Sakhalin-1, Sakhalin-2 and Sakhalin -3 projects. The Sakhalin region is already getting a real return on oil and gas projects. Thus, the potential recoverable reserves in the Sakhalin-1 framework amounts to 307 million tons of oil and 485 billion m3 of gas. The possible recoverable resources of the next project Sakhalin-2 could comprise 182,4 million tons of oil and 633,6 billion m3 of natural gas [3].

In Table 1, the mentioned projects are placed one by one with recoverable or estimated reserves and with the operators.

Table 1. Sakhalin Offshore Projects [2], [4]

Project	Reserves	Operator
«Sakhalin-1» (Chayvo, Odopty, Aruktun-Dagi)	recoverable: 307 million tons of oil, 485 billion m^3 of gas	«Rosneft» (20%), ExxonMobil (30%), Sodeco (30%), ONGK (20%)
«Sakhalin -2» (Piltun-Astokhskoe, Lunskoye)	recoverable: 150 million tons of oil, 500 billion m^3 of gas	«Gazprom» (50% + 1 stock), Shell (27,5%), Mitsui (12,5%), Mitsubishi (10%)
«Sakhalin -3» (Veninsky block)	recoverable: 164 million tons of oil, 258 billion m^3 of gas	«Rosneft» (74,9%), Sinopec (25,1%),
«Sakhalin -3» (Kirinsky block)	recoverable: 75,4 billion m^3 of gas, 8,6 million tons of condensate	«Gazprom» (100%)
«Sakhalin -3» (Vostochno-Odontinsky block)	Estimated proved: million tons of oil, 30 billion m^3 of gas	«Gazprom» (100%)
«Sakhalin -3» (Ayashsky block)	Estimated proved: 97 million tons of oil, 37 billion m^3 of gas	«Gazprom» (100%)
«Sakhalin -4» (Zapadno-Shmidtovsky block)	Estimated proved: 235 million tons of oil, 396 billion m^3 of gas	«Rosneft» (51%), BP (49%)
«Sakhalin -5» (Vostochno-Shmidtovsky block)	Estimated proved: 212 million tons of oil, 245 billion m^3 of gas	«Rosneft» (51%), BP (49%)
«Sakhalin -5» (Kaigan-Vasiukansky block)	Estimated proved: 650 million tons of oil, 500 billion m^3 of gas	«Rosneft» (51%), BP (49%)
«Sakhalin -5» (Lopukhovsky block)	Estimated proved: 130 million tons of oil, 500 billion m^3 of gas	«Gazprom neft» (100%)
«Sakhalin -6»	Estimated unproved: 1,1 billion tons of oil equivalent	97% «Petrosah» (Urals Energy), 3% «SNK»
«Sakhalin -7»	Estimated unproved: 0,5 billion tons of oil equivalent	Not defined yet
«Sakhalin -8»	Estimated unproved: 320 million tons of oil equivalent	Not defined yet
«Sakhalin -9»	Estimated unproved: 295 million tons of oil equivalent	Not defined yet

In general, during the development of the Sakhalin-1 and Sakhalin-2 Projects, the volume of planned investments was: Under the Sakhalin-1 Project, $ 8.3 billion. (in the period 1999 - 2015); for the Sakhalin-2 Project - 12.7 billion dollars. (between 2003 and 2015) [8].

The Sakhalin-3 project includes four prospective blocks: Kirinsky, Veninsky, Ayashsky and East-Odoptinsky [3].

1. Environmental conditions of the Okhotsk Sea on the Sakhalin island shelf

1.1. Geography and resources of the Sakhalin region

The Sakhalin region generally could be considered as included in the zone of Arctic (subarctic) environment conditions. In Figure 2 below the Arctic region is placed above the red line, which is considered to be the polar circle. Alaska, Northern Canada, Northern Norway and Northern Russia are located in this region. The Russian Arctic shelf is located above the Polar line. Nevertheless, some regions on the globe could also be included in the list of places with harsh environmental conditions. Areas such as the Newfoundland, Caspian Sea and Sakhalin region have quite a harsh environment with the huge difference in annual temperatures, presence of ice, strong winds and currents [8].

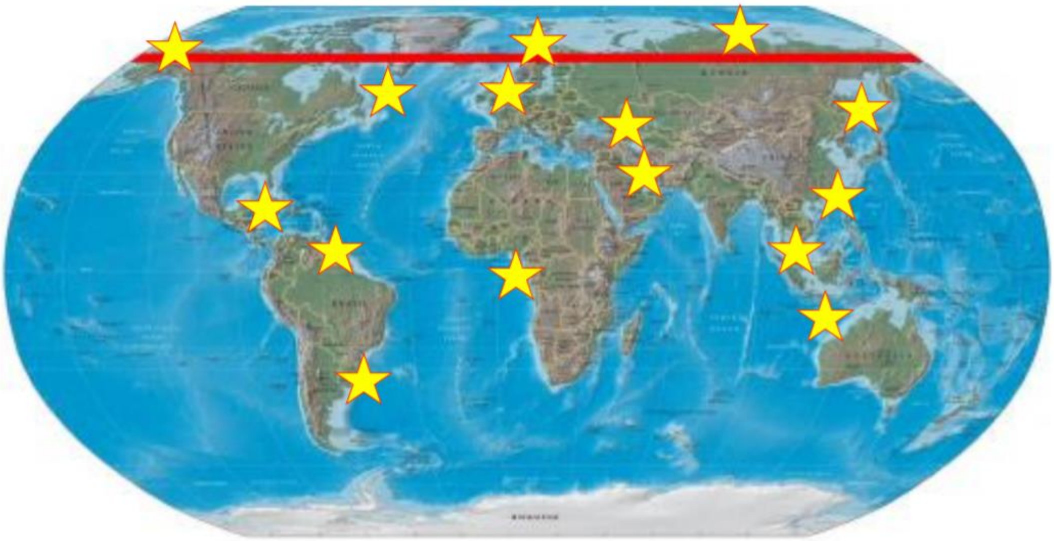


Figure 2. Offshore Petroleum Production Areas [1]

The island of Sakhalin is the largest among the Russian islands. Two seas wash the island: The Sea of Okhotsk on the east coast and the Sea of Japan on the south coast. It is separated by Tatar Strait from the mainland. The whole area is about 78 000 square kilometres. The island extends from north to south part over 950 km, and the width varies from 30 to 160 km [9]. The Sakhalin island is turned up as one of the most valuable Russian assets. Figure 3 demonstrates that Sakhalin offshore is considered to be in the second position of oil and gas resources of the Far-East of Russia. The region is also of great importance since it's shelf is the primary source of fishery production. Moreover, the presence of a unique nature, both flora and fauna, the rare endemics leads to the highest level of awareness of the requirements for offshore development projects [10].

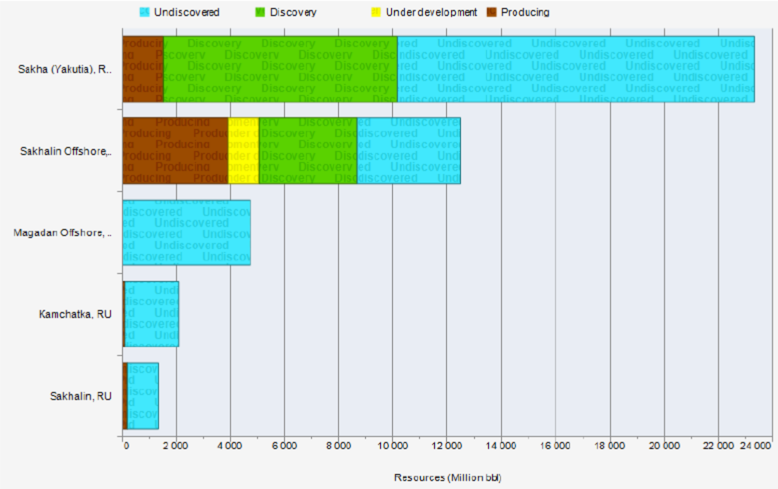


Figure 3. Oil and gas resources of Russian Far-East [8]

1.2. Geography of Okhotsk Sea

The Sea of Okhotsk is located in the Pacific Ocean. It is separated from the ocean by the peninsula of Kamchatka, the Kuril Islands and the island of Hokkaido (Figure 4). From the adjacent Sea of Japan is separated by Sakhalin Island. The sea washes the coast of Russia and Japan. It had the previous name of Kamchatka Sea. The area is about 1603000 km². The average depth of the sea is 821 m, the maximum extent is 3916 m. The western part of the sea is located above the sloping continuation of the continent and has a shallow depth. In the centre of the sea there are depressions of Deryugin (in the south) and the depression of TINRO. In the eastern part is the Kuril basin, in which the depth is maximum. The sea is located on the Okhotsk subplate, which is the part of the Eurasian Plate. The crust under the greater part of the Sea of Okhotsk is of the continental type [11].

Figure 4. Sea of Okhotsk location [12]

There are several human activities in this region: fishery (salmon, herring, pollock, capelin, navaga, and so on), seafood (Kamchatka crab), production of hydrocarbons on the Sakhalin shelf. The main ports: on the mainland - Magadan, Ayan, Okhotsk (port); on the island of Sakhalin there is port Korsakov, on the Kuril Islands - Severo-Kurilsk [11].

In the absence of data of the specific region of Ayshskoye license block, the present study uses the assumption that all weather and climate conditions would be the same as for the Chayvo or Piltun-Astohskoye fields due to quite small distances between hydrocarbon deposits (less than 30-40 km).

1.3. Weather conditions

The climate in the project area is determined by the northern position of the region and the mutual influence of atmospheric processes and the adjacent seas - the Sea of Okhotsk and Japan. These processes, in turn, affect weather conditions, geochemical processes, diversity and abundance of life forms of land and the marine environment (freshwater and marine ecosystems). The North Sakhalin climatic area, which includes the development areas of the Chayvo and Odoptu fields, occupies the northern lowland part of the island. This is the area of invasion of cold continental air in winter and cooled air masses from the Sea of Okhotsk in summer. It is characterised by severe, windy, relatively little snowy winter and cold overcast, with frequent foggy summer, excessive soil moisture. The duration of the frost-free period is from 50 to 154 days. The northeast coast is most exposed to the Sea of Okhotsk and is characterised by the coldest misty summer on Sakhalin [11].

1.3.1. Air temperature

The Sakhalin island is characterised by the short summer and continuous cold winter. The coldest month is January with average monthly air temperature from -19.7 °C to -21.3 °C (data for the sites - Chayvo, Odoptu, Nogliki and Pogibi). The absolute minimums for the listed points are from –44 °C to -47 °C. The average monthly temperature in winter is -22.8 °C. The temperature of the coldest five days in winter can reach from -30 °C up to -37 °C. Usually, the temperature below zero point remains to be approximately 200 days during the year. However, sometimes due to the thawing temperature could surpass the mark of zero degrees and go up till 1.6-2 °C. The transition of the average daily air temperature through 0 °C towards positive values occurs in late April - early May. The warmest month is August. In the territory under consideration, the average air temperature of this month varies from 11.5 °C to 15.2 °C, and the absolute maximum air temperature reaches 37 °C.

During the whole summer period, frosts are possible to form due to the invasion of the Arctic air and additional night cooling. The air temperature in July-August may drop from -1 °C to -3 °C. The average transition of daily temperatures over the point of 0 °C towards negative values is observed during October. The average air temperature from July to October is 8.9 °C - on the coast and 9.5 °C – in the sea. Usually, the first frosts in the north are observed at the end of September, and the latest ones are commonly seen in early June [13].

The values of temperatures are presented in Table 2 below.

Table 2.Monthly characteristics of air temperature (° C) on coastal weather stations [13]

Weather station	Month											
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Average temperature (°C)												
Nogliki	-18.7	-15.9	-9.9	-1.8	3.6	8.9	13.0	14.3	10.4	3.1	-7.4	-15.3
Chayvo	-20.3	-18.4	-12.2	-3.8	1.0	5.3	10.1	12.2	10.0	3.1	-6.7	-15.9
Average maximum temperature of air (°C)												
Nogliki	-14.0	-10.6	-4.7	2.5	8.8	15.2	18.7	19.5	15.4	7.7	-3.0	-10.9
Absolute maximum (°C)												
Nogliki	0.9	3.2	11.9	20.0	30.0	32.8	35.0	37.0	28.0	23.0	12.0	3.0
Chayvo	4.0	0.0	5.0	14.0	23.0	29.0	30.0	32.0	26.0	19.0	9.0	4.0
Average minimum air temperature (°C)												
Nogliki	-22.8	-20.6	-15.1	-5.4	0.0	4.5	9.1	10.7	6.6	-0.7	-11.1	-19.2
Absolute minimum (°C)												
Nogliki	-48.0	-44.0	-40.0	-28.0	-10.0	-5.0	-0.7	-1.0	-5.0	-19.9	-28.3	-39.0
Chayvo	-44.0	-44.0	-37.0	-31.0	-12.0	-4.0	-1.0	3.0	-5.0	-13.0	-27.0	-39.0

1.3.2. Air moisture

The relative humidity takes the most practical significance from all of existing moisture characteristics. It characterises the degree of air saturation with water vapor. On the coastal line and offshore zone, the change of relative humidity is negligible. The highest degree is achieved during summer due to the humid maritime air intake from southern latitudes which is cooled by the Sea of Okhotsk. During spring, there is air heating because of the cloud decreasing and increasing the degree of temperature. Thus, it gives a lower level of humidity. Vice versa, in autumn, the minimum of relative humidity is observed owing to the highest differences in temperatures. The amount of days with relative humidity less than 30% is approximately 12 per year. Also, for the maximum (more than 80%) is observed during 100-122 days per year [14]. The statistics from the onshore weather station Nogliki is presented in Table 3.

Table 3. Characteristics of relative humidity [13]

Weather station	Month												Year
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	
Average monthly and annual relative humidity (%)													
Nogliki	75	75	76	78	79	80	84	84	81	77	74	77	79
Amount of days with a relative humidity lower than 30%													
Nogliki	0.0	0.1	0.9	2.2	2.9	2.1	0.8	0.3	1.1	1.6	0.3	0.0	12.2
Amount of days with relative humidity higher than 80%													
Nogliki	6	5	7	9	11	9	12	12	8	8	6	8	100

1.3.3. Wind conditions

The leading transfer of air masses on Sakhalin is associated with monsoonal circulation in the atmosphere. Seasonal change of air currents due to thermal contrast between the continent and the ocean and a shift in the position of the main pressure elements (Pacific anticyclone, tropospheric fronts), affects the wind regime throughout the territory. In winter, in the northern part of Sakhalin, where the distorting influence of the relief is minimal, the winds of the north, north-west and west are predominant. The total repeatability in these areas is 55-77% [11].

Table 4. Wind conditions [15]

Latitude	Longitude	Wind velocity, m/s											
		Average				Minimum				Maximum			
		April	June	August	November	April	June	August	November	April	June	August	November
51.5	144	5.7	4.3	5.6	8.2	2.6	0.2	0.9	3.8	9.6	11.4	13.5	12.6

In Table 4, average, minimum and maximum velocities of wind in the nearest dot near the Ayashkinskoye license block are presented. The maximum velocities are observed during summer months (summer monsoon). The probability of no-wind conditions is relatively small, less than 5% cases per year. Figures 5 and 6 below present the frequency of wind direction. As can be seen from Figures, the dominant direction during the summer period is from the south or south-east direction; for the winter period, the north-east direction of the wind is prevailing. On the coastal line, one could observe approximately 24 days per year with the high-velocity wind. There are some observations, placed in Table 5, of very high-velocity wind till the 38 m/s during passed by deep cyclones [13].

Table 5. Maximum wind velocities [13]

Frequency (years)	**Maximum speed (m/s) on average during:**			
	1 hour	**10 min**	**1 min**	**3 sec**
100	28.6	31.4	35.0	39.7
50	27.5	30.1	33.5	37.9
25	26.4	28.9	32.1	36.3
10	25.1	27.4	30.4	34.2
5	23.6	25.7	28.4	31.9
2	20.5	22.2	24.4	27.2
1	19.5	21.1	23.1	25.8

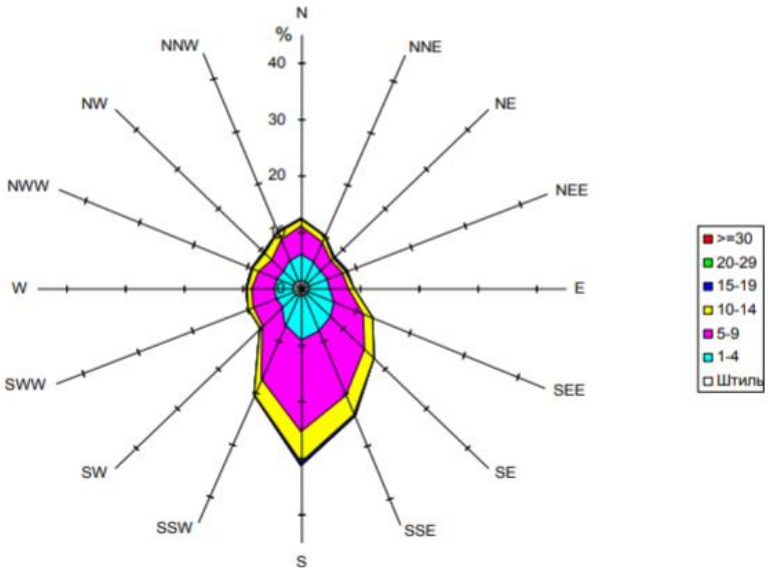


Figure 5. Frequency of velocities and directions of wind for the summer period [13]

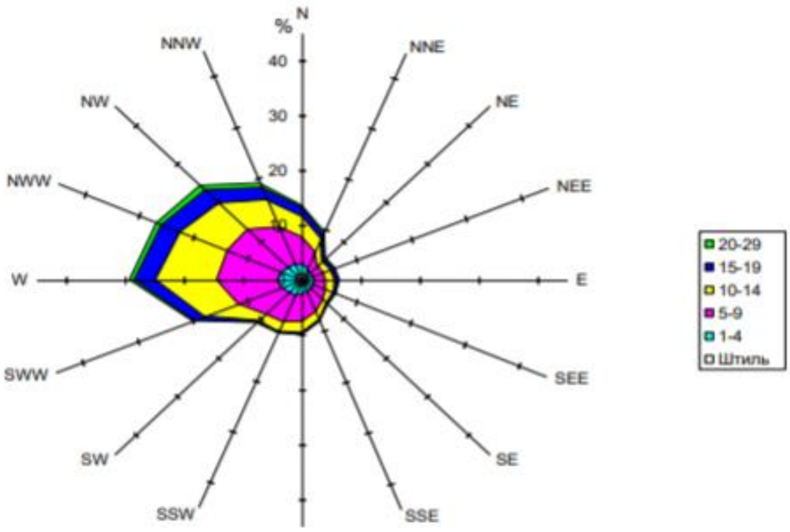


Figure 6. Frequency of velocities and directions of wind for the autumn period [13]

1.4. Hydrological conditions

The surface water temperature of the Okhotsk Sea in general decreases from the south to the north. Surface water layers are being cooled to the freezing temperatures, which are equal to -1.5: -1.8 °Celsius in the winter period. Spring heating at the beginning of the season is mainly connected with spending energy on ice accumulations melting, that is why that only at the end of the spring season the increase of temperature is observed. During the summer season, the water temperature distribution is quite distinct. In August the highest temperatures of water are observed on the territory of Hokkaido island adjacent waters. In the central part, the water temperature could rise to 19 °C. The most cooled surface waters were observed near the island of Iona and Krusenstern Strait (+6 °C) [16].

1.4.1. Wave conditions

The northern-eastern part of Sakhalin offshore is characterized by the undulation from the south and south-west directions with the wave heights less than 2 meters and periods on average 4.6-5.2 seconds (Table 6). During the period from October to November, there is 40% of wave frequency, which can be observed in the north-west quarter with heights of 2-3 m.

Table 6. Average values of wave heights and periods on the south-east Sakhalin offshore [17]

Parameter	**Months**		
	July – August	**September**	**October – November**
Average wave height, m	1.4	1.7	2.5
Average period, s	4.6	5.2	5.7
Predominant direction	South, South-East	South, South-East	South-West

The frequency of storm-generated waves with the heights of 4 meters and higher is relatively small (less than 7%) during the summer period. During the autumn period, it could increase up to 20%. The most hazardous in that case would be wind from the north-east direction which could generate waves with heights of more than 4 meters near the coastal line and heights in offshore zones with the height of 6 meters and higher. The highest wave height during the summer season could achieve the values of 7.8 meters, and for the period from October to November it could raise till 8-12 meters. In Figure 7, wave roses are presented during several annual periods [17].

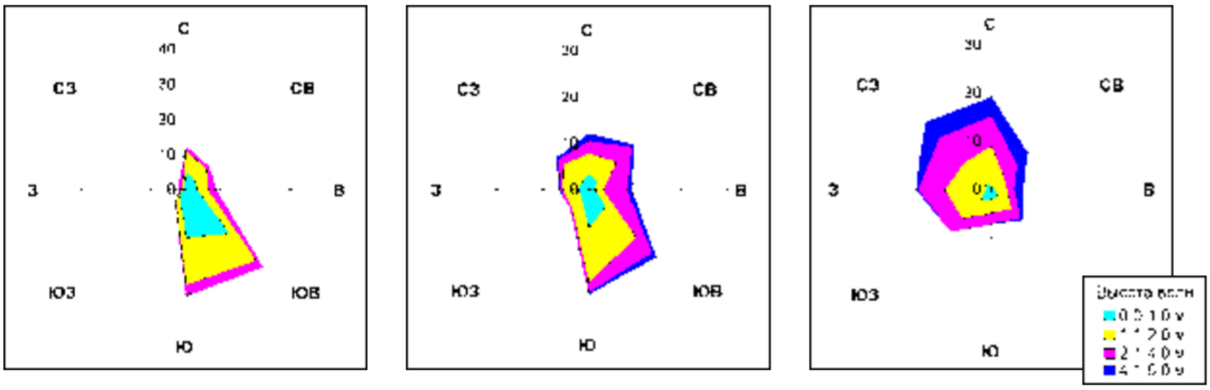


Figure 7. Wave roses during July-August, September, October-November in accordance [17]

1.4.2. Currents

Affected by winds and the flow of water through the Kuril Straits, characteristic features of the system of non-periodic currents of the Sea of Okhotsk are formed (Figure 8). The main one is the cyclonic system of currents, covering almost the whole sea. It is due to the predominance of the cyclonic circulation of the atmosphere over the sea and the adjacent part of the Pacific Ocean.

Besides, stable anticyclonic gyrals and extensive areas of cyclonic water circulation are traced in the sea [16].

Figure 8. Surface currents of the Sea of Okhotsk [16]

During the spring period, the average velocity of Eastern Sakhalin current is usually reduced until the values of 0.07-0.10 m/s. During the summer period, it slightly increases until the values of 0.1-0.15 m/s. The three-dimensional structure of such currents is not consolidated and could be inhomogeneous due to the presence of multidirectional flows both in shallow waters and deep offshore zones. During the autumn season, the picture of currents becomes more structural; the average velocities could be 2-2.5 times higher in comparison with the summer season [17].

The maximum velocities of reversing tidal currents, which are predominant in the region of North East of Sakhalin Island, are often observed during periods of May – June and December – January. The amplitude of the tidal current of daily waves K1 and O1 is, respectively, 0.40-0.45 and 0.30-0.40 m / s, and semi-daily M2 and S2 waves - 0.10 m / s. Amplitude total tidal flow is 0.70 m / s. In along the coast, tidal currents are asymmetric: maximum high tide speeds (south) are 10% higher than low tide speeds (on North). The south and southwest currents have the most repeatability, which reflects the combined effect of tides and the coastal periphery East Sakhalin Current. Second place in repeatability North and North-East (in the bottom layer - North-West) currents due to the ejection components of the total flow [17].

The averaged velocities of tidal currents of the northern part of Sakhalin island are presented in Table 7 below.

Table 7. Return period depth velocities [10]

Sea depth, m	Return period n, years		
	100	5	2
	Depth Velocity Profile (cm/s)		
0	189	165	165
5	184	149	148
10	184	149	148
20	178	144	143
25	152	118	117
30	87	53	52

1.5. Soil conditions of an area near the Chayvo Bay

The coastline of Northeastern Sakhalin in the Ayashkinskoye license area is characterized by a predominance of sandy sediments and active wave mode. The coastline is indented by lagoon bays, connected to the sea by narrow straits, entrances of various widths. Largest harbours are Piltun, Chayvo, Nyisky (the northern part is Dagi), Nabilsky and Lunsky.

Table 8.Sea bottom conditions [18]

Title	Description
Sea bottom topography	Sloping flat-bottom land (slightly hog-backed and hilly in local places
Sea depth (average level), м	63-93
Sea bottom soil	Tight hard-packed sands and gravel with some boulders (4-6m) in local places

In Table 8 the topography and type of the soil cover are presented. Figure 9 shows bathymetry and kind of soil distribution at the sea bottom. The structure of the relief indicates that within this section of the Sea of Okhotsk, tidal currents play the key role in the formation of sea bottom relief. They erode parts of the bottom and create sandy ridges and hollows between them [17].

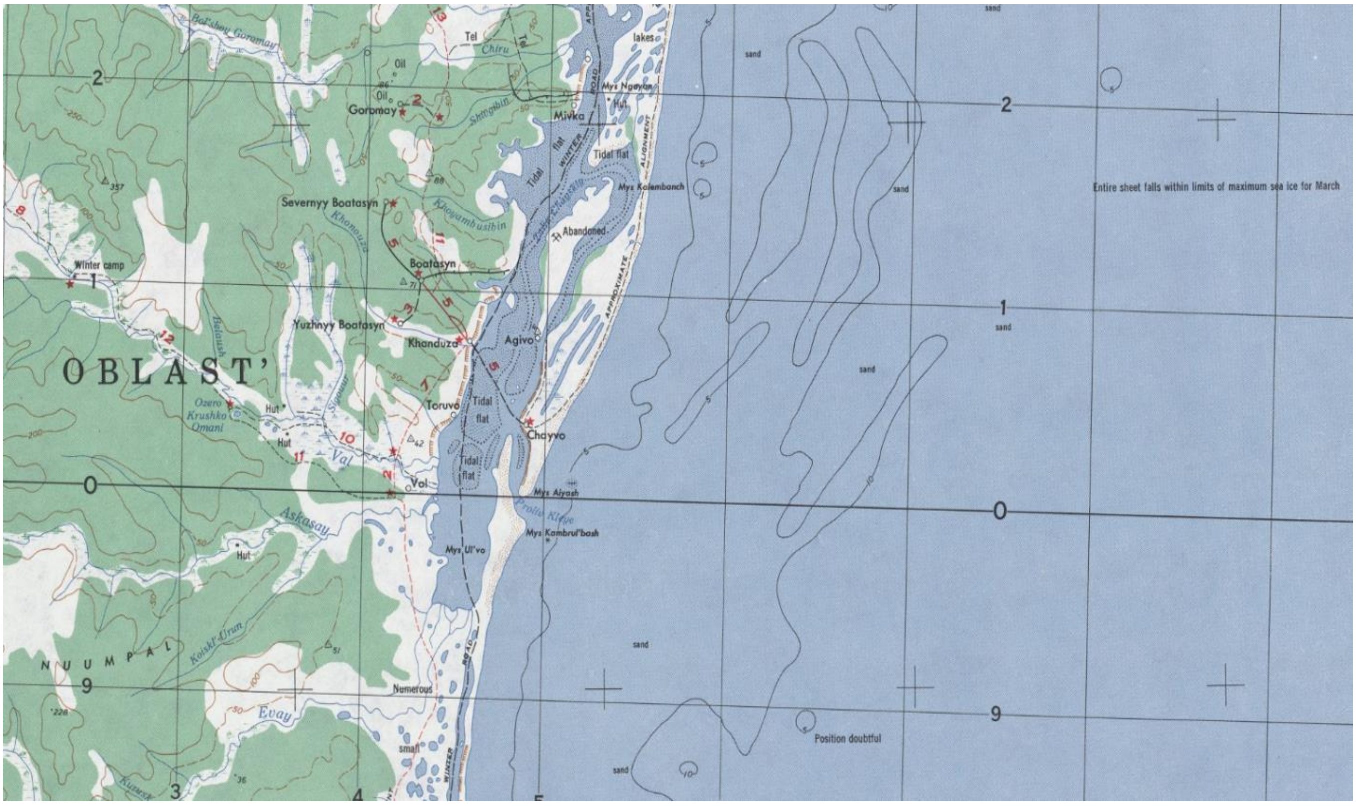


Figure 9. Bathymetry near Chayvo Bay [18]

1.6. Tsunami occurrence

Seismic events leading to the formation of waves with a height of 2.9 meters are estimated to be observed off the northeast coast of Sakhalin Island once every 50 years. Mathematical modelling for predicting a tsunami with a period of recurrence once every 100 years gives a wave size of Nabil 3.1 m, Katangli 3.9 m and Chayvo 5 m. The primary source of a tsunami in the Sea of Okhotsk are earthquakes occurring in the Pacific Ocean. Fortunately, the Kuril ridge assumes the bulk of the tsunami energy that would otherwise have spread to Sakhalin Island. As expected, the wave heights in the Tatar Strait and the Nevelsky Strait will be much smaller, reaching only 0.7 m in the case of a tsunami with a repetition period of 1 time in 100 years. However, as a result of the earthquake of September 29, 1878, a tsunami with a height of 2 to 5 m was recorded in the Tatar Strait [11].

1.7. Ice conditions

Ice forms, as a rule, at the end of the third week of November along coastal waters of the northeastern shelf (extending from 16 to 24 km from the coast). By February, the entire coastal zone is covered with ice, and ice hummocks begin to form. Ice hummocks, also known as stamukhas (ice formation, which could generate the ice keel during the collision of two layers of ice, making them tighten to form a keel beneath the waterline), occurring in this case, have a significant impact on bottom erosion, resulting in the disturbance of large areas of the seabed in areas of the sea with depths less than 30 m. Strong winds from the west or north-west drive pack ice into the sea, creating extensive wormwood along the coast. Conversely, strong winds from the northeast or east drive drifting pack ice back to the coast, creating even more ice ridges and hummocks. Many of these thickened pieces of ice are stranded and are often held to destruction. In years with typical weather conditions, the sea is cleared of ice by mid-May, and in years of severe winter by the end of June. The ice period can last up to 210 - 220 days a year [19]. The average ice concentration per 3 months is presented in Figure 10.

Ice cohesion on the northeast Sakhalin shelf may vary but usually remains high during the entire ice season. The thickness of the ice reaches 1.2 - 1.5 m in normal winter conditions. However, the ice formed in the sea off the coast of Sakhalin is almost always deformed, so it is difficult to describe it using only one measure of ice thickness. The total thickness of the drifting ice in the region is usually 3–4 m, with a maximum draft (ice keel) of the order of 10–15 m. Extreme ice keel depths can reach 20 m, but this is considered a rare occurrence [17].

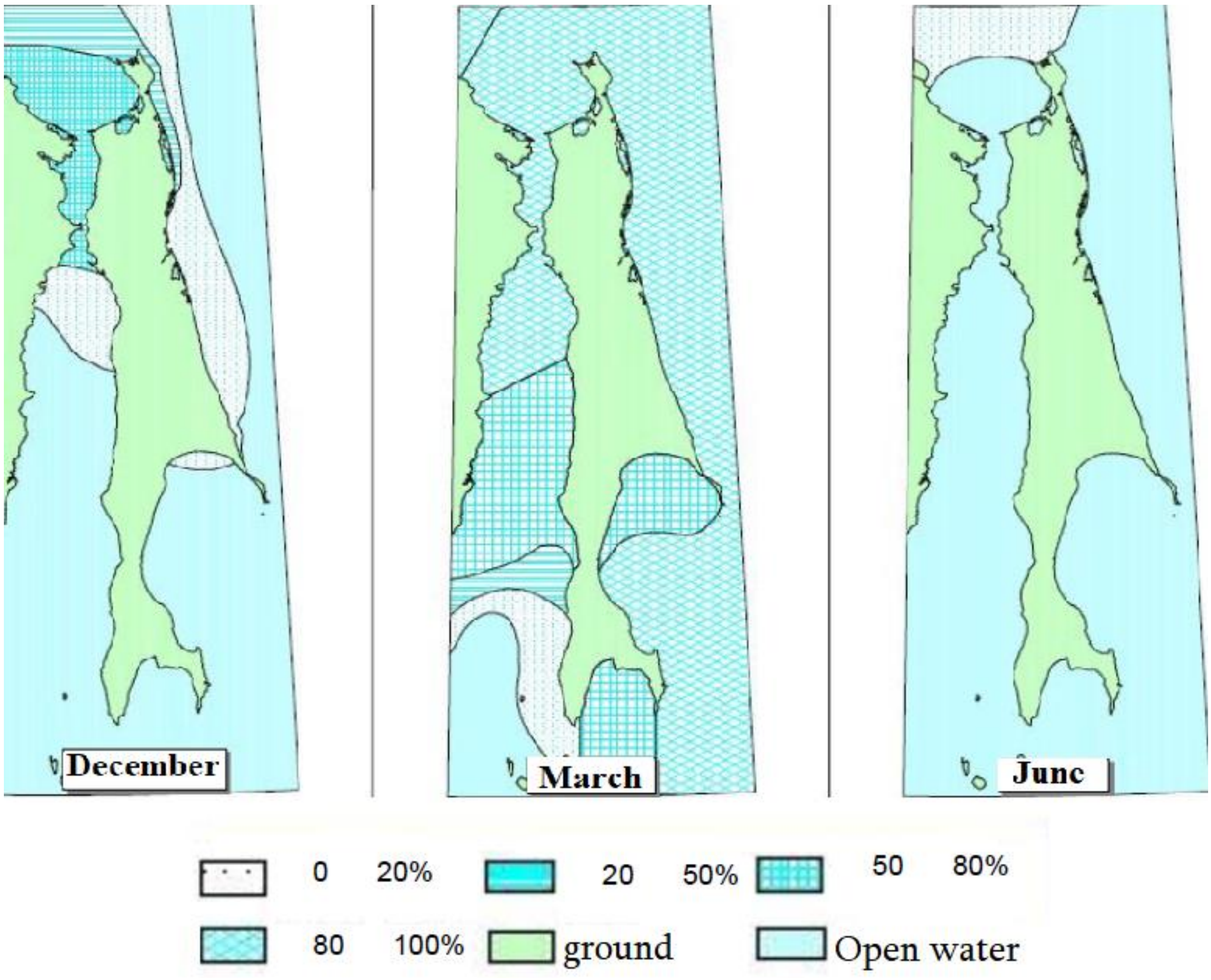


Figure 10. Average concentration of ice in December, March, June [17]

The drifting ice of the northeast Sakhalin shelf is very dynamic; the average drift velocity of ice floes is 0.4 m / s, sometimes reaching 1.5 m / s or more. Drifting ice moves mainly to the south, but in March, April and May one can observe the movement of ice to the north and in other directions. Tides can also affect the movement of ice (cyclical tidal drift). In practice, this means that the ice can move in any direction and at any time [8]. Table 9 presents the average annual and range of yearly values of region ice conditions.

Table 9. Ice conditions according to ISO 19606 [19]

Parameter		Southern Okhotsk Sea off the northeastern Sakhalin Island coast	
		average annual value	Range of annual values
Occurrence	First ice	20 Dec.	6 Dec to 1 Feb
	Last ice	10 May	19 Apr to 28 Jun
Level ice (FY)	Landfast ice thickness, m	0.8	0.4 to 1.7
	Floe thickness, m	0.8	0.3 to 1.5
Rafted ice	Rafted ice thickness, m	2.4	2.00 to 3.30
Rubble fields	Sail height, m	3.5	1.1 to 5.2
	Length, m	110	80 to 160
Ridges (FY)	Sail height, m	3.5	1.1 to 5.2
	Keel depth, m	13	5.0 to 23.5
Stamukhi	Water depth range, m	0 to 26	0 to 26
	Sail height, m	11.5	9.3 to 18.0
Ice movement	Speed nearshore, m/s	1.79	1.60 to 2.01
	Speed offshore, m/s	1.6	1.5 to 1.8

2. Present challenges of Sakhalin Offshore

As mentioned above the climate, hydrological and seismic conditions of the North-East Sakhalin offshore region provide the terms which could create the unfavourable meteorological and physical challenges. The main criteria, which defines the presence of adverse conditions, are all processes which could potentially increase the accident rate. Among the unfavourable meteorological conditions, which could make the marine operations more complex are fog, thunders, low visibility, snowstorms, hails or glazed rains, atmospheric icing and sea spray icing [21].

2.1. Snowstorms

The most unfavourable conditions characterise the winter period. One of them is snowstorms. The mechanism of forming severe snowstorms is during the movement of far-reaching cyclones from the adjacent seas: The Sea of Japan, Yellow Sea, East China Sea. The snowstorm is characterised by high wind velocities (more than 20 m/s) and severe snowfalls. The average duration of snowstorms on the coastal line as it showed in Table 10 could take up to 9-10 hours [20].

Table 10. Amount of days and snowstorm duration monthly [20]

Weather station	**Month**								**Year**
	I	**II**	**III**	**IV**	**V**	**X**	**XI**	**XII**	
The average amount of days with snowstorms									
Nogliki	0.6	5	8	7	7	8	4	0.8	40
The highest amount of days with snowstorms									
Nogliki	3	9	16	17	14	16	11	6	63
The average duration of snowstorms (amount of hours)									
Nogliki	4	40	86	71	71	78	42	6	398

2.2. Fog

The presence of fogs is frequent on the eastern coast of Northern Sakhalin. Fog is observed during the period from April to September. The absolute maximum of days with the presence of fogs could be up to 87 days annually. The Sakhalin fog conditions are created by the motion of heated air masses above the surface of the cold flow. The average duration of one fog case from the data of coastal weather stations for the warm period of the year is 8 hours and for the cold one about 4 hours.

Further away to the sea, the frequency and duration of fogs in the summer months increases substantially. The average duration of one case of fog for the navigation period reaches 18 hours. Highest average monthly duration of summer fogs ranges from 110 to 130 hours. In winter, fog is infrequent and short. The average long-term number of days with fog at this time of year (from December to March) is 1.1 days per month [20].

2.3. Thunders and glazed rains

According to the data of coastal weather stations, the probability of occurrence of thunders and glazed rains is rare. Moreover, the duration of such phenomenon is short. According to the data from coastal weather station “Nogliki” thunder frequency could take 4-5 days annually. For the glazed rain, the frequency is four days per 10 years. The local maximum of such natural phenomenon is found during September when there is a tendency of cyclonic activity expansion in the region. The duration of such events usually takes no longer than 1-2 hours, and the maximum period could be up to 6 hours [20].

2.4. Atmospheric and sea spray icing

The process of icing of ships and other offshore structures in the area of the proposed works, as well as in nearby areas of the Sea of Okhotsk, including routes of ships, is observed during the entire cold period of the year (from November to May), and in some cases, even in June, September. The area of heavy icing is presented in Figure 11 [20].

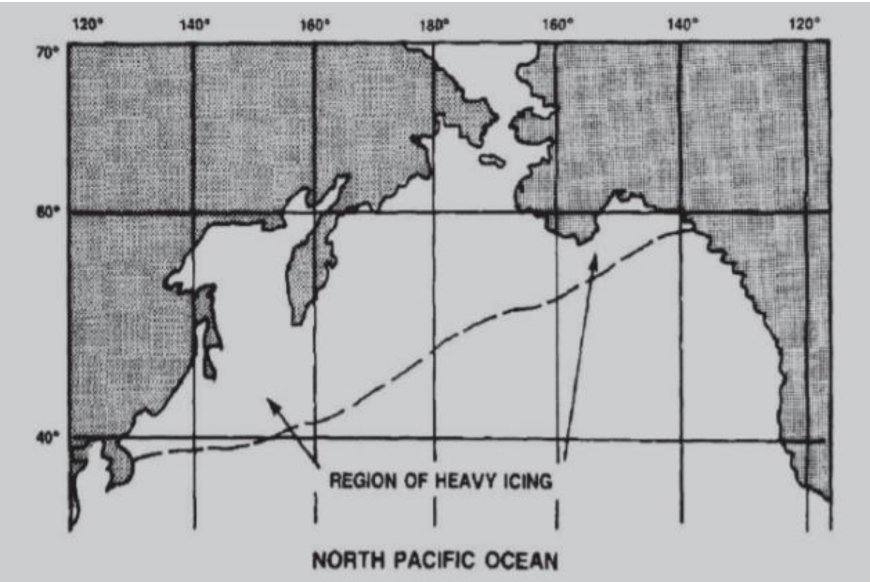


Figure 11. Icing region in North Pacific Ocean [5]

The icing effect plays one of the critical roles in offshore operations in northern waters. It has a tremendous negative impact in terms of vessel loss of stability. An example of such an accident is shown in Figure 12. Fishing boats, service and research vessels are under the significant influence and could capsize due to the decrease of safely level [22].

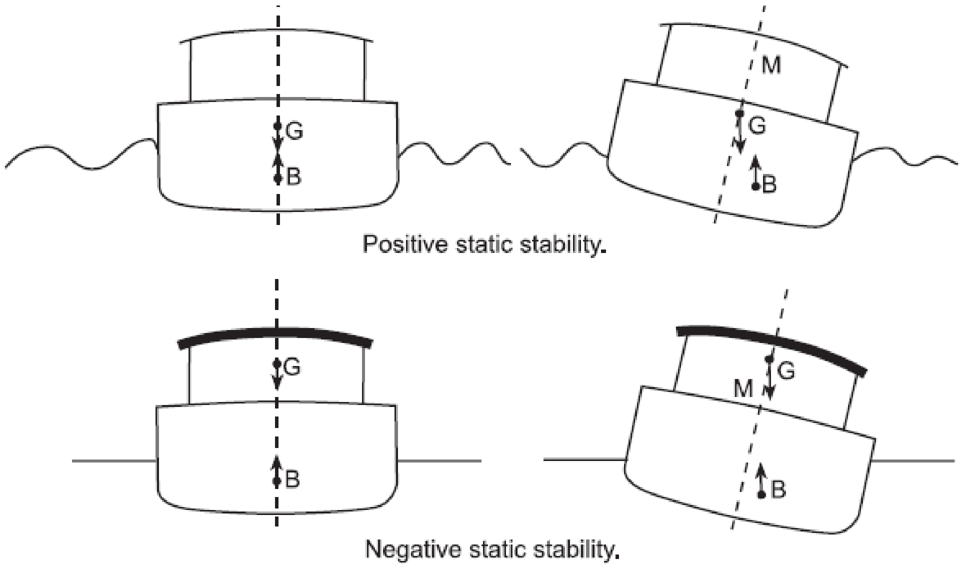


Figure 12. Example of positive and negative stability of the vessel [23]

The icing phenomena generally could be subdivided into two main parts:

- atmospheric icing;
- sea-spray icing.

The icing phenomenon is the ice growth accumulation which occurs while liquid water droplets or water vapor freeze on the vessel open surface and generate the ice layers. Water vapor, fog, cloud droplets, freezing rain could cause atmospheric icing. The origin of sea-spray icing is generally caused by wave interaction, or mostly, the interaction between wave body and the vessel's structure. Among the two mentioned above methods of ice generation, the sea-spray icing is the one which is the most significant, since the fact that its density and frequency is much higher [23].

The difficulty of prediction of ice accretion is because of numerous factors:

- upper water layer temperature;
- presence of waves and currents;
- wind direction and velocity (concerning the vessel's course);
- vessel speed and orientation (concerning wave, wind direction);
- vessel shape (open area of the deck, freeboard) [24].

It also should be noted, that the process of sea-spray icing could be subdivided into several stages: impact of the wave, wave breakup by the hull, droplet breakup, formation of cloud sea-spray, cloud acceleration and deceleration, droplet fall on the free surface. After the stage of breaking down the wave, there is a formation of sea-spray cloud. Numerous water droplets are being affected by drag and body forces. The body force refers to the gravity, which affects the droplets. Drag force occurs due to the relative velocity of these droplets and wind. Due to the effect of such forces, the vertical and horizontal component of velocity decreases until it reaches zero. At the moment of entering the zero velocity point, the droplet has its maximum height. Then, gravity forces again start to work, during the downward movement. The wind generates the horizontal component of droplet velocity. Acceleration of the droplets has both horizontal and vertical components and continue to grow until the moment of droplet hits the free area of the vessel's deck. In terms of droplets distribution, several factors play a crucial role: the various size of droplets, different velocity make the different trajectory of droplets [25].

The principal scheme of droplet distribution is presented in Figure 13.

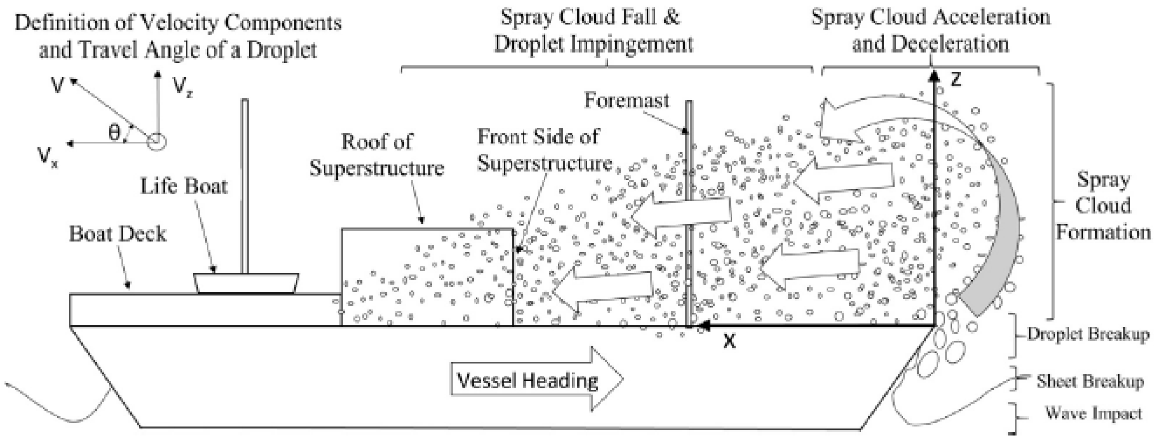


Figure 13. Stages of sea-spray development over the fishery vessel [13]

According to data from ship's observations, during the period from 1976 to 2016, more than 800 cases of icing are registered. The maximum is observed in December (35%), November (30%) and May (15%). Generally, the whole region of the North-East Sakhalin offshore is considered to be frequent and intensive in terms of icing accidents. The absolute maximum of all icing accidents is due to the sea-spray exposure (89%), other phenomena take a far lesser degree: fogs – 1%, precipitation – 2.1%, sprays with fog – 0.3%, sprays and precipitation – 1.9% [20]. The average amount of days per icing period is presented in Table 11.

Table 11. Number of days with sea-spray icing occurrence on the vessel decks [20]

Characteristic	**Month**		
	October	November	December
Maximum	2.0	14.0	21.0
Average	0.2	6.4	11.7
Minimum	0.0	3.0	6.0

Taking into account all challenges of the North-East Sakhalin Offshore, it should be noted that the Sakhalin offshore region is characterised by harsh conditions which could affect all human activity. Taking into account the possibility of forecasting, there is no possibility to predict with a high degree of accuracy regarding strong winds, precipitation, snowstorms. The accuracy is not high due to the fact that the mentioned phenomena are related to cyclone motions, which trajectories and development trends could be predicted for several days. For the case of fog generation/diminishment, it is possible to predict the situation with an advance time of one day or less, thunderstorms and glazed rain – only up to 1-6 hours. The confidence level to such forecasts is relatively low [20].

The summarized data of unfavourable conditions for the navigational season is presented in Table 12.

Table 12. Average and maximum number of days with unfavourable weather conditions for navigational season months [20]

Unfavourable conditions	**Month**						
	June	**July**	**August**	**September**	**October**	**November**	**Navigational season**
Wind higher than 15 m/s							
Average	1.9	2	2	4.9	7	9.4	27
Maximum	6	5	6	11	14	16	58
Fogs							
Average	18	22	12	5	2	1	60
Maximum	23	29	24	13	7	5	87
Snowstorms							
Average	0	0	0	0	2	13	15
Maximum	0	0	0	0	5	20	25
Thunderstorms							
Average	0.6	1	1	0.7	0.1	0	3.4
Maximum	3	5	4	4	1	0	10
Precipitations higher than 5 mm							
Average	3	4	4	5	4	4	24
Icing							
Average	-	-	-	-	0.1	6.4	6.5
Maximum	-	-	-	-	2	14	16

3. Existing Field Development Projects of Sakhalin Offshore

As it was mentioned before, the Sakhalin offshore zone is one of the most valuable Russian Federation assets in terms of resources and geographical position of the island. One of the main advantages of the region is a unique location in the Far-East region. This fact allows transporting energy resources to the world markets by shipping routes, especially to the Asia-Pacific markets.

It is essential to mention that oil production on Sakhalin has been conducted for a long time. By the end of 1928, the Sakhalinneft Trust produced 6,000 tons of oil in the Okha region, 240,000 tons by the end of the first five-year plan. The Northern Sakhalin itself could not consume that volume of oil, and in the most challenging war period for the country in 1942, the Okha-Sofiysk oil pipeline was designed and manufactured to join the island and the mainland. In the 1970s, exploration of the Sakhalin shelf has been already carried out, and soon the first wells were drilled at the promising structures, which gave a commercial flow of oil. Thus, the first large oil and gas deposits of the Russian shelf were discovered near the already developed and producing onshore ones. It turned out that the area of the shelf which could contain hydrocarbons is approximately equal to the area of the entire island. Most of the deposits are located in a zone of relatively small depths - up to 200 m. The first deposits were explored closer to the coast: Odoptu - in 1977, Chayvo - in 1979, Lunskoye - in 1984, Piltun-Astokhskoye - in 1986, Arkutun-Dagi - in 1989, and then others. But not yet appraised promising structures are much more; they stretch from the south, from the Cape Terpeniya, along the entire eastern coast of the island, and go beyond its northern tip to the sea, far to the north. To conclude, reserves of the Sea of Okhotsk make up 15% of the stocks of the shelf of Russia as a whole. Almost all of them belong to the Sakhalin shelf [26].

Already open deposits and prospective structures are divided geographically into nine parts. Relevant development projects were named from Sakhalin-1 to Sakhalin-9. To the present moment, only three of nine existing projects are being developed: Sakhalin-1, Sakhalin-2 and Sakhalin -3.

3.1. Sakhalin-1 project

Sakhalin-1 comprises the development of the Chayvo, Odoptu, and Arkutun-Dagi fields located in the north-east of the island. Potential reserves - nearly 307 million tons of oil and almost 485 billion cubic meters of gas. Exxon Mobil (30%), Rosneft (20%), Japanese Sodeco (30%) and Indian ONGC (20%) own stocks in the project. In 2006, the Chayvo-De-Kastri oil pipeline, the onshore oil processing complex and the export terminal in the De-Kastri port were commissioned, from where tankers ship oil to Japan and South Korea. The concept itself consists of three fields on the Sakhalin shelf: Arkutun-Dagi, Odoptu and Chayvo. Figure 14 illustrates the project [27].

Figure 14. Facilities of Sakhalin-1 [27]

Chayvo Offshore Field is the first of three fields in the block of Sakhalin-1 project. The project was developed by options from the shore by the Yastreb drilling rig and by the marine drilling with the help of the Orlan Offshore Platform. This platform is a reconstructed GBS platform CIDS (Alaskan Concrete Island Drilling System). This option was chosen in order to have savings via the development of the field. The result of savings gave the reduction of more than 100 mln USD in comparison with manufacturing the new platform. The platform was towed to Russia, then repair works were conducted, mainly for the strengthening to withstand heavy ice, wind and wave loads, ice load is presented in Figure 15. The whole topside equipment was also have been modernized to fulfil all the conditions and requirements. Offshore processing equipment is at the required minimum; the entire processing process is conducted at the Chayvo Onshore Processing Facility (OPF). The sea depth in a field location is approximately 15 m [28].

Figure 15. Orlan production platform [27]

The onshore arctic drilling rig “Yastreb” at Chayvo then was relocated to the field Odoptu in 2008, in order to conduct ERD operations. A specially built onshore processing facility transports hydrocarbons via the flow line from the Odoptu field to the OPF at Chayvo site. The drilling rig “Yastreb” is designed for offshore operations. The new technology makes it possible to do without significant CAPEX and OPEX for large offshore structures, as well as a low level of negative impact on sensitive coastal areas.

Using the Yastreb drilling rig, it is possible with the precision of the cluster pad located on the island to accurately guide the well up to 3 km vertically, and then with a deviation of more than 10 km in the horizontal direction for accurate penetration of offshore oil and gas deposits. The dimensions of the “window” of displacement (i.e., the tolerance) of the bottom hole relative to the target object position are within 1/3 m (1 ft.) vertically and 6 m (13 ft.) horizontally). The unit is fully prepared for operation in winter conditions and is the largest and most powerful unit used in the oil industry [28].

Another facility was put in development for other fields of Sakhalin-1 block development. The field Arkutun Dagi is located 25 km to the East of Chayvo field. Again, the gravity-based structure was chosen for that field. The platform named Berkut was installed. It is a specially designed GBS, as for the case of Chayvo field development. The structure is also designed to withstand high ice, wind, wave loads, including seismic loads. It is a four-column gravity-based structure (Figure 16); the sum weight of the construction is approximately 50,000 tones. The platform is placed at the site with average sea depths 15 to 40 meters [27].

Figure 16. GBS Berkut platform [27]

Chayvo Processing Facility (OPF)

Produced volumes of hydrocarbons are being transported to the shore on Onshore Processing Facility. The designed facility capacity could process nearly 35,000 tons of oil and approximately 22 million m 3 of natural gas per day. The oil, after being processed on the OPF, is shipped to the De-Kastri terminal. Natural gas processing is aimed to achieve two goals. The first one is to supply the Russian Far-East, and another one is to reinject some volume of the gas to control the reservoir pressure [28].

The modular concept of the processing unit was taken to fulfil all the requirements. OPF processing plant consists of several blocks, including:

- inlet slug catchers;
- three phase separators;
- handling of natural gas and its compression;
- export oil pumps;
- water treatment of produced water and its disposal with the help of onshore wells;
- Control rooms, machinery blocks, living quarters, warehouses and so on [29].

Figure 17 summarises the principal scheme of Sakhalin-1 development. All produced hydrocarbons are pumped to the Onshore Processing Facility. The separation and stabilization process takes place there to prepare oil and gas for further transportation and shipping. Oil is then being transported via pipeline transport across the Sakhalin island and Tatar Straight. Water and gas treatment is performed to reinject them to the reservoir to maintain the pressure. Other natural gas volumes are being transported for sale, including personal usage on the platforms as an energy source [27].

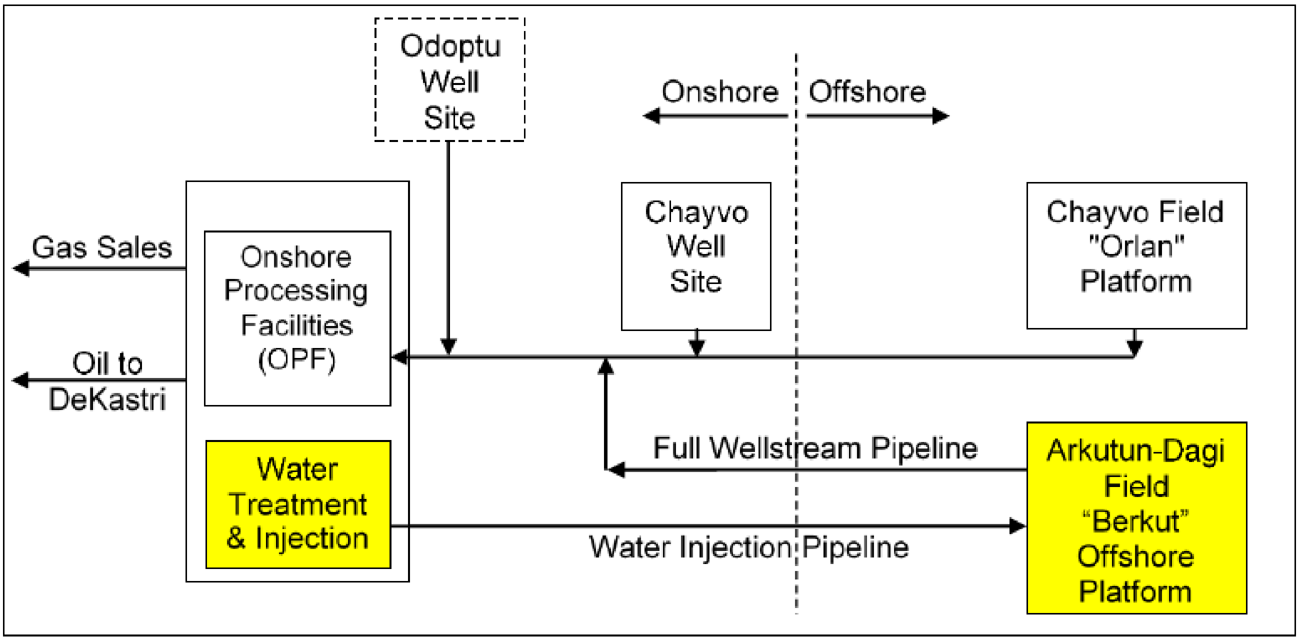


Figure 17. Integration of Arkutun-Dagi integration into system of Sakhalin-1 Project [27]

3.2. Sakhalin-2 project

Sakhalin-2 involves the development of the Piltun-Astokhskoye oil, gas and condensate field and Lunskoye gas field, located 15 km off the northeast coast of the Sakhalin Island. Total recoverable reserves - 307 million tons of oil and 485 billion cubic meters of gas. It is the first Russian offshore project with the construction of offshore oil platforms and a gas liquefaction plant. The operator is the Sakhalin Energy company, formed in 1994 by Royal Dutch Shell, Mitsui and Mitsubishi, which created a joint venture for the development of Sakhalin-2. In 2006 Gazprom entered the consortium, given that the company bought 50% plus one stock [28].

Generally, the Sakhalin-2 project is considered as a twin brother of Sakhalin-1. There are two fields: Piltun-Astokhskoye oil field and Lunskoye natural gas fields. The development infrastructure includes three GBS platforms for offshore drilling and production, subsea pipelines, OPF, oil export terminal, LNG plant, onshore Trans-Sakhalin pipeline transportation system which are presented in Figure 18 [28].

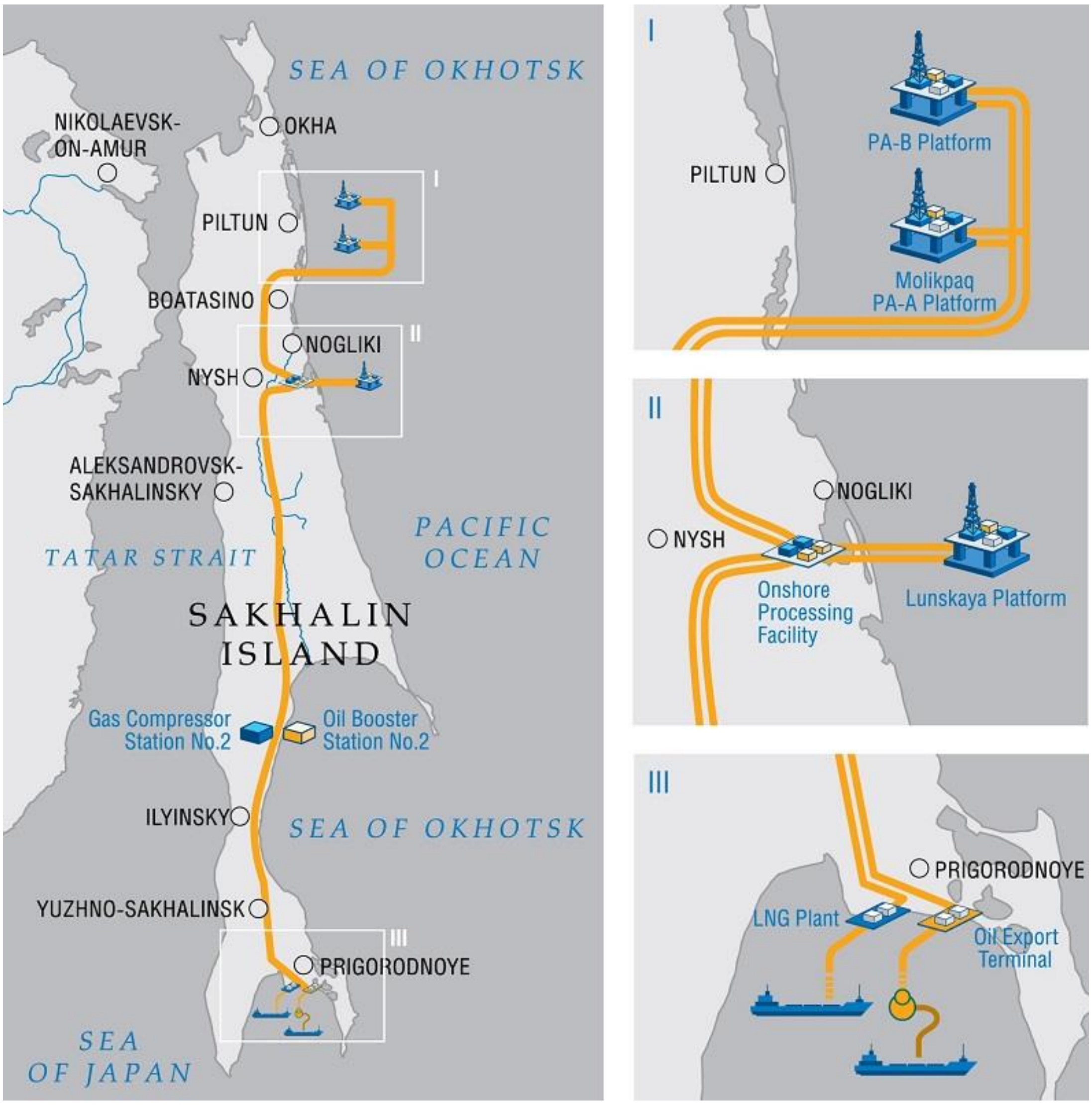


Figure 18. Sakhalin-2 project facilities (Picture courtesy of Sakhalin Energy company)

The development process began in 1996; then, the project partners established the plan. The first stage of development consisted of the installation of a platform on the Piltun-Astokhskoye oil field. The oilfield is located on 16 km distance from the Sakhalin coast to the East. The average depth is nearly 30 m. It was decided to use the Molikpaq offshore oil production platform, which should be redesigned for new conditions. Also, the FSO unit was considered to be installed (Figure 19) [27].

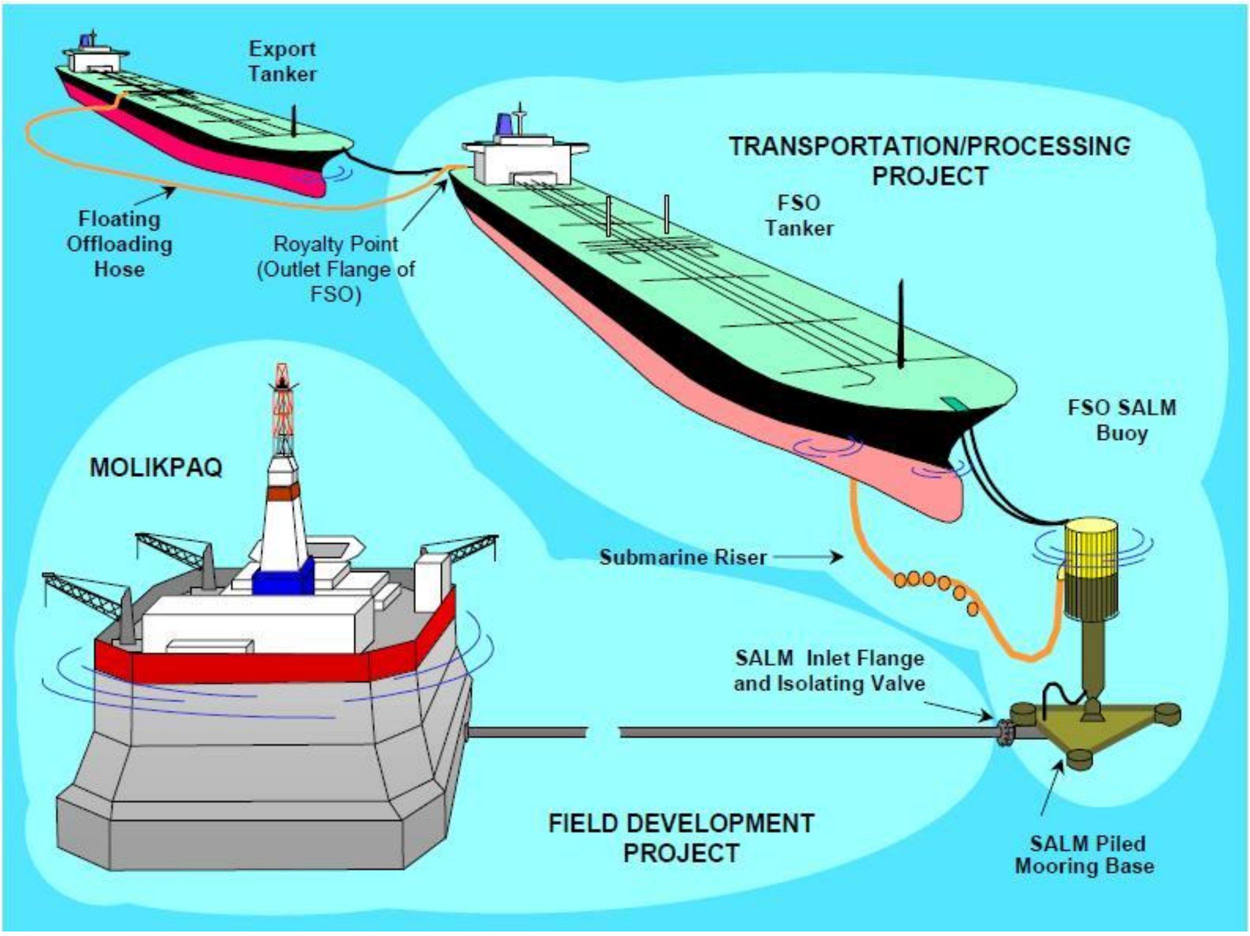


Figure 19. PA-A Phase-1 Development plan (Picture courtesy of Sakhalin Energy company)

The Vityaz production complex is a massive modernization of the Molikpaq platform, which was manufactured in 1984 as an octagon structure. The American Bureau of Shipping assigned 1AA Ice Class to this drilling unit. It has been used only as a drilling rig in the Beaufort Sea. Then, in 1997, it was towed to South Korea to provide all needed equipment for the production function [30].

In order to operate in Sakhalin conditions, especially at greater depths, than it was initially designed for, it was decided to make a steel basement for depths greater, than 15 m. This basement, named "Spacer" was manufactured in Russia and then combined with the Molikpaq platform as it showed in Figure19 [28]. After the successful installation the central platform core, presented in

Figure 20 was filled with sand in order to provide stability against the wave, ice, wind and seismic loads during the whole production life of the platform.

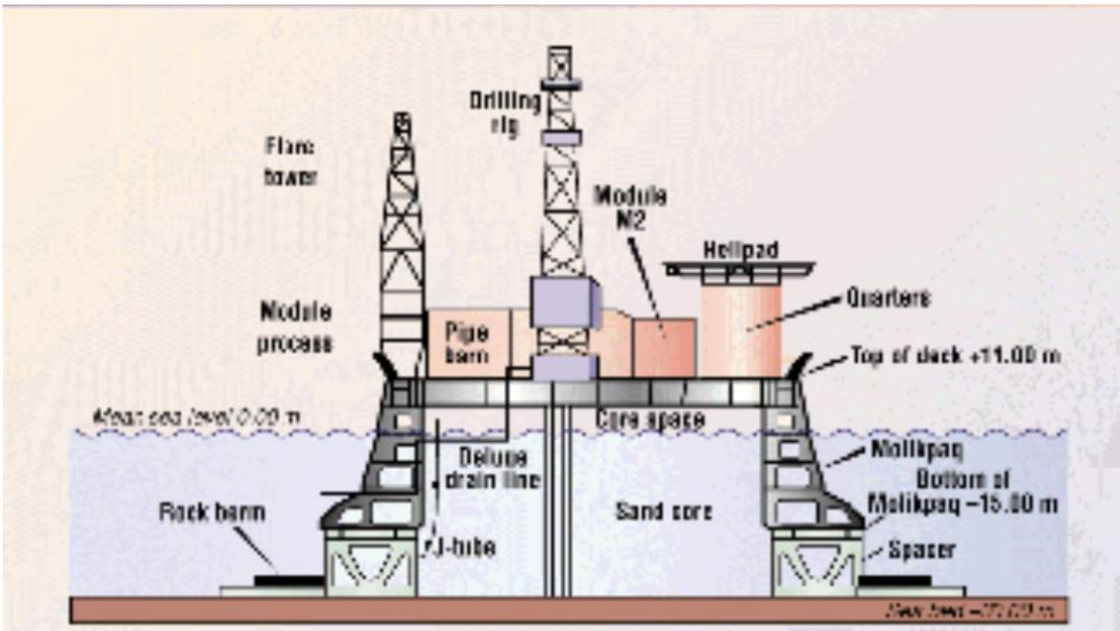
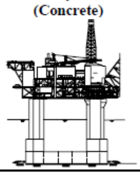
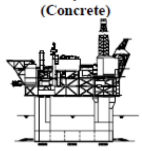


Figure 20. Cross section of Vityaz Production Complex (Picture courtesy of Sakhalin Energy Investment)

To offload produced oil, the subsea pipeline of 324 mm was installed between a platform and a Single Anchor Leg Mooring buoy (SALM). Then it was transported by double hull vessel “Okha” [30].

The second stage of development started in 2003. It involved the further development of the Piltun-Astokhskoye (PA) field and touched the new area of Lunskoye field. It was considered to use to platforms: one on the PA field (PA-B platform) and Lunskoye-A (or Lun-A) at Lunskoye field (Figure 21). The produced hydrocarbons then were pumped via multiphase subsea pipelines to the Sakhalin shore on the Onshore Process Facility (Sakhalin-2). Then, treated gas was transported via onshore Trans-Sakhalin pipeline system to the LNG plant in the south of the Sakhalin island [31].

Platform name		Lunskoye	Piltun-B
Foundation Type		Gravity based (Concrete) 	Gravity based (Concrete) 
Sea depth, m		48	34.5
Topside clearance, m		21	21
Topside steel mass, t		21000	23000
Foundation mass, t		38400	26500
Solid ballast mass, t		111000	79300
Product storage mass, t		-	-
Wave	Horizontal	320	151
	Vertical	440	427
	Overturning moment	4800	4200
Ice	Force	237	255
	Overturning moment	11020	9600
Seismic	Force	790	648
	Overturning moment	58600	16480

Note: 1 Force is in MN, Moment is in MN*m

Figure 21. Features and environmental loads on GBS platforms [31]

The development concept was taken as for the first stage; two gravity-based structures were decided to be installed. The principal design is identical: four-column GBS platforms with an integrated deck. The design also includes Friction Pendulum Bearings (FPB) which allows isolating the influence of seismic activity. The main platform features are listed in Figure 21.

Trans Sakhalin onshore pipeline system

For the transportation of the produced oil and gas Sakhalin Energy company has built an extensive pipeline system, which goes through the whole island (Figure 22). The Trans-Sakhalin pipeline system comprises nearly 300 km of offshore pipelines, more than 1,600 km of onshore pipelines, 105 shut-off valve nodes, five emergency recovery points and two booster pump stations (BPS), one of which is located at the OPF. Oil and gas pipelines go from the point where offshore pipelines reach the Piltun-Astokhskoye field in the north of the Sakhalin island, through the Onshore Processing Facility (OPF) to the south of the island, where the LNG plant and the oil export terminal are located. Each of the two tranches of pipelines (one for oil, the other for gas) has a length of 800 km [28].

The distance from the pipeline access point from the Piltun-Astokhskoye field to the OPF is 172 km (the diameter of the pipeline in this part of the route is 508 mm for both the oil and gas pipelines). The distance from the OPF to the LNG plant and the Oil Export Terminal (OET) is nearly 640 km (this part of the route: 610 and 1220 mm for the oil and gas pipeline respectively). Two short pipelines for multiphase transfer (diameter 762 mm, length of the coastal part of 7 km) and monoethylene glycol (MEG) pipeline 102 mm in diameter, along the same route, they connect the point of coastal contact in the Lunskoye field area with the OPF. The path of oil and gas pipelines passes through 19 tectonic faults. Each pipeline was laid in its trench (with backfilling of at least 0.8–1 m above the pipe). The outer surface of the pipelines has a three-layer polyethene coating to protect against external corrosion [28], [32].

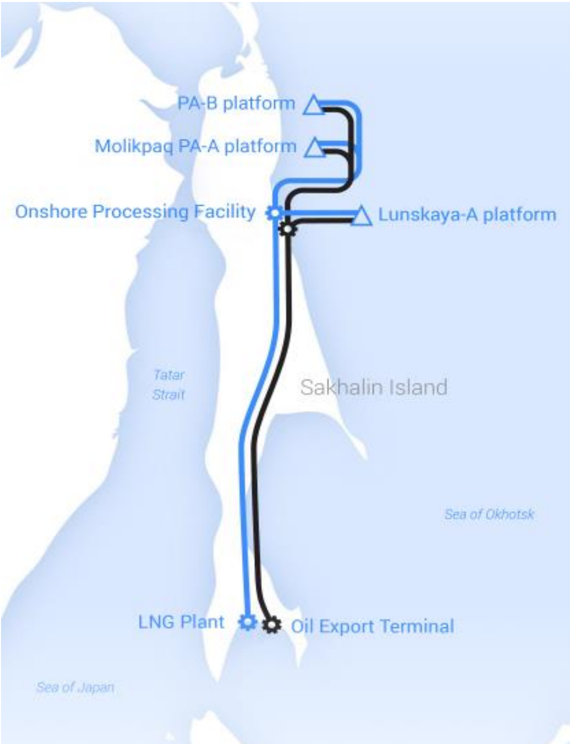


Figure 22. Pipeline route [Picture courtesy of Gazprom]

The facilities of the Prigorodnoye Production Complex located in the south of Sakhalin on the coast of the almost non-freezing Aniva Bay include an LNG plant with a loading boat landing and an Oil Export Terminal (OET) with a suspended flexible docking device (SFDD) which is located in the sea about 5 km from the coast. Prigorodnoye Port is the first Russian seaport built specifically for servicing LNG vessels and oil tankers. In May 2008, by order of the Government of the Russian Federation, the port was open for international communication [33].

LNG plant

The plant, located on an area of 490 hectares, includes two parallel production lines with a nominal capacity of 4.8 million tons of LNG per year and general-purpose facilities. Production consists of five stages: compression, purification, dehydration, fractionation and, finally, gas liquefaction. Especially for the Sakhalin Energy plant, Shell has developed a gas liquefaction technology using a dual mixed refrigerant. This technology, taking into account the Sakhalin climate, ensures maximum production efficiency in cold Sakhalin winters with the optimum operation of compressors. After liquefaction, LNG is delivered to storage in two tanks with a capacity of 100 thousand cubic meters each. LNG is stored in tanks until a gas carrier approaches. LNG is delivered through a special pier that can take gas tankers with a capacity of 18 to 145 thousand cubic meters. LNG is transported to the customers' regasification terminals by both specialized buyers and gas tankers operated by Sakhalin Energy, including vessels. The vessels (Grand Elena, Grand Aniva, and Grand Mereya) were built specifically for the project. Depending on the size of the tanker, loading may take from 6 to 16 hours. In 2013, Sakhalin Energy produced 10.8 million tons of LNG (166 deliveries) [32].

Oil Export Terminal

Oil goes to OET from the Piltun-Astokhskoye and Lunskoye fields via the trans-Sakhalin pipeline system. After mixing condensate, the oil is transported to storage tanks equipped with a floating roof. The capacity of each tank is about 95 thousand cubic meters. m. From storage tanks, oil flows through a subsea pipeline to TLU (Tanker Loading Unit, Figure 23), which performs the function of a single-point mooring device and is located at a distance of 5 km from the coast. The water depth at its installation site is about 30 m. The total height of the TLU is 73.7 m. The TLU can take over oil tankers with a capacity from 40 to 150 thousand cubic meters. In 2013, the company produced over 42 million barrels of oil, which was shipped to 60 tankers [28].

Figure 23. Tanker Loading Unit (TLU) (Photo courtesy of Sakhalin Energy Company)

3.3. Sakhalin-3 project

The Sakhalin-3 project comprises four main blocks, listed in Table 13 below.

Table 13. Sakhalin-3 estimation of reserves [33]

License Block	Oil and condensate, mln tones	Natural gas, bln m^3
Kirinskiy	453	720
Vostochno-Odoptinsky	70	30
Ayashsky	97	37
Veninsky	88	578

Currently, Gazprom company owns licenses for the East-Odoptinsky (Block I), Ayashsky (Block II) and Kirinsky (Block IV) of the Sakhalin-3 project. These sites are located in the North-East of Sakhalin offshore in the North Sakhalin trough. The East Odoptinsky and Ayashsky are located in the northern hypsometrically elevated part of it and the Kirinsky section in the southern lowered part. The Veninsky license block is being held by Venineft company, which is a JVC of Russian company Rosneft (74.9%) and Chinese Sinopec (25.1%) [34].

Currently, only one field is put on the production phase. Subsidiary company Gazprom Dobycha Shelf is developing Kirinsky gas and condensate field. It was discovered 1992 on Sakhalin offshore and then started to be developed in 2009. All reserves after geological exploration, conducted in 2011, are within the C1 category (explored) are approximately 162.5 billion m3 of gas and 19.1 million tons of gas condensate. It was decided to use SPS systems, which were implemented on the Russian shelf for the first time. The full capacity was reached in 2013. The field comprises seven wells; then in operation, there are only two of them. The gas flows to the manifold (Figure 24). Then produced gas is being transported to the shore via subsea pipeline to OPF. There are no additional compression stations; natural gas flows under the influence of reservoir pressure. After the OPF treatment, gas goes by 139 km pipeline system “Sakhalin-Khabarovsk-Vladivostok” [29].

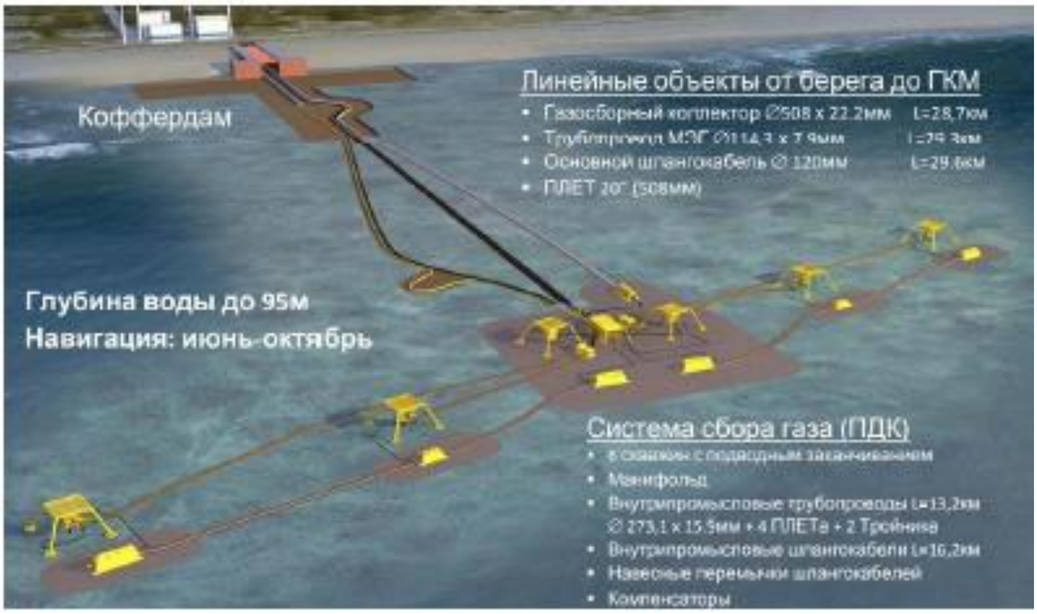


Figure 24. Kirinskoye Field layout [35]

4. Ayashkinskoye license block description

The Ayashkinskoye license area, located in the Sea of Okhotsk, is currently part of the Sakhalin-3 project. The site is located near the already discovered and developed fields of the Sakhalin-1 and Sakhalin-2 projects, which have already proven the oil and gas potential of the region [37].

The licensee of the block is LLC “Gazprom Neft Shelf”, the license was received in 2017. The operator is LLC “Gazpromneft-Sakhalin” [36].

At this moment only two fields of the block, which present commercial value, are taken into account by the company. The first one is Ayashskaya structure, and the second one is Bautinskaya structure, presented in Figure 25.

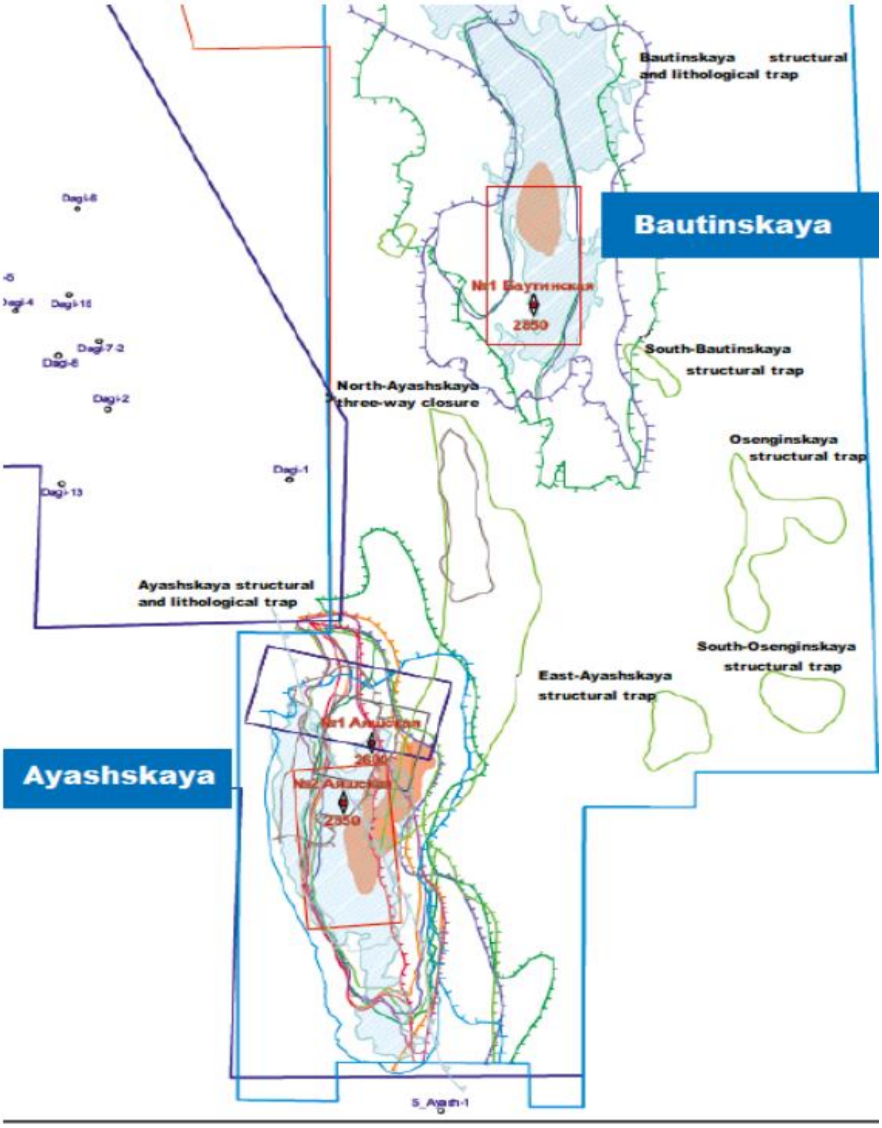


Figure 25. Map of Ayashskaya and Bautinskaya structures [48]

Earlier, 3D seismic exploration in the volume of 2150 square kilometres was performed at the Ayashkinskoye license area. At this moment, three prospecting and appraisal wells have been already drilled to ensure the productive potential of the structures (Figure 26).

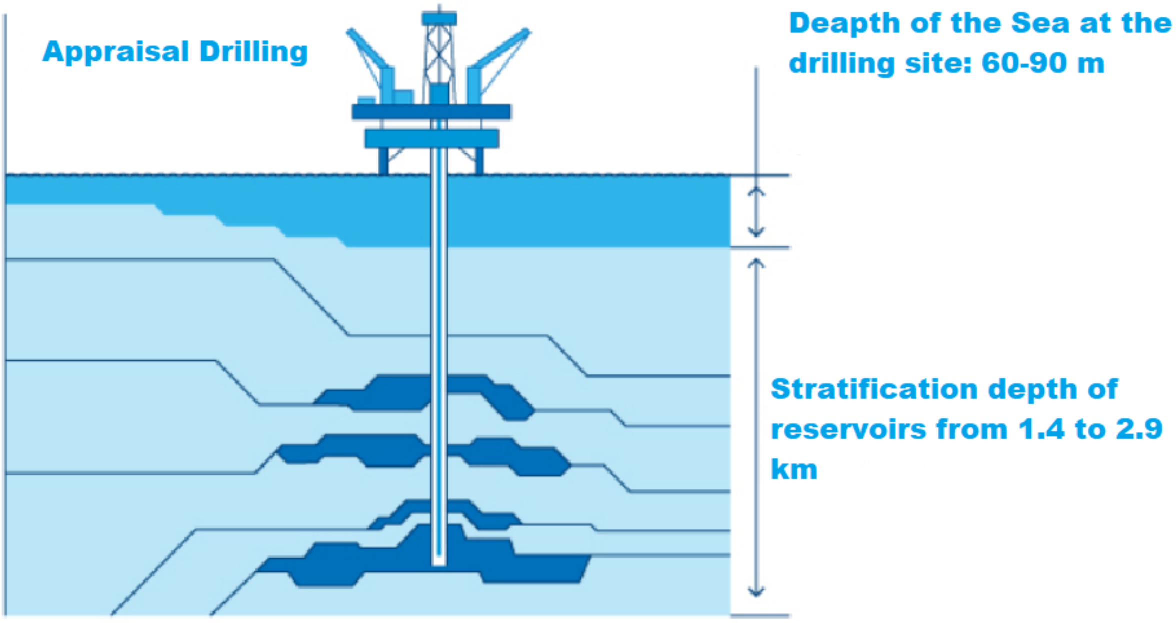


Figure 26. Appraisal drilling [36]

Two were already drilled in 2017 on the site of Ayashskaya structure, and one well in 2018 on Bautinskaya site. The Japan Drilling Company drilled the first in the Ayashkinskoye area, but then its installation Hakuryu 5 was attracted to Rosneft for drilling in the Vietnamese block 06.1 in the South China Sea. Then Gazprom Neft took the Chinese drilling platform Hai Yang Shi You 982 (HYSY982) owned by COSL to drill the second well in the Ayashkinskoye area (Bautinskaya structure). COSL is a subsidiary of CNOOC, the third largest Chinese state oil company, which specializes in offshore production [2]. According to this appraisal works both structures seems to be commercially efficient for future development. It was considered to give more pronounceable names to these fields. The Ayshkinskaya structure received the name "Neptun" (Neptunus – the god of seas in ancient Rome mythology); the Bautinskaya received the name "Triton" (the son of Neptunus – the messenger of the seas). Table 14 shows the volumes of probable reserves (P50) [36].

Table 14. Possible reserves of Neptun and Triton fields [36]

	Reserve appraisal (P50)		**Sea depth**	**Source**
Neptun	**Oil**	190 mln metric tones	63-73 m	3 appraisal wells
	Gas	11 bln m^3		
Triton	**Oil**	415 mln metric tones	60-100 m	
	Gas	3 bln m^3		

This experience suggests the creation of a new oil-producing cluster on the Sakhalin shelf and makes the Far East a new strategic region on the Gazprom Neft assets map.

5. Selection of development technologies for Ayashkinskoye license block

The principal selection for offshore field development is based on a considerable number of factors. That is why it is highly essential to have stage flexibility to perform the best result while having potential corrections in the development stages.

Some of the most important factors are listed below:

- feasible technologies with a clear assessment of needs in research and development needs;
- the satisfaction of all environmental and safety requirements;
- CAPEX and OPEX considerations, which include initial investments, maintenance, operating cost, etc.;
- environment conditions [38].

The most feasible solutions require technical and technological ideas which suit the particular field. In terms of offshore projects, the following factors should play a crucial role in choosing the right scenario:

- depth of the water on the field's site;
- distance from the field to the shore;
- the volume of reserves (with recovery rate correction);
- presence of closest reserves to the region being under consideration;
- environmental factor:
    - presence of ice (icebergs, ridges, ice fields, stamukhas, ice-free window, etc.)
    - waves (significant wave height, wave period, etc.)
    - a seismic factor of the region
    - wind loads;
- means of hydrocarbon transportation (remoteness from main markets);
- presence of sufficient technologies;
- emergency response time;
- high risks of capital investments (including political and economic instability) [8], [38], [39].

A typical project is carried out in several phases. The project starts from the screening of potential exploration areas and at the end, it finishes with the abandonment process. Among the two mentioned stages, there are several of them, which are initiated by a company in case of the successful first stage, see Figure 27 [39].

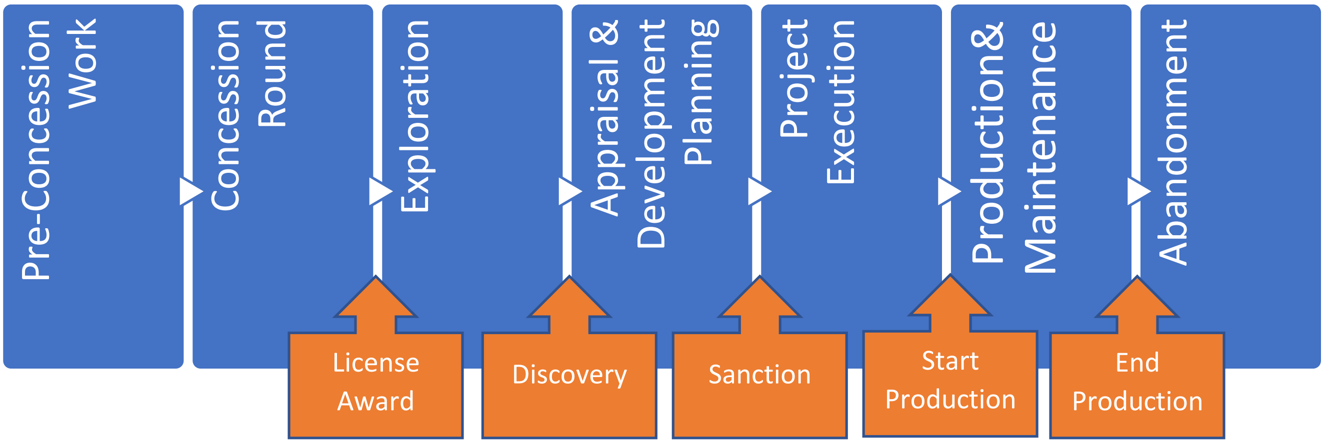


Figure 27. Phases of E&P venture [39]

The purpose of this Chapter is to evaluate the most efficient concept of development. Due to the complexity of evaluation, some assumption would be made due to the absence of some data related to both fields. The main idea is to focus on the already existed projects of the Sakhalin offshore zone, which were presented above.

It is necessary to highlight several main factors, which are crucial for project development.

The efficiency of the projects is primarily being defined by:

- sufficient production volumes;
- economic effectiveness;
- high flexibility and reliability of the technical and technological parts of the project [39].

To ensure meeting all the factors-requirements mentioned above the project development should be carefully analyzed.

5.1. Decision Making upon Front-End-Loading (FEL)

Front-End-Loading (FEL) is one of the proven technologies in Project Management, aimed to provide the optimum decision of capital and human resources, to reduce the critical information uncertainty, to ensure coherent view to all stages of field development. It is necessary to mention that this methodology comprises a robust plan of the project at an early time of development. This stage of development is characterized by a wide range of factors, able to influence some changes in design. This methodology is usually applied to the industries with high CAPEX and aimed at the long lifecycle of the project. The cost of changing design and concept on this stage is relatively small in comparison with the next steps of the project, where the change of idea could cause even shut down of the project [41].

Generally, FEL methodology could be described as a staged process, which can be visualized as in Figure 28.

The final products of the FEL process are usually a project information package that can be used to support the production of detailed design documentation and estimation of costs of suitable accuracy for obtaining an AFE project (Authorization for Expenditure) or Project Authorization [40]. FEL process covers all stages, from pre-FEL to Operations.

Typical FEL analysis consists of three main phases:

- typical conceptual phase (FEL-1);
- typical feasibility phase (FEL-2);
- typical Definition phase (FEL-3).

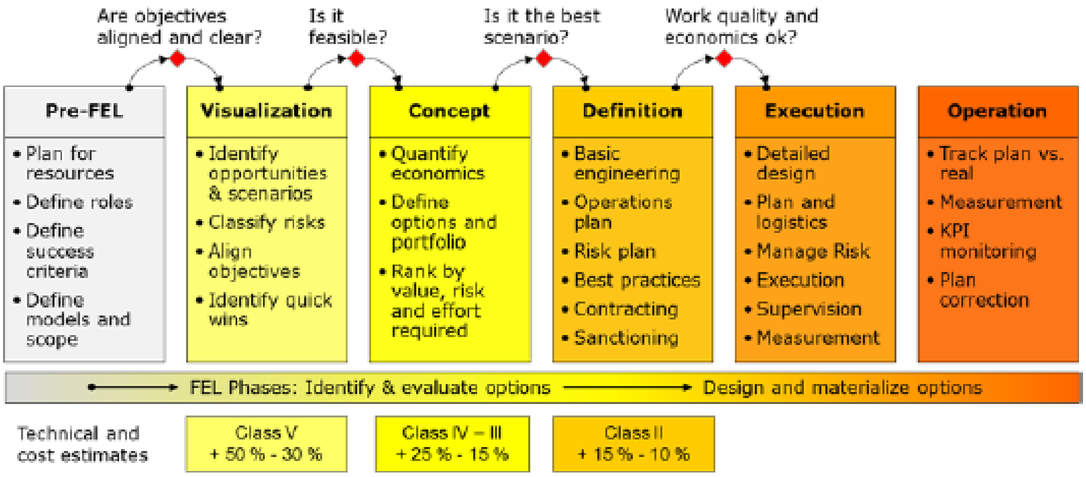


Figure 28. Front End Loading engineering methodology [41]

FEL-1 stage consists of the identification of potential sites, selection of technologies, cost estimations (+/-40 to 50%), project schedule [40].

FEL-2 stage comprises reduction of cost estimation (+/- 30%), overall execution strategy, equipment list and specifications, process hazards report, risk matrix [41].

FEL-3 stage improves costs estimation till the fluctuation up to +/-10%, accurate schedule of a project, equipment list with all specifications and technological schemes, completed environment permit submittal, critical equipment layouts and so on [40].

Due to the absence of data, inability to cover all stages, this study aims to focus on the primarily the first three stages of the field development.

5.1.1. Front End Loading – 1 (FEL-1 Phase)

This phase aims to give a rough estimation of some economic viability of the conceptual project and to take into account all technologies of future development. Summarizing all previous observations and data, several concepts should be considered for the development.

The rough estimation of economic profitability is required in the preliminary stages of field development. The typical offshore project could be subdivided into four main categories of projects costs:

- exploration costs;
- development costs;
- operating costs;
- transportation costs.

Generally, it could be considered that the project itself consists of two categories of investment: capital expenditures (CAPEX) and operating expenses (OPEX) [43]. In terms of the Ayashkinskoye license block development, the exploration costs should be omitted as a company-operator has already conducted it, and the data is a restricted source since it is only known that there are three exploration and appraisal well being drilled on the sites of license block. The cost of offshore exploration wells could significantly vary, but generally, it costs more than 15-20 mln. USD [44]. Taking into account all limitations for this development feasibility evaluation, the price of 30 mln. USD per well was taken into account.

Development costs are considered to cover a variety of development structures and works. In most cases, development costs or CAPEX account for approximately 60-70% of the CAPEX. CAPEX includes:

- well drilling;
- offshore structures;
- processing facilities;
- pipelines (trunk and infield ones)
- compressors;
- onshore terminals and other facilities [43].

Operating costs usually comprise all indirect investments, including labour, maintenance, inspections and repair, logistics, power, fuel and lubricants, and so on [43,44].

Transportation costs could depend on several factors; typically, the price is affected by market distance, presence of infrastructure, operating environment. In this study, the idea of per-volume of hydrocarbons transportation basis is taken into account.

The next development costs, presented in Table 15, are being taken into account in the rough feasibility field evaluation [43, 44, 39, 18, 8].

Table 15. Suggested offshore exploration costs [43, 44, 39, 18, 8]

Category	**Type of Expenditures**	**Cost, mln. USD**
Exploration costs	Drilling of exploration and appraisal wells	90
Development costs	Well Drilling	150
	Offshore constructions	No greater than 650
	Pipelines	No greater than 300
	Well downhole equipment	50
	Other	60
	Summary (CAPEX)	**1300**
Operational costs +Transportation costs	Considered as a certain value per volume of produced hydrocarbons	70/1000a m^3

In order to decide to make or not to make investments, the particular cost-effective analysis should be conducted. One of these analyses is CBA-analysis. The result of CBA-analysis are the indicators of the economic performance of the project. The specific values of these indicators provide evidence of future investments. The set of major economic indicators consists of:

1. **NPV**-Net Present Value of the project (in mln $)
2. **IRR** – Internal rate of return (in % on investment)
3. **PB-** payback period (in years)
4. **DPB-** discounted payback period (in years)
5. **BEP** - Break-Even Price (in $/unit of energy e.g. $/bbl)
6. **PI -** Profitability Index (ratio) (**B/C –** benefit/cost ratio) [47].

5.1.1.1. Economic evaluation

Revenue calculation

To calculate revenue, or the amount of money, which a company receives exchanging its product, the following formula is used:

$$Revenue = Q * P, \tag{1}$$

where

Q – the volume of produced hydrocarbons, barrels;

P – hydrocarbon price, USD/1 barrel [46].

OPEX evaluation

Mentioned above operational expenses was amounted to 70 USD per 1000 m^3 of natural gas or 5,2 barrels of oil.

Taxes

Due to the fact that offshore projects on Russia are placed in severe environmental conditions and political circumstances such as sanctions on the offshore development equipment, the government makes tax remissions to develop such deposits. According to [38] the tax on the shelf project in Russia is divided into two parts: mineral extraction tax and tax on income. Summarizing both the total tax to the project equals 25%. This value was taken in the feasibility estimation [45].

Net Present Value

Net Present Value accounts for the value of money in the present moment. It also one of the parameters of analysis of project profitability.

NPV could be calculated by the equation:

$$NPV = \sum_{i=0}^{T} \frac{Cashinflow_i - Cashoutflow_i}{(1+d)^i}; \tag{2}$$

where

$Cashinflow_i = Revenue_i – Depreciation_i$;

$Cashoutflow_i = CAPEX + Taxes + OPEX$;

i – number of the year;

d – discount rate, considered as 12%, which is common for O&G projects [46].

The Internal Rate of Return

The IRR is a criterion that shows the average annual percentage rate of the project. The project would be economically feasible if only IRR is higher than the discount rate [47]. The Internal Rate of Return shows the discount rate of the project, where the NPV is equal to zero:

$$NPV = \sum_{i=0}^{T} \frac{Cashinflow_i - Cashoutflow_i}{(1+IRR)^i} = 0\,; \tag{3}$$

Discounted Payback Period

DPB shows a certain time during the life of the project when it covers the cost of initial investments [47].

Profitability Index

It is a ratio that shows the relationship between the costs and benefit of the projects. It could be presented:

$$PI = 1 + \frac{NPV}{CAPEX} \tag{4}$$

PI should be higher than 1 or the project should be rejected [47].

BEP point

The Break Even Point is a point when the market price of a company's asset is equal to the original cost. It could be calculated by the following formula:

$$BEP = \frac{\frac{\sum(I_i+O_i+F_i)}{(1+IRR)^i}}{\sum_{i=1}^{T}\frac{Q_i}{(1+IRR)^i}}; \qquad (5)$$

where

Qi – oil and gas production, barrels and cubic meters;

Ii – CAPEX during the lifetime of the project, mln. USD;

Oi – OPEX during the lifetime of the project, mln. USD;

The obtained BEP should be higher than established O&G prices in order to match the profitability. The evaluation of the project feasibility was conducted in Excel format. The following criteria were taken into account for the estimation analysis (Figure 29 and Table 16).

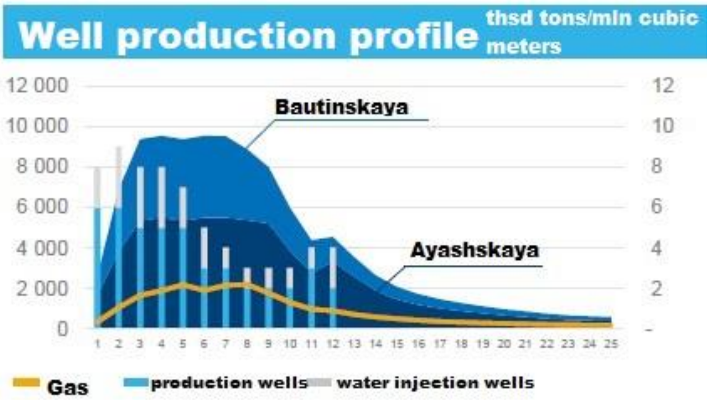


Figure 29. Well production profiles [48]

Table 16. Input Data for the CBA analysis

Parameter	**Figure**	**Unit**
Annual oil production rate	106302052	barrels
Annual gas production rate:	2000000	1000 m^3
Lifetime of the project	25	years
After 8th-year production rate is decreasing on	0,06	6 % per year
Investment (CAPEX):	1300000000	$
Oil price	75	$
Gas price	100	$/1000 m^3
Operating expences	70	$/1000 m^3
Depreciation and Annual fixed cost	0,06	of initial investment
Taxes on profit	0,25	25%
Discount rate:	0,12	12%

The whole yearly table is presented in Appendix A. As it stated there, the DPB point occurs between the fourth and the fifth year of development. Figure 30 and Table 17 summarizes the results of economic evaluation.

Table 17. Obtained results of CBA-analysis

NPV	**196 460 460**	>0
IRR	**30%**	> Discount rate
BEP	**133,29**	< initial gas cost
DPB	**4**	year
PI	**1,15**	>1

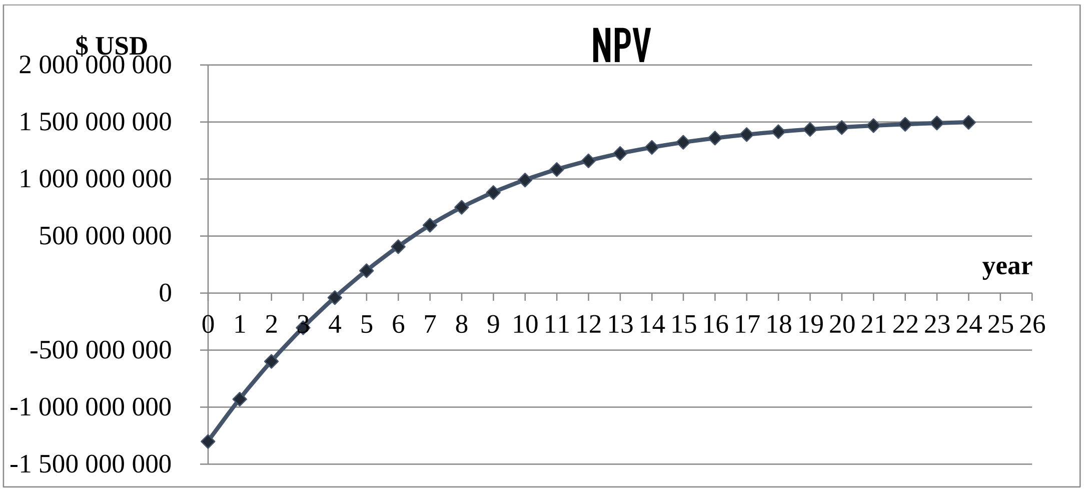


Figure 30. Net Present Value plot

To conclude, it should be noted that the economic estimation was conducted in terms of now hydrocarbon prices. The gas price was considered for the internal market of Russia. Although inner gas price is much lower than the export one, the project seems to be feasible, taking into account all mentioned above criteria of choice.

The second step of FEL-1 stage is to develop potential development scenarios. Since this study is conducted in the absence of some data of the development, it would have been carried out regarding the previous experience on the Sakhalin shelf and other projects with similar features (Hebron project, White Rose project, etc.)

Strong sub-Arctic environmental conditions require a thoughtful approach to choosing the right concept. Figure 31 provides several technologies of development of the Arctic region. Among the list of potential development technologies, some of them have been already put in operation and have proved the efficiency. Some of them are used in less severe conditions, and some considered as prototypes and have never been used. FEL-1 phase aims to define the most relevant ones, which might be taken into account as potential ones for the detailed future considerations.

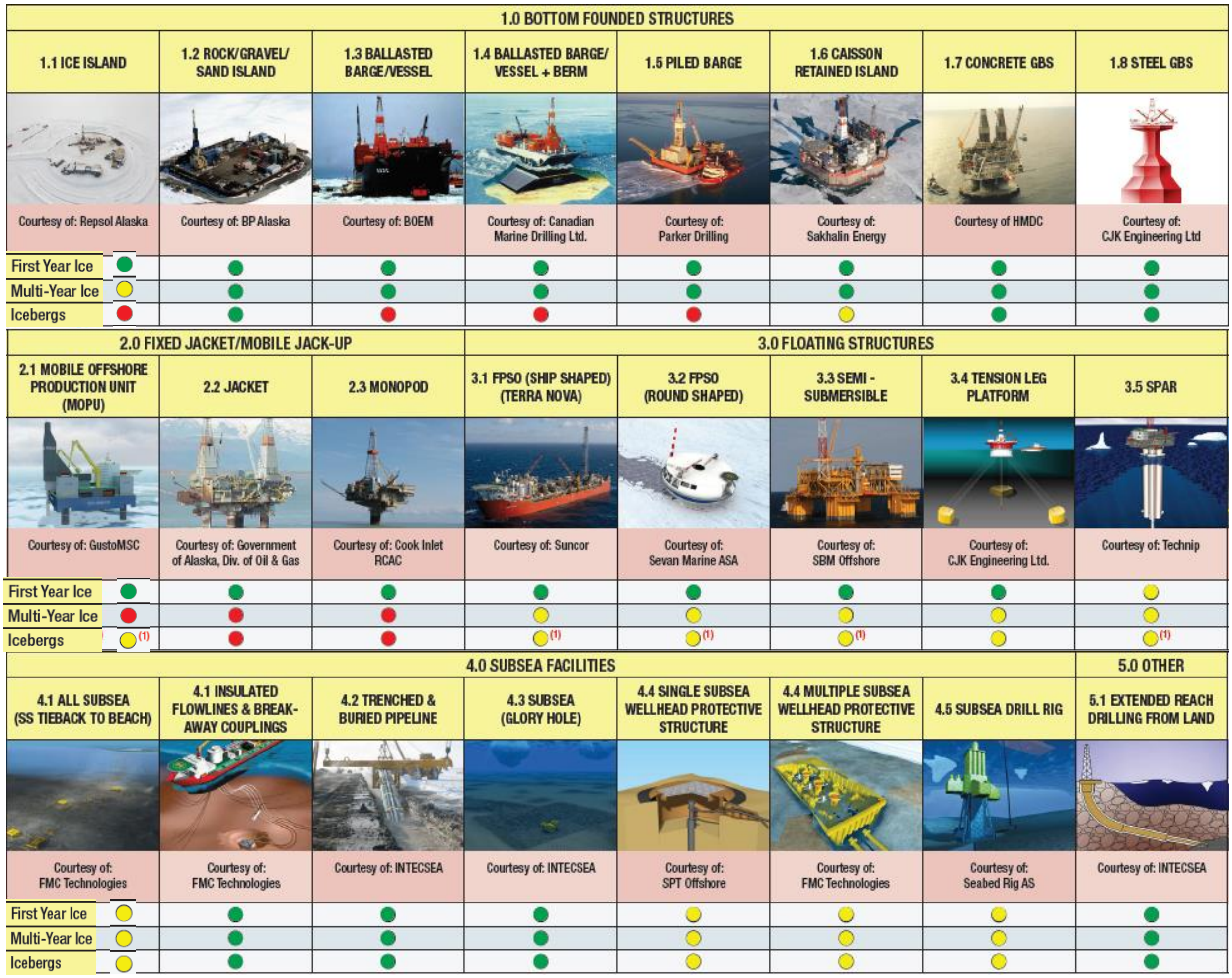


Figure 31. Exploration & field development concepts (legend: ● - field proven; ● - concept/ considered to be implemented; ● - not considered/ does not fill the requirements, (1)- could be operated with ice management) [49]

One of the ways of choosing is to make a comparative analysis of all mentioned technologies. Having values of all mentioned above parameters which can affect the development, one can make a rank of these data. Below in Table 18, the comparison ranking is presented on the basis of the criteria, which have been already described above. On this stage, it is essential to decide several key technologies suitable for that region with particular conditions. For that case, a rank matrix is being used. It provides to systematically identify and analyze technologies and factors which might affect the project. The choice is stated upon the existed experience, and some open-source existed classifications [49] of the current state of offshore development worldwide.

The outcome of this rank analysis is several solutions which have an overwhelming majority of favourable solutions. Among them are:

- Rock/gravel/sand island;
- Caisson retained island;
- Concrete GBS;
- Steel GBS;
- FPSO;
- SPS.

Table 18. Matrix of possible concepts (based on [42])

	Technology / Criteria	Ice Island	Rock/grave/sand island	Ballasted barge/vessel	Ballasted barge/vessel +berm	Piled barge	Caisson retained island	Concrete GBS	Steel GBS	Mobile Offshore Production Unit (MODU)	Jacket	Monopod	FPSO (ship shaped)	Semi-sub	Tension leg platform	SPAR	All subsea	Subsea (glory hole)	Extended reach drilling
Major capability	exploration	G	G	G	G	Y	G	G	Y	G(1)	NO	NO	G(1)	G(1)	NO	NO	N/A	N/A	N/A
	production	NO	G	Y	Y	Y	G	G	G	Y	G	G	G	G	R	R	G	G	N/A
	Hydrocarbon storage	NO	NO	G	G	Y	Y	G	G	NO	NO	NO	G	R	R	Y	NO	NO	N/A
	water depth of suggested area	R	NO	NO	NO	NO	NO	G	Y	G	NO	G	Y	Y	Y	No info	Y	G	R
Ice impact	First year ice	G	G	G	G	G	G	G	G	G	G	G	G	G	G	Y	G	G	G
	Multy-year ice	Y	G	G	G	G	G	G	G	R	R	R	Y	Y	Y	Y	G	G	G
	Iceberg impact	R	G	R	R	R	Y	G	G	R	R	R	Y	Y	Y	Y	Y	Y	G
	Ice ridges	Y	Y	Y	Y	Y	Y	G	G	Y	R	R	Y	Y	Y	Y	G	G	G
	Disconnectable (*)	NO	NO	NO	NO	NO	NO	NO	NO	R	NO	NO	G	Y(5)	Y(5)	Y(5)	N/A	N/A	N/A
Tree type	wet tree	NO	NO	NO	NO	NO	NO	NO	NO	G	NO	NO	G	G	G	G	G	G	R
	dry tree	G	G	Y	Y	Y	G	G	Y	NO	G	G	NO	NO	G	G	NO	NO	G
Field remoteness	Field remoteness	G	G	G	G	G	G	G	Y	NO	NO	NO	G	NO	G	G	G	G	R
Export/Disposal methods	Oil export pipeline	N/A	G	R	R	R	Y	G	Y	Y	G	G	Y	G	G	G	G	G	N/A
	shuttling	N/A	R	R	R	R	G	G	Y	Y	Y	Y	Y	Y	Y	Y	N/A	N/A	N/A
	oil to wire (convert to electricity)	N/A	R	R	R	R	R	R	R	R	R	R	R	R	R	R	N/A	N/A	N/A
	Gas export pipeline	N/A	G	R	R	R	Y	G	Y	Y	G	G	Y	G	G	G	G	G	N/A
	Gas to wire (convert to electricity)	N/A	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	N/A
	Gas reinjection	N/A	G	R	R	R	G	G	Y	Y	Y	Y	G	Y	G	G	G	G	N/A

(1) - Only open water season; (5) - Issues with mooving in ice environment

Legend						
G	Field Proven	R	Concept	N/A	Not applicable
Y	Qualified	NO	Does not meet requirements	No info	no inforamtion/data

5.1.2. Front End Loading – 2 (FEL-2) Phase

After all step evaluation of the FEL-1 phase, this phase aims to define which scenarios hit the target. As it was mentioned above, several development technologies have been taken into account future planning. In that case, the first step of this phase is to drop out possible but unfeasible solutions.

In terms of feasibility, not all technologies fit the necessary factors. Rock/gravel /sand island and caisson retained islands are considered not to be used in terms of the sea depth. The maximum depths, where such technology could be used are 22 and 28-30 meters, respectively [49].

Another necessary factor is the current geopolitical situation. Russian companies currently have difficulties in technologies and equipment to develop unconventional and offshore reserves. The key feature is that international sanctions put a limit on access to modern technologies of the companies worldwide [50].

At present, the sustainable development of the Arctic region almost relies on international cooperation. However, as for the level of project involvement, the distribution could be quite different. The most demanding are new technologies and investment attraction. In those cases, establishing a consortium is the most feasible solution. For example, such projects as Prirazlomnoye and Shtokman, Sakhalin-1, 2, 3 are successful in terms of significant contribution either technologies or investments from large international players. According to the Russian law "Subsurface Resources", there is a limitation on the number of companies which can develop Russian shelf. In other words, only a few of them have a license on offshore subsurface reserves. At present only two Russian companies PAO NK Rosneft and PAO Gazprom (publicity held companies) have access to the Russian shelf. Rosneft has seven licensed sites in the Barents Sea; 8 – in the Pechora; 4 – in the Kara; 5 – in the Laptev; 1 – in the East Siberian, and 3 – in the Chukchee Sea [44]. Gazprom has seven licensed sites in the Barents Sea; 3 – in the Pechora; 13 – in the Kara Sea; 8 – in the Gulf of Ob, and 1 – in the East Siberian Sea [45]. Currently, only the Prirazlomnoye project could be considered as fully Arctic one. The operator is PAO Gazprom, which have already started the commercial production of oil and received a unique experience in comparison with PAO NK Rosneft company which has no active offshore production projects on the Arctic shelf [53].

Nevertheless, the Russian industrial sector still strongly depends on the number of different technologies and equipment. The principal shortage is referred to lack offshore drilling platforms, subsea production systems, pipe-lay ships, wellheads, specialized software, etc. One could say that it goes positively for the Russian industrial sector to develop such thing inside the country, as well as there are some reports, for example, that Gazprom is planning to start local production of SPS systems by 2023-2025 [54].

Taking into account all mentioned above features of the development of Russian offshore reserves, the following concepts, presented in Figure 32 are suggested for the development of Ayashskoye and Bautinskoye structures.

Concept I. ice-resistant FPSO unit, placed on one of the structures. Subsea tieback from another structure to the FPSO unit. Drilling procedures from Semi-submersible drilling rig. Offloading from the buoy. Hydrocarbon transportation by tankers.

Concept II. GBS production platforms on both structures (drilling, production, processing, storage of produced hydrocarbons). Offloading from a platform, further tanker transportation.

Concept III. Two SPS units, drilling from a semi-submersible drilling platform, hydrocarbon transportation via subsea pipeline to the OPF, placed on the shore.

Concept IV. Two SPS units, drilling from a semi-submersible drilling platform, hydrocarbon transportation via subsea pipeline to the PA-A platform, then hydrocarbon transportation to the shore.

Concept V. SPS unit + GBS platform. Drilling both from semi-sub on the one structure, and from GBS on another one. Processing and temporary storage on the platform. Transportation via subsea pipeline to the OPF on the shore (either existed or a new one).

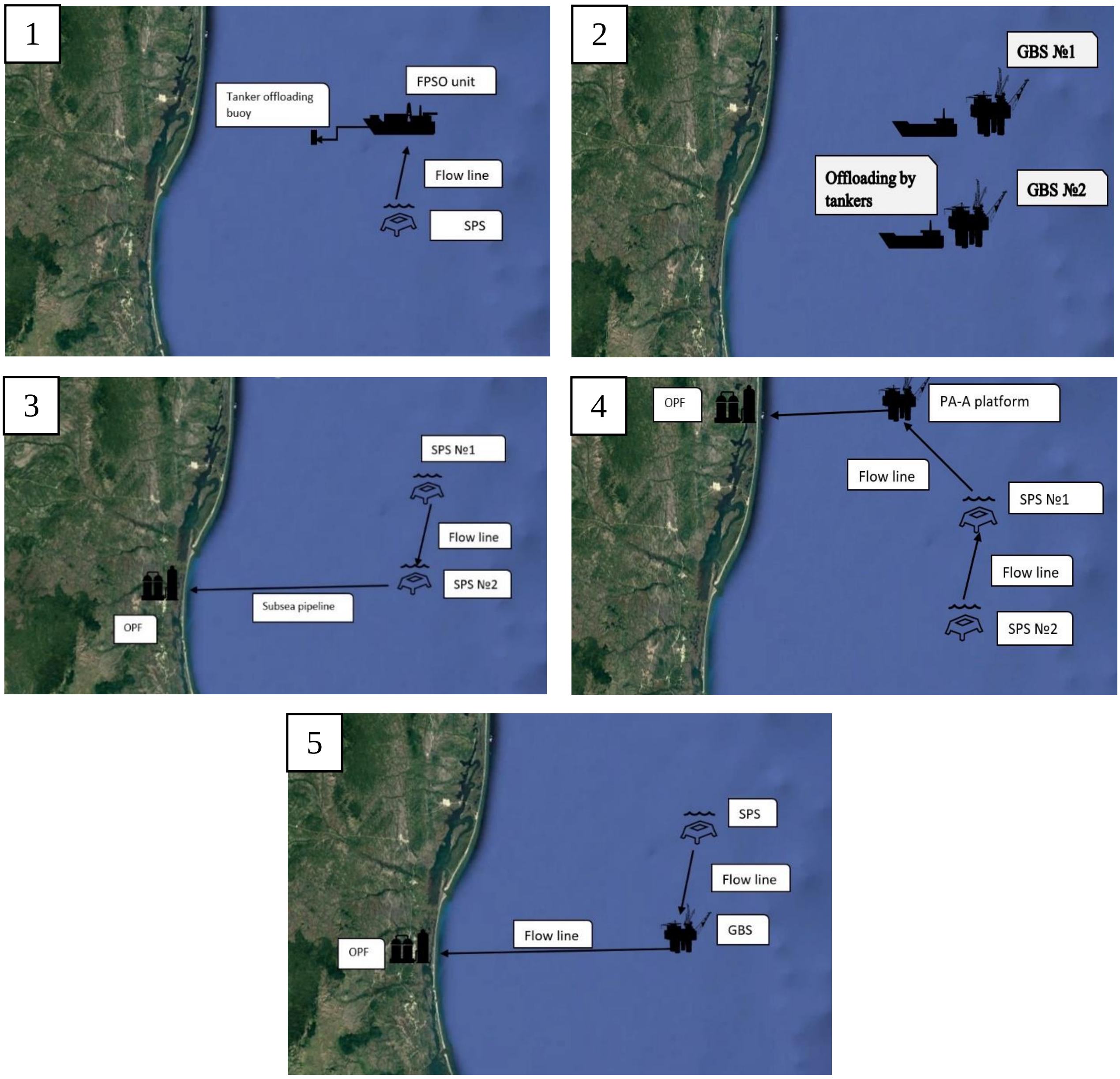


Figure 32. Five possible concepts of development (map of the Sakhalin zone is made with the help Google Earth software [42])

All of these concepts seem to be feasible in terms of future development in terms of already existed experience worldwide. Due to the fact that at this moment there is no any trustworthy information about the trap sizes, P90 estimated reserves, properties of hydrocarbons in the reservoir in the open source information, all options are considered to be applicable in all cases of development. The goal of this study is to provide a comprehensive analysis of possible development and configuration setup.

As for the less feasible concepts mentioned above, the first two scenarios seem to be less realistic. As it was mentioned above the main difficulty of the Russian shelf development is the absence of sufficiently effective and reliable technologies and equipment which could provide sustainable and safe development. As for the first case, the FPSO unit is considered to be a unique option for the Russian shelf since there have not been any relevant experience of implementing such vessel in the Russian projects. Despite the fact of high prices on FPSO units, there should be mentioned above complexity, connected with sanctions on its kind of equipment. For example, the average price of non-ice-resistant vessels is considered to be nearly 700 mln. USD [55]. In terms of sub-Artic conditions, an FPSO unit should be designed to withstand FY ice loads on the hull or have the opportunity of immediate disconnection.

Moreover, the special system should be designed for the offloading of the produced hydrocarbons. The buoy system should also be ready to operate in severe conditions in the presence of ice fields. All these options substantively increase the price and management of the project.

For the second case with two GBS platforms, the development scenario is still considered to be unrealistic, since one the main important parameters of development – water depth – is considered to be quite challenging for such type of the structures. All previous cases are put at the moderate depths not exceeding 40-45 m. As for the case of Neptun and Triton fields, the fabrication and installation of such massive structures might be considered as unfeasible.

The fourth scenario of a tie back of SPS units to already existed in Sakhalin-2 platform PA-A is considered to be realistic. Two SPS units are placed on the Neptun and Pluton field sites with the subsea pipeline going to the platform, where it could be initially handled, then pumped to the shore. However, there some features that might affect the success of the development scenario. The capacity of PA-A platform should be carefully calculated and taken into account. Also, the absence of full exploration picture gives the uncertainty about existing nearby potentially commercially viable structures.

Both scenarios under positions 3 and 5 in Figure 32 are considered as the most feasible. However, both cases of development require SPS units' implementation, which is deemed to be a challenge mentioned above factors of foreign equipment and technologies for the Russian offshore zone. However, it also should be mentioned that according to Government authorities the need of Russian oil and gas companies in the elements of Subsea Production Systems (SPS) to 2035 is estimated at 400 units, the mass production of such equipment in Russia can be started in 2021 [56].

According to the Ministry of Industry and Trade, in 2015 the share of imports in this segment was a critical 90%, so the task was set to reduce the dependence to 70% by 2020. Resource testing of Russian SPS is scheduled for 2020. Mass production is expected to begin in 2021. Russian oil and gas companies - Gazprom, Gazprom Neft, Rosneft, Novatek and Lukoil estimate the need for equipment for subsea production complexes until 2035 as significant [56, 57]. The point of rejecting the third scenario is that it would require subsea separation systems, initial treatment facilities so that the field layout would be quite sophisticated. In the case of relatively low experience in subsea production (Kirinskoye field), the fifth scenario is considered to be the most feasible, reliable and efficient.

The workflow chart of potential development, according to scenario № 5 is presented in Appendix B.

5.1.3. Front End Loading – 3 (FEL-3) Phase

After the evaluation of all possible concepts, the fifth one is chosen. The pair of GBS platform and SPS unit is taken into consideration. Also, yet another reason for taking that concept is to have the GBS production platform as a central hub which can potentially comprise all connected subsea facilities. As it was mentioned that exploration works are being conducted so other potential commercially feasible structures could be found and then be connected to the hub platform. The hub unit could comprise a primary treatment facility to separate produced fluid from mechanical impurities and to prepare for further transportation via pipeline to the shore. GBS platform is an autonomous structure and has excellent strength properties to withstand all severe conditions mentioned above in Chapter 1. In terms of environmental safety GBS structures already proved that could be reliable in terms of water pollution, which is very important in such unique areas. Based on the previous experience in the Sakhalin shelf region the multiple column concrete structure is the best variant for the suggested area.

5.1.3.1. GBS platform suggestion

The present challenge of GBS structure is the water depth at the sites of deposits. It directly depends on the CAPEX of a potential structure since a lot of construction material should be used for manufacturing. All previous projects of the Sakhalin shelf were designed for shallower depths. It is suggested to place the GBS platform on the Neptun deposit sites (Ayashskaya structure). There are the main reasons for such a decision:

- the lowest water depth;
- location, which is suitable for further potential connection of other structures which are arranged radially to the Neptun deposit;
- this site has less distance to the shore in terms of subsea pipeline installation.

The existing record of GBS installation on the Sakhalin shelf was set at the Lun-A (Sakhalin-2 project) at a water depth of 49 m. As for the present site, the assumed water depth of 65-70 meters, measured at the sites of the Neptun deposit should be taken into account. In worldwide terms, this depth is considered as quite shallow. For example, Condeep structures, as Draugen Condeep (251 m), Gullfaks C Condeep (216 m) and Troll Condeep (303 m) are installed at much deeper locations. Nevertheless, the following factors make Sakhalin platforms more unique than these colossal structures:

- Operation in ice presence conditions;
- Seismically active areas of installation.

Both mentioned above factors have severe restrictions on the height of GBS structures in terms of the overturning moment [58].

For the specified characteristics of water depth, the platform should meet the following requirements:

- the topsides mass: 60000 t;
- the total area of substructure: approx. 22000 m^2;
- oil storage capacity: 232000 t.

The structure should consist of 4 main elements, as topsides, support caisson, columns and basic pontoon of the structure, as it presented in Figure 33.

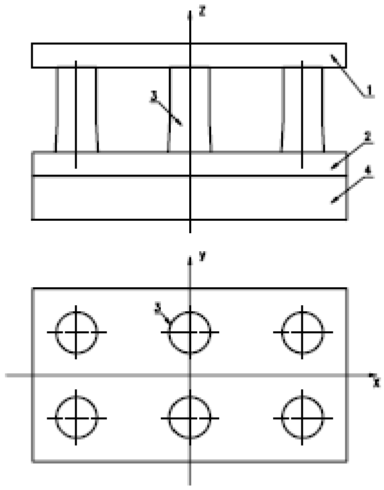


Figure 33. Layout of substructure of the proposed GBS unit [59]

The support caisson has several purposes, such as fixation of the columns to the integral deck with the topsides; location of the solid ballast, a possible place for oil storage. The size of the structure's columns is based on requirements of strength for particular conditions (ice, seismic loads, which cause bending), features of the equipment placed inside the column, floatation and stability issues [59].

The reinforced concrete material is considered as most favourable for the substructure due to the following reasons:

- good strength and ability to maintain the loads at low temperatures;
- better insulating properties in comparison with steel, which could also be as a construction material for GBS (Figure 31);
- Concrete has high quality in terms of abrasion resistance;
- In terms of mass concrete structure would have a higher weight, which will increase damping effects. This leads to less noticeable vibrations caused by ice crushing [60].

5.1.3.2. Ice load calculations

In order to check the stability criteria in terms of the overturning moment, the following calculations were taken into account. The calculated according to different standards values of ice field loads on the column of GBS structure should be compared with the announced design limiting loads for the concept of the platform, which is described in [60]. It is necessary to mention that there are several national and international standards and norms for the calculation of global ice loads from the level ice fields: API RP*2N-95, ISO 19906:2010(E), Elforsk rapport 09:55, GL 2005, SP 38.13330.2012, STO Gazprom 2-3.7-29-2005 [61].

In this case, 4 of listed above norms are taken into consideration: API RP*2N-95, STO Gazprom 2-3.7-29-2005, ISO 19906:2010(E), Elforsk rapport 09:55.

API RP*2N-95

The first option to calculate the ice load is to use the similar to API RP 2N [63] Korzhavin equation:

$$F = m * I * f_c * \sigma_c * D * h \tag{6}$$

where:

m – structure shape factor, m=0.9 for cylinder structures;

I – indentation factor;

f_c – contact factor;

σ_c – compressive strength of ice, MPa;

D – diameter of column, D = 23.6 m;

h – thickness of ice, h = 1.7 m.

For platform leg, according the CNOOC standard [62], the value of “I*fc” should be derived from the equation:

$$I * f_c = \frac{3.57 * h^{0.1}}{D^{0.5}}, \tag{7}$$

where:

D - diameter or column (cm);

h - the thickness of ice (cm).

Calculating the equation (7), the received value of $I * f_c = 0.775$

Then, the total load could be calculated according to (6). The received value is 67.16 MN

STO Gazprom 2-3.7-29-2005

According to the inner standard of Gazprom LLC company 2-3.7-29-2005 [64], the ice load on the vertical stationary structure could be calculated with the following equation:

$$F = m * k * R * d * h, \tag{8}$$

where:

m – shape structure coefficient, expected to be 0.85 for cylinder structures;

k - coefficient taking into account the leakiness of the contact of the ice formation with the construction and the effect of ice constraint during the destruction, expected to be 0.95;

R_c - standard value of ice strength for uniaxial compression, MPa, 2.4 MPa for Okhotsk sea;

d – diameter of the structure;

h – ice thickness.

The total load could be calculated according to (8). The value F is 77.75 MN

ISO 19906:2010(E)

Ice load from ice fields could be derived from the equation in ISO 19906:2010(E) [65]:

$$F = \sigma * h * d, \tag{9}$$

where

σ – ice pressure, MPa;

$$\sigma = R * \left(\frac{h}{h_1}\right)^n * \left(\frac{d}{h}\right)^m, \tag{10}$$

where

h_1 – basic thickness, taken as 1 m;

m – empirical coefficient, taken as -0.16;

n – empirical coefficient, taken as -0.3;

d – diameter of a column;

R - - a standard value of ice strength for uniaxial compression, MPa, 2.4 MPa for Okhotsk sea.

The calculation of ice pressure (σ) according to the (10) gives the value of 1.34 MPa. Then the total force calculation (9) gives the value F of 53.9 MN

Elforsk rapport 09:55

Ice load calculation, based on Elforsk rapport 09:55 [61] could be obtained using the following equation (if the ratio between the thickness of ice and diameter of the column is less than 1):

$$F = 0.45 * d * h * R * \sqrt{1 + 5 * \frac{h}{d}}, \tag{11}$$

where

h – ice thickness, taken as 1.7 m;

d – diameter of the column, taken as 23.6 m;

R - the standard value of ice strength for uniaxial compression, MPa, 2.4 MPa for Okhotsk sea [21].

According (11), the F value of 50.53 MN is received.

Figure 34 demonstrates the comparison of ice loads calculated with the help of listed above standards.

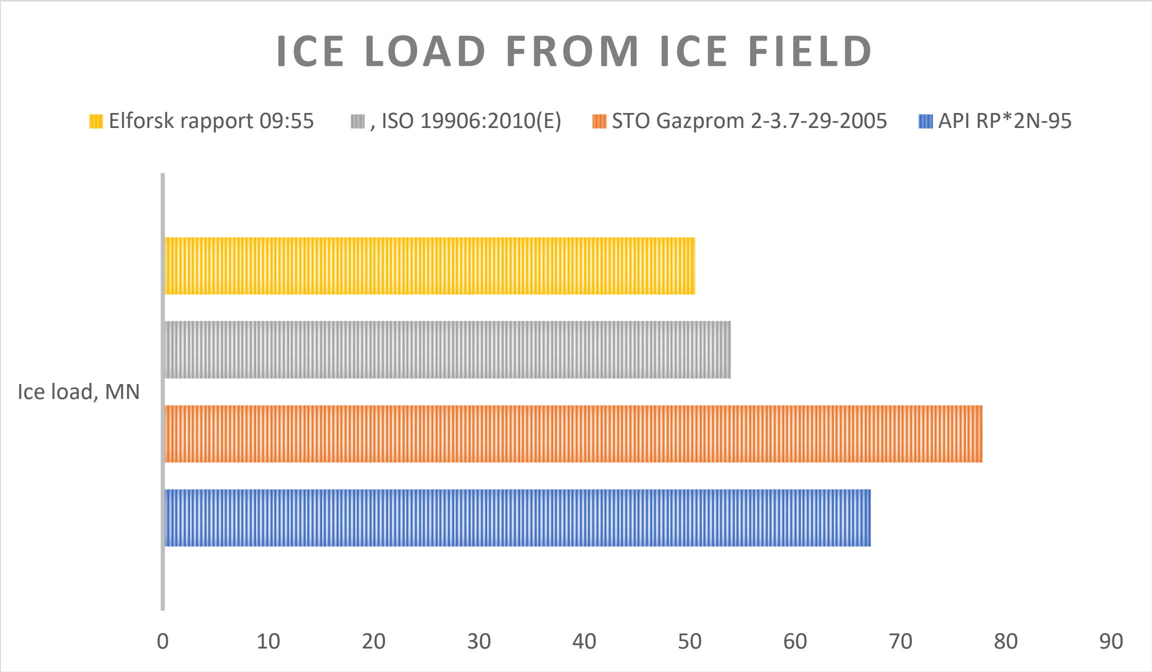


Figure 34. Ice load from ice field

Standards for calculating ice loads on the ice-resistant stationary platform in Russia and foreign countries are based on different approaches to assessing their reliability. Thus, the Russian Gazprom standard gives the highest value, especially in comparison with Elforsk rapport.

Table 19. Proposed limiting loads on GBS platform [59]

Load	Concrete		Concrete	
	Fy, MN	Mx, MN*m	Fx, MN	My, MN*m
Ice *	324	21,004	310.8	19813.8
Waves (irregular, 0.1% of exceedance)	630	12,931	481.8	10131.3
Wind	0.721	43.26	0.681	40.9
Current	50	1,200	38.7	748
Ice*+wind+current	344.3	22,140.5	330.1	21602.7
Wave+wind+current	649.3	14,255.5	511.2	10,920.2
* load from adhered ice				

As it is stated in Table 19, these loads among X and Y axis of the platform are several times higher in comparison with the obtained values of ice loads.

In terms of fabrication, the platform could be manufactured at the sites of port Vostochny. The existed experience of manufacturing platforms as Lun-A and PA-B in this dock proves the ability to make the fabrication possible. It is also of great importance to construct there in term of towing the platform to the site [59], [60].

5.1.3.3. Subsea Production System

As it was mentioned before, the Triton field (Bautinskaya structure) is suggested to be developed utilizing SPS units. The average depth of the sea on the site is deeper than on the Neptun field and account for approximately 70 to 90 m. Among two existed systems of development such as clustered well system and template system, the last is considered. It is associated with several features of such project development. First of all, clustered systems are deemed to require more time for the installation [66]. In the same time, the template system gathers inside the one structure several well slots (standard units could comprise from 4 to 12 well slots [67]). For the template one system, it should be noted that in terms of severe climatic conditions installation time of such systems is reduced by putting several wells into one -structure system.

Additionally, the manifold equipment could also be installed on such template structures, as presented in Figure 35. Implementation of such systems could also reduce time and investments in terms of flowline and wireline installations since the distances between modules are considered to be smaller (compared to a cluster one). It also reduces the issues of flow assurance. On the over hand, there are some drawbacks. It should be noted that such systems are much more massive than satellite ones. Hereof it follows that lifting and transportation operations are considered to be more complicated. Such huge structures are more susceptible to the flows occurring at the bottom of shallow waters. Also, on-bottom stability in terms of soil conditions should be considered [66].

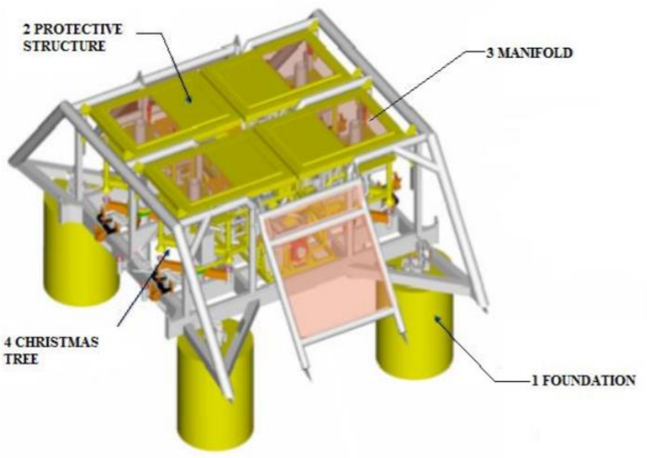
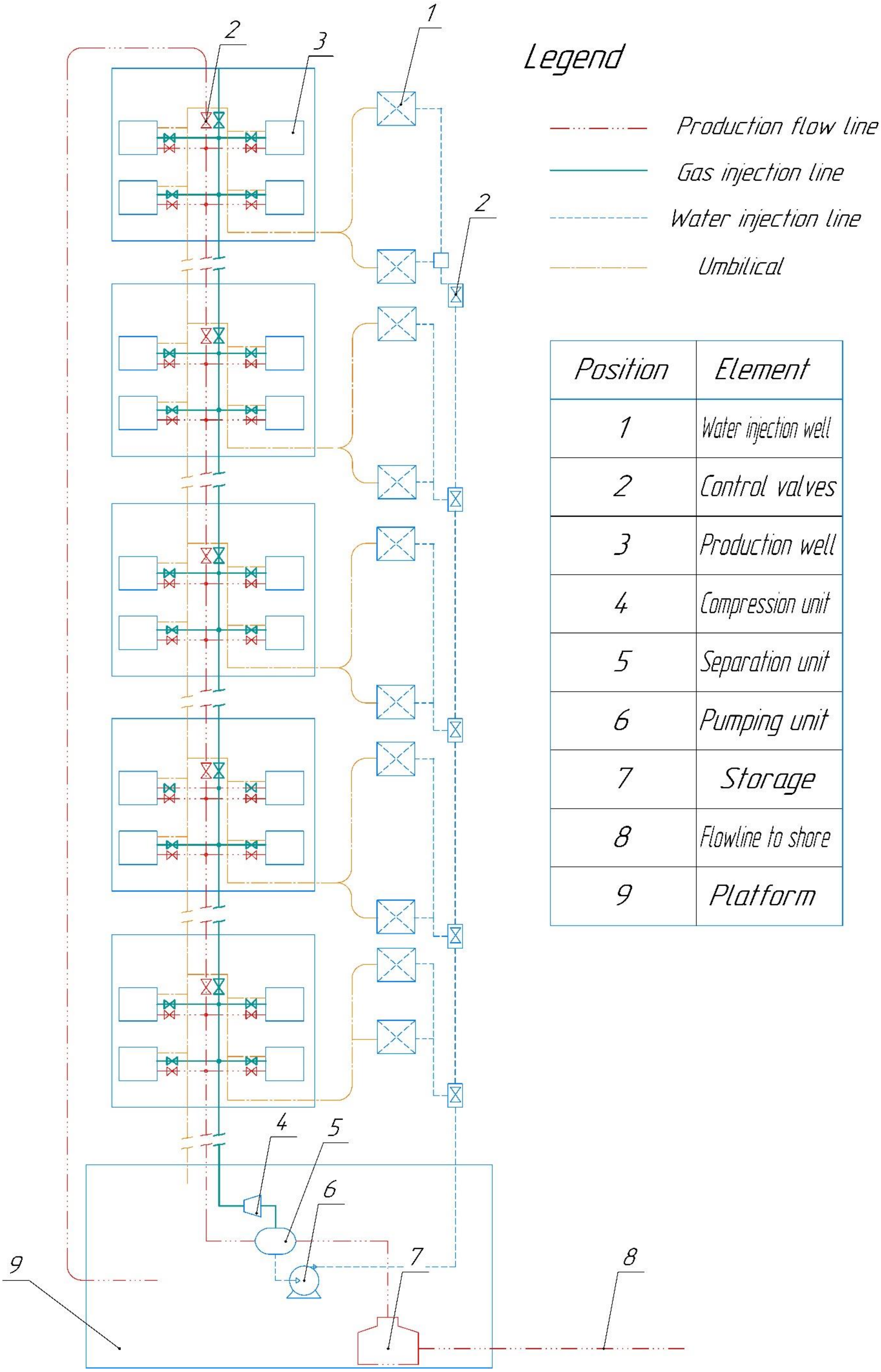


Figure 35. Template/manifold interface [65]

It is suggested to use the ITS with four well slots as for the case of the Kirinskoye field development. According to [48] it is proposed to drill 20-22 wells. Fourteen of them are considered as production ones. The other 7-8 are water injection ones for the reservoir pressure maintenance. It is suggested to omit the installation of subsea processing since the processing facility is designed on the basis of the GBS platform. In that case, a multiphase flow line should connect the subsea field layout and the production hub platform [68].



Position	Element
1	Water injection well
2	Control valves
3	Production well
4	Compression unit
5	Separation unit
6	Pumping unit
7	Storage
8	Flowline to shore
9	Platform

Figure 36. SPS layout suggestion

Figure 36 demonstrates the suggestion of subsea development system. Five templates with manifold system comprise four wellhead facilities. The gas lift system of production is considered after the depletion of reservoir energy supplement. The method is based on gas injection in the annulus between casing and tubing string through the valve as it presented in Figure 37. The idea is to reduce the density of the produced fluid in order to decrease the bottom hole pressure. In that case, the resistance to flow would be diminished, resulting in an increased flow rate [69].

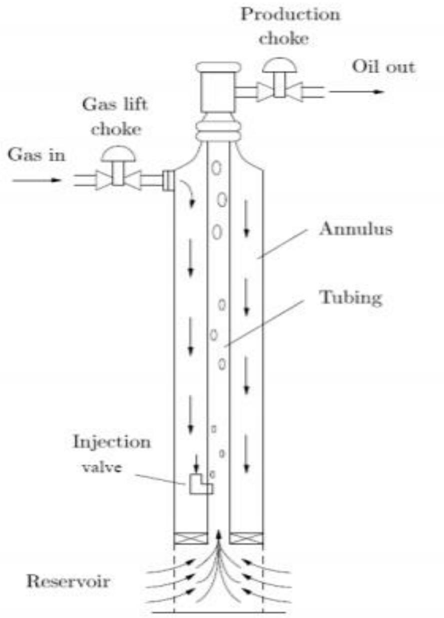


Figure 37. Gas lift system [69]

The production flow line connects all five templates. It has the pigging loop in order to maintain works inside the pipe. The flexible riser then connects the SPS unit to the GBS platform. The processing unit separates multiphase flow into 3 phases: water, oil and gas. Oil is being gathered in the storage tanks and then pumped via the subsea flow line to the shore. Separated natural gas is moved by the compressor to the gas injection line and then is injected into the gas lift system. The separated water is being pumped to the water injection line then to water injection wells in order to maintain the reservoir pressure. System of control valves could maintain the flow regime. It could be electric, hydraulic or combined electro-hydraulic one. System of umbilicals could control the system of valves and send all updated information from gauges. The operating control unit is placed on the platform.

6. Assessment of the impact loads on subsea pipeline protection covers from dropped objects

At present, there is a tendency to change the concept of field development from the construction of huge and expensive platforms to relatively compact subsea production systems (SPS) — solutions for hydrocarbon production installed directly on the seabed. Subsea oil and gas production systems include various equipment, such as Christmas trees, pipelines, manifolds, subsea processing units, etc. Each of these components must withstand harsh working conditions throughout its lifetime [70], [71].

Since such structures are placed underwater, they are more likely to be exposed to various influences. The most important impact that could lead to equipment damage and further environmental disaster is the damage from dropped objects. Dropped objects can have a different mass, shape, but in general, it is one of the most important factors that can lead to disastrous consequences [92]. In 2014/15 98 cases of equipment fallen from offshore structures or supply vessels were recorded. According to Lloyd's report from 1980 to 2010, there were 90 cases of objects falling during marine operations. It is also noted that there is a high probability of underestimation of these figures due to the lack of data in the report on the Gulf of Mexico, the Asia-Pacific region, where there are many offshore structures [93], [94].

At the beginning of the development of offshore fields, there are many offshore operations associated with the installation of various structures, such as floating drilling rigs/platforms or subsea equipment, such as templates, pipelines, manifolds, BOPs, etc.

A typical offshore project requires a large number of marine operations over the entire life cycle. In this case, the human factor becomes extremely relevant. The statistics clearly show that during the entire life cycle of a field, there are many unforeseen cases of the risk of falling objects, shipped by sea. Following the annual report "Annual Offshore Statistics and Regulations Report of Health and Safety Executive (HSE)" [72], in 2013/2014 there were 35 incidents with dropped objects, in 2014/2015 - 95 incidents. The diagram presented in Figure 38, demonstrates that the risk of dropped objects during operations is considered the most common, even more than the leakage of hydrocarbons, which, respectively, can be caused by the exposure mentioned above [80].

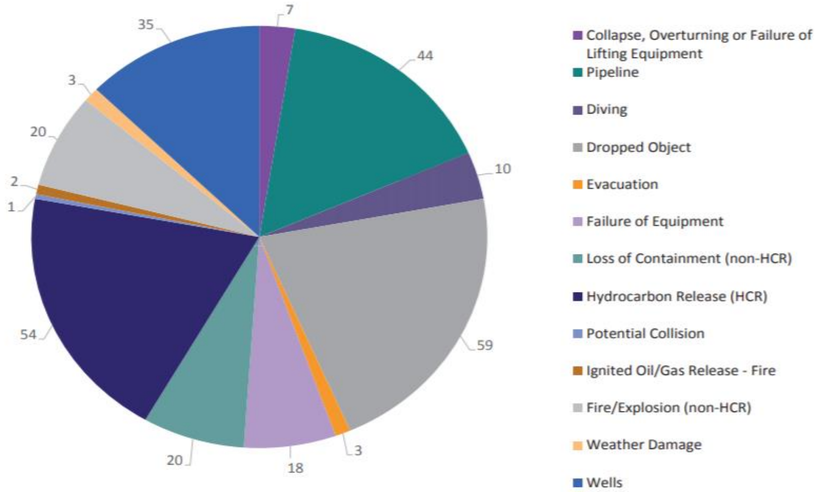


Figure 38. Incidents offshore [80]

The vast majority of cargo lost cases occurs during tripping operations. Since the development of offshore fields requires a large number of marine operations, the protection of subsea structures is required in places of increased risk of emergencies during tripping operations [74].

It is worth noting that it is almost impossible to give a classification of all dropped objects that can be dropped from an offshore structure or vessel. Such objects may be engaged in oil and gas activities, fisheries, etc. The offshore oil and gas activity includes thousands of objects that can be classified according to different mass, shape, and volume. In addition, the complexity is associated with different approaches to the design of equipment by different manufacturers. The same unit in different companies may vary significantly in all parameters mentioned above [73].

Since there is no data available in open sources, some classification of dropped objects should be taken into account. The DNV RP-107 "Risk Assessment of Pipeline Protection" standard provides a brief descriptive classification of such objects according to their forms [77]. This classification is presented in Table 20.

Table 20. DNV RP-107 classification [77]

no	*Description*	*Weight in air (tonnes)*	*Typical objects* [1,2]
1	Flat/long shaped	< 2	Drill collar/casing, scaffolding
2		2 – 8	Drill collar/casing
3		> 8	Drill riser, crane boom
4	Box/round shaped	< 2	Container (food, spare parts), basket, crane block
5		2 – 8	Container (spare parts), basket, crane test block
6		> 8	Container (equipment), basket
7	Box/round shaped	>> 8	Massive objects as BOP, Pipe reel, etc.

This classification concerns the form (and the contact area), as well as the mass of the potential dropped objects. A large number of studies were conducted on the subject of dropping objects, and the probabilities of cargo loss were determined [79]. According to the report, items such as scaffolding, drill pipes, casing have a high frequency of being lost during open source software. A lower frequency of abnormal situations is observed in the case of tripping of BOPs, underwater X-mas tree valves [75], [91].

According to statistics, the main types of dropped equipment are containers, pipes. The typical number of lost items is associated with a fall on the topsides of the platform (75%), on the ship's deck (10%), overboard (15%) [80].

Taking into account all the presented statistical data from open sources, two objects were taken into account for assessing the impact on subsea protection structures: the drill pipe and the container. For the drill pipe, a 6-inch drill pipe was taken as a prototype with some simplifications. In the case of a container, the 1C container according to the ISO-10855-1 standard was taken into account [82].

6.1. Subsea protection

At the moment, the world continental shelf has many marine structures and pipeline networks. All facilities are interconnected by a huge network of pipelines that transport hydrocarbons from the developed fields to the shore. The trunk pipeline is at great risk during its operation. Operational integrity may be violated due to the failure of only one element of its entire structure. Potential consequences are associated with leaks, spills, emissions that may damage the sensitive environment. It should be also noted that it is more cost-effective to protect the pipeline than to repair an already damaged one. Different approaches can be taken into account to protect the ecosystem and ensure proper pipeline operation [81].

According to the standard, DNV "Risk Assessment of Pipeline Protection", there are various options for protecting subsea pipelines:

• concrete coating;

• polymer coating;

• gravel or rock dumping;

• trenching;

• concrete blanket

• tunnel covers [76].

The main purpose of such protective measures is to resist external influences (impact loads from dropped items, loads from trawling systems during the fishing vessels operations in the area of the deposit) [74], [78].

The experience of Norway - one of the world leaders in the development of offshore fields - demonstrates the widespread use of GRP or concrete / steel protection of underwater structures. The main qualities of protection from steel are high rigidity, great weight, which ensures stability on the seabed and the ability not to move under the action of hydrodynamic forces. Compared to concrete / steel protection, GRP solutions are more cost-effective from the point of view of the cost of manufacturing, transportation, installation on the seabed, require less material, do not corrode, and require virtually no maintenance. The main disadvantage of this solution is associated with a relatively light weight and, therefore, a relatively high risk of displacement due to hydrodynamic forces. However, this problem can be solved by adding ballast to the design of such protections [97], [98].

6.2. GRP cover design

The design selection is based on the previous work [95], [96].

The geometry of GRP cover is primarily defined by the dimensions of subsea equipment. In that case the geometry is designed to fit the dimensions of steel pipes laid at the seabed. The typical diameter of 1 m is taken into account in this study, so the geometry, based on previous work, is based on these two points. The length of the GRP over is considered to be 10 meters' long. Other dimensions are dependent on the profile geometry of each structure. Figures 39 -41 demonstrate proposed design of GRP protection covers.

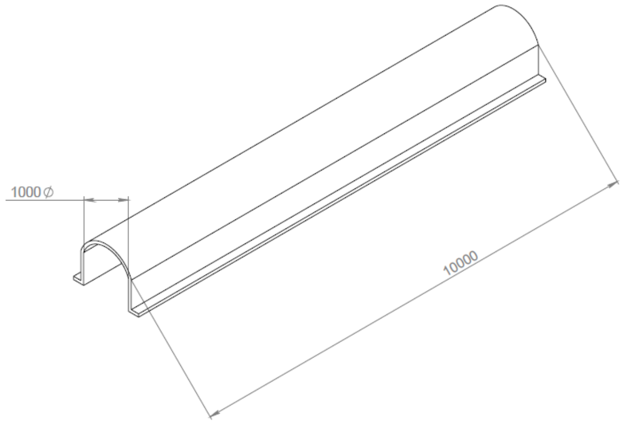


Figure 39. Round form protection cover

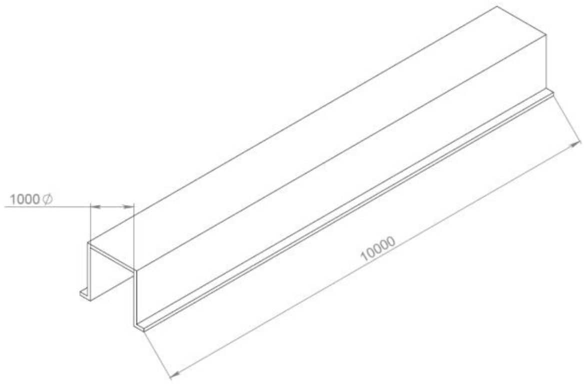


Figure 40. Square form protection cover

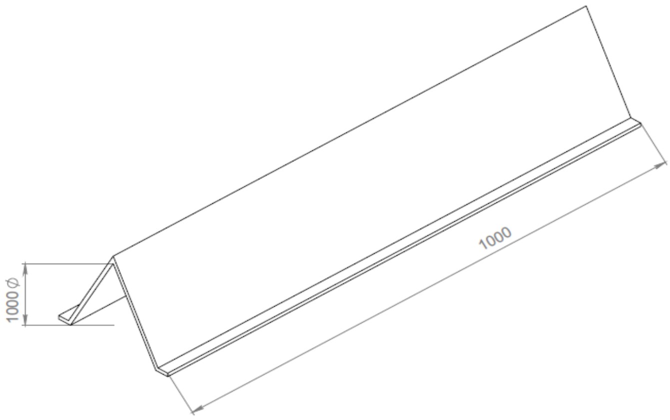


Figure 41. Triangular form protection cover

6.3. Impact energy

The dropped object could be any object that has the potential to impact subsea structures or even cause a failure by falling on it under its own weight. It is difficult to consider a classification for dropped objects due to the fact that potential hazard could be caused by every part of the equipment, machinery component or cargo, which can have different mass and shape.

Impact loads from drop-objects could be divided into two groups: impact energy and object diameter [88], as shown in Table 21.

Several parameters influence the impact energy of dropped objects: impact speed, area of contact in the moment of impact, stiffness of the structure, the weight of the dropped object, object stiffness, velocity vector, type of material, material thickness [98].

Table 21. Groups of dropped objects [88].

Group	Impact energy kJ	Impact area	Object diameter mm
Multi well structures	50	Point load	700
	5	Point load	100
Other structures	20	Point load	500
	5	Point load	100

The energy which is applied from one object to another over the short period of time, then absorbed by the second body is called the impact energy [81]. When this type of energy is transferred from one body to another, the second body needs to absorb the energy in order to stay in an equilibrium state. The impact energy is currently equal to the kinetic energy of the dropped object with certain mass:

$$I = \frac{m * V^2}{2} \qquad (12)$$

where,

I - impact energy (or kinetic energy);

m – mass of dropped object;

v – velocity of dropped object.

In the scope of this work an assumption was made that the object would have a terminal velocity, considered a free fall [84].

6.4. Dropped object velocity in different media

6.4.1. Velocity in air media

As shown in equation (6.1) above, the impact energy of a falling object is proportional to the square of the velocity. When falling, the object has several speeds depending on the environment in which it is located.

While moving through the air media, for example, falling after the breakage of the crane system sling, the speed of the falling object can be calculated by equation (6.2):

$$V_1 = \sqrt{2 * g * h}, \qquad (13)$$

where,

h – the height from the water surface till the level of object;

g – gravity acceleration [66], [74].

6.4.2. Water collision

When an object reaches the surface of the water, it passes through the water at a speed of V2, as shown in equation (6.3). The integral equation shows that the momentum loss when the impact occurs between the object and water surface:

$$V_2 = V_1 - \int_0^t \frac{P(t)}{M} dt, \qquad (14)$$

where,

M – mass of the object;

P(t) – impact force [81].

6.4.3. Velocity in water media

After the water surface hit the object will start to accelerate from the gained speed V_2 until its terminal velocity through the water medium:

$$V_t = \sqrt{\frac{2 * (W - O)}{C_D * A * \rho}} \qquad (15)$$

Or

$$V_t = \sqrt{\frac{2 * (mg - O)}{C_D * A * \rho}} \qquad (16)$$

where,

W - gravity force (in the air);

O - buoyancy force;

ρ – density of sea water;

A – cross-sectional area of a dropped object;

C_D – object shape coefficient (depends on Reynolds number) [95].

In terms of defined objects one should take into account that the inner volume of pipe and container would be filled by water. Then, the (5) equation shall be transferred into:

$$V_t = \sqrt{\frac{2 * (m_{obj} + m_w)g - O)}{C_D * A * \rho}} \tag{17}$$

where,

m_{obj} – mass of the dropped object;

m_w – mass of the water in inner volume.

The buoyancy force (O) could be found:

$$O = \rho Vg \tag{18}$$

here, ρ – the density of sea water - 1025 kg/m3, g = 9,81 m/s^2, V – displaced volume of water [86].

6.5. Drag coefficient selection

To calculate the terminal velocity in a water media of a dropped object, the value of the coefficient C_D is required. Due to the already mentioned complexity of equipment classification and the presence of a complex geometric shape, it is not possible to determine the exact coefficients. Since it was not possible to use exact drag coefficients, an assumption was made to simplify the calculations in order to approximate the drag coefficients for already known forms. The analysis examines two objects: a container for marine equipment and a drill pipe. It is almost impossible to determine the exact drag coefficient for such objects without performing complex calculations on computational fluid dynamics for a particular geometry. Given this fact, several assumptions have been made [96].

First, the geometry was simplified. Figure 42 and 43 shows the container and drill pipe.

Figure 42. Offshore container (1c) [90]

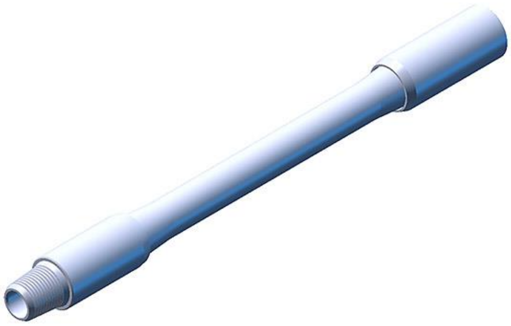


Figure 43. Drill pipe [90]

The following simplifications were performed. The ribbing part of container flanks was suppressed, in order to obtain the typical rectangular shape. In the case of drill pipe, the following idea was implemented: pipe nipple and socket were considered to be the same shape. For both cases, it was considered not to use smooth edges for better mesh construction.

Figures 44 and 45 show the principal simplification of models. Dimensions are presented in Figure 46.

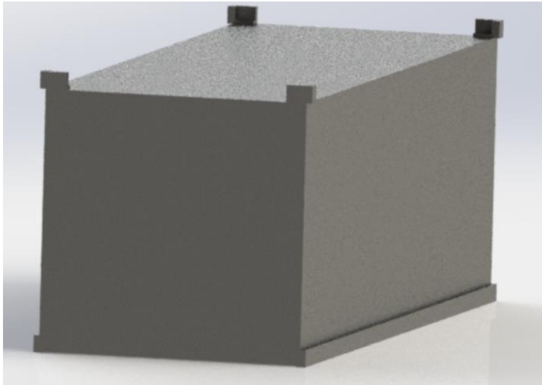


Figure 44. Simplified version of container
(SOLIDWORKS 2016 modeling)

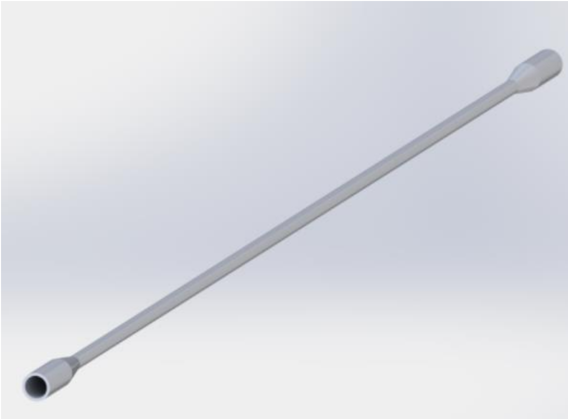


Figure 45. Simplified version of drill pipe
SOLIDWORKS 2016 modeling)

6.6. Terminal velocity calculation

To define terminal velocity V_t for both objects the initial data should be suggested.

The assumption of simplified geometry is necessary in order to get the approximate drag coefficient. With this aim in view the typical geometry, mostly fitted to the geometry of discussed dropped objects should be taken to estimate the value of drag coefficient. In Appendix C the necessary calculations are presented in Tables 23 and 24.

It is also necessary to determine the Reynolds number to select the drag coefficient from the list. The critical point is that for Reynolds number estimation, the terminal velocity Vt is needed. In that case, the iterative approach should be implemented [95], [96].

In that case, firstly the initial guess of terminal velocity should be made. Then the Reynolds number could be obtained.

Reynolds number is defined as:

$$Re = \frac{V_t * L}{\upsilon} \tag{19}$$

where,
L – characteristic length;

υ – kinematic water viscosity (assumption, the temperature is closed to 0 °C, in that case the value of viscosity = 1.83×10^{-6} m^2 s^{-1}) [85].

The range of changing terminal velocity is quite narrow in the case of offshore drop objects [95]. The typical range of velocity fluctuates from the values of less than 1 m/s to 15-20 m/s in case of very heavy objects. If we consider terminal velocity as 1 m/s, the Reynolds number would be Re= 3 278 688. The change of velocity will get a higher number of Reynolds, but according to [89] it would not influence the choice of drag coefficient (see Appendix D).

Then, getting the Reynolds number allows determining drag coefficient from the listed forms in the table. Calculation the terminal velocity with the help of equation (17) could be done. If the initial guess does not hit the obtained result, the iteration needs to be repeated.

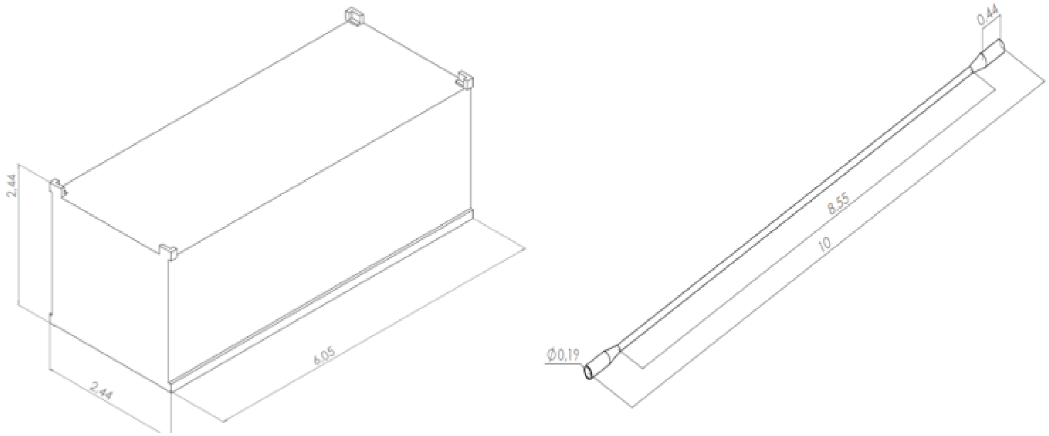


Figure 46. Dimensions of the modeled objects

The dynamic Finite Element Analysis could be conducted in Explicit Dynamics package in ANSYS Workbench, Release 19.2. 3D models of dropped objects and protection covers were done in Solidworks, release 2016 software [101].

6.7. Finite element Modeling

To this moment, a lot of research works have been published about the variety of methodologies in determination of the impact response during the drop testing. The variety of methods could be distinguished into the following chart, presented in Figure 47 [85].

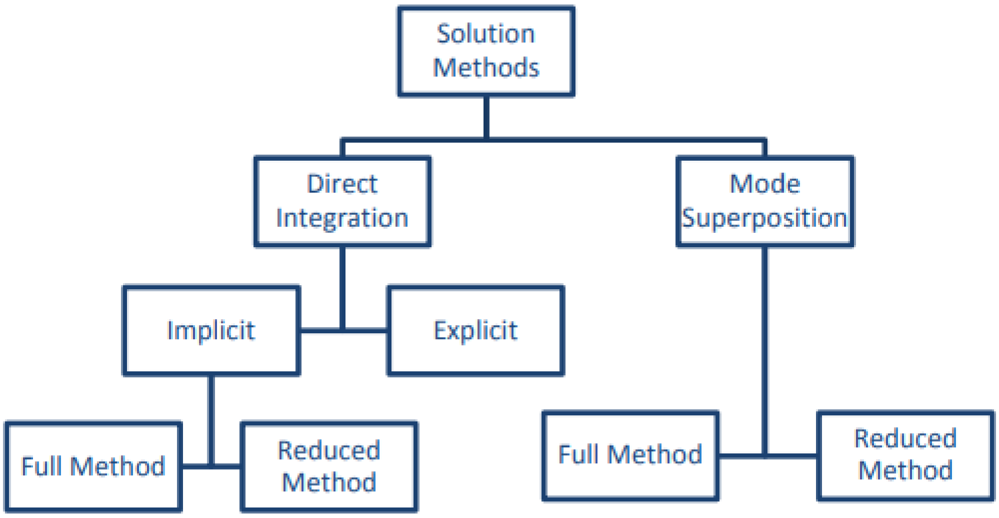


Figure 47. Different solution methods [85]

The most popular methods of calculation are bonded with direct integration. For direct integration, there are two techniques: implicit and explicit iteration scheme. Both explicit and implicit methods are designed on time integration in order to give a solution for unknown quantitates if the correct force and initial boundary conditions are given. In terms of the subject of work, the proper method should be chosen. The implicit scheme is highly preferred in terms of static analysis. But for the dynamic response, as for the dropped object impact, the more likely scheme is the explicit one. Generally, the main difference between these methods is encompassed in the nature of application/response. The explicit scheme gives the user the time history of responses and the implicit one   The first one cannot deal with static problems, while the second scheme provides most stable static deformation. In the case of this work, the module of Explicit Dynamics in ANSYS Workbench 19.2 package would be performed.

6.8. Implementation of explicit scheme in dynamic contact

Dynamic impacts are always associated with the short time duration of dynamic contact. The typical example of such impacts is the car hitting the safety fence. Since the scope of this work requires to solve nonlinear partial differential equations, it could not have been done analytically, there comes an approximate solution which could be performed by Finite Elements Method (FEM) with the help of Explicit Dynamics.

The integration with the explicit scheme mostly comprises the central difference scheme. The equilibrium equations for the considered single degree of freedom damped system are shown below [101]:

$$M\ddot{u}(t) + R[u(t), t] = P(t); \tag{19}$$

To receive the full motion equation, the damping variable should be added. In a certain time t_n we obtain (in order to simplify the view of notation the reference to time (t) disregarded:

$$M\ddot{u} + C\dot{u} + R(u) = P \tag{20}$$

That motion equation could be written as a first order algebraic differential equation using the independent variables $\dot{u} = \dot{v}$ and $\ddot{u} = \dot{v}$.

In a next time step t_{n+1} one could obtained the next equation (with the change of $\dot{u} = v$ and $\ddot{u} = a$):

$$Ma_{n+1} + Cv_{n+1} + R(u_{n+1}) = P_{n+1} \tag{21}$$

where

M – mass matrix;

R[u(t),t] – stress divergence;

P(t) – time-dependent applied loads;

u(t) – time dependent solution.

In this method, the following velocities and accelerations at a certain time step t_n are approximately equal to:

for velocity

$$v_n = \frac{u_{n+1} - U_{n-1}}{2\Delta t}; \tag{22}$$

for acceleration

$$a_n = \frac{u_{n+1} - 2U_n + U_{n-1}}{(\Delta t)^2} \tag{23}$$

Putting these variables into the equation of motion gives the following result at the time t_n:

$$M(u_{n+1} - 2u_n + u_{n-1}) + \frac{\Delta t}{2} C(u_{n+1} - u_{n-1}) + (\Delta t)^2 R(u_n) = (\Delta t)^2 P_n \tag{24}$$

Transforming this equation at the next time step t_{n+1} gives the following equation:

$$\left(M + \frac{\Delta t}{2} C\right) u_{n+1} = (\Delta t)^2 [P_n - R(u_n)] + \frac{\Delta t}{2} C u_{n-1} + M(2u_n - u_{n-1}) \tag{25}$$

where M and C could be calculated only once and do not change. Since the explicit method needs the previous step to calculate the next one, the additional treatment is required to start iteration [100]. The value of u_{n-1} is needed to be derived from initial conditions of u_0 and v_0. A Taylor series expansion should be performed at time t_{n-1}:

$$u_{-1} = u_0 - \Delta t v_0 + \frac{(\Delta t)^2}{2} a_0 \tag{26}$$

Acceleration at the time step t_0 comes from the equation of motion:

$$a_0 = \frac{-Cv_0 - R(u_0) + P_0}{M} \tag{27}$$

The following approximations are taken into account (Wood, 1990):

$$u_{n+1} = u_n + \Delta t v_n + \frac{(\Delta t)^2}{2} a_n \tag{28}$$

$$v_{n+1} = v_n + \frac{1}{2}\Delta t(a_n + a_{n+1}) \quad (29)$$

With the equation of motion this leads to the equation:

$$\left(M + \frac{\Delta t}{2}C\right)a_{n+1} = P_{n+1} - R\left(u_n + \Delta t v_n + \frac{(\Delta t)^2}{2}a_n\right) - \frac{\Delta t}{2}Ca_n \quad (30)$$

The right part of the equation depends on the known loading function, which is denoted by **P**. The initial conditions could be implied at the start of the program process.

In order to prove the stable process and exact accuracy of the generated solution, the time step size in Explicit scheme is controlled by Courant-Friedrichs-Levy condition.

The idea of the condition is that the certain time step which is implied by an algorithm is limited so that the stress wave cannot continue to go through than the smallest characteristic mesh element dimension. This is implied in one single time step.

For solution stability the following criteria for time step:

$$\Delta t \leq f * \left[\frac{h}{c}\right]_{min} \quad (31)$$

where

Δt – time incremental change;

f – stability factor of the time step;

h – element characteristic dimension;

c – the local speed of the sound in the certain material.

In other words, the maximum time step is in inverse dependence of the speed in the material (c):

$$\Delta t \infty \frac{1}{c} = \frac{1}{\sqrt{\frac{C_{ii}}{\rho}}} = \sqrt{\frac{m}{V * C_{ii}}} \quad (32)$$

Where
C_{ii} – material stiffness;
ρ – material density;
m – material mass;
V – element volume.

6.9. ANSYS shell elements

To ensure the proper work of chosen simulation elements, the proper way should be chosen. Since the fact that all included objects (all cover protection forms, drill pipe and container) are the objects of thin wall structure, the best scenario is to choose shell element analysis for such case. The shell element analysis has several advantages, such as:

- Shell mesh much easier to create and to be generated;
- The time, required to perform simulations and post-processing is much less in comparison with solid simulation;
- The mesh quality, as a rule, is better than for solid one.

6.10. Meshing

ANSYS explicit meshing tool is used to generate the mesh on all geometries of protective covers and both drill pipe and container as dropped objects. To ensure the quality of the mesh the Multizone method was used. It generates the mesh of hexahedral elements where it is possible and generates more difficult shape for regions with unstructured mesh. For all 6 cases, it was considered to take this method. Figures 48-53 demonstrate the mesh quality of each case.

For round form and drill pipe mesh comprises 17424 nodes and 17144 elements.

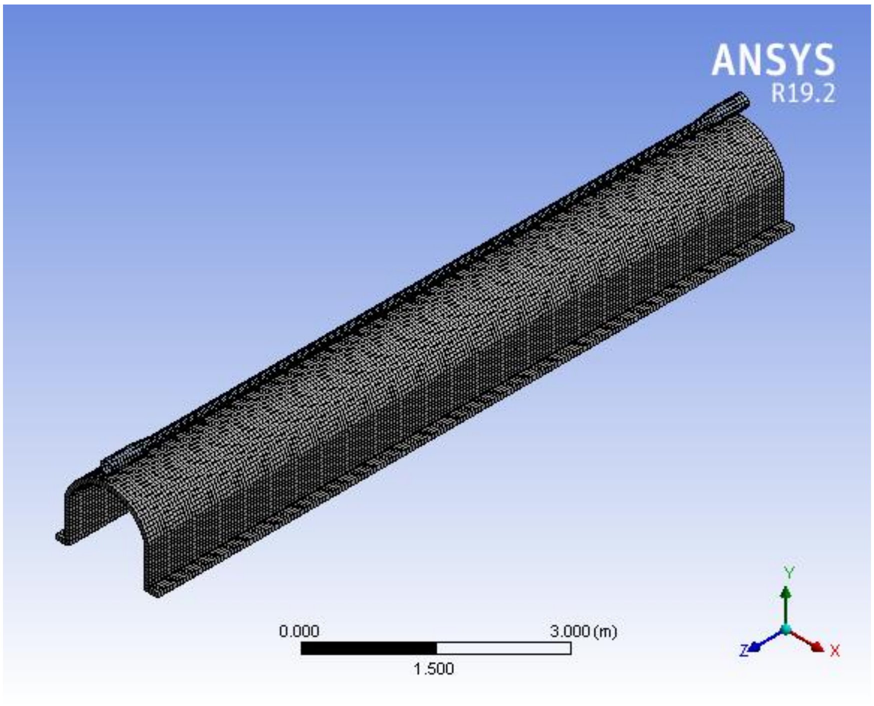


Figure 48. Mesh for round cover and drill pipe

For square form and drill pipe mesh comprises 19587 nodes and 19296 elements.

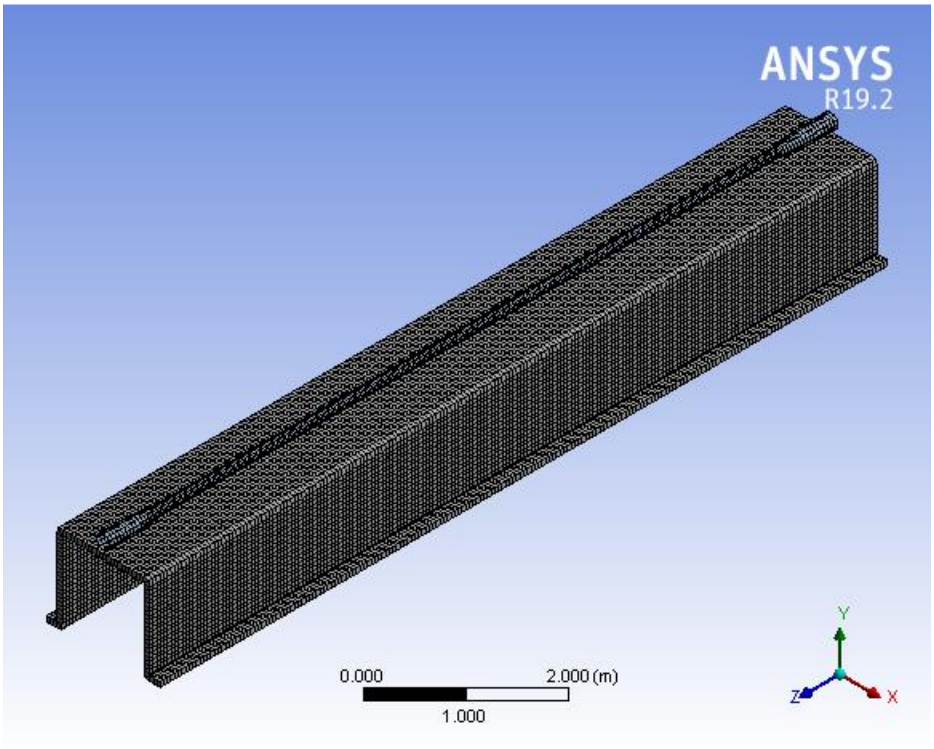


Figure 49. Mesh for square cover and drill pipe

For triangular form and drill pipe mesh comprises 21975 nodes and 21672 elements.

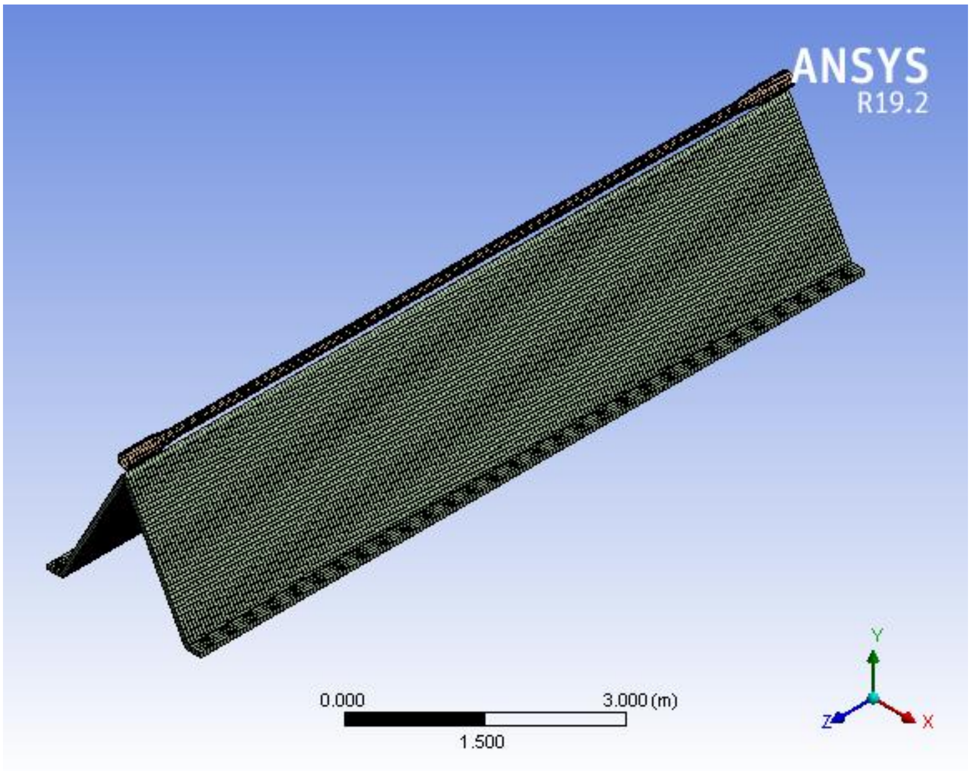


Figure 50. Mesh for triangular cover and drill pipe

For round form and container mesh comprises 10462 nodes and 10335 elements.

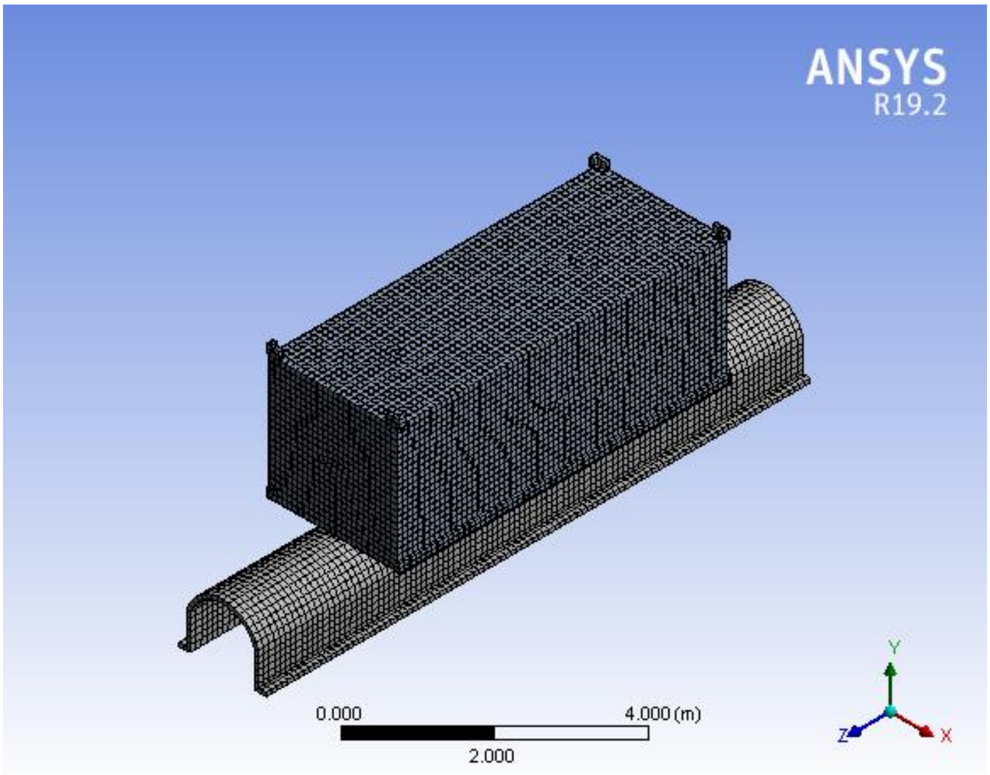


Figure 51. Mesh for round cover and container

For square form and container mesh comprises 11535 nodes and 11396 elements.

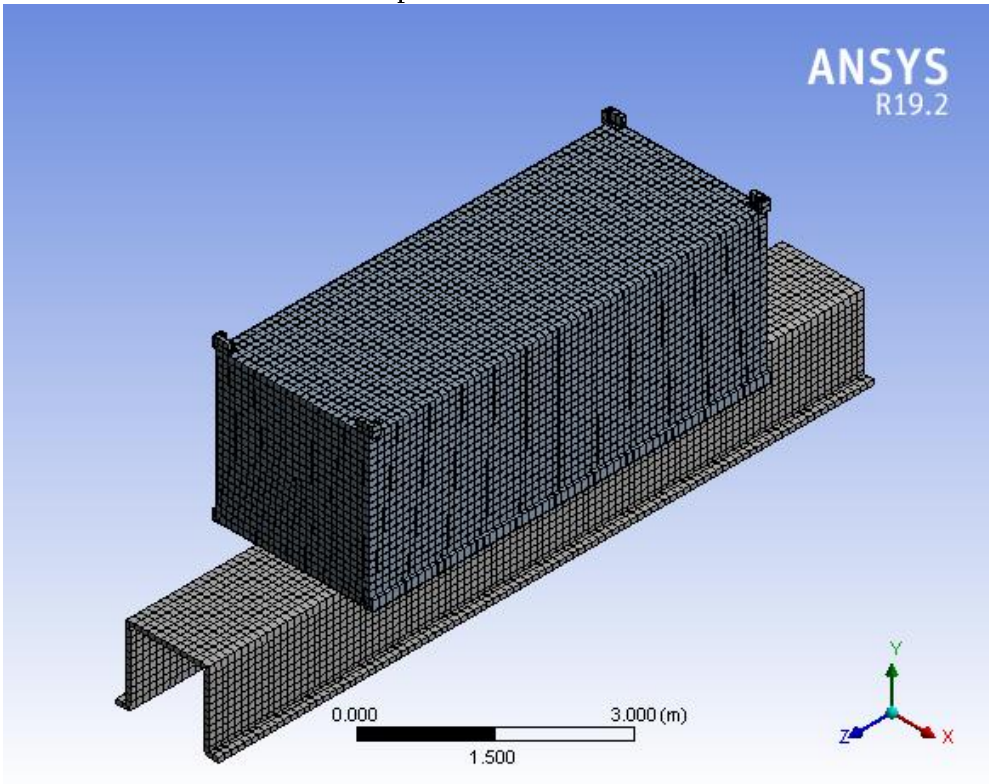


Figure 52. Mesh for square cover and container

For triangular form and container mesh comprises 11684 nodes and 11546 elements.

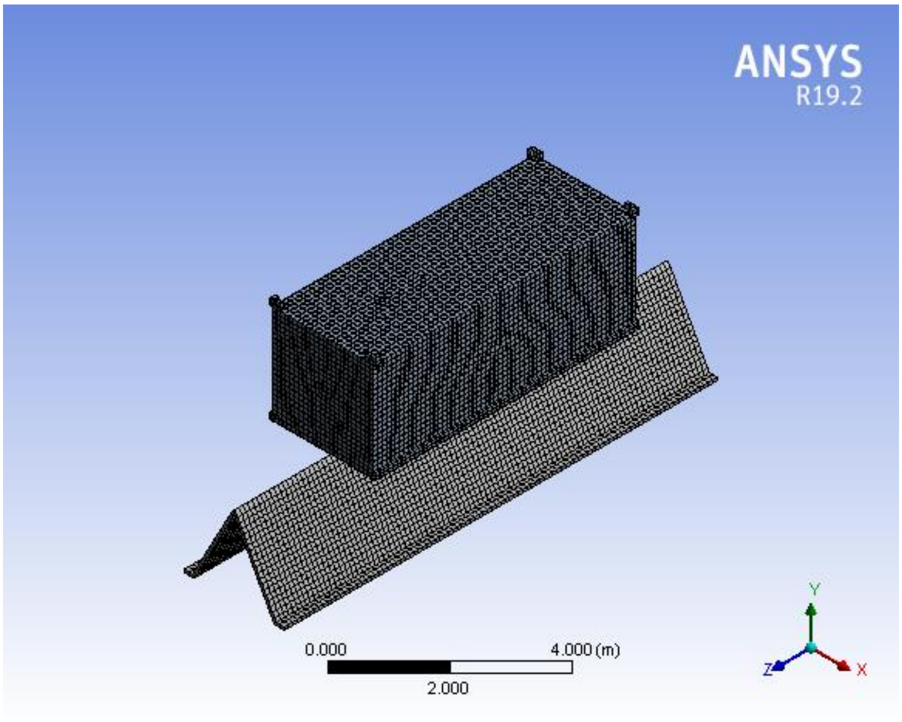


Figure 53. Mesh in triangular cover and container

6.11. Considered assumptions when modelling impact load

There are several assumptions that play a key role in the scope of this study:

it is assumed that the object has already reached the terminal velocity when hitting the GRP protection cover;

- the drop model is considered to be horizontal or vertical without any angle deviation, so the surface area of impact load would be one of the sides of an object;
- the vector of dropped object velocity is normal to a protection cover;
- the length of pipe protection cover is considered infinite, so the place of dropped object hit is considered on the main body of the cover, the probability of hitting mating area is negligible;
- drag coefficients are taken from the already known quantities for simplified geometry;
- properties of grp cover assumed to be homogeneous.

6.12. Obtained results

The following results were obtained after simulation drop test in ANSYS 19.2 Workbench. In all cases, all mentioned above approximations were taken into account.

Obtained results of 6 cases are presented in Table 22.

Table 22. Obtained results

GRP form	**Drill pipe**		**Container**	
	Equivalent stress [Pa]	Total deformation [m]	Equivalent stress [Pa]	Total deformation [m]
Round	$9.26*10^6$	$3.23*10^{-4}$	$8.42*10^6$	$3.6*10^{-4}$
Square	$11.6*10^6$	$5.1*10^{-4}$	$15.7*10^6$	$10.4*10^{-4}$
Triangular	$2.86*10^6$	$0.29*10^{-4}$	$9.53*10^5$	$0.46*10^{-4}$

From the obtained results triangular form has the lowest values of stress and deformation. It may be explained by high stiffness of the shape since the hit was placed on the edge of the structure. The highest figures of equivalent stress and total deformation are observed in the case of square GRP form. The round form is in the middle of all output parameters figures, obtained for the equivalent stress and deformation are shown in Appendix E.

7. Environmental concerns

Needless to mention, that Arctic region is considered one of the most sensitive areas in terms of environmental contamination. The Arctic's earth bowels conceal such valuable hydrocarbons and rare earth metals in the modern world; coast waters are full of commercial fish; in these latitudes, there are pass transport routes of world importance. The Arctic has great power and potential. However, on the other hand, the Arctic is a fragile system, violations in which rapidly affect the life of the entire planet. Presence of unique creatures of flora and fauna, permafrost accumulations make the development of such region a real challenge. The human activities in that region may cause irreparable harm to nature by marine transport. The total majority of vessels work on the diesel fuel which contains a lot of heavy metals which are being thrown to the air during the combustion process. In addition to this, defects in the motor systems allow the fuel to enter the water masses. Both processes could potentially contaminate vast regions and poison local creatures since the accumulation of these metals in the media is considered toxic [102].

The huge impact on the environment also take place in terms of water contamination during accidents on the drilling wells and floating drilling units. Petroleum products spills are considered as the most dangerous contaminations of nature. The water clearance is known as one of the less effective ways since only 10-15 % of spilt oil could be gathered and disposed of. There were plenty of cases with environmental impacts during offshore field development. For example, in 1989 there was a shipwreck of the tanker Exxon Valdez which transported oil. It was one of the biggest ecological disasters in the Arctic region. It resulted in oil leakage of approximately 260 thousand oil barrels. It caused the shortage of rare fish population, mammals, birds. According to some forecasts the recovery of the population of the environment could last for at least 30 years [103].

In the case of water contamination with oil products, one should carefully choose the right method of OSR management. There are several ways of oil spill liquidation:

- monitoring;
- mechanical spill gathering;
- in-situ burning;
- burning oil at the spill site using slick chemical bars (biodegradable surfactants);
- dispersant application.

7.1. Monitoring

Spill response strategies have different levels of risk. For example, if an on-site risk assessment concludes that the existence of an oil spill will not be extended and the oil will not reach the shoreline, in this case, monitoring may be considered the preferable option.

The circumstances in which the monitoring option may be considered the most appropriate include the following:

• The spill occurred at a great distance from the shore. The threat to populations of waterfowl and marine mammals is absent, and oil, according to calculations, should decompose and dissipate naturally, before reaching land;

• There are conditions for rapid natural removal of the spill from the surface of the water (for example, light distillates in many cases will evaporate naturally);

• The degree of oil pollution is low, and the spill stain is not resistant;

• Complicated hydrometeorological conditions or the presence of volatile compounds in the spilt product could cause a serious danger to the liquidators [104].

7.2. Mechanical spill gathering

Slick bars and skimmers are commonly used to collect a spill by mechanical means, which localize the spill and remove it from the surface of the water (Figure 54). In addition, slick bars can oil from areas of particular sensitivity. The mechanical collection is the preferred spill response strategy at the coastline or on land and is best suited for level 1 spill response. The effectiveness of mechanical means is determined by the effectiveness of the s barriers. However, if wind speed, wave heights, or current speeds exceed limits, implementation of slick bars can be difficult, inefficient, and unsafe. Sea ice may also limit the ability to safely and efficiently use mechanical facilities. However, practice shows that even under ideal conditions for the elimination of a large spill on open water by mechanical means, it is possible to collect only a small part of the spilt oil. The remaining ungathered oil disappears over time and decomposes naturally [104].

Figure 54. Mechanical means of OSR [69]

7.3. In-situ burning

When this method is implemented, the controlled burning of spilt oil occurs directly at the spill site as it presented in Figure 55. Burning quickly removes a large amount of oil from the surface of water or land. This high-intensity method removes more than 90 % of the oil from a water surface. To ensure the burning of oil on the surface of the water in the absence of ice, its film thickness should be 2-3 millimetres and be supported by fire-resistant slick bars. The rapid removal of oil from the water surface can protect marine mammals, birds and the coastline from oil pollution. Regulations and methods developed for the in situ combustion process allow this operation to be carried out in a safe manner. The negative effects of using this method include the formation of unburned residue and smoke plume. Their analysis showed that they are much less toxic and dangerous to the environment than crude oil. In remote arctic regions, the effects of smoke plume formation are quickly neutralized due to its rapid dispersion and remoteness from populated areas [105].

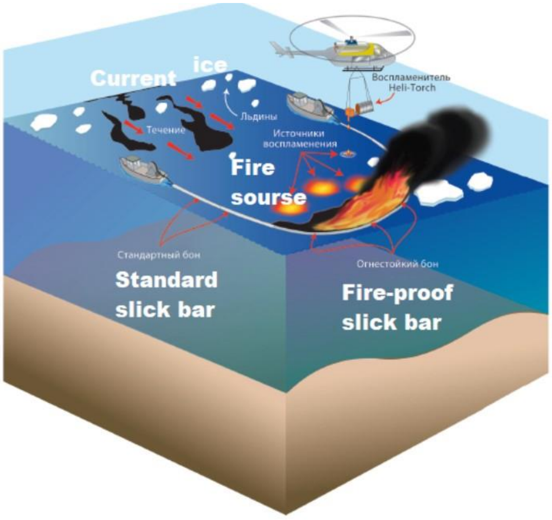


Figure 55. Scheme of oil burning operation at the spill site [69]

7.4. Burning oil at the spill site using slick chemical bars (biodegradable surfactants)

Low-toxic and biodegradable surfactants (slick chemical bars) sprayed around the perimeter of the spilt oil stain can alter the surface properties of water and prevent the spread of the oil slick. If the spill has already begun to spread, the surfactant "drives" the oil into a spot of smaller area and thicker. Thus, the surfactant plays the role of a slick bar, supporting the thickness of the oil layer sufficient for burning. In the open sea and calm conditions, a surfactant layer with a thickness of only one molecule is sufficient for localizing oil. Therefore, a minimal amount of surfactant can localize a large amount of spilt oil [104].

7.5. Dispersant application

The use of dispersants is often the optimal strategy for covering large areas of oil spills and allows you to speed up the process of natural biological decomposition of hydrocarbons. Interacting with the spilt oil, dispersants increase the rate of oil penetration into the water column and removal of oil from its surface. This significantly reduces the likelihood of oil impact on the coastal zone, as well as on mammals and birds living near the surface layer. Upon completion of dispersion, the oil is quickly diluted to a concentration below the toxic threshold. Compared to oil in a surface film or oil deposited on the coastline, diluted oil is much faster biodegradable by microorganisms, which contributes to the rapid restoration of the natural environment. Dispersants are biodegradable surfactants in the form of a low-toxic solution that can be sprayed directly onto the surface of an oil spill spot from a ship or aircraft [104].

To conclude, it is of the first-rate importance to take into account all challenges and potential risks which might occur in the process of offshore field development. The following challenges are currently stated for Russian offshore production.

- Oil production under the ice is currently not carried out due to the fact that, to date, oil fields on the shelf in ice conditions at the depths of the sea more than 40 m have not been detected. The first fields in such conditions with supposedly significant oil resources are the recently discovered Yuzhno-Kirinskoye (Sakhalin) and Pobeda (Kara Sea)

- The current regulatory field of the Russian Federation does not contain any restrictive conditions for oil production from underwater wells in ice conditions
- Restricting access during the year due to ice cover does not increase the risk of accidental oil leaks and any additional difficulties for subsea production equipment, and can be effectively managed by monitoring equipment status and preventive maintenance measures.

Conclusions

The Sakhalin Island shelf has significant prospects in terms of hydrocarbon resources. The consistent development of the deposits of the shelf leads to the economic stability of the region, its energy security. The Ayashkinskoye license area considered as part of this work has an approved commercial value. The prospects for its development in the coming years can be regarded as very high.

The purpose of this work was to consider the prospects for the development of this area. For a detailed understanding of the region, the climatic conditions of the region, the hydrological conditions of the sea, the soil characteristics of the seabed, etc. were considered. The main difficulties were taken into account, based on the above conditions, which could potentially affect the development process of this area. The existing experience in the development of the Sakhalin-1 - Sakhalin-3 project fields was also taken into account.

The study reviewed the existing world practices in the development of offshore oil and gas fields. Based on the stage analysis, a study was conducted on the development scenarios for the development of the Triton (Bautinskaya structure) and Neptun (Ayashsky structure) deposits in this license area.

The staged analysis included three successive stages of the study. At the first stage, an economic analysis of the profitability of development was carried out, and existing technologies for the development of offshore oil and gas fields were also considered. A compliance matrix based on open sources has been compiled.

The second stage involved narrowing the circle of scenarios to five potentially possible ones. Analyzing the existing global and regional (Sakhalin shelf) development experience, a single scenario was chosen: installing a gravity platform on the Ayashsky structure (Triton field), installing an SPS unit on the Bautinsky structure (Neptune field) and further connecting the Bautinsky structure to the platform node. Hydrocarbons are transported via a subsea pipeline to the onshore processing facility.

In the third stage of the analysis, the design of a gravity-based concrete platform was proposed from open sources of literature. The loads from ice fields were considered according to different standards for the proposed platform option. The scheme of SPS layout and further connection of the Bautinskaya structure to the platform was developed.

Also, unforeseen situations were considered related to marine operations in this work. It was decided to consider the most frequent emergency situation - loss of cargo during tripping operations.

Simulations were carried out based on Solidworks 2016 and ANSYS Workbench 19.2 software in order to consider the impact load on subsea pipeline protective structures. Two dropped objects (container and drill pipe), and three proposed protection structures (triangular, square and circular cross-section) were presented in the paper. According to the obtained results, it was proposed to use a triangular shape to protect the pipeline near the platform and in other potentially dangerous areas, where there may be a risk of loss of cargo from the platform/service vessels.

References (in order of appearance)

1. Sakhalin Government website: https://sakhalin.gov.ru/index.php?id=168
2. Annenkova, A.: The island in the oil sea, Neft Rosssii, 2009, №11, pages 62-65. (Остров в нефтяном море / А. Анненкова // Нефть России. – 2009. – № 11. – С. 62 – 65.)
3. Stephanenko, S.: Nearest perspectives of Russian Far East, Neft Rossii, №10, 2009 (Стефаненко, С. Близкие перспективы дальнего края / С. Стефаненко // Нефть России. – 2009. – № 10).
4. Sakhalin Offshore projects website: http://www.sssc.ru/shelf/, JC "OOO Sakhalin-Shelf-Service", Сахалинские шельфовые проекты. [Электронный ресурс] //Сайт компании СП ООО «Сахалин-Шельф-Сервис» –. – Режим доступа: http://www.sssc.ru/shelf/
5. Grigorenko, Yu.: Integrated development of resources and hydrocarbon reserves of the Far East / Grigorenko, Yu.N., Margulis, L.S. // The Fuel and Energy Complex of Russia: Regional Aspects. – Saint-Petersburg, 2004. (Григоренко, Ю.Н. Комплексное освоение ресурсов и запасов углеводородов Дальнего Востока / Ю.Н. Григоренко, Л.С. Маргулис // Топливноэнергетический комплекс России: региональные аспекты. – СПб., 2004.)
6. Uvarova, T.E.: The abrasive effect of drifting ice cover on marine hydraulic structures, thesis for the degree of doctor of technical sciences. - Vladivostok: FEFU, 2014. (Уварова Т.Э. Истирающее воздействие дрейфующего ледяного покрова на морские гидротехнические сооружения, Диссертация на соискание степени доктора технических наук. - Владивосток: ДВФУ, 2014.)
7. Gritsov, G.V.: Prospects for the development of the oil and gas complex of Sakhalin Island // PSE. 2011. №4. (Грицов Г. В. Перспективы развития нефтегазового комплекса острова Сахалин // ПСЭ. 2011. №4. URL: https://cyberleninka.ru/article/n/perspektivy-razvitiya-neftegazovogo-kompleksa-ostrova-sahalin).
8. Zolotukhin, A.B.: Offshore Field Development with Emphasis on the Arctic. Course lections, Prof. Anatoly Zolotukhin, Gubkin Russian State University (NRU) of Oil and Gas, University of Stavanger, 2018.
9. Sakhalin Island https://ru.wikipedia.org/wiki/%D0%A1%D0%B0%D1%85%D0%B0%D0%BB%D0%B8%D0%BD
10. Gudmestad, O.T., Zolotukhin, A.B., Ermakov, A.I., Jakobsen, R.A., Mitchenko, I.T., Vovk, V.S., Løset, S. and Shkhinek, K.N.: «Basics of offshore petroleum engineering and development of marine facilities», pages 348-370, Oil and Gas Printing House, Moscow, 2000.
11. Exxon Neftegas Limited: Материалы предварительной оценки воздействия на окружающую среду, Южно-Сахалинск, Россия, Сентябрь 2001 г. (Exxon Neftegas Limited, Materials of the preliminary assessment of environmental impact, Project Sakhalin-1, Yuzhno-Sakhalinsk, Russia, September 2001)
12. https://www.worldatlas.com/aatlas/infopage/okhotsk.htm
13. Sakhalin Energy: Oil spill prevention and response plan for the Piltun - Astokhskoye field, Book 4, list of environmental protection measures, Volume 1, Part 1. Sections 1-4, Sakhalin Energy Investment Company Ltd., Moscow - Yuzhno-Sakhalinsk, 2016 (План предупреждения и ликвидации разливов нефти и нефтепродуктов для Пильтун – Астохского месторождения, Книга 4, перечень мероприятий по охране окружающей среды, Том1, Часть 1. Разделы 1-4, «Сахалин Энерджи Инвестмент Компани Лтд.», Москва - Южно-Сахалинск, 2016).

14. Hydrometeoizdat: Hand book on the climate of the USSR. Issue 34, part 4. L: Hydrometeoizdat, 1968 (Справочник по климату СССР. Вып.34, ч.4. Л.: Гидрометеоиздат, 1968)
15. Rosgidromet website: http://rus.ferhri.ru
16. Dobrovolsky A.D., and Zalogin B.S.: Sea of the USSR. M., Publishing House of Moscow State University, 1982 (Добровольский А. Д., Залогин Б. С. Моря СССР. М., Изд-во МГУ, 1982 г.)
17. SKF, GEO: Program of marine geophysical explorations of the Northern Eastern part of Sakhalin island shelf, Volume №2: The environmental impact assessment, SKF GEO, Moscow, 2017.
18. Gazprom: Plan for the prevention and elimination of oil and petroleum products spills during the construction of exploration well No. 6 of the South-Kirinskoye field in the Sea of Okhotsk using the Doo Sung gas pumping station, Gazprom, Moscow, 2013 (План по предупреждению и ликвидации разливов нефти и нефтепродуктов при строительстве разведочной скважины №6 Южно-киринского месторождения в акватории Охотского моря с использованием ППБУ «Doo Sung», ОАО «Газпром», Москва, 2013).
19. ISO/FDIS 19906, Petroleum and natural gas industries -- Arctic offshore structures, ISO/TC 67/SC 7 Offshore structures, 2010, ISO Geneva, Switzerland
20. Exxon Neftegas Limited, Материалы предварительной оценки воздействия на окружающую среду, Южно-Сахалинск, Россия, Сентябрь 2001 г. (Exxon Neftegas Limited, Materials of the preliminary assessment of environmental impact, Project Sakhalin-1, Yuzhno-Sakhalinsk, Russia, September 2001).
21. Hydrometeoizdat: Scientific and Applied Handbook on Climate of the USSR, Series 3, Issue 34, Part 4. L.: Hydrometeoizdat, 1990 (Научно-прикладной справочник по климату СССР, Серия 3, вып.34, ч.4. Л.: Гидрометеоиздат, 1990).
22. Chumikov, M.: Subsea Template Lifting Operations in the Sea of Okhotsk, Master Thesis, Faculty of Science and Technology, University of Stavanger, 2018.
23. Løset, S., Shkhinek K.N., Gudmestad, O.T., and Høyland K.V.: Actions from Ice on Arctic Offshore and Coastal Structures: Student's Book for Institutes of Higher Education. — St. Petersburg: Publisher "LAN", 2006. — 272 pp, ill. — (Student's Books for Institutes of Higher Education. Special Literature).
24. Kobylinski, L.: Safety of Ships in Icing Conditions, Foundation for Safety of Navigation and Environment Protection, the 12th International Conference on the Stability of Ships and Ocean Vehicles, 14-19 June 2015, Glasgow, UK.
25. Dehghani, S.R., Naterer, G.F. and Muzychka, Y.S.: Droplet size and velocity distributions of wave-impact sea spray over a marine vessel, Department of Mechanical Engineering, Faculty of Engineering and Applied Science, Memorial University of Newfoundland, St. John's, NL A1B 3X5, Canada, 2016.
26. Osadchiy, A.: Sakhalin: Far-remote area or new Eldorado? Journal "Science and Life" M № 3б 2007 – Russian source. (А. Осадчий, Сахалин: отдаленная провинция или новое эльдорадо, журнал «Наука и Жизнь» №3, 2007)
27. Russell, G.: Arkutun-Dagi Field Development., 22nd World Petroleum Congress, 9-13 July, Istanbul, Turkey, 2017
28. Beltcov, A.: Development concepts for Sakhalin's offshore field development, Master Thesis, University of Stavanger, 2016

29. Roxburgh, S..and Kostiuk, E.A.: SS: Sakhalin-1: Project Execution Risks and Management. Offshore Technology Conference. doi:10.4043/20212-MS, 2009.
30. Golder, G.D.: "Sakhalin II Project Overview" OTC paper 10815, In: Proceedings of Offshore Technology Conference held in Houston, 1999
31. Zhukov, G.V.; Karlinsky, S.L.: Production Platforms for Russian Offshore, International Society of Offshore and Polar Engineers, ISOPE-P-04-040, ISOPE, 2004
32. http://www.gazprom.com/projects/sakhalin2/
33. http://www.sssc.ru/page_24.htm
34. Mansurov, M.N. and Zakharov, E.V.: "Sakhalin 3: The Geological and Engineering Principles," ROGTEC, no. 30, pp. 48-57.
35. Golubev, V.A.: "Gazprom activities on Russian Shelf". International Conference and Exhibition for Oil and Gas Resources Development of the Russian Arctic and CIS Continental Shelf, Saint Petersburg, 2013
36. "Gazprom neft" website https://www.gazprom-neft.ru/press-center/news/2021843/
37. https://www.kommersant.ru/doc/3663812
38. Gudmestad, O.T., Alhimenko, A., Løset, S., Shkhinek, K., Tørum,A.And Jensen,A., Engineering aspects related to Arctic offshore developments, Student's Book for Institutes of Higher Education, pages 24-25, 2007, LAN, St Petersburg.
39. Kurchatov, I.: Comparative analysis of the possible development concepts of the North Wrangel license area based on Arctic best available technologies, Master thesis, Faculty of Science and Technology, University of Stavanger, 2018.
40. https://www.kbr.com/Projects/
41. Saputelli, L. A., Black, A., Passalacua, H. and Barry, K., Front-End-Loading (FEL) Process Supporting Optimum Field Development Decision Making, Society of Petroleum Engineers, doi:10.2118/167655-MS, 2013.
42. Google Earth website: https://earth.google.com/web/.
43. Ermakov, A.I.: Methodology for design and Project Management in Oil and Gas Industry. Challenges of the Offshore Project Development. Course lections, Prof.Alexander I. Ermakov, Gubkin Russian State University (NRU) of Oil and Gas, Moscow, 2018.
44. Oil and Gas Technologies for the Arctic and Deepwater, Washington, DC: U.S. Congress, Office of Technology Assessment, OTA-O-270, May 1985.
45. Tax Code of the Russian Federation. Part 2: [Adopted by the State. By the Duma on July 19, 2000, federal law of 05.08.2000 No. 117-ФЗ, as amended. dated 04.04.2014], Art. 322 // Meeting of the legislation of the Russian Federation. - 2000. - №32. - Art. 3340. (Налоговый кодекс РФ. Часть 2: [Принят Гос. Думой 19 июля 2000 года, федеральный закон от 05.08.2000 № 117-ФЗ, в ред. от 01.04.2014], ст. 322 // Собрание законодательства РФ. – 2000. - №32. - Ст. 3340.
46. Rusakov, D.: The concept of developing HP/HT Silurian and Lower Devonian age deposits of Prirazlomnoye field, Master thesis, Faculty of Science and Technology, University of Stavanger, 2018
47. Zelenovskaya, E.: Economics and Management of Petroleum Industry. Course lections, Associate Prof. E. Gubkin Russian State University (NRU) of Oil and Gas, 2017.
48. Gazpromneft-Sakhalin internal data, n.d., Information regarding the Ayashkinskoye license area was obtained during the internship
49. DeGeer, D., Mike Paulin, etc.: 2014 Survey of Arctic & Cold Region Technology for Offshore Field Development, Intecsea, Inc, Offshore Magazine, February 2014, Houston, USA. URL: https://www.offshore-mag.com/content/dam/offshore/print-articles/volume-74/02/0214ArcticPoster-012014Ads.pdf

50. Mitrova, T.: Western Sanctions on Russia's Oil and Gas Sector: a Damage Assessment, Carnegie Moscow Center, 2018 https://carnegie.ru/commentary/76909
51. Offshore projects//PAO NK Rosneft web-page. URL: https://www.rosneft.ru/business/Upstream/offshore/
52. Panichkin, I.: Development of offshore oil and gas Arctic reserves. Today's condition and perspectives, web resource: https://russiancouncil.ru/arcticoil#russia.
53. Makhmutov, T., Polosina, D., Kosivets A.: Sanctions Activity of the US and the EU in Regard to Russia: Consequences for Arctic Projects, Russian International Affairs Council, 2018, URL: https://russiancouncil.ru/en/analytics-and-comments/analytics/sanctions-activity-of-the-us-and-the-eu-in-regard-to-russia-consequences-for-arctic-projects/#16
54. https://www.worldoil.com/news/2019/2/17/gazprom-sign-subsea-production-equipment-contract.
55. https://www.investopedia.com/terms/f/fpso-floating-production-storage-and-offloading.asp
56. https://tass.ru/ekonomika/5484592 (in Russian).
57. https://rogtecmagazine.com/russia-aims-test-domestic-subsea-production-systems-2020/
58. Jackson, G., Raine, B., Powell, J., Suwan, S., and Safaqah, O.: Gravity Based Substructure Solutions for Arctic LNG, International Society of Offshore and Polar Engineers, The Eighteenth International Offshore and Polar Engineering Conference, Vancouver, Canada 2008.
59. Malyutin, A. A., & Karlinsky, S. L.: Concept of Ice-resistant Production Platform On Gravity Base Substructure for 70 - 80 M Water Depth. International Society of Offshore and Polar Engineers, The Seventeenth International Offshore and Polar Engineering Conference, Lisbon, Portugal, 2007.
60. Eie, R., & Rognaas, G.: Fixed Platforms - Development Challenges in Ice Infested Arctic, Offshore Technology Conference, OTC Arctic Technology Conference, 10-12 February, Houston, Texas.
61. Kim, S.D., Finagenov, O.M., Uvarova, T.E.: Definition of ice loads on the structures of the continental shelf according to the norms of various countries // Vesti gazovoy nauki. № 3 (14) 2013.
62. Hou, J., Shao, W.: Structural Design for the Ice-Resistant Platform, Twenty-fourth International Ocean and Polar Engineering Conference, Busan, Korea, June 15-20, 2014
63. API RP 2N. Recommended practice for planning, designing and constructing structures and pipelines for Arctic conditions/ American Petroleum Institute Bulletin. – Dallas, USA, 1995.
64. СТО Газпром 2-3.7-29-2005 Методика расчета ледовых нагрузок на ледостойкую стационарную платформу, открытое акционерное общество "Газпром", "Научно-исследовательский институт природных газов и газовых технологий - ВНИИГАЗ", Москва 2005. (STO Gazprom 2-3.7-29-2005 Method for calculating ice loads on ice-resistant stationary platform, Open Joint-Stock Company Gazprom, Scientific Research Institute of Natural Gases and Gas Technologies - VNIIGAZ, Moscow 2005).
65. ISO/FDIS 19906, Petroleum and natural gas industries -- Arctic offshore structures, ISO/TC 67/SC 7 Offshore structures, 2010.
66. Bai, Q., Bai, Y.: Subsea Engineering Handbook, Elsevier Science, *January 2012*, ISBN: 9780123978042
67. Pribytkov, E. A., Zolotukhin, A. B., and Gudmestad, O. T.: Optimization of Integrated Template Structures for Arctic Subsea-Production Systems. Oil and Gas Facilities, 3(04), 47–53.doi:10.2118/166879-pa, 2014.

68. Zheleva, N.: Challenges in Subsea Structures Design – Dropped Objects Analysis of Multiwell Template/manifold System, Master Thesis, University of Stavanger, 2016.
69. Scibilia, F., Hovd, M., Bitmead, R.: Stabilization of gas-lift oil wells using topside measurements, Proceedings of the 17th World Congress, The International Federation of Automatic Control Seoul, Korea, July 6-11, 2008.
70. Alexander, C., Assessing the Effects of dropped objects on subsea pipelines and structures, Paper No. IOPF2007-110, ASME International Offshore Pipeline Forum, Houston, Texas USA, 2007.
71. Alexander, C., Manimala Y. etc., Evaluating the performance of a pipeline protection system to prevent damage to subsea pipelines from dropped objects, ASME International Offshore Pipeline Forum, Houston, USA, 2008.
72. Annual Offshore Statistics and Regulations Report of Health and Safety Executive (HSE), 2015
73. Arabzadeh, H., Zeinoddoni, M., Dynamic Response of Pressurized Submarine Pipelines Subjected to Transverse Impact Loads, PNU University, Boushehr, Iran, 2011.
74. Bai, Y., Marine Structural Design, Elsevier Science, UK, 2003.
75. Bhagwan, D. Agarwal, etc., Analysis and performance of fiber composites, third edition, Wiley, 2015.
76. DNV-RP-F107, Risk assessment of pipeline protection, recommended practice, Det Norske Veritas, 2010.
77. Explicit Dynamics Basics, Workbench LS-DYNA Training, lecture 1, Ansys, Inc, 2016.
78. Fossan, I., Pappas J.n A. and etc., Next Generation 3D Dropped Object Risk Assessment, SPE-179238-MS, 2016.
79. Hardy, J., A. Gril, Subsea Dropped Objects report, Wild Well Control, Subsea EXPO 2017, February 2017.
80. Health & Safety report, Oil&Gas^{UK} , 2017.
81. Institution of Mechanical Engineers, Foreign Object Impact and Energy Absorbing Structure. 1st Edition, Wiley, New York, 1998.
82. ISO 10855-1, Offshore containers and associated lifting sets, part 1: design, manufacture and marking of offshore containers, 2018.
83. Jones R.M., Mechanics of Composite Materials, Hemisphere Publishing Corporation, 1999.
84. Karpanan, K., & Hamilton-Smith, C., Dropped Object Impact Analysis of Subsea Tree Frame. Volume 4: Fluid-Structure Interaction. doi:10.1115/pvp2014-28742, 2014.
85. Mahmood, A., Computational Analysis of Impact Loading on Water Level Chip Scale Packages Mounted on Printed Circuit Boards of Varying Thickness, Master Thesis, University of Texas, 2016.
86. Nikolic, M., Protection Structures of Glass Fiber Reinforced Plastic – Static Analysis, Master Thesis, Stockholm, Sweden, 2010.
87. NORSOK Standard U-001, Subsea production systems, Norwegian Technology Centre, Oslo, 2002.
88. NORSOK Standard N-003, Actions and action effects, Standards Norway, Lysaker, 2007.
89. Sadraey, M., Aircraft Design, A Systems Engineering Approach, Daniel Webster College, USA, 2009.
90. Sari, A., Azimov, U., Nguyen, H., An improved Risk-Based Approach for Accidental Loadings, AIChE Spring Meeting and Global Congress on Process Safety, 2016.

91. Selker, R., Liu P, etc., Impact of Dropped Objects and Anchor Dragging on Pipeline Integrity, ISOPE-I-18-537, The 28th International Ocean and Polar Engineering Conference, Japan, 2018.
92. Seward, S., Shell DROPS Implementation in SEA, Shell Malaysia E&P, DROPS forum – Singapore, 6th April 2011.
93. Shim, A., 3-D Dropped Object Risk Assessment Leads to Greater Understanding of Risk, Lloyd's Register Consulting, 2014.
94. Taghizadeh, S., Edalat P., Accidental Limit State of Submarine Pipeline: Trawl Gears Pull-Over Loads and Effect of Free Span, International Journal of Maritime Technology, 2017.
95. Tauqeer, M. A., Assessment of Impact Damage Caused by Dropped Objects on Glass Reinforced Plastic (GRP) Covers, 36th International Conference on Ocean, Offshore and Arctic Engineering OMAE2017, 2017.
96. Tauqeer, M. A, Geometry Optimization of Glass Reinforced Plastic (GRP) Subsea Protection Covers, Master Thesis, University of Stavanger, 2016.
97. Waldeland, A. S., Structural design and application of concrete protection covers in shallow waters, Master Thesis, University of Stavanger, 2015.
98. Wenger, A., Design for Impact of Dropped Objects, OTC 4471, 15th Annual Offshore Technology Conference, Texas, USA, 1983.
99. Wong, S. V., Eng B., Development of Explicit Finite Difference-Based Simulation System for Impact Studies, Thesis for Doctor of Philosophy, Dublin City University, 200.
100. Wood, W.L., Practical Time-stepping Schemes, Clarendon Press, Oxford, 1990.
101. Wriggers, P., Computational Contact Mechanics, second edition, Springer, 2006.
102. Threats to the Arctic // Greenpeace Russia (Угрозы Арктике // Гринпис России) - URL: http://www.greenpeace.org/russia/ru/campaigns/protect-the-arctic/threat-to-the-Arctic/
103. Kizhaeva, AV: Ensuring the environmental security of the Arctic region as an important vector of Russian policy // Actual problems of modern international relations. 2016. №7.(Кижаева, А.В.: Обеспечение экологической безопасности Арктического региона как важный вектор Российской политики // Актуальные проблемы современных международных отношений. 2016. №7.).
104. Prevention and response of offshore oil spills in arctic conditions and emergency preparedness, brochure, Exxon Mobil Corporation, 5959 Las Colinas BoulevardIrving, Texas 75039-2298.
105. Scholz, D., S.R. Warren Jr., etc.: Risk Communication for In-Situ Burning: The Fate of Burned Oil, Regulatory and Scientific Affairs Department, American Petroleum Institute Publication 4735. April 2004. Washington, D.C. 41pp.

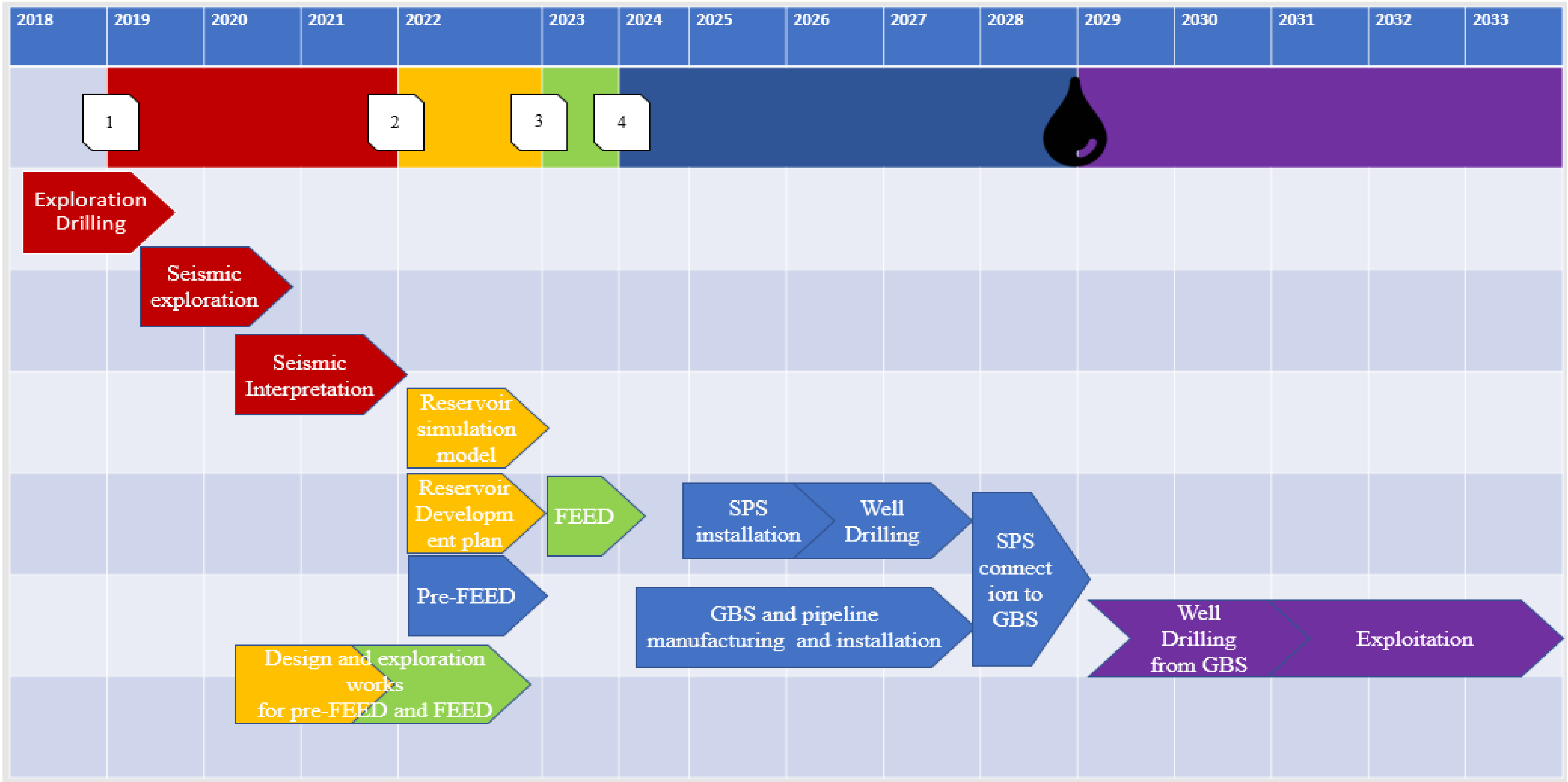
Appendix A (CBA-analysis for FEL-1)

Year	2018	2019	2020	2021	2022	2023	2024	2025
Number of the year	0	1	2	3	4	5	6	7
							OPERATING ACTIVITY	
Volume of oil production (tnes)		***106302052***	***106302052***	***106302052***	***106302052***	***106302052***	***106302052***	***106302052***
Volume of gas production, 1000 m3	0	2 000 000	2 000 000	2 000 000	2 000 000	2 000 000	2 000 000	2 000 000
Revenue, $	0	8 172 653 900	8 172 653 900	8 172 653 900	8 172 653 900	8 172 653 900	8 172 653 900	8 172 653 900
Operating cost	0	7 541 143 640	7 541 143 640	7 541 143 640	7 541 143 640	7 541 143 640	7 541 143 640	7 541 143 640
Other costs	0	78 000 000	78 000 000	78 000 000	78 000 000	78 000 000	78 000 000	78 000 000
Profit	0	553 510 260	553 510 260	553 510 260	553 510 260	553 510 260	553 510 260	553 510 260
Tax	0	138 377 565	138 377 565	138 377 565	138 377 565	138 377 565	138 377 565	138 377 565
Profit after tax	0	415 132 695	415 132 695	415 132 695	415 132 695	415 132 695	415 132 695	415 132 695
Operating cash flow	0	415 132 695	415 132 695	415 132 695	415 132 695	415 132 695	415 132 695	415 132 695
							INVESTMENT ACTIVITY	
Investment:	-1 300 000 000	0	0	0	0	0	0	0
Operating cash flow	-1 300 000 000	0	0	0	0	0	0	0
Project CF	-1 300 000 000	415 132 695	415 132 695	415 132 695	415 132 695	415 132 695	415 132 695	415 132 695
PV	-1 300 000 000	370 654 192	330 941 243	295 483 253	263 824 333	235 557 440	210 319 143	187 784 949
PV (sum)	-1 300 000 000	-929 345 808	-598 404 565	-302 921 313	-39 096 980	196 460 460	406 779 602	594 564 551

Year	2026	2027	2028	2029	2030	2031	2032	2033
Number of the year	8	9	10	11	12	13	14	15
Volume of oil production (tnes)	***96734867,32***	***88028729,26***	***80106143,63***	***72896590,7***	***66335897,54***	***60365666,76***	***54932756,75***	***49988808,64***
Volume of gas production, 1000 m3	1 820 000	1 836 200	1 654 742	1 687 273	1 502 887	1 552 013	1 363 206	1 429 325
Revenue, $	7 437 115 049	6 785 774 695	6 173 434 972	5 635 971 625	5 125 481 056	4 682 626 342	4 256 277 377	3 892 093 128
Operating cost	6 862 440 712	6 253 821 048	5 690 167 154	5 187 125 010	4 718 657 198	4 303 197 341	3 913 453 283	3 570 682 845
Other costs	78 000 000	78 000 000	78 000 000	78 000 000	78 000 000	78 000 000	78 000 000	78 000 000
Profit	496 674 337	453 953 646	405 267 818	370 846 615	328 823 858	301 429 001	264 824 094	243 410 283
Tax	124 168 584	113 488 412	101 316 955	92 711 654	82 205 965	75 357 250	66 206 024	60 852 571
Profit after tax	372 505 752	340 465 235	303 950 864	278 134 961	246 617 894	226 071 751	198 618 071	182 557 712
Operating cash flow	372 505 752	340 465 235	303 950 864	278 134 961	246 617 894	226 071 751	198 618 071	182 557 712
Investment:	0	0	0	0	0	0	0	0
Operating cash flow	0	0	0	0	0	0	0	0
Project CF	372 505 752	340 465 235	303 950 864	278 134 961	246 617 894	226 071 751	198 618 071	182 557 712
PV	150 448 826	122 775 177	97 864 043	79 957 155	63 300 671	51 809 810	40 641 192	33 352 611
PV (sum)	745 013 377	867 788 554	965 652 597	1 045 609 752	1 108 910 423	1 160 720 233	1 201 361 426	1 234 714 037

Year	2034	2035	2036	2037	2038	2039	2040	2041	2042
Number of the year	16	17	18	19	20	21	22	23	24
Volume of oil production (tnes)	***45489815,87***	***41395732,44***	***37670116,52***	***34279806,03***	***31194623,49***	***28387107,37***	***25832267,71***	***23507363,62***	***21391700,89***
Volume of gas production, 1000 m3	1 234 567	1 318 214	1 115 928	1 217 780	1 006 328	1 127 211	904 879	1 045 772	810 759
Revenue, $	3 535 192 888	3 236 501 309	2 936 851 513	2 692 763 479	2 440 229 513	2 241 754 132	2 027 907 933	1 867 629 444	1 685 453 476
Operating cost	3 246 015 459	2 963 611 959	2 692 704 543	2 460 475 436	2 233 940 020	2 043 458 056	1 853 502 667	1 697 804 039	1 537 957 017
Other costs	78 000 000	78 000 000	78 000 000	78 000 000	78 000 000	78 000 000	78 000 000	78 000 000	78 000 000
Profit	211 177 428	194 889 351	166 146 969	154 288 044	128 289 493	120 296 077	96 405 266	91 825 404	69 496 459
Tax	52 794 357	48 722 338	41 536 742	38 572 011	32 072 373	30 074 019	24 101 316	22 956 351	17 374 115
Profit after tax	158 383 071	146 167 013	124 610 227	115 716 033	96 217 120	90 222 057	72 303 949	68 869 053	52 122 344
Operating cash flow	158 383 071	146 167 013	124 610 227	115 716 033	96 217 120	90 222 057	72 303 949	68 869 053	52 122 344
Investment:	0	0	0	0	0	0	0	0	0
Operating cash flow	0	0	0	0	0	0	0	0	0
Project CF	158 383 071	146 167 013	124 610 227	115 716 033	96 217 120	90 222 057	72 303 949	68 869 053	52 122 344
PV	25 835 710	21 288 398	16 204 263	13 435 416	9 974 518	8 350 919	5 975 380	5 081 707	3 433 930
PV (sum)	1 260 549 747	1 281 838 145	1 298 042 408	1 311 477 824	1 321 452 341	1 329 803 260	1 335 778 640	1 340 860 346	1 344 294 276

Appendix B (Work Flow Chart)



Legend: Estimation | Decision Making | Specification | Execution | Exploitation

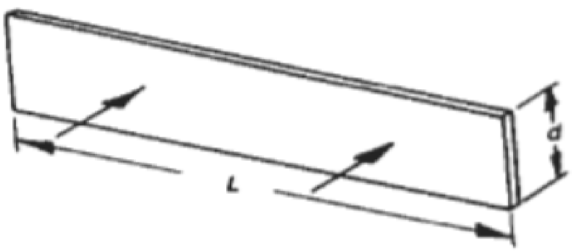
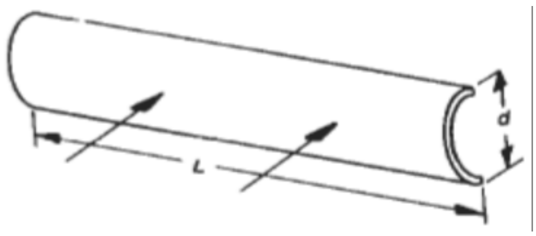
1 - Discovery of a deposit
2 - Approbation of reserves in State Reserves Committee
3 - Decision upon Field Development
4 - Final investment Decision
(oil drop) - First Oil

Appendix C (Terminal Velocity calculation)

Table 23. Initial data obtained from the modeling of dropped objects

Parameter	Container	Drill pipe
Mass, m, [kg]	4851	323
The density of sea water, ρ, [kg/m^3]	1025	
Gravitational constant, g, [m/s^2]	9,81	
Outer volume, V_{out}, [m^3]	32,64	0,144
Inner volume, V_{in}, [m^3]	31,59	0,085
Projected area, A, [m^2]	14,77	1,33

Table 24. Terminal velocity calculation

Container	Drill pipe
Reynolds number (assumption for velocity of container = 1.5 m/s; for drill pipe = 2 m/s	
Re_c= 1.5*6/1.83*10^{-6} = 3 278 688	Re_p=2*10/1.83*10^{-6} = 10928961
Selection of the drag coefficient	
	
C_d = 1.15 (Sadraey, 2009)	C_d = 0.82 **(**Sadraey, 2009)
Buoyancy force	
O=9,81*1025*34,= 347911,7 N	O=9,81*1025*0,144= 1452,984 N
Terminal velocity	
$V_{t\ c} = \sqrt{\frac{2*(4851+32386)*9.81-347911.7)}{1.15*14.77*1025}} = 1.413 m/s$	$V_{t\ p} = \sqrt{\frac{2*(323+87.125)*9.81-1452.984)}{0.82*1.33*1025}} = 2.144 m/s$
Impact energy	
$Ic = \frac{1.413^2*4851}{2} = 4.84$ kJ	$Ic = \frac{2.144^2*323}{2} = 0.742$ kJ

Appendix D (Drag coefficient selection)

Table 25. Drag coefficient selection

No	Body	Status	Shape	C_D
1	Square rod	Sharp corner		2.2
		Round corner		1.2
2	Circular rod	Laminar flow		1.2
		Turbulent flow		0.3
3	Equilateral triangular rod	Sharp edge face		1.5
		Flat face		2
4	Rectangular rod	Sharp corner	L/D = 0.1	1.9
			L/D = 0.5	2.5
			L/D = 3	1.3
		Round front edge	L/D = 0.5	1.2
			L/D = 1	0.9
			L/D = 4	0.7
5	Elliptical rod	Laminar flow	L/D = 2	0.6
			L/D = 8	0.25
		Turbulent flow	L/D = 2	0.2
			L/D = 8	0.1
6	Symmetrical shell	Concave face		2.3
		Convex face		1.2
7	Semicircular rod	Concave face		1.2
		Flat face		1.7

No	Body	Laminar/turbulent	Status	C_D
1	Cube	Re > 10,000		1.05
2	Thin circular disk	Re > 10,000		1.1
3	Cone ($\theta = 30^0$)	Re > 10,000		0.5
4	Sphere	Laminar $Re \leq 2\times10^5$		0.5
		Turbulent $Re \geq 2\times10^6$		0.2
5	Ellipsoid	Laminar $Re \leq 2\times10^5$		0.3-0.5
		Turbulent $Re \geq 2\times10^6$		0.1-0.2
6	Hemisphere	Re > 10,000	Concave face	0.4
		Re > 10,000	Flat face	1.2
7	Rectangular plate	Re > 10,000	Normal to the flow	1.1 - 1.3
8	Vertical cylinder	$Re \leq 2\times10^5$	L/D = 1	0.6
			$L/D = \infty$	1.2
9	Horizontal cylinder	Re > 10,000	L/D = 0.5	1.1
			L/D = 8	1

Appendix E (Visualization of equivalent stresses and deformations of protective structures)

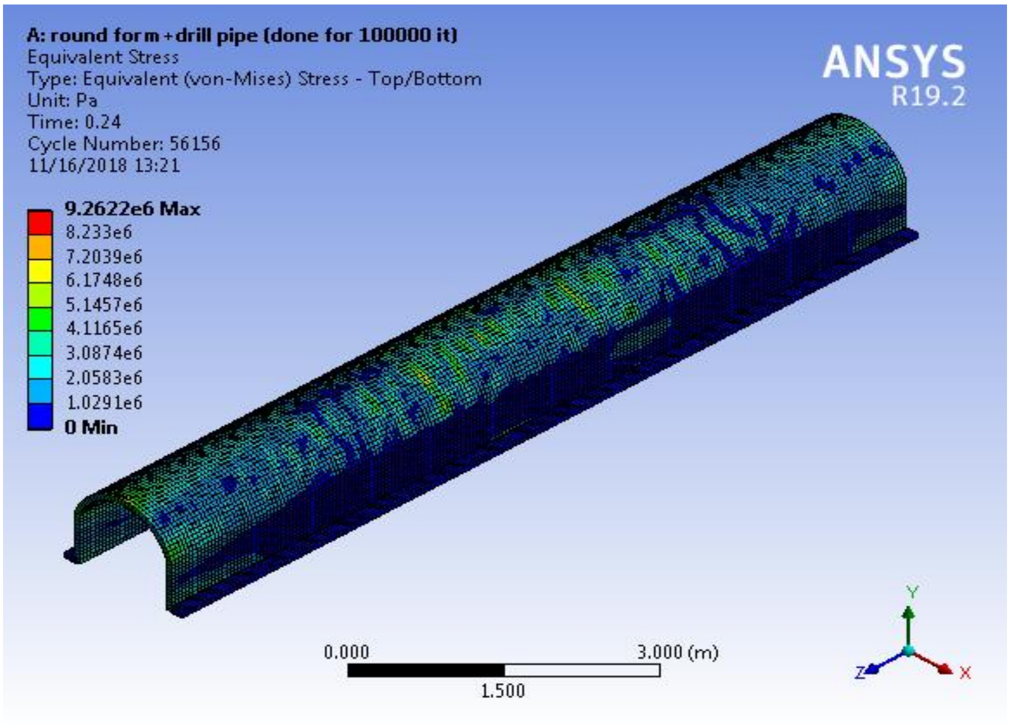


Figure 56. Maximum equivalent stress for round form from drill pipe

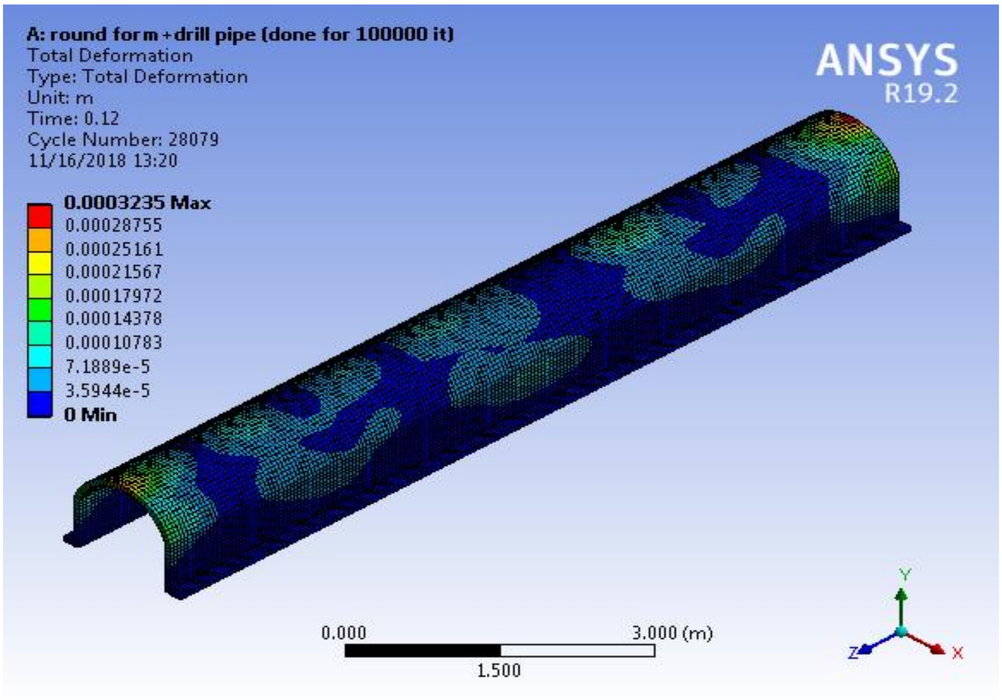


Figure 57. Total deformation for round form from drill pipe

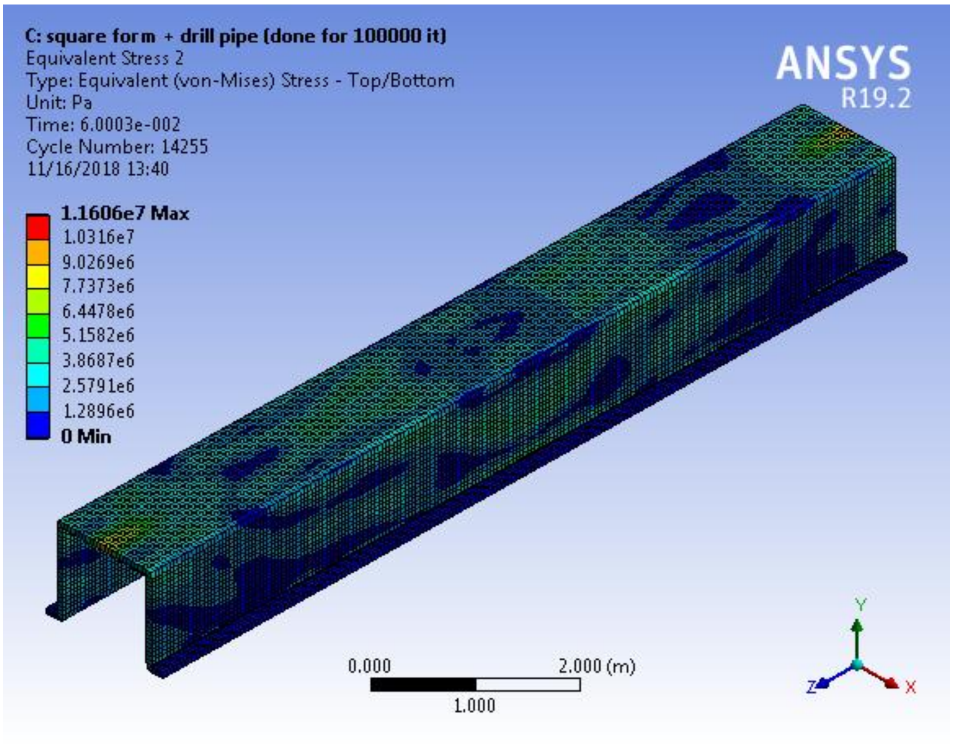


Figure 58. Maximum equivalent stress for square form from drill pipe

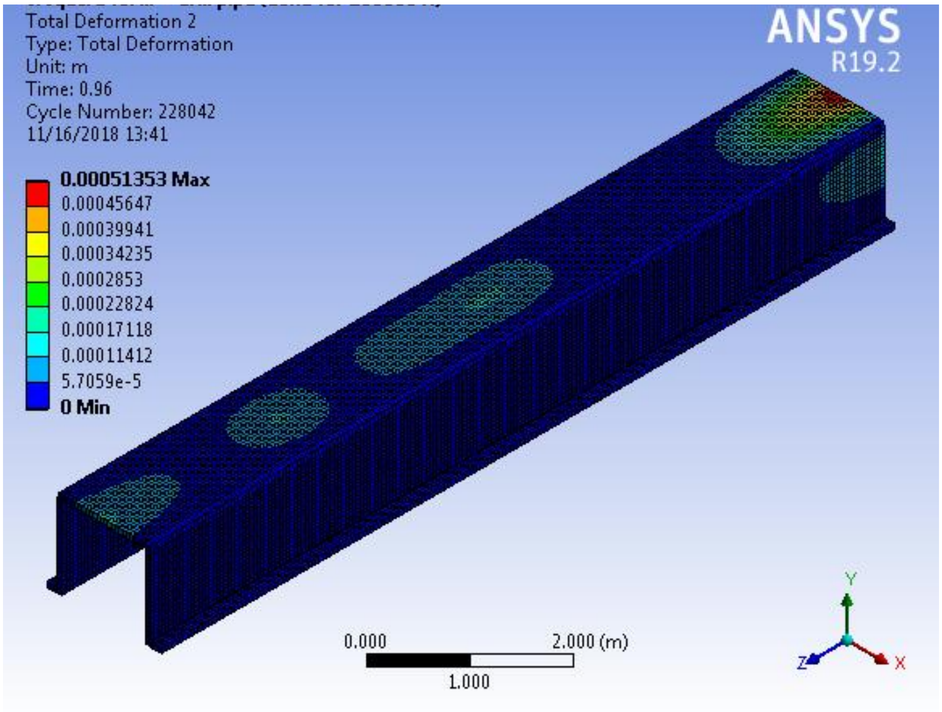


Figure 59. Total deformation for square form from drill pipe

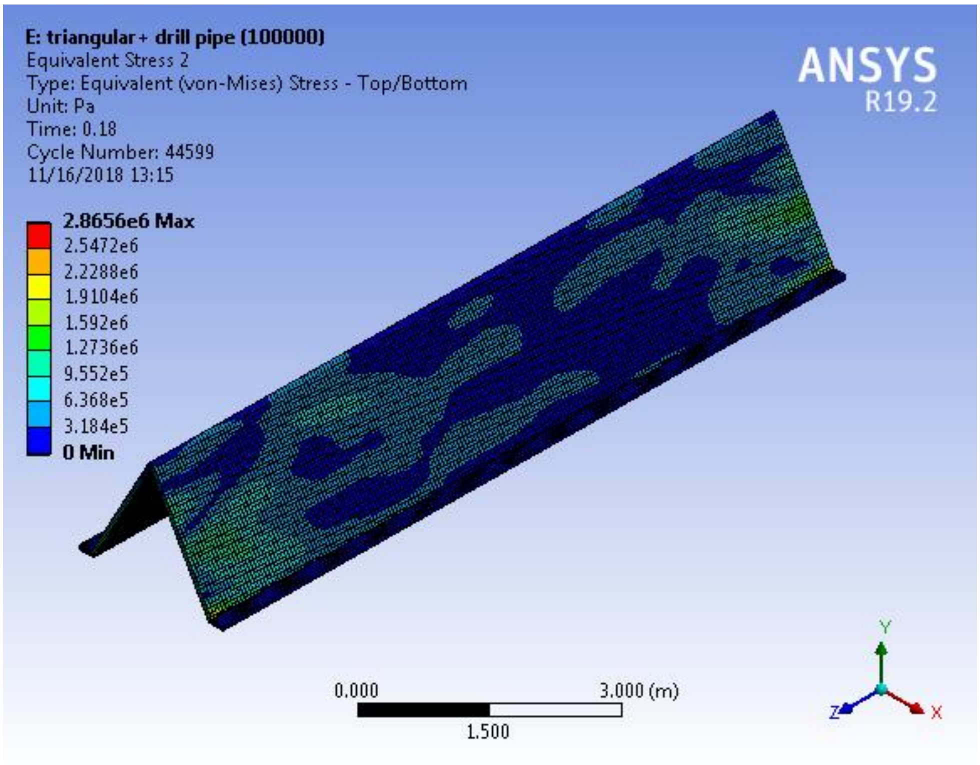


Figure 60. Maximum equivalent stress for triangular form from drill pipe

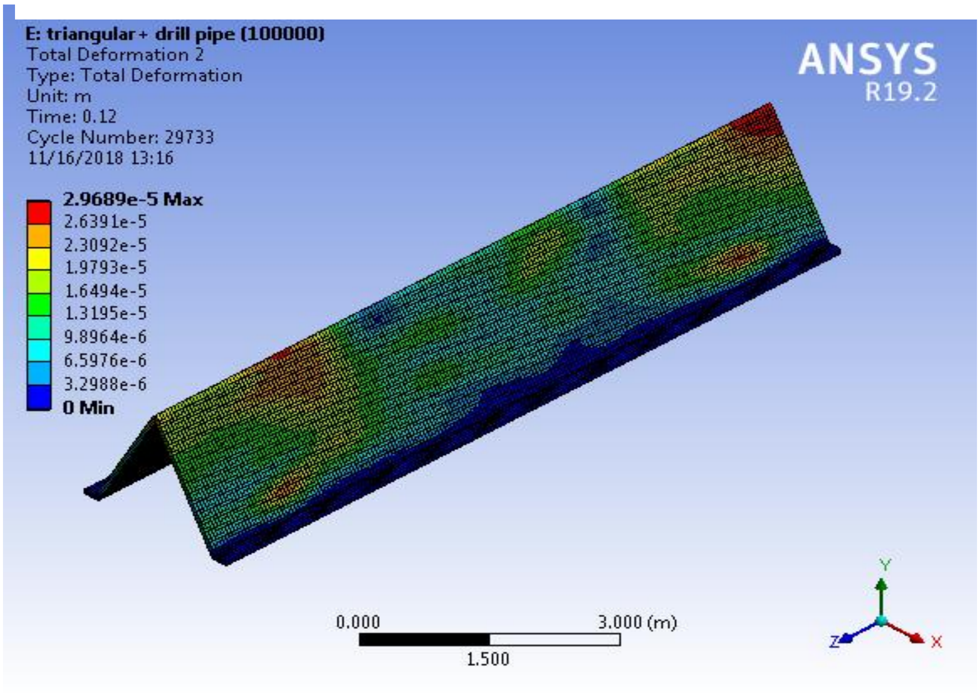


Figure 61. Total deformation for triangular form from drill pipe

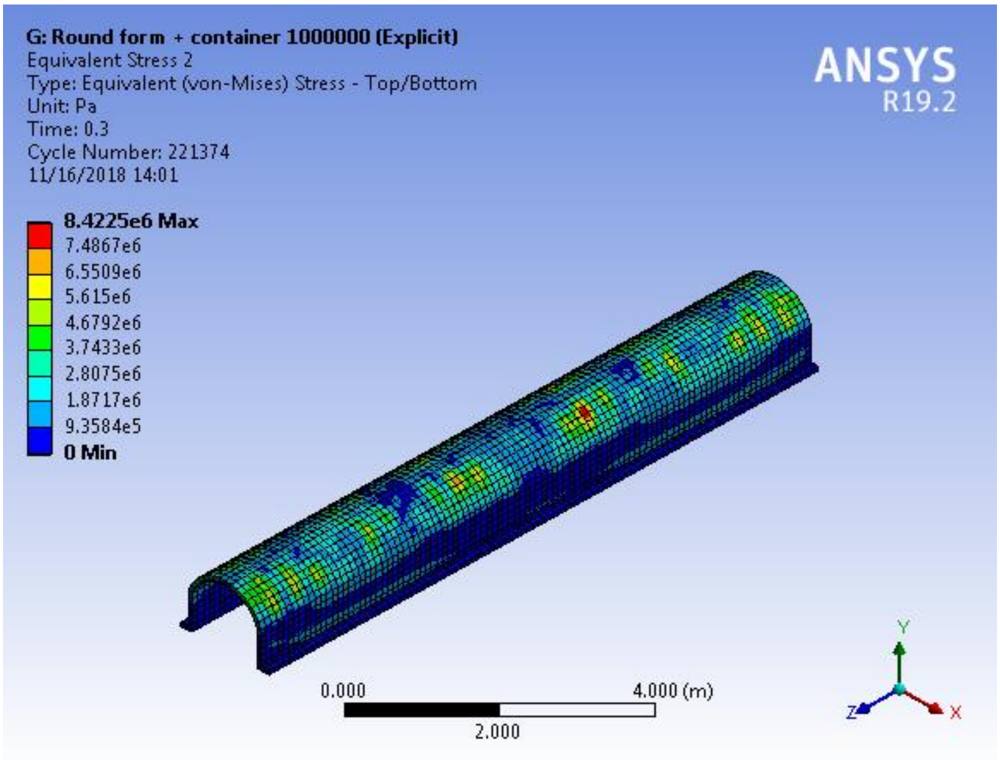


Figure 62. Maximum equivalent stress for round form from container

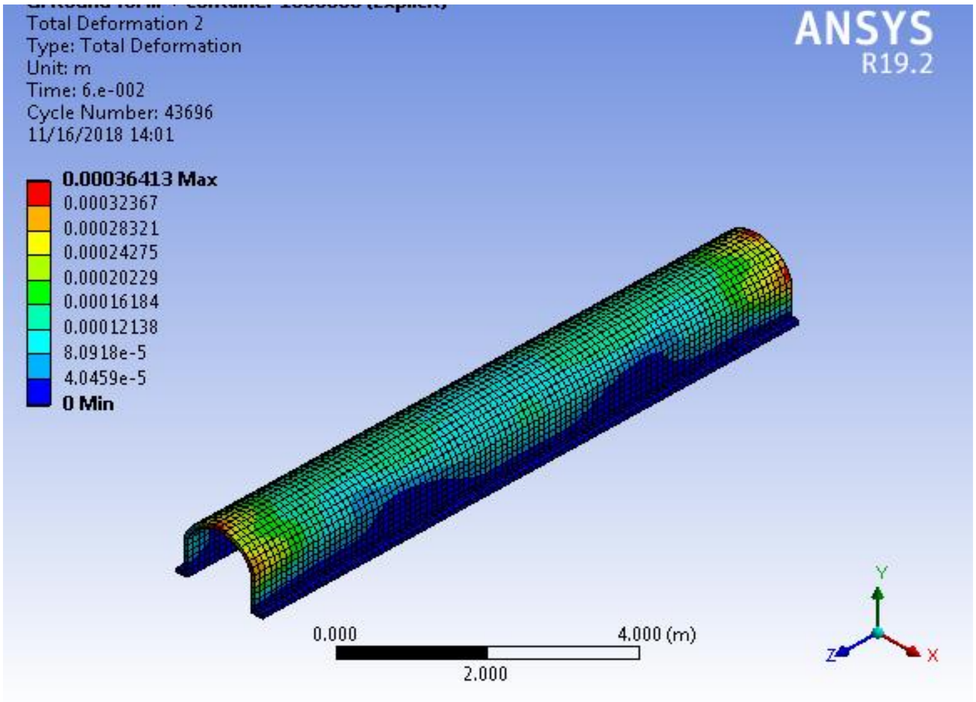


Figure 63. Total deformation for round form from container

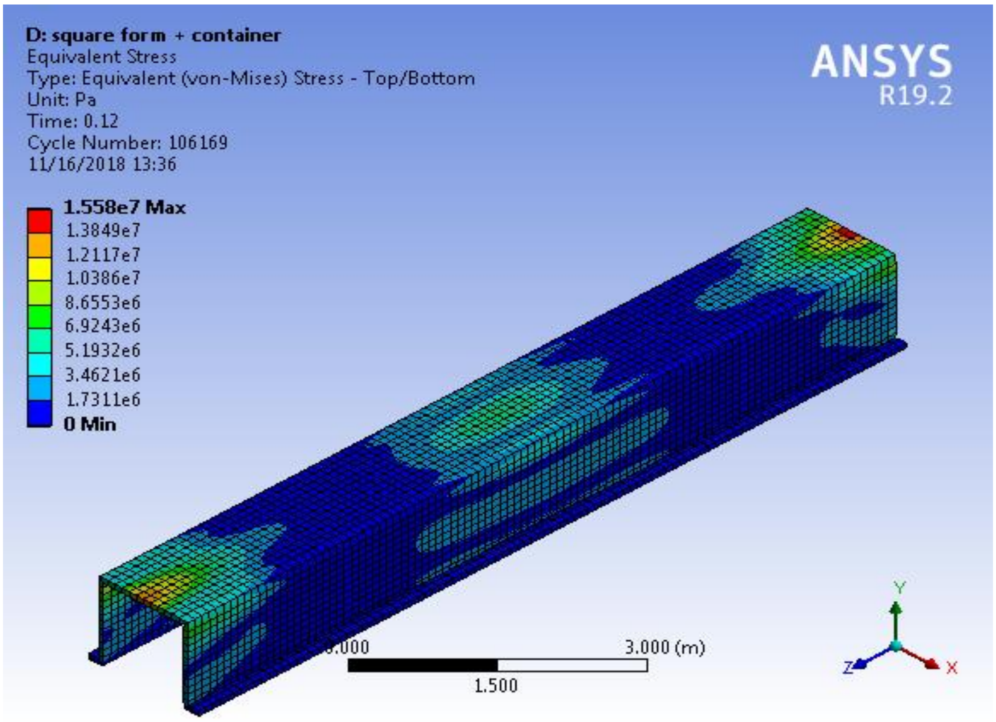


Figure 64. Maximum equivalent stress for square form from container

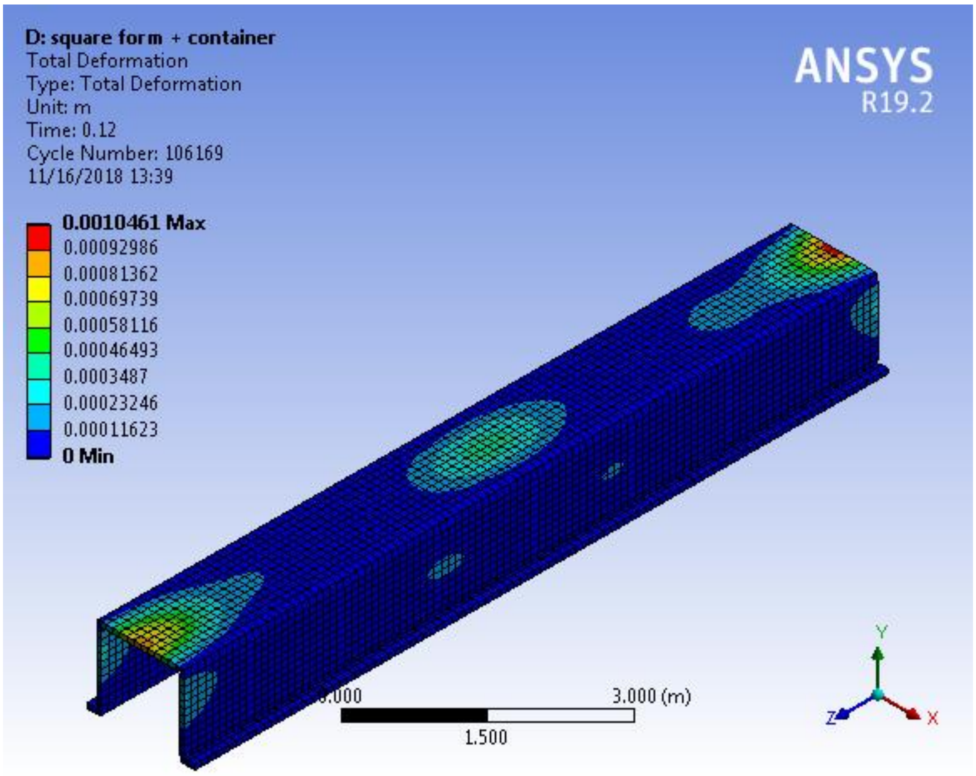


Figure 65. Total deformation for square form from container

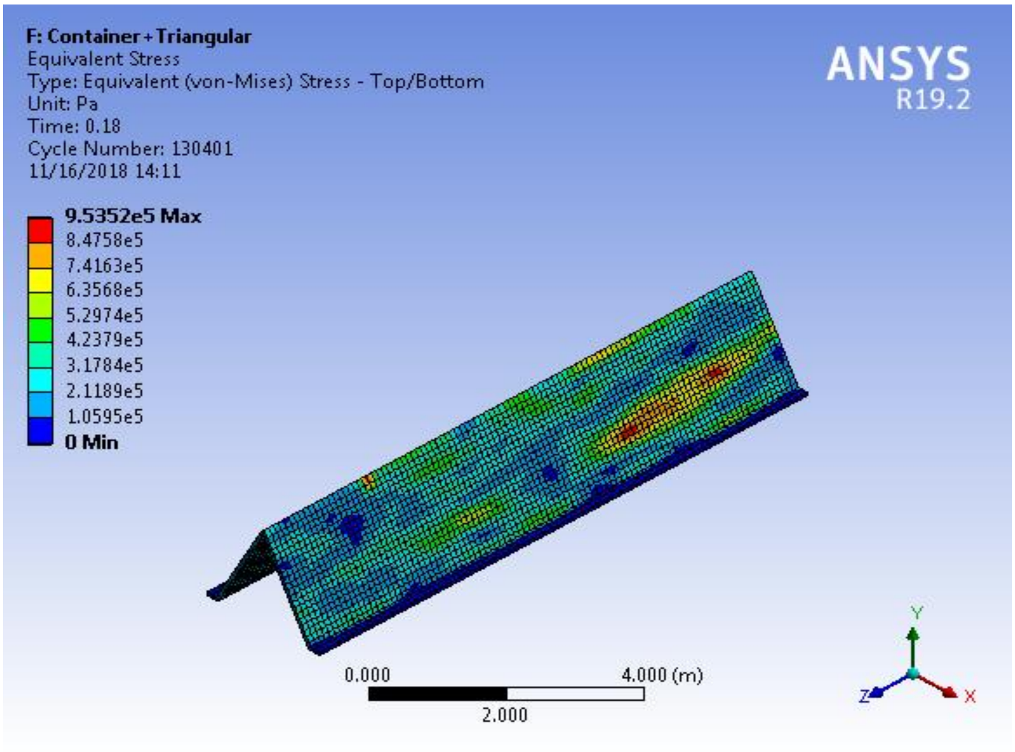


Figure 66. Maximum equivalent stress for triangular form from container

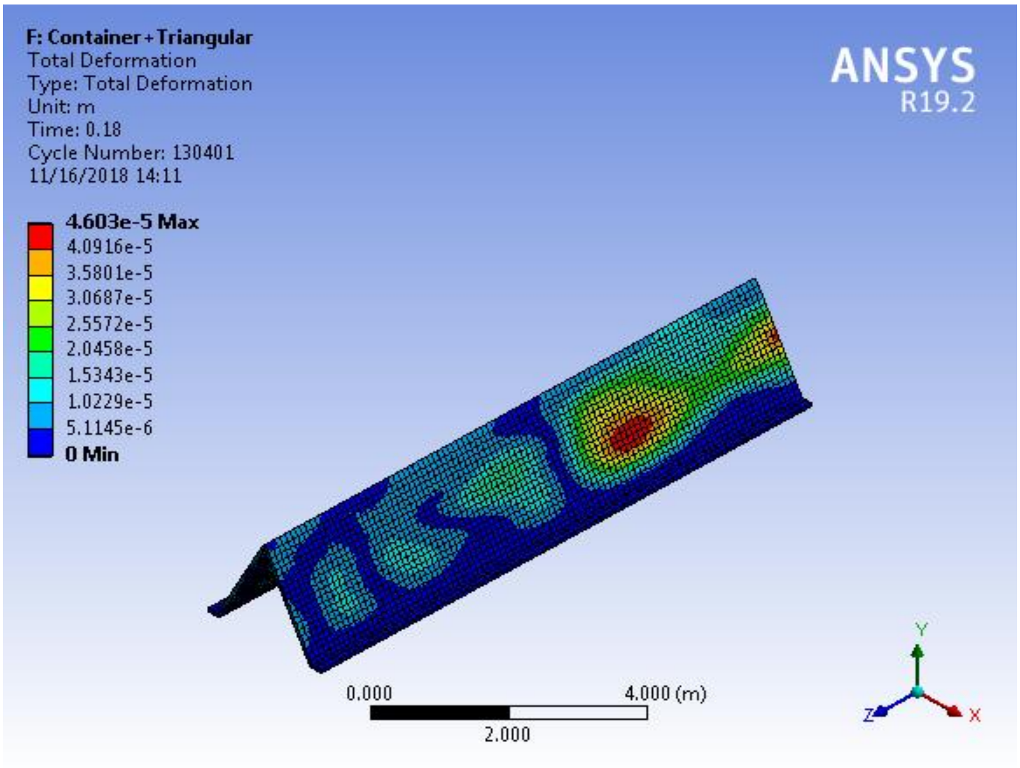


Figure 67. Total deformation for triangular form from container