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PIPELINE SHORE CROSSING APPROACH IN THE ARCTIC CONDITIONS

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Abstract

The energy demand will increase the development of new offshore areas including the Arctic region. The construction of new infrastructure will be required in the region, in particular, subsea pipelines. Considering the lack of much practice, vulnerability of the ecosystem and lack of common international standards for the Arctic region, their development will be a technological and environmental challenge. In particular, in the transition zones.

Master thesis ambitions to analyze the characteristics of the design of the offshore pipelines on the coastline in the Arctic.

Several Arctic projects with the shore crossing transitions exist nowadays, such as Northstar, Ooguruk and Nikaitchuq in the Beaufort Sea developed under the trenching method. Two additional projects – Sakhalin 1 and Bovanenkovo-Ukhta – were also reviewed as part of the thesis. Another project located not in the Arctic that was considered is the Langeled pipeline from Norway to UK.

There are exist three possible methods: trenching; tunneling and Horizontal Directional Drilling (HDD). All of these methods have advantages and disadvantages mainly related to the environmental conditions cost implications.

The Arctic region re-emphasizes the critical role of the environmental conditions on the selection of the right crossing methods:

- Ice encroachment increases the stress on the infrastructure and can damage the shore infrastructure and artificial gravel pads can be used to minimize their impact.
- Ice ridges tend to scour the sea bottom and damage the subsea pipeline. To protect the pipeline from ice ridges it is recommended to bury it.
- Shoreline erosion can be the cause of pipeline stability loss.

These implications are illustrated with a practical case on Leningradskoe field. Firstly environmental conditions such as the characteristics of the shore and offshore geology or the shoreline erosion rate were determined to confirm that the region is located in harsh environment.

Reviewing the environmental conditions led to conclude that the tunneling method is the recommended shore crossing approach for Leningradskoye Field due to high cliff, unstable soil, presence of constant permafrost and fragile ecosystem.

The shield penetration method is recommended to be applied to lay the pipeline the tunnel. To pull the pipeline in tunnel pulling force is calculated by applying Russian Set of Rules (Russian «Свод Правил») 42-101-2003 General provisions for the design and construction of gas distribution systems of metal and polyethylene pipes.

Comparative analysis with the 5 projects in the Beaufort and Russian offshore as well as the Langeled pipeline through 4 parameters was performed. The analysis showed the most compatibility with Langeled project and Bovanenkovo-Ukhta in the Russian offshore.

The final aspect of design was the protection of pipe from ice ridges. Above mentioned Force model was used to calculate the recommended burial depth that tend to be 3.52 m.

To sum up, the microtunneling method was recommended to be used for the Leningradskoye field in combination with a cofferdam corridor to protect from waves and buried pipe in the nearshore area. To estimate possible negative environmental impact and risks the detailed risk analysis was performed. Using the risk matrix the key possible negative risks were determined and reduction measures were introduced in the work.

Therefore on the basis of environmental conditions study and conducted practical case the basic choice making diagram was established in order to determine the best method for certain arctic region.

Acknowledgment

I would like to sincerely thank my scientific supervisors Prof. Anatoly Zolotukhin and Prof. Ove Tobias Gudmestad for giving me an opportunity to study at this double degree master programme and for giving me valuable knowledge that will stay with me through whole life.

These two years were incredibly intense, challenging and sometimes very difficult but at the same time very productive, exciting and fun. I would not be able to go through it without my mom, family and friends who most of the time believed in me more than I did.

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List of Abbreviations

BTOE – Billion ton of oil equivalent;

HDD - Horizontal directional drilling;

ISO – International Standard Organization;

OPF - Onshore Processing Facilities;

SCD - Seasonal cooling devices;

TAPS - Trans-Alaska Pipeline System;

TBM - Tunnel-boring machine.

1. Introduction

Based on the latest report from the International Energy Agency, the energy demand will increase by 25% by 2040. In these forecasts, the demand for natural gas and oil will grow by 42% and 10% respectively (International Energy Agency World Energy Outlook 2018 (WEO 2018)). To meet the global demand for hydrocarbons, the development of unconventional resources and the exploration of new regions are becoming critical, including in the Arctic offshore. In the McKinsey Global Oil Supply and Demand Outlook 2035, it is estimated that still, to meet demand, exploration and production companies need to add more than 40 MMb/day of new crude production [between now and 2035], mostly from offshore and shale unsanctioned projects. Roughly 4-5% of this new production will need to come from yet-to-find resources. With reference to A. Kontorovich (Forum RAO/CIS Offshore-2009), the world ocean resources are estimated to be around 265 BTOE. 54% (143 BTOE) of these reserves are located in the Arctic region, with the majority within the Russian waters (91 BTOE or 64%). Despite all the current environmental and geopolitical challenges, the oil and gas upstream companies are therefore considering the Arctic region as a strategic play for current and future hydrocarbon exploration and production.

The growth of the global energy demand will undoubtedly accelerate the development of the Arctic region and lead to the development of new projects. Considering the severe conditions (low temperatures, presence of ice, permafrost, etc.) in the region, these new developments will require additional innovative technologies and techniques to sustainably and profitably produce the hydrocarbons. In addition to overcoming the natural challenges related to the harsh environment, the climate change will rapidly transform the landscape and add complexity to the development of Arctic infrastructure (e.g. production sites, pipelines, roads). Anticipating these transformations, new technologies and technical solutions become crucial.

Indeed, the discovery of new offshore oil and gas basins and the construction of the infrastructure to extract them will require the expansion of the hydrocarbon transportation system, in particular, the subsea pipelines. Considering the previously exposed constraints, the design and construction of subsea pipelines bring many technological challenges amongst which the protection from ice ridges, thermal expansion and thaw settlement, flow assurance in the cold ambient temperatures, corrosion protection, shore crossing areas, etc.

The shore interface is one of the main design challenges for subsea pipelines. The design of the subsea pipelines in the Arctic conditions requires an in-depth awareness of geological, hydrodynamic and biological factors that have formed the shore relief. The lack of common standards and methodologies for shore crossing design area brings additional challenges for the subsea pipelines construction and design.

It is also important to take into account the presence of ice ridges in the coastal area during the pipeline design and installation. Buried pipelines are experiencing significant loads and strains from soil interaction, causing upheaval buckling, thaw settlement causing the formation of pipelines free spans.

Finally, climate change causes ice-melting and leads to bigger open water area evolving coastline erosion. The accelerated coastline erosion should, therefore, be factorized in the pipeline design and installation. Since the instability of a pipeline can lead to its destruction and negatively impact the environment in case of leakage, the upstream companies should focus on mitigating these risks and adapt the design to these extreme climatic conditions.

The aim of this thesis is to analyze the influence of physical environmental factors and the climate change process on the pipeline shore crossing methods and the stability of pipelines in the Arctic region. It provides the assessment and analysis of the environmental conditions influence the pipeline shore crossing methods.

The following areas of research have been prioritized:

- Description of the existing projects and used technologies
- Review of the Arctic environmental conditions and their impacts on the design and construction
- Review of a practical case with the Leningradskoye field with a comparative

analysis with existing projects

– Analysis of the key risks

Chapter 1 (Introduction) gives a brief overview of the addressed issues and related challenges; it also includes the scope of work of the thesis.

Chapter 2 (Existing practices in Arctic Pipeline Shore Crossing Areas) provides a comprehensive review of the existing Arctic subsea pipelines projects such as Northstar, Ooguruk and Sakhalin I. This Chapter also describes the best practices used for the design and construction of pipeline shore crossing areas. These practices are trenching, tunneling and horizontal directional drilling. The chapter also highlights the technical requirements for three of these methods in accordance with international and regional standards.

Chapter 3 (Arctic challenges for subsea pipeline installation and design) addresses key issues related to the pipeline design and construction in the Arctic region. The following challenges will be reviewed: cold ambient temperatures, limit of weather window, ice gouging, permafrost thaw settlement, strudel scour, corrosion protection in cold temperatures and upheaval buckling. The most attention is paid to the issues of ice ride-ups and pile-ups, ice ridges and ice scouring; coastline erosion as well as the influence of climate change on the coast erosion acceleration.

Chapter 4 (Practical case studies) contains the practical part: choice of shore crossing method for specific natural and climatic conditions of the Leningradskoye field located in the Kara Sea.

The final Chapter 5 (Environmental Impact Assessment. Risk Analysis) is devoted to the estimation of possible environmental impacts of pipeline shore crossing area construction and installation. The Chapter also includes the risk analysis.

References to Introduction

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McKinsey Global Oil Supply and Demand Outlook 2035 [https://www.mckinsey.com/solutions/energy-insights/global-oil-supply demand-outlook-to2035/~/media/231FB01E4937431B8BA070CC55AA572E.ashx available on 30.03.2019]

2. Existing Practices in Arctic Pipeline Shore Crossing Areas

2.1. Existing Projects

Several Arctic projects with the shore crossing transitions exist nowadays. One of the best- known is the **Northstar** project in Alaska (Beaufort Sea) which is the first subsea pipeline constructed in the Arctic conditions. The Northstar field reserves are estimated to be 25 million cubic meters of crude oil (Lanan, G.A., Nogueira, A.C., 2000). The concept of the field includes the implementation of sea island that is located 9.7 km offshore from the Alaskan Beaufort Sea coast, at water depth approximately 11.3 m and 18 km northwest of Prudhoe Bay, 273.1 mm (10-inch) pipeline is used to transport processed on the island oil to the shore crossing at Point Storkersen, further on the pipeline elongates 18 km more to the Trans-Alaska Pipeline System (TAPS) Pump Station 1. Natural gas is transported within a 273.1-mm pipeline for fuel and reservoir management purposes. These two subsea lines were buried as a bundle (Ishita, S., 2013). The ambient temperature of the area can reach up to -46°C and oil can be cooled, in order to minimize the heat loss the 51 mm thick polyurethane foam was used. (Lanan, G.A., Nogueira, A.C., 2000). For the land design, special techniques were also used and among them are thermal expansion loop (Z and U shape), low-temperature pipe steel specifications, gas compressor station. The thickness of the pipe wall was chosen to be 15.1 – mm to guarantee stability during subsea trench backfill operations. Cathodic protection system with a dual layer fusion bonded epoxy coating and aluminum anodes were implemented for certain subsea pipeline (Lanan, G.A., Nogueira, A.C., 2000).

Since the pipeline was constructed in the conditions of the Arctic a lot of additional design aspect had to be taken into account. First one is the protection of subsea pipeline from seabed ice gouging. In order to prevent the pipeline from ice gouging damage, the method of trenching was chosen. The collected data let to calculate the minimum pipeline depth of cover to be 2.1 m. Due to the long history of the project, the data for ice gouging was available and showed that deepest gouge observed during 10 separate years' surveys has been 0.6 m. The maximum depth was estimated to be 1.0 m.

The shore crossing part consists of a vertical 90-degree transition between the below ground subsea pipelines and the above-ground onshore pipelines. The 90-degree transition results in deep excavation between the shoreline and the pipeline's daylight location. To protect the vertical segment from thermal expansion special corrugated metal pipe culvert was used. According to the data from borehole samples, the predicted depth of thermal influence of pipeline was estimated to be 0,6 m in the horizontal pipeline segment. Therefore, to protect the thermal expansion over excavation beneath the pipeline was implemented. Further, this method was replaced with thaw stable gravel. This solution was introduced by Heuer, C.E. (1983) to reduce pipeline strain caused by thaw settlement. (Eisler, B., 2016). Figure 1 illustrates the scheme of the Northstar pipeline design.

The maximum elevation of shore at the pipeline daylight location is 2.4 m while the shorelines bluff rises approximately 0.6 m above sea level. The shore crossing area is located in the shallow water lagoon with a barrier island which causes the relatively small shoreline erosion rate for the Beaufort Sea.

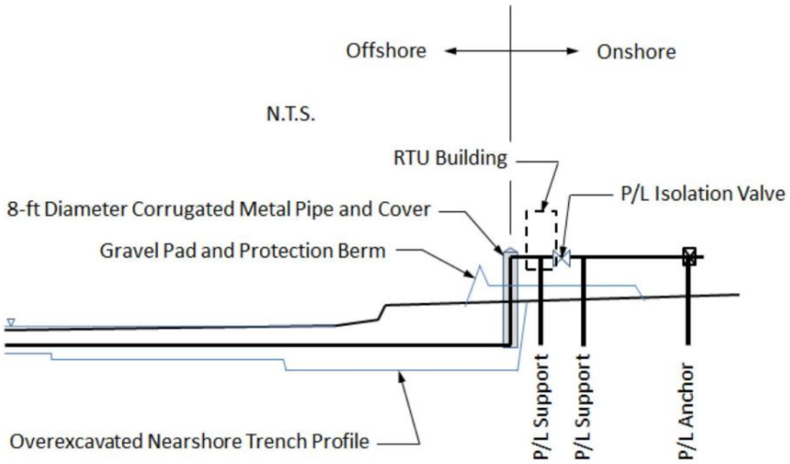

Figure 1 Northstar Shore Crossing Scheme (Eisler, B. 2016)

The distance between the shore crossing point and the pump station (Trans Alaska Pipeline System) access to which is provided either by helicopter or the ice road. To support communication and power generation remote terminal unit is built. The pipeline daylight area also contains remotely controlled isolation valves, leak detection equipment, pressure, and temperature measurement instrumentations.

During the installation, blasting method was used to break down the permafrost. To make a trench and backfill it the conventional backhoes were used. The trench was backfilled with the same soil. Due to the large vertical transition, the installation required a lifting plan involving both cranes and conventional sidebooms (Eisler, B. 2016).

Similar to such approach the protection of pipeline from thawing was used at another Beaufort Sea project **Ooguruk**. Ooguruk is the third offshore production facility that has been installed in the Alaskan part of the Beaufort Sea. To produce hydrocarbons the artificial island "Offshore Drillsite" was constructed. The island is located at the water depths of 1,5 meters approximately 64 km away from Prudhoe Bay. The subsea flowline bundle connects the island and the shore, having a length of 9 km (Leidersdorf, C., et.al., 2008). This flowline was buried in the trench due to the presence of ice ridges in the installation area. The climatic conditions for the Ooguruk project are not as severe as for the Northstar, but all wave, current, ice characteristics were taken into account during the design and installation of a flowline.

Bathymetric data form Leidersdorf, C., et.al., (2008) work indicates the water depths on pipe route to vary from 0 to 2.2 m. The design life of the project's facilities was estimated to be 20 years, while the return period was adopted to be 100 years. According to the analysis and data collecting in work (Leidersdorf, C., et.al., 2008) summarized four key findings:

- Wave heights are limited by the shallow water depths. The most severe wave conditions come up from west storms, due to the substantial surges.
- The predicted storm surge in the project area range from 2.1 to 2.4
- The predicted wave heights in the project area are estimated to range from 2 m to 2.8 m (from the 100-year westerly storm). While the spectral peak wave period is 10.1 sec.
- The predicted wave heights in the project area are estimated to range from 0.4 m to 1.2 (from the 100-year easterly storm). While the spectral peak wave period is 11.3 sec.

The area of Ooguruk shore crossing flat tundra is characterized by an elevation of 1.8 – 3 m high and represents steep bluff leading to a sandy beach below. According to aerial photographic data presented in (Leidersdorf, C., et.al., 2008) the average annual bluff erosion rates for a long-term varies from 0.9 m/year to 1.12 m/year and the average to be 0.97 m/year. The maximum rates of erosion were observed between 1998 and 2004 and reached 2.7 m/year. These high rates are consistent with the presence of major westerly storm events during this period of time. The results of annual bluff erosion rates are presented in Figure 2.

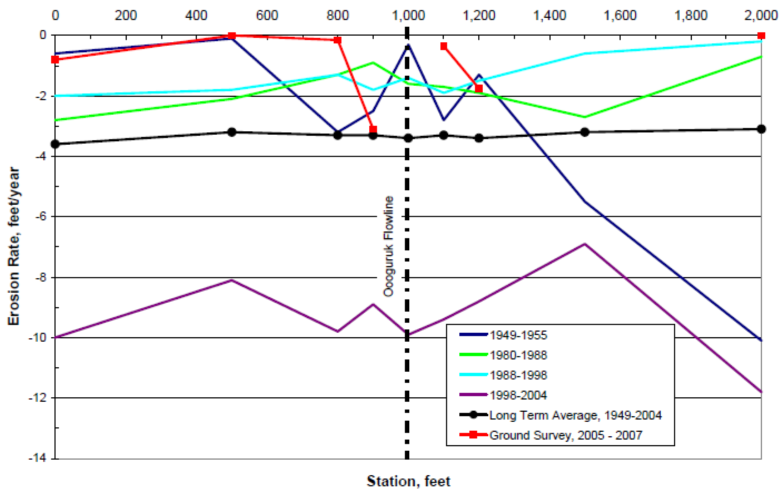

Figure 2 Average Annual Bluff Erosion Rates, 1949-2007 (Leidersdorf, C., et.al., 2008)

The area of Ooguruk project is also characterized by the presence of ice ridges and strudel scours, the presence of which brought a significant impact in the design and construction of a flowline. A lot of measurements and monitoring activities have been performed to collect data on ice ridges and strudel scour in the project area were carried out. The results showed that the scour depths of the circular features ranged from 0.09 to 2.2m below the surrounding sea bottom, while the scour depths of the linear features ranged from 0.17 and 0.7 m. The studies presented in Leidersdorf, C., et.al. (2008) also showed that the ice gouging is of negligible importance in the Ooguruk project area. All obtained environmental data allowed to design and construct the flowline in a most efficient and technically safe way.

The Ooguruk flowline consists of 0.32 m x 0.4 m pipe-in-pipe multiphase production flowline, 0.22 m insulated water injection flowline, a 0.168 m gas injection flowline, 0.06 m liquid Arctic heating fuel line, three power cables, two fiber optic cables. The shore crossing area is protected by the barrier island – Thetis and Spy Islands. The shore heights vary from 1.2 m to 1.5 m with a maximum from 2.4 m to 3 m. The Ooguruk shore crossing design is similar to the one implemented in the Northstar project. The over-excavation beneath the flowlines was implemented. Over-excavation was filled with thaw stable gravel to maintain thaw strains within the offshore flowlines within maximum allowable strain limits when exposed to estimated differential permafrost thaw settlement within the approach to shore. In opposite to Northstar 90-degree vertical transition, the long-radius vertical transition was designed (Eisler, B. 2016). The sketch of the long-radius vertical sweeping transition is presented in Figure 3. This all allowed also to decrease the excavation costs and eliminated the use of a metal pipe to accommodate thermal and pressure expansion displacement. However, the described design is characterized by both vertical and horizontal displacements.

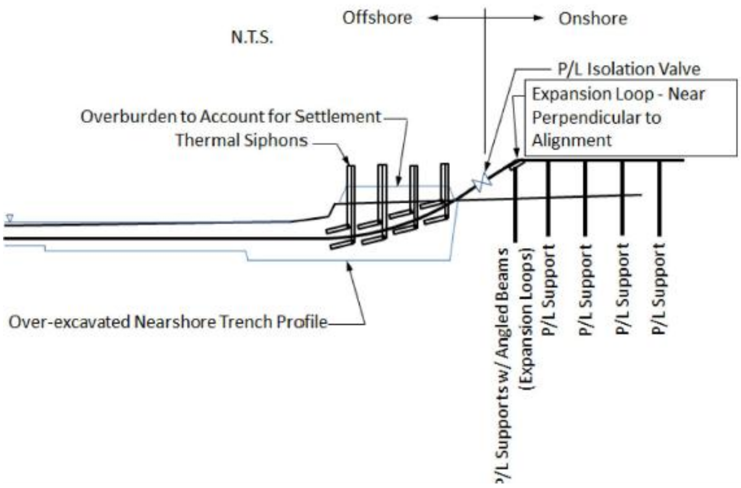

Figure 3 Ooguruk Shore Crossing Scheme (Eisler, B. 2016)

According to Eisler, B. (2016), the expansion loops and connection hardware were adjusted for different permafrost thaw settlement. The manual isolation valves were installed onshore. Power, pad, communication infrastructure was not installed at the shore crossing. To draw heat out of the ground and protect the permafrost the thermal siphons were installed as well. Thermal insulation sheets were laid beneath the flowline. Blasting of permafrost was also used similar to the Northstar project.

Another Alaskan project is Nikatichuq project located at a depth of 3m off the shore of the North Slope of Alaska in the Beaufort Sea. The flowlines and cables of Nikaitchuq include 0.35 m x 0.45 m pipe-in-pipe multiphase production flowline, 0.32 m insulated water injection flowline, 0.17 m spare flowline, 0.06 m x 0.11 m pipe-in-pipe liquid Arctic heating fuel line, three power cables, two fiber optic cables (Eisler, B. 2016). The uniqueness of this project is that the shore crossing location was placed at a man-made offshore gravel pad extended from the shore. The flowlines and cables are protected by barrier islands similar to Ooguruk project. In order to manage the shoreline erosion, the use of gravel bag protection armor was implemented (similar to Ooguruk project). The same techniques were also implemented for shore transition – vertical sweeping curve transition. The difference is that flowline alignment is oriented with a small acute angle of approximately 25° with the western edge and slope of the gravel pad at which the flowlines transition. Such angle required elongated transition through the slopes of the gravel pad, the vertical portions of some of the thermal siphons, which protrude above grade, had to be placed in the slope of the gravel pad or very close to the slope.

Another project located in the Arctic-like conditions is Sakhalin-I. There are three fields included in Sakhalin I project: Chayvo (developed initially), Odoptu and Arkutun Dagi (developed as subsequent phases) operated by Exxon Neftegas Limited. Among the main facilities of the project are:

- The Orlan Platform
- Chayvo Well Site with the onshore Yastreb Drilling Rig
- Chayvo Onshore Processing Facilities (OPF)
- Two pipelines (flowlines) from the Orlan platform to onshore processing facilities
- The Export Pipeline System: 206 km onshore and 20 km offshore 24” Oil Export Pipeline westward across Sakhalin Island and Tatar Strait to the Russian mainland and then southwards to De Kastri
- Crude Oil Export Terminal and SPM Offloading Facilities at De Kastri

The overview of the Sakhalin I project is presented in Figure 4.

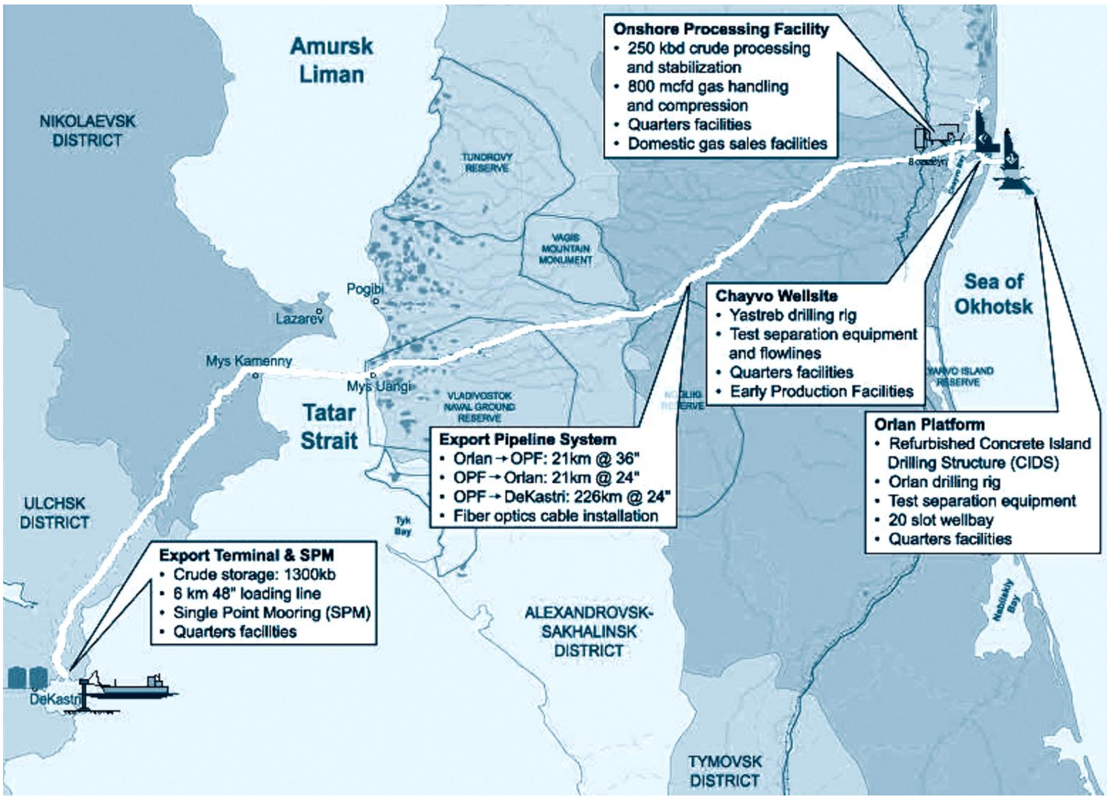

Figure 4 Overview of the Sakhalin-1 project including the Chayvo OPF, Chayvo Wellsite, Orlan Platform, Export Pipeline System crossing the Tatar Strait, and the Export Terminal and SPM Offloading Facilities at De Kastri (Joep Athmer and Teus Gijzel, 2006)

The oil exporting pipeline crosses the Tatar Strait from the coast at Mys Uangi (Sakhalin Island) and coast at Mys Kamenny (Russian side) and represents concrete coated pipeline with 610 mm outside diameter. The length of this pipeline is 226 km while 20 km of which is an offshore part. The pipeline was installed using the S-lay method with two pipe pulls at the landfalls and one additional pull on the western tidal flats. To connect and provide transportation of well stream between Chayvo Well the Orlan Platform and the OPF onshore and two offshore pipelines are used. Flowlines also contains pig launchers (in Russian: устройство запуска скребков), valves and other instrumentation equipment for flowlines operation and control. Subsea flowline (diameter 914 mm) is concrete pipeline running for 11 km offshore and gas re-injection flowline (diameter 610 mm) connecting Chayvo OPF to Orlan platform is epoxy coated thick pipe (Athmer, J. and Gijzel, T., 2006).

In the shore crossing area, the cofferdam corridor with perpendicular wing walls was constructed in order to protect the trench and backfill soil from waves. The dredging was done by the self-propelled cutter suction dredger Aquarius connected to a 500 m floating discharge line with a moored spray pontoon, which delivered the dredged soil into the designated temporary storage areas (4). In sum, 1.3 million m^3 was dregded out and the discharged sediments were stored in temporary storage areas. The wing walls strengthen shields to provide protection of excavated sand soil which temporary was stored between the wing walls and shore (Figure 5). Sheet piles were driven into the sand. Burial requirements for the flowlines necessitated dredging to a trench depth of up to 5 m in places in water depths ranging from 8 m to 20 m. Side slopes were generally 1 in 4 and the seabed consisted of dense to very dense sand.

Figure 5 Sakhalin I shore crossing area (Eisler B. 2016)

Further excavated sediments were used for backfilling the trench, constituted around 1 million m^3. The backfilling was performed by through suction tube in order to avoid pipelines shifting. Due to the climatic conditions, the installation of two pipe spool in the area between pipeline and Orlan platform could not be performed, it was needed to cover the pipelines' ends with backfill sand. To uncover these ends the trailing suction hopper dredger HAM 312 was mobilized from Dubai and used for Sakhalin project. The process of uncovering was performed by pumping water through the suction pipe that eroded backfilled sand and created into suspension that further was transported by tidal currents. This system successfully removed 20 000 m^3 of sand but started to lose its efficiency the deeper the trench became. Therefore, in order to remove the rest of the covered material a submersible pump frame on a barge was used.

Similarly to above-mentioned concept of cofferdam corridor, the Arkutun Dagi pipeline was installed. The difference was that for this pipeline two sets of sheet piles were used. These two sets provided self-stability and the trench corridor allowed the use of a backhoe with increased chassis height between the tracks and the cab (Athmer, J. and Gijzel, T., 2006).

Even though Sakhalin I project is not necessarily Arctic region, this area is characterized by the presence of the first-year ice but there is no permafrost. Thus the ice necessitates the offshore burial and absence of permafrost let the shore burial as well. The Figure 5 shows that natural shoreline retreated farther than the pipeline shore crossing area that is armored with gravel bags.

Therefore, only several projects with the shore crossing areas exist in the Arctic region.

The method of shore crossing (excavation of cofferdam corridor) can also be used in the Arctic areas where the climatic conditions limit the installation of a pipeline to the summer season and in areas where there is no barrier island to protect the shore from waves. In the areas of permafrost, the special pre-blasting techniques might be needed, as well as the use of steam for sheet piles installation. Eisler, B., (2016) highlighted two main concerns associated with summer installation of shore crossing areas:

- Permafrost degradation due to removing thermally protective Tundra vegetation and opening up the permafrost to warm air temperatures and exposure to warm seawater during summer
- Non-Technical risks of subsistence hunting in summer.

Another unique Arctic project is Bovonenkovo – Ukhta pipeline, 67 km of which was laid offshore on the bottom of the Bayadatskaya Bay. Underwater transitions are designed from three lines of steel pipeline with a diameter of 1420 mm, of which two are main ones and one is back-up. The wall thickness of the pipeline adopted 33.4 mm, based on the operating pressure in the pipeline 11.8

MPa. It should be noted that the construction of the main gas pipeline from pipes with a diameter of 420 mm with a working pressure of 11.8 MPa in domestic practice is planned for the first time. Also, a high-strength steel grade, K65, was used for the construction of the pipeline for the first time, Regulatory documentation for pipelines with a pressure of over 10 MPa are currently not designed and developed. In addition, the construction of underwater transitions is a challenging task due to the presence of gravel and pebble areas in the geological structure with soil with a large inclusion of boulders, which does not allow to apply the technology of laying pipelines by the method of horizontal directional drilling, and also creates significant difficulties in the construction of underwater trenches (Mironuk,S., 2014).

The total length of the gas pipeline crossing through the Bayadaratskaya Bay is about 72 km, the actual offshore section is 67 km, the maximum depth of the sea in the transition area reaches 22–23 m. Since the pipeline is located in the Arctic area, the Bayadaratskaya Bay has ice cover over 8-10 months/year. The bottom relief of the Baydaratskaya Bay has a rather complicated structure. The modern sub equal topography is more pronounced within the limits of the submarine coastal slope in the depth range from 0 to 15 m. This is the zone of the most active hydrodynamic impact on the bottom, where longshore shafts and hollows are formed. Mostly in this area, the surface of the bottom of the Bay is complicated by gouging furrows. Analysis studies also showed that engineering-geological conditions of the transition area are complicated by the presence of permafrost soils as well as ejection of the bottom with ridges keels. Figure 6 shows the ice ridges traces of plowing (Mironuk, S., 2014).

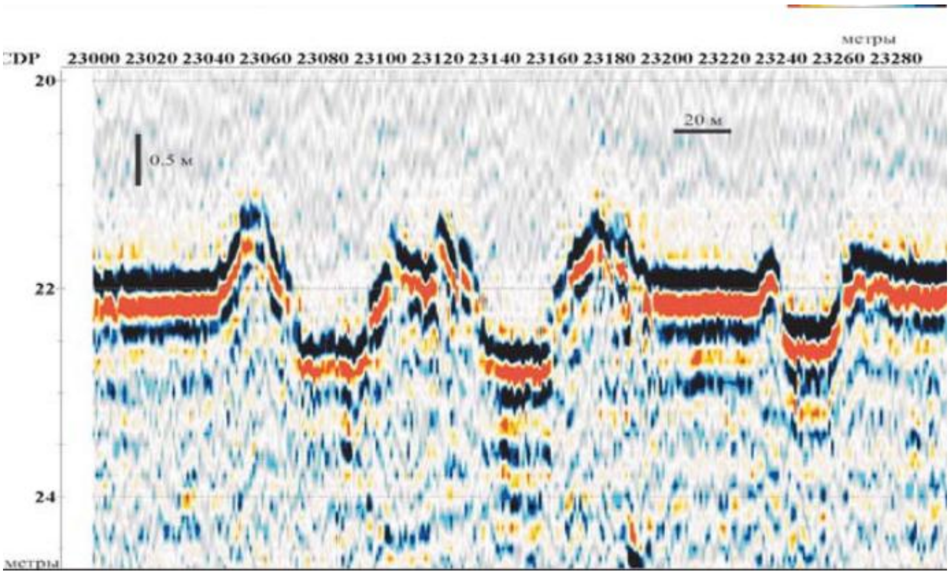

Figure 6 Ice Ridges Traces of Plowing (Mironuk, S., 2014)

The coastline transition area was constructed with by the trenching and backfilling. In the areas of coast, the cofferdam corridor was used. However, the technological information on the method of coast crossing is not available in the open sources.

Therefore, 5 subsea pipeline projects with the shore crossing area in the Arctic region (sub-Arctic for Sakhalin I) were considered and analyzed. The general information on these projects is presented in Table 1.

Table 1 Pivot Table of Analyzed Arctic Pipeline Shore Crossing Projects

Project	Area	Water depth	Ice gouge protection	Trench depth	Average gouge depth	Max gouge depth	Shore crossing method	Bluff height
Northstar	Beaufort Sea	11.3 m	Trenching	2.1 m	0.6 m	1.0 m	Trenching. Vertical 90-degree transition	0.6 (max 2.4)
Ooguruk	Beaufort Sea	1.4 m	Trenching Ice gouge effect negligible	-	1 m	2.09 m	Trenching. Long-radius vertical transition	1.8 -3 m
Nikaitchuq	Beaufort Sea	3 m	Trenching	-	-	-	Trenching. Artificial offshore gravel pad extension from the shore	-
Sakhalin I (Orlan platform)	Okhotsk Sea	15 m	Trenching	5 m	-	-	Trenching. Cofferdam corridor with wing walls	-
Bovonenkovo – Ukhta pipeline (Bayadaratskaya Bay)	Kara Sea	22-23 m	Trenching	-	12-13 m	20 m	Trenching. Cofferdam corridor []	

Thus, three of the pipelines are located in the Beaufort Sea in the Alaskan part. The location of these three projects is presented in the Figure 8.

Figure 7 The Beaufort Sea Pipelines with Shore Crossing Areas (made by author with the use of Google Earth)

Three of these pipelines are buried in trenches in order to be protected from ice ridges. The difference between these three pipelines is the coast transition area: Northstar (vertical 90-degree transition); Ooguruk (Long radius vertical transition); Nikaitchuq (Long radius vertical transition with man-made gravel pad extension).

Among Russian projects are Bovonenkovo-Ukhta located in the Kara Sea and Sakhalin I located in the sub-Arctic region. The locations of both projects are presented in Figure 9 and Figure 10. Shore crossing areas of both of the projects are designed with use of trenching and further coast transition with construction of cofferdam corridor.

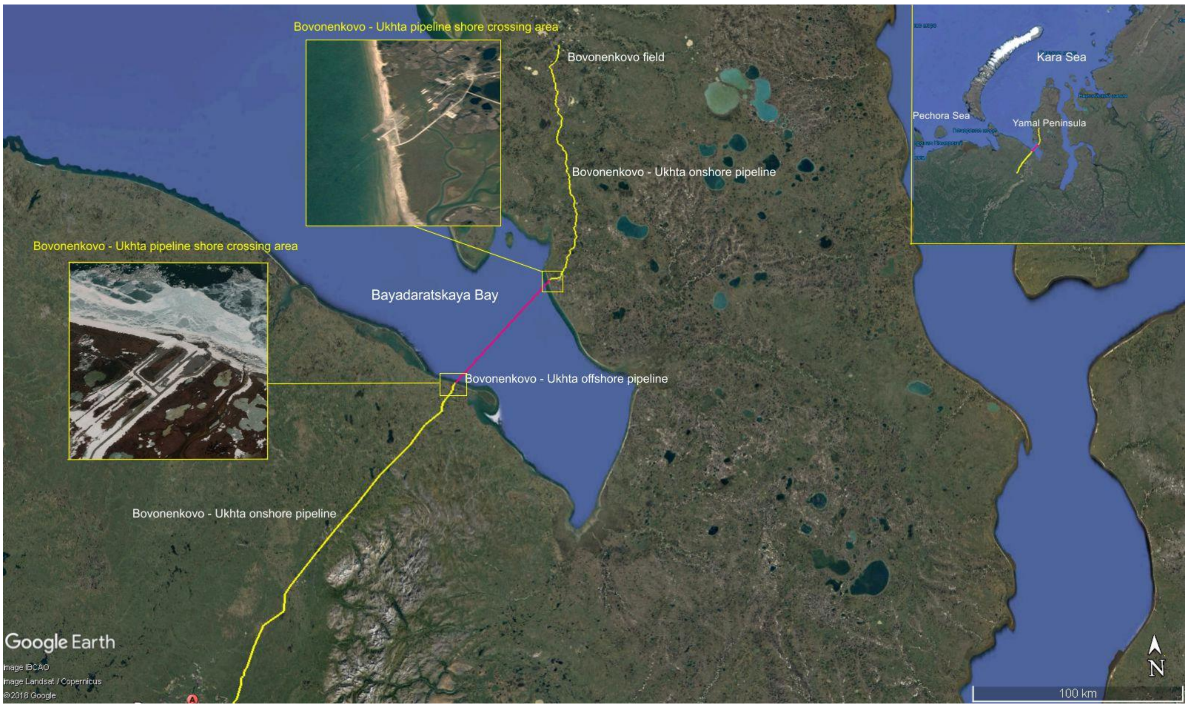

Figure 8 Bayadaratskaya Bay Crossing Area (made by author with the use of Google Earth)

Figure 9 Sakhalin I Shore Crossing Area (made by author with the use of Google Earth)

All of these projects are main examples of the Arctic subsea pipelines with the coast transitions. The method used for these projects is trenching, however, there exist other methods as well, and that will be described in the next sub-topic of the Chapter. Above mentioned projects will be taken into account and considered as analogs for further studies.

2.2. Pipeline Shoreline Crossing Methods

There exist three methods to design and construct the pipeline shore crossing area. Among these methods are trenching, tunneling and horizontal directional drilling (HDD). The method used for the above mentioned existing projects is trenching. Trenching method is based on the burial of pipelines in a trench and further the concrete or gravel covering can be used as well as pipeline strengthening or anchoring. Cowing et. Al. (2005) described steps of trenching technology as following:

1. Pre-fabrication of line pipe
2. Ice road construction and maintenance
3. Ice cutting and slotting
4. Trenching (dragline or a cutter-suction dredger)
5. Pipe string make-up (welding, anodes, field joints)
6. Bundle make-up
7. Bundle installation
8. Cable installation
9. Backfilling the pipeline trench

In order to protect the mound, a special armor is installed. This technique makes a strong nibble mound breakwater with the pipeline under it. Breakwater has to be armored heavily so that it can withstand all the possible wave and ice loads on it. Sheet pile wall is used to protect buried the pipeline from erosion of the shore. In addition, the cellular sheet pile is constructed. In turn to protect pipeline from permafrost thawing, additional thermos siphons are used.

Another method similar to trenching is tunneling; however, this method has not yet been used in the Arctic region. Tunneling is based on building a tunnel initiated onshore and terminated in the seabed. It should also be noted that tunneling should be set at the depth where a pipeline is completely safe from scouring. For the onshore part, the vertical tunnel initiation is required. Then pipes are placed inside the submerged tunnel made of concrete. Tunneling plays protection role from water and permafrost thawing. Thus, it should not heat the surrounding soil and permafrost and also not to let pipe cool down or freeze. In order to bore the tunnel special tunneling boring machine is used. Eisler, B., (2016) outlines several aspects influencing the depth of the tunnel.

- Depth to top of tunnel at which sub-gouge soil displacements from ice gouging are zero or close to zero.
- Depth to top of tunnel at which the sub-gouge soil displacements are not zero, but based on structural analyses and design of the tunnel, the displacements will not cause an opening of the segment joints to a point that allows water ingress.
- Depth required avoiding frac-out of tunneling fluids.

If tunnel is located in permafrost thawing area a special additional cooling pipes are used in a tunnel. The technique of constructing a tunnel for the shoreline crossing area is a quite costly and technically challenging solution.

Horizontal directional drilling (HDD) is another feasible method that can be used for shore crossing tasks, however it has not been yet implemented in the Arctic conditions. One of the main advantages of such solution is ability to use for long distance and quite large pipe diameters (up to 56’’) (Heuer, 2011). By choosing the direction the areas with permafrost thawing can be avoided. Also on ground equipment such as thermosyphons can be used to control permafrost thawing. Also a special cooling pipe may be required as well as insulation layer, spacers and straps. So, bundle may look similar to the DrakeF-76 bundle.

In general, the HDD method excludes the trenching which is significantly reduces the environmental impact.

Every described method has its challenges. Warm pipelines buried underground will radiate heat. According to Eisler, B., (2016) within the frozen permafrost pipelines can heat it out 50 ft. or more, and in the case of thawed oil for hundreds of feet. In order to illuminate this problem thermal insulation, cooling pipes, thaw stable gravel, thawed non-frost susceptible gravel might be required. Distance between two project locations may be relatively close. However, site-specific condition differences can be significant enough to require different thermal remediation solutions. Burial, drilling or tunneling can also increase the process of coastline erosion in the phase of pipeline installation. It can be obtained by damaging thermally protective tundra vegetation, altering the geometry of the shoreline, introducing hard points (armoring) that refocus wave energy and interrupt longshore sediment transport (Eisler, B., 2016). The differential settlement between the offshore pipelines and the onshore pipelines will require some adjustable onshore pipeline supports near the shore crossing transition. Thus, the pipelines themselves can be a source of permafrost thawing and further coastline erosion and in addition with natural environmental changes happening due to the climate change the pipeline can lose the stability and free spans can be formed.

A lot of technical and environmental aspects should be taken into account for design and construction of subsea pipelines shore crossing areas. The appeared challenges associated with subsea pipeline installation in the Arctic region are described in the next Chapter 3.

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3. Arctic challenges for subsea pipeline installation and design

The design and installation of subsea pipelines is a challenging task especially in the Arctic region characterized by severe cold temperatures, permafrost, presence of ice, presence of ice ridges, and erosion of the coastline. All these aspects should be taken into account when designing a subsea pipeline.

There are a number of unique aspects of the lying and operation of pipelines, characteristic of the marine Arctic environment. The main features outlined in the Working document on the US National Petroleum Council are as follows:

- the interaction of ice keels with the seabed and underwater offshore pipelines;
- the presence of continuous sea ice cover in winter;
- low ambient temperature;
- the end duration of the open water season;
- the effect of "strudel" during the thaw;
- the presence of near-surface permafrost in the burial zone of the pipeline, as well as in the areas of pipeline access to the shore.

<u>The presence of solid sea ice in winter</u>

During the winter months in most Arctic sea areas, the thickness of sea ice increases to 1.5-2.2 meters and covers 90 +% of the sea surface. Beyond the edge of the ice cover, this sea ice is mobile and usually severely deformed. The presence of thick, drifting ice makes it difficult to access subsea pipelines, thereby causing operational problems and maintenance of subsea pipelines. The presence of ice cover also makes inefficient traditional methods of ground observation for detecting leaks in the pipeline.

<u>Low ambient temperatures.</u> Underground pipelines installed at low ambient temperatures should be designed in such a way as to prevent the pipeline from upheaval buckling due to strong thermal expansion during subsequent heating of the pipeline with production.

<u>The end of the open water season.</u> As a rule, the open water season in arctic marine areas containing hydrocarbons may vary depending on location and year from two to four months. This limits the time available to install the equipment, or requires that installation work to be carried out in the presence of ice. For a very

long pipeline, the installation may require several seasons due to the complexity of the maintenance of the station and the direction of the pipe-laying vessel in the drifting sea ice using conventional pipe-laying equipment.

Ice erosion of the bottom, the “strudel” effect is a type of hydraulic erosion in which melted water from a river or from large bodies of water on the ice cover during destruction flows out of the ice, thaws a hole in the ice and then vigorously drains through the hole, destroying the seabed. Ice erosion of the bottom is one of the main problems for pipelines located near river outlets. Observations have shown that such a process creates erosion depressions on the seabed tens of meters wide and several meters deep to a water depth of about 5-6 meters. Such flushing can remove soil from underground pipelines.

Presence of near-surface permafrost in the pipeline burial zone

Sea permafrost is relatively common in shallow waters in the Arctic; it is often located at a depth of several meters below the seabed due to the gradual warming of the overlying seawater. However, in some marine arctic regions, shallow permafrost exists near the seabed. This permafrost will be thawed due to the non-insulated pipeline and, therefore, can cause difficulties to pass through the trench, and will also be a source of significant potential pipe deposition. In areas where the submarine permafrost is intermittent, significant differences in precipitation may occur, as the pipeline settles in thawed permafrost zones and remains stable in the permafrost-free zones.

There are also design and installation challenges that occur for the subsea Arctic pipelines laid in the shore crossing areas. Some of these aspects are described in Chapter 3.1.

3.1. Challenges associated with the pipeline shore crossing area

The shore crossing area is considered in this work and shallow water areas (3–4 km from the coastline and 10 m water depth) (Gudmestad et al. 2007) create additional problems for pipeline installation methods since the critical water depth at which the pipe-laying vessel can operate is 10-12 meters. Coastal geomorphology is formed from the complex interaction of geological, hydrodynamic and biological factors.

<u>Ice ride-ups and Pile-ups.</u> During the beginning of the winter and during spring the shore crossing area is characterized by ice ride-up and pile-up, which are known as ice encroachment. Midwinter, bottom-fast and ice-fast ice tend to stabilize and restrict the movement of ice from invading shore. However, such a process can occur at any season.

According to Final report on ice encroachment made by Coastal Frontiers Corporation Chatsworth, California Vaudrey & Associates, Inc. San Luis Obispo, California, the process when sheet ice remains intact or nearly intact as it is driven ashore is “ice ride-up”. If the advance of the ice is halted by the slope and the ice fails in buckling or bending, it breaks up into individual blocks that form an “ice pile-up” either at the shoreline or somewhere on the above-water slope. These two phenomena can occur at the same time

One of the main factors that influence ice encroachment is wind stress, which can cause the loss of confinement of the ice sheet. Other parameters that also influence the ice encroachment are ice thickness and storm intensity. Even though their role is secondary, long-term storms can keep the ice moving to the shoreline. Such shore characteristics as coast exposure, subaerial beach morphology, and local bathymetry are also an important factor for ice ride-ups and pile-ups. In above mentioned Final report all parameters that influence ice encroachment are summarized and presented in Table 2.

Table 2 Parameters that Influence Ice Encroachment (Coastal Frontiers Corporation Chatsworth, California Vaudrey & Associates, Inc. San Luis Obispo, California, 2012)

Parameter	**Influence**		
	Slight	**Moderate**	**Significant**
<u>Driving Force</u>			**X**
1. Wind reversal			
2. Storm intensity		**X**	
3. Storm duration	**X**		
<u>Ice Property</u>			
1. Ice thickness		**X**	

2. Ice cracking			**X**
3. Flexural strength	**X**		
Shoreline Characteristics			
1. Beach slope	**X**		
2. Beach friction		**X**	
3. Coastal exposure		**X**	
4. Bathymetry	**X**		

As described above ice encroachment can occur even during the freeze-up period or break-up period. The window for freeze-up is early October and mid-January that is characterized by strong storms. The break-up period is characterized by shorter duration and fewer storm events. The intensity of ice encroachment in the freeze-up period is due to the fact that ice needs some time to form thickness, and young ice remains mobile and susceptible to movements caused by wind. With the growth of ice thickness, the mobility rate decreases and the possibility of ice encroachment to the shoreline decreases as well. According to the report of Coastal Frontiers Corporation Chatsworth, California Vaudrey & Associates, Inc. San Luis Obispo, California (2012) the greatest encroachment distances on natural shorelines result from combined ride-up/pile-up events in which 10-15-m wide "fingers" of sheet ice slide as much as 50 to 75 m onto the beach between pile-ups.

The break-up periods last for 2 - 3 weeks from late June through early July. However, the duration of exposure may vary depending on wind characteristics and ice sheet strength characteristics. During the break-up ice cracks and breaks up into floating pieces that may tend to pile up at the shoreline. Even though the period of a break-up is much shorter than the freeze-up the impact can be much higher due to the smaller thickness of the ice that allows to extend the ice encroachment to greater distance and bring additional load on the shoreline and infrastructure, including pipelines in the shore crossing area. There exist a lot of fixed ice encroachment events including the Northstar project. In the Final report, it is mentioned that the largest encroachment, 27 m, was recorded on Northstar Production Island in late January 2008. As shown in Figure 12, a 30- to 40-kt (15- to 21-m/s) westerly storm produced a 14.3-m pile-up that engulfed the concrete mat slope protection system but was contained by a sheet pile wall that encircles the island work surface.

Figure 10 14.3-m Pile-Up on Northstar Production Island in Late January 2008 (60- 90 cm thick ice blocks encroached 27 m onto concrete mat during 30- to 40-kt westerly storm; Coastal Frontiers, 2012)

In order to calculate the prediction of ice encroachment it is important to understand the geometry of the process. Figure 11 shows the geometric parameters that are used to predict encroachment.

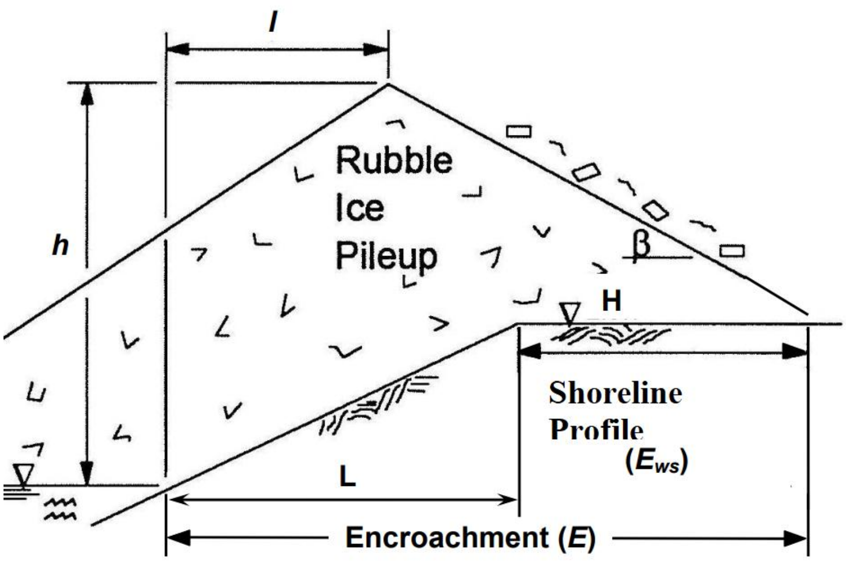

Figure 11 Geometric Parameters Used in Predicting Encroachment (Coastal Frontiers, 2012)

The location of the peak (l) is usually between ½ and 2/3 of the horizontal distance (L) from the waterline to peak elevation of the shoreline profile. For sheltered sites, it is appropriate to use l=0.5L, while for exposed areas the largest value can be obtained as l=0.67L. The slope of the landward side of the pile, β also influences the ice encroachment prediction. According to Final report by Coastal Frontiers Corporation Chatsworth, California Vaudrey & Associates, Inc. San Luis Obispo, California, the value β=30° is adopted as a conservative lower bound for the purpose of developing predictions. In addition, the value of shoreline profile elevation (H) should also be required.

In the work Coastal Frontiers Corporation Chatsworth, California Vaudrey & Associates, Inc. San Luis Obispo, California, Final Report (2012) the encroachment (E) is calculated according to Equation (1)

$$E = l + \frac{(h - H)}{tan\beta} \tag{1}$$

Where *h* is a predicted pile-up elevation.

Shoreline profile encroachment is calculated according to Equation (2)

$$E_{sp} = E - L \tag{2}$$

Since ice encroachment can damage the onshore pipeline and shore infrastructure, therefore, it is important to keep distance when designing and installation of pipeline in the shore crossing area. Eisler (2016) in his work mentions that the total set-back distance of above ground pipeline components from the shoreline is the additive sum of estimated shoreline erosion and the estimated ice encroachment distance.

High bluffs shores are less exposed, while among artificial protection methods Eisler, B., (2016) outlines artificial gravel berms that can reduce estimated ice encroachment distance along the pipeline. The gravel berms can reduce the setback distances for the initial design, thereby slightly reducing the trench for the coastal transition. Gravel berms can also be used as a mitigating solution during operations if the total coastal erosion and icing rating is exceeded. Eisler, B., (2016) in his work presented the scheme of ice ride-up and pile-up at the shore. Details of ice encroachment distance and height are site-specific and depend on the bluff height and offshore driving potential in terms of sheltering from barrier islands. (Figure 12)

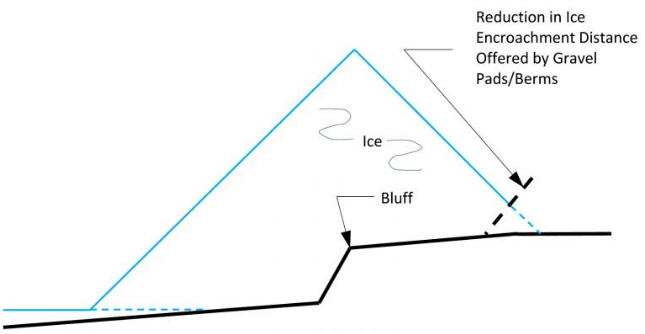

Figure 12 Shoreline Ice Encroachment (Eisler, B., 2016)

Ice Ridges and Ice Scouring. Another important issue that should be taken into account while design of subsea pipelines is protection from ice ridges in the nearshore area. Ice ridges are ice features which were formed during stress appeared within the ice plane. Colliding with each other under the pressure the ice ridge is formed. Ice ridge consists of two parts: above water part called "sail" made of small ice rubble accumulation; underwater part called 'keel' and is formed chaotic conglomeration of broken ice. Typically, the height of the keel is four times bigger than the sail one. The largest ridge to be recorded had a sail about 12 meters and keel – 45 meters. Average total thickness of ice ridges is recorded to be between 5 and 30 meters with the mean sail height below 2 meters. Ice ridges and ice scouring are common phenomena for the nearshore area.

Ogorodov, S., and etc. performed work on ice effect on coast and seabed in Baydaratskaya bay, Kara Sea and made a model of Subdivision of coastal zone by types of ice formations and their effects on coasts and seabed (Figure 13). As can be seen from the Figure the ice can drift to the shore and therefore protection of pipelines from ice ridges in the nearshore area is also important.

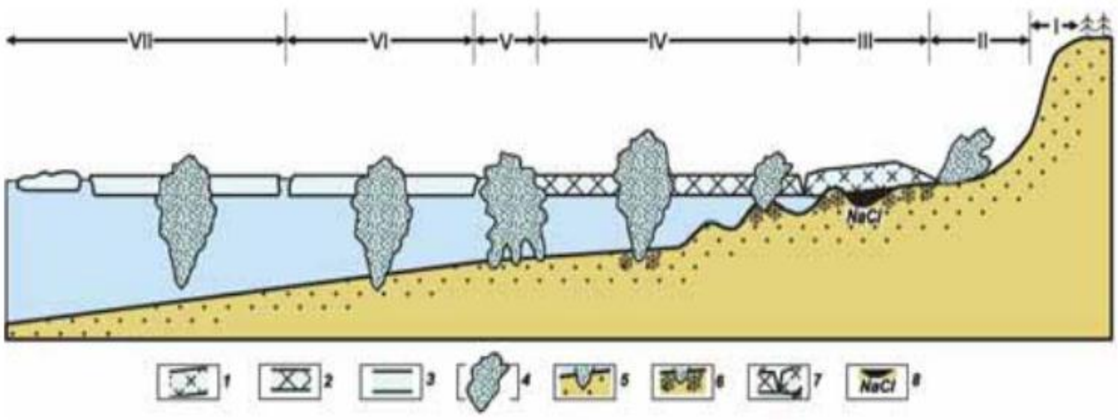

Figure 13 Subdivision of coastal zone by types of ice formations and their effects

on coasts and seabed:

1 – fast ice frozen to the bed; 2 – floating fast ice; 3 – drift ice floes; 4 – hummocks ice formations (ice ridges, grounded hummocks and ice dam), ice piles and overthrusts; 5 – hummock keel penetration into the ground; 6 – seasonally frozen ice forming at contact between ice and bed; 7 – tidal crack; 8 – high-salinity water in longshore troughs, cryopegs

Main drivers for ice ridges formation are wind and current. When pressure ridges are grounded due to interaction between fast ice and drifting pack ice they are called “stamukhi”.

ISO 19906 presents a typical cross-section view of a ridge (Figure 14).

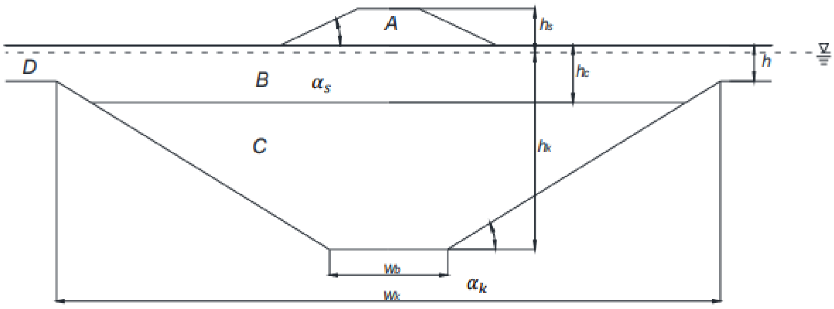

Figure 14 Cross section view of a ridge (ISO 19906)

On a Figure h_c – thickness of consolidated layer; h_s – sail height; h – level ice thickness; h_k – keel height; w_k , w_b – keel width at the sea level and bottom respectively. However the shape of ice ridge can vary, therefore, correlations between above mentioned parameters were developed and are following: $h_k=3.95h_s$; $w_k=3.91h_k$; $w_b=w_k-2h_k\cot\alpha_k$

Another important factor that should be taken into account is ice ridge morphology, since it is not homogeneous for all levels of ice ridge. Research by Grishenko, V.D., (1988): has shown the keel macro porosity dependency on the block thickness

The macro porosity, used in subsequent calculations, should be distinguished from total porosity represented by brine pockets inside ice blocks. Brine inclusions strongly affect the ridge strength and demand additional study. Under assumption that brine volume is small and all pores are occupied either by water or by air, the density of porous keel part of the ridge therefore will be outlined as:

$$p_{iw} = \eta p_w + (1 - \eta) p_i \tag{3}$$

The upper sail part has density:

$$p_{ia} = \eta_s p_a + (1 - \eta_s) p_i \approx (1 - \eta_s) p_i \tag{4}$$

Where η_s – sail porosity.

While moving, these ice ridges can be a significant danger for subsea pipelines and subsea production units. Ice ridges can scour the sea bed causing the possible damage to the underwater equipment if they are not buried on sufficient depth. Ice scouring is the process of ice ridge interaction with the soil. One of the main methods to protect pipeline from ice scouring is its trenching. However, it also should be noted that essential deformations can occur beneath the gouge with pipeline being damaged by being dragged with soil. Therefore, in design we should also consider the cover depth *(b)*. It is economically and environmentally to correctly calculate the trenching depth. Duplenskiy, S. (2012) in his master thesis outlined all works that have been studying different models to estimate gouge depth. He also established and analyzed two models: force scouring model and energy scouring model and compared them. In this work for future studies the force model will be implemented. The goal is to estimate the maximum thickness of the upper sediments with which the ridge can interact. The main assumption here is that initially the ridge does not exert any load. Then the ridge begins to move, and there is resistance, which limits movement at a certain critical depth (Duplenskiy, S., 2012).

The model introduced by Duplenskiy, S. (2012) is based on the assumption that friction forces depend on the gouging depth. The more top sediments on the front surface, the greater the friction. At the maximum gouging depth, the steady forces are in balance with the resistance force. The scheme of such model is presented in Figure 15:

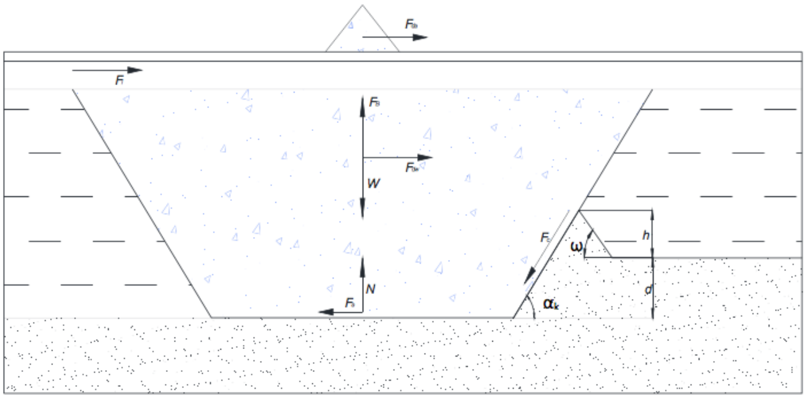

Figure 15: Force System on Ice Ridge (Duplenskiy S., 2012)

Assumptions to be made:

• It is assumed that the ridge is initially motionless, so that all forces have maximum values. Otherwise, the resistance force of the flow can act in the opposite direction: the wind accelerates the ridge, and it moves faster than the flow;

• Bottom of ridge keel has infinite power; it is not destroyed by contact with the seabed;

• The surface of the ice limits the movement of the ridge;

The overall model is based on the following force equilibrium:

Horizontal direction:

$$F_{da} + F_{dw} + F_i - F_a - F_c \cos a_k = 0 \quad (5)$$

Vertical direction:

$$F_b - W - F_C \sin a_k + N = 0 \quad (6)$$

<u>Wind drag force:</u>

As a rule, the frontal and upper components of the wind force push the ice. As for the ice ridge limited by the level, the value is calculated by the component:

$$F_{da} = \frac{1}{2}\rho_a C_{da} A_{a1} u_a^2 + C_{sa}\rho_a A_{a2} \quad (7)$$

Projection area:

$$A_{a1} = \left(h_s - \frac{\rho_w - \rho_i}{\rho_w} h_i\right) \quad (8)$$

$$A_{a2} = w_k B \quad (9)$$

Where: ρ_a – air density (kg/m^3); ρ_w – water density (kg/m^3); ρ_i– ice density (kg/m^3);

C_{da} – wind drag coefficient; C_{sa}– wind friction coefficient;

u_a – wind speed (m/s);

h_s – ridge sail height (m); h_i – level ice thickness (m); $h_k = 3.95h_s$ – keel draught (m);

B – keel breadth (m);

w_k – keel width at the water line =3.95 h_k

Current drag force:

Since the force acts only transversely, its value is determined by one component:

$$F_{da} = \frac{1}{2}\rho_w C_{dw} A_w u_c^2 \quad (10)$$

Effective area of current impact:

$$A_w = \left(h_k - \frac{\rho_i}{\rho_w} h_i\right) B \quad (11)$$

Where:

C_{dw} – current drag coefficient; u_c – current speed (m/s);

Weight:

To estimate the weight of the ridge density, it is necessary to take into account heterogeneity and shape features.

$$W = \rho_{iw} B g \left[\frac{\rho_{ia}}{\rho_{iw}} (h_s - \frac{\rho_w - \rho_i}{\rho_w} h)^2 \cot a_s + \frac{\rho_i}{\rho_w} h w_k + \frac{1}{2}(w_k + w_b)(h_k - \frac{\rho_i}{\rho_w} h)\right] \quad (12)$$

Where:

ρ_{iw}= η*ρ_w+(1-η)* ρ_i – ridge density in water; where: η=0.11*ln(T_b)+0.37; T_b – ridge block size (m);

$\rho_{ia=\eta_s} p_a + (1 - \eta_s) p_i$ – ridge density in air; η_s- ridge sail porosity;

h- consolidated layer thickness (m); a_s-sail angle (rad)

From this equation it follows that the dependence of the weight of the ridge depends on the minimum dimensional parameters, such as the thickness of the consolidated layer and the height of the sail.

Buoyancy force:

By analogy with respect to the weight equation, buoyancy forces affect the trapeze of the keel bar and a part of the underwater consolidated layer as follows:

$$F_b = \rho_w \nabla g = \rho_w g B \left[\frac{1}{2}(w_k + w_b)\left(h_k - \frac{\rho_i}{\rho_w} h\right) + \frac{\rho_i}{\rho_w} h w_k\right] \tag{13}$$

Ice force:

The ice concentration up to the ridge adjusts the maximum horizontal force in the state of limited ice strength (MN):

$$F_i = 0{,}43 \cdot 4{,}059 \cdot B^{0{,}622} \cdot h_i^{0{,}628} \tag{14}$$

Passive friction force:

The theory of passive pressure of the earth is used to calculate the resistance of the upper sediments. The pressure on the ground usually acts on the inclined surface of the keel and causes additional friction depending on the angle of friction of the wall. (Vershinin et al., 2007).

Front resistance:

$$F_c = \mu P cos(\varphi_w) \tag{15}$$

Upper sediments increase pressure before the ridges:

$$P_f = \frac{1}{2} K_p \rho_s g (h' + d)^2 B + 2c\sqrt{K_p} \tag{16}$$

Where c is the cohesion of the upper precipitation, Kp is the passive pressure coefficient (Duplenskiy, S., 2012):

$$K_p = \frac{cos\varphi^2}{cos\varphi_w\left[1-\sqrt{\frac{\sin(\varphi+\varphi_w)\sin(\varphi+\beta)}{\cos(\varphi_w)\cos(\beta)}}\right]^2} \tag{17}$$

$$h' = \sqrt{\frac{d^2cot\varphi}{cot\varphi+\frac{d}{3B}cot\varphi cot\beta}} \tag{18}$$

$$P_s = \frac{1}{6}K_p\rho_s g d^2 w_b(w_b + d \cdot cot\alpha_k) \tag{19}$$

Horizontal:

$$F_{cx} = F_c cosa_k = \mu \cdot P_f cos\varphi_w \cdot cos\alpha_k + \mu \cdot P_s \cdot cos\varphi_w \tag{20}$$

Vertical:

$$F_{cy} = F_c sina_k = \mu P_f cos\varphi_w sin\alpha_k \tag{21}$$

Active friction force:

This force is a function of the reaction of the upper sediments:

$$F_a = \mu \cdot N \tag{22}$$

The reaction force of the support from the equation:

$$N = W - F_b + F_{cy} = F_{cy} \tag{23}$$

Calculating:

$$F_{da} + F_{dw} + F_i - \mu F_{cy} - F_{cx} = 0 \tag{24}$$

This equation can be solved using Maple. For further analysis, the gouge depth for three different cases are to be estimated using the force model in Maple.

Coastline characteristics. Coastline Erosion. Sea coastline is one of the most dynamic parts of the Earth because in this area natural spheres are actively interacting between each other: hydraulic (waves and currents), lithological (coastal sediments), atmospheric (winds, storms) and biological. In the board of sea and cost constant relief changes are happening. At the same time the coastline is the important area in terms of household and allocating of different facilities. In many cases, it carries an anthropogenic load, often exceeding its natural resistance potential (AO “Roscartography” National Atlas of the Arctic, 2017). Therefore, the loss of the coastal zone as a result of natural and anthropogenic pressures will entail both negative environmental and economic, as well as legal, social and aesthetic consequences. Formation, further development and change of the coastline are largely dependent on the wave effect. Other factors influencing the formation of the coastal zone are coastal currents, tides, surges.

It should be noted that the Arctic region is characterized by a larger scale of coastline erosion due to climatic conditions as well as structural-geological profile. Low temperatures and luck of sun radiation cause prolonged conservation of the coast by sea ice and contributes to the development of permafrost. Bank-forming factors: wind, currents, storms largely depend on the ice regime of the sea. Therefore, it is important to take into account periods of open water, when the ice edge is located at a considerable distance from the coast, which entails an increase in wave and storm processes, and consequently, the level of coastline destruction. (AO “Roscartography” National Atlas of the Arctic, 2017). In addition, the Arctic coast is also characterized by thermal effects of sea water on clay-loamy high-ice deposits. Thermal exposure causes solifluction, which significantly weakens the stability of cliffs and facilitates wave erosion. A distinctive feature of the northern seas are thermal abrasion coasts, which make up 1/5 of the total length of the coastline (AO “Roscartography” National Atlas of the Arctic, 2017).

The Arctic costs are characterized by three main types (AO “Roscartography” National Atlas of the Arctic, 2017).

- Abrasion shores (abrasion-denudation; abrasion; thermos-abrasive; ice shores)
- abrasion-accumulative (aligned and cove)
- accumulative (beach and lagoon – caused by wave processes; drains - created by tides; delta - created by river mouth processes).

Coastal stability is provided by various natural and anthropogenic conditions. The banks composed of crystalline and metamorphic rocks are actually stable, and the shores of small and narrow gulfs, where wave acceleration is significantly reduced, can also be stable. The banks that experience a tectonic uplift differ in their peculiar stability, as a result of which the cliffs die and their terraces appear at their bottom, scattering the energy of the waves. A detailed description of the Russian Arctic coasts is presented based on the information from AO “Roscartography” National Atlas of the Arctic, 2017. Morphogenetic maps of the coast of the Barents; Kara and Laptev seas as the perspective areas of the hydrocarbon exploration and production are presented in Figure 16, 17, 18. The legend for the maps is available in Table 3.

Table 3 Legend for the morphogenetic maps (AO “Roscartography, 2017)

Legend	
Low changed by the sea coasts	
Glacial-tectonic dismemberment	
Transformed by sea	
Abrasive	
Abrasion-denudation	Abrasive
Abrasion dead	Thermo-abrasive and ice
Abrasion-accumulative	
Abrasion-accumulative	
Accumulative	
Created by wave processes, beach	Created by wave processes, lagoon
Created by tidal and surging processes (dry)	Created by estuary processes (delta)
Other conventions	
1,5; 4,7	Modern abrasion rate, m / year. Middle left (1.5), maximum right (4.7)
10	Cliff height, m

Barents Sea. Two types of shores prevail in the Barents Sea: thermal abrasion - 34% and unchanged by the sea - 29%. This is primarily due to the wide development of segments of the coast, composed of icy rocks and ice - in the first case, and strong crystalline and metamorphic rocks - in the second.

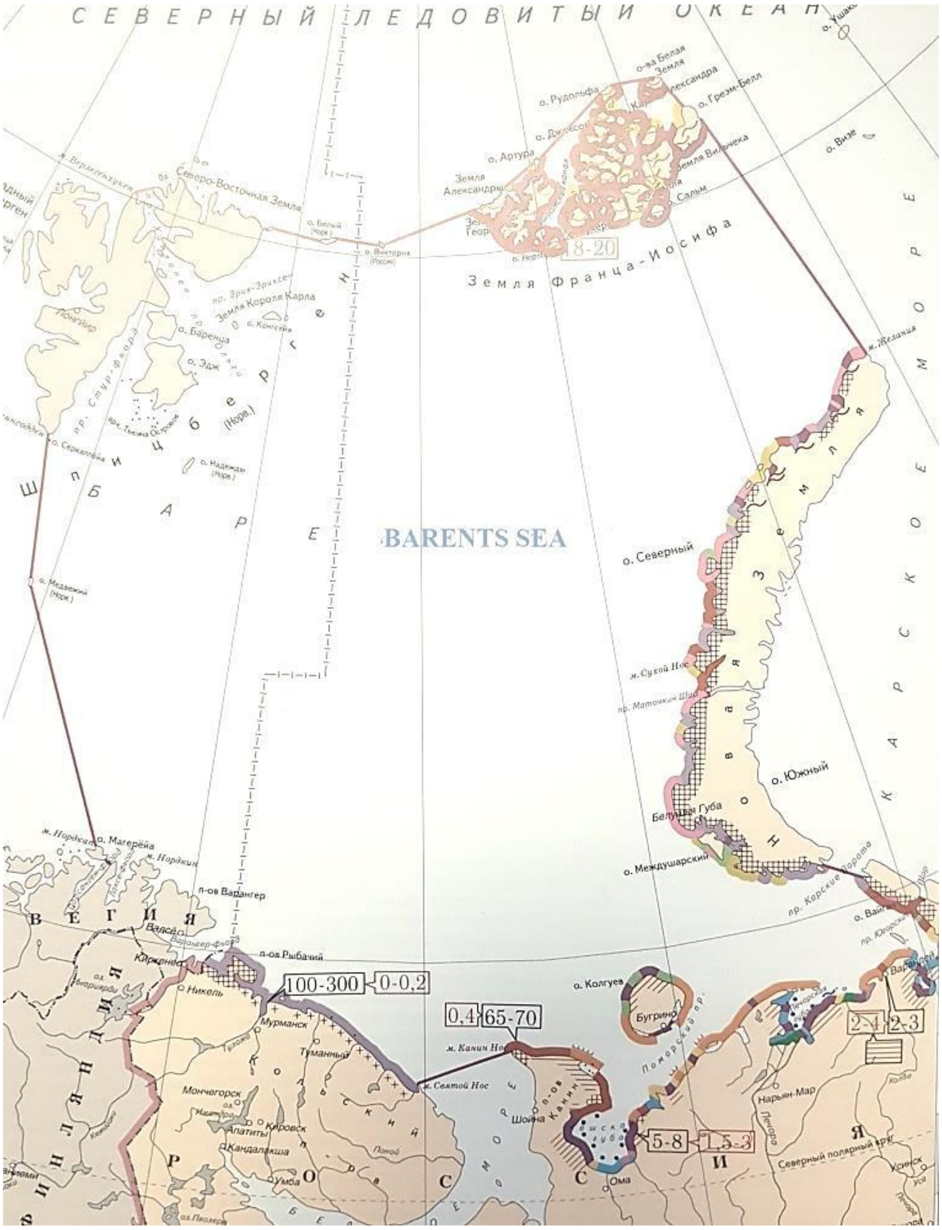

Figure 16 Morphogenetic map of the Barents Sea (AO "Roscartography" National Atlas of the Arctic, 2017)

<u>*Beloe Sea.*</u> Analysis made it possible to determine that more than a third of the shores are primary dissected and slightly modified by wave processes (34%). The fourth part of the shores is subject to abrasion (26%), including the abrasion-denudation and thermos-abrasive shores. The other quarter is accumulative and dry shores.

<u>*Kara Sea.*</u> Sea shores in general are highly heterogeneous: abrasion-accumulative (23%); unchanged and slightly altered by sea (23.5%); vast deltas (11%).

Figure 17 Morphogenetic map of the Kara Sea (AO "Roscartography" National Atlas of the Arctic, 2017)

Laptev Sea. The coastline consists of abrasive (35%) and accumulative (31%); unchanged sea shore (8%); thermal abrasion shores (16%).

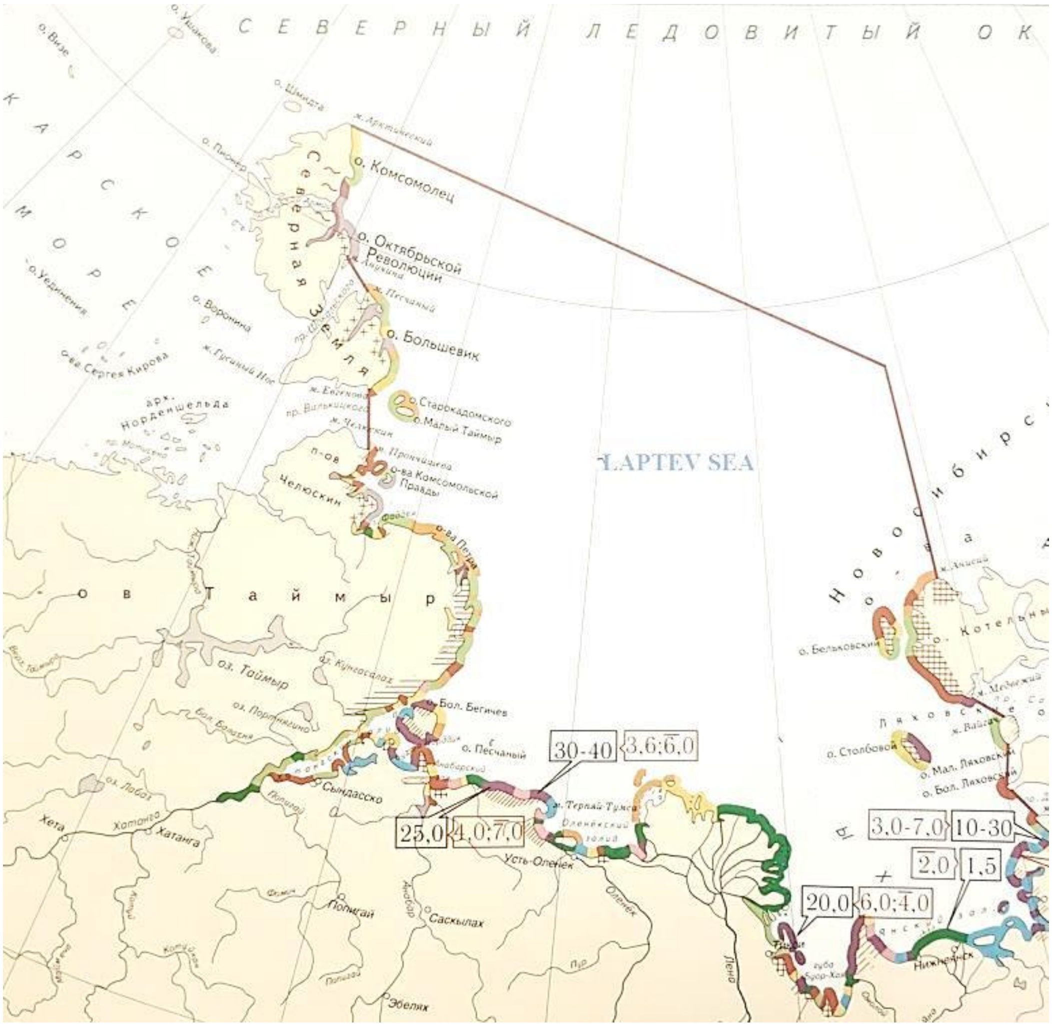

Figure 18 Morphogenetic map of the Laptev Sea (AO "Roscartography" National Atlas of the Arctic, 2017)

East-Siberian Sea. The peculiarity of this sea is a large number of extended shallows up to 3 km wide. In the western part, surging phenomena in combination with thermo-abrasive processes prevail. In the eastern part there are abrasion processes in combination with wave accumulation.

Chukchi Sea. The predominance of accumulative processes in the Chukchi Sea led to the formation of lagoon shores, including Wrangel (49%). The eroded shores in the Chukchi Sea make up 33% of the total shoreline length. Thermal abrasion coasts predominate on the Matrik coast; abrasion coasts dominate on Wrangel Island.

The main danger to the coastlines is sea swell, which determines the erosion and retreat of the coast, which entails the loss of land. For the damage caused, coastal erosion plays a leading role among hazardous coastal processes, especially with the current global trend towards erosion of the coast in conditions of rising sea levels. The main measure of the risk of coastal erosion is the intensity of the abrasion process, which can be fully expressed by the coastal destruction rates per unit time (m / year). The simplest and most obvious characteristic of the intensity of coastal processing is the linear speed of coastal retreat.

The average speed of retreat of the Russian sea coast is about 1.2 m / year. Experimental data allowed authors of AO “Roscartography” National Atlas of the Arctic, 2017 to establish numerical characteristics for the Arctic seas: a practically safe category with a possible abrasion rate of less than 1 m / year (usually 0.5 m / year); poorly dangerous category with a washout rate of 1-3 m / year and a dangerous category when the speed of processing the banks exceeds 3 m / year.

The morphodynamic map of the Russian Arctic seas is presented in Figure 19. This map represents the rates of coastal abrasion and was build based on the numerical characteristics listed above.

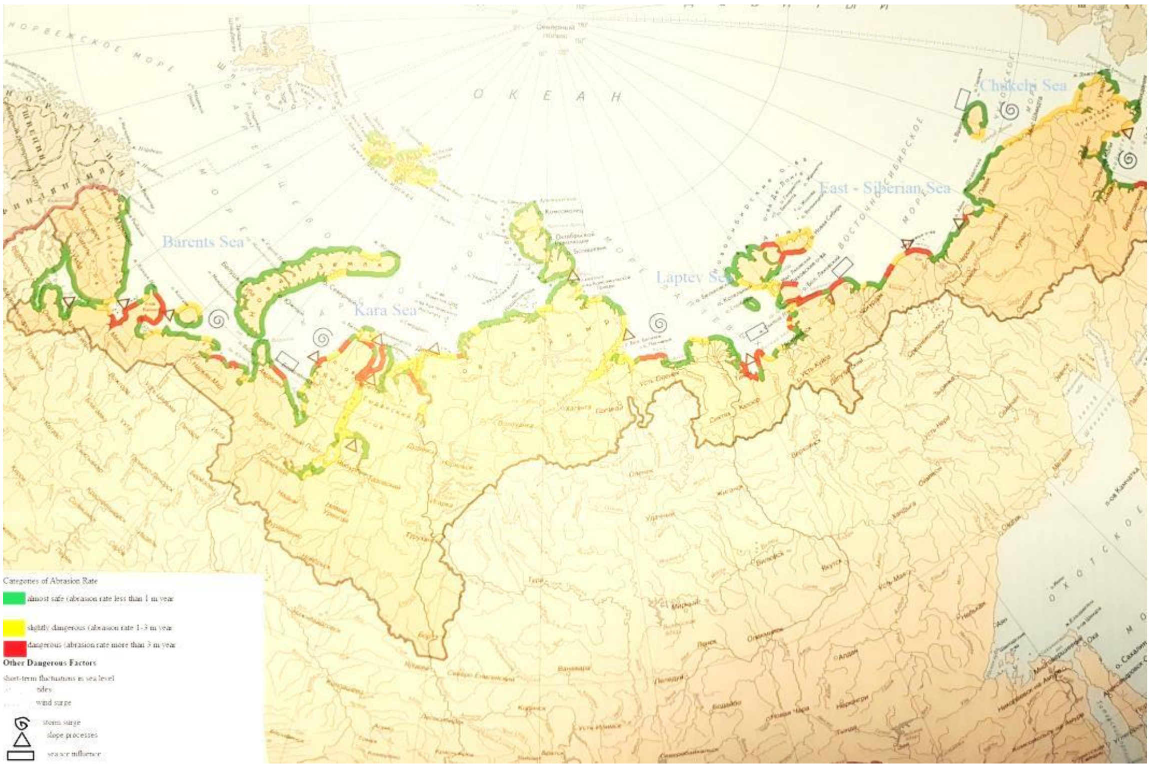

Figure 19 Morphodynamic map of the Russian Arctic seas (AO “Roscartography” National Atlas of the Arctic, 2017)

As can be seen from the above map, an almost safe category of abrasion fully dominates in the two western seas — the White and the Barents (77–73% of the long maternal data line of the seas), where stable shores of strong crystalline and metamorphic rocks are widely developed. 13 -17% of these shores are classified with dangerous abrasion. The Kara Sea and the Laptev Sea have the first category of abrasion hazard of 50–52%; the second category is 34-37%. In the East Siberian Sea, the safe category is 63% and the third dangerous category is 26% due to the wide distribution of thermoabrasive coastlines with a powerful ice complex, which, under the thermal influence of sea water, increases the erosion rates of the coast to 4–5 and even up to 11 m / year.

On the whole, the practically safe category of coastal erosion (58% of the total length of the continental coast) is almost typical for the Arctic coast of Russia, almost two of the lower value (28%) of the second category - slightly dangerous and even lower value (about 14%) of the dangerous category. The comparatively low percentage of the latter category shows the specificity of the northern sea - their small iceless period (from 2-3 months in the Kara, Laptev and East Siberian seas to 5-6 months in the Barents and Chukchi seas), which significantly reduces the duration of wave impact on the coast. However, in addition to the passive restriction of wave dispersal by ice fields in freezing seas, sea ice can directly produce a mechanical destructive impact on the coast and the sea bottom. During periods of thawing, ice blocks squeezing out on the land can significantly disturb the integrity of the coastal ledge to a height of 10–15 m above the edge, plow the beach, leaving holes, hollows, head ridges, and plow the surface of the submerged slope.

Thermal abrasive niche is formed during a storm rise of sea level in a short period of time. Precipitation begins to fall and serves as protection for the cliff until it is completely destroyed. Then the deposits are washed away. From now on, a new niche formation cycle begins. The process of coastal erosion is presented in Figure 20.

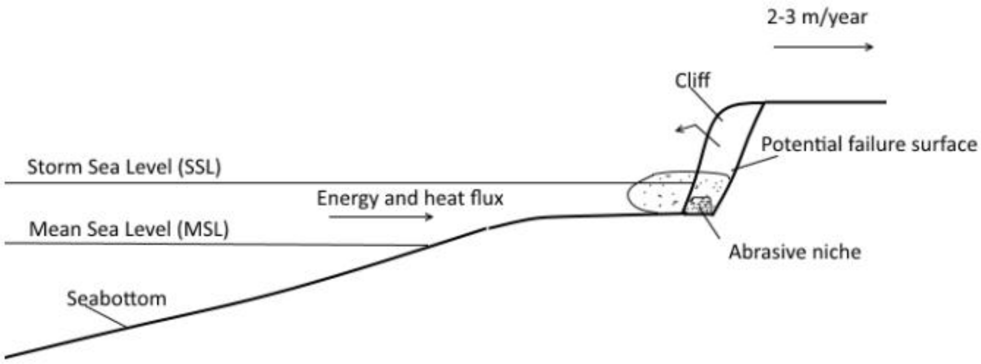

Figure 20 Coastal erosion process (Gudmestad et al. 2007)

The erosion of the coastline usually lasts several days during a strong storm rise. During a storm, the wave energy flow increases and leads to an increase in the contact area of the warm sea water and frozen cliffs. During extreme storms, the erosion cycle can be completed within a few days.

Another important factor that influence the coastal area is the heat transfer from pipeline. When the pipeline is operating, its temperature is higher than the surrounding temperature, which leads to an increase in the temperature of the soil. This process changes the bearing properties of permafrost associated with ice. As the temperature rises, the permafrost begins to melt, and the entire load carrying load is transferred by the soil. This factor leads to the melting of the soil. The result of the above phenomena is an unevenly loaded, unsupported span of the pipeline. Such a settlement causes stress in the pipe and must be taken into account in the design.

To calculate the heat loss and soil thermal resistance for a single buried uninsulated pipeline Jianguang Y (2018) in his work uses the following formula:

$$R_S = \frac{ln\left\{\left(\frac{d}{r_{op}}\right)+\left[\left(\frac{d}{r_{op}}\right)^2-1\right]^{\frac{1}{2}}\right\}}{2\pi k_s}; \quad \left(\frac{d}{r_{op}} > 2\right) \tag{25}$$

$$R_S = \frac{ln\left(\frac{d}{r_{op}}\right)}{2\pi k_s}; \quad \left(\frac{d}{r_{op}} > 4\right) \tag{26}$$

Where:

R_S – thermal resistance of soil, (m*K)/W

d – burial depth to centerline of pipe, m

r_{op} – outer radius of pipe, m

k_s – thermal conductivity of soil, W/(m*K)

For the insulated pipe the iterative method should be used when thermal conductivity when thermal insulation material is temperature function. As a rule, the thermal resistance of the pipe itself and the protective casing is less than 5% of the total thermal resistance when the pipe is insulated. To simplify the calculation, the thermal resistance of the pipe itself and the protective casing can be neglected for an insulated pipe. Jianguang, Y (2018) suggested the following formula:

$$R_p = \frac{ln\left(\frac{r_{op}}{r_{ip}}\right)}{2\pi k_p} \tag{27}$$

Where:

R_p – thermal resistance of pipe wall, (m*K)/W

r_{ip} – inner radius of pipe, m

k_{sp} – thermal conductivity of pipe, W/(m*K)

Using these formulas heat loss per unit length and temperature distribution can be calculated.

<u>The Effect of Climate Change on the Arctic Environment.</u> The effect of permafrost melting, soil settlement, coastline erosion is also caused by the current world climate change. According to Anisimov, O. and Reneva, S., (2006) mathematical modeling results showed that by the middle of the 21st century near-surface permafrost may shrink by 15-30%. That will consequently cause the complete frozen ground thawing in the upper maters, this layer is called «active layer». Global Terrestrial Network for Permafrost conducted the observations and indicated that even short-term (decadal) variations in temperature can distinctly impact mean annual upper layer permafrost temperature (Anisimov, O., Reneva, S., 2006). The climate change is characterized by the air temperature increase. Such raise does not only influence the permafrost externally by its thawing but also leads to sea ice thawing. One of the functions of sea ice is to protect the shore from storms. As described above storms are main reason of the coastline erosion. Thus, since the sea ice is thawing and melting and cannot stop or reduce the storms the coastline erosion rate increases. Both the permafrost thawing due to increase of temperature and the strengthening of the storm accelerate coastline erosion. Unfortunately, forecasts for the temperature change are not positive. According to Danish Meteorological Institute (Figure 21) the daily mean temperature in 2018 is significantly higher than the mean one for the years 1958-2002. Data was recorded north of the 80th northern parallel and the plot is presented in Figure 24. Kostopoulos, D.; Yitzhak, E.; Gudmestad, O.T**.,** (2019) also analyzed the effect of decreased ice coverage and increased wave actions and permafrost melting on the coastal erosion. The results showed the total erosion as number of storm surges (Figure 22). As can be seen from the figure the increase of number of storms will lead to the total erosion increase.

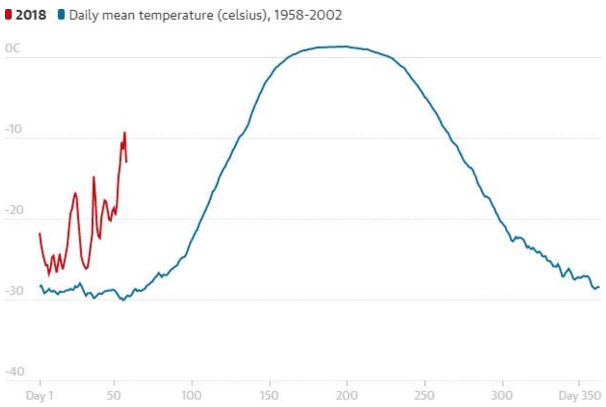

Figure 21 Daily temperature change (Danish Meteorological Institute)

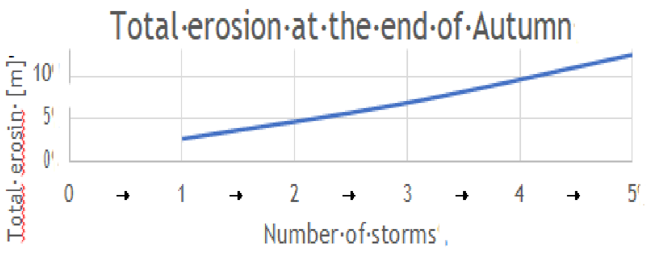

Figure 22 Total erosion rate in terms of number of storms (Kostopoulos, D.; Yitzhak, E.; Gudmestad, O.T., 2019)

With the development of climate warming in the coming century, we should expect an increase in the degree of danger of coastal processes. With increasing water temperature, the rate of thermal abrasion and the intensity of destruction of such banks will increase several times. In addition, climate warming will lead to a decrease in the ice cover of the Arctic seas, an increase in the duration of their ice-free period, increased winds and wind surges, increased storm activity, which will intensify the physical effects of waves on the shores and intensify the overall process of their erosion and destruction.

References to Chapter 3

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4. Choice of Shore Crossing Approach Method with Example on Leningradskoye Field

Leningradskoye field located in the Kara Sea, the Yamal Peninsula, was chosen as a practical case for the design of the subsea pipeline shore crossing case. The Leningradskoye field was discovered on the Kara Sea shelf, with initial reserves estimated at 3.0 trillion. m3. One of the concepts of field development introduced by Gazprom was the use of subsea production systems. One of the options for the transportation of produced products is the laying of the offshore pipeline was developed by Morev Y.A., et al. Under this option, the offshore pipeline is planned to be brought to shore to the gas processing plant. The scheme of possible field development concept is presented in the Figure 23.

Figure 23 Leningradskoye Field Development Scheme (Morev Y.A. et al.)

Thus, to select the method of crossing the coastline and further design, following scheme for choosing the optimal method was developed.

4.1. Natural and climatic characteristics of the study area

Geotechnical characteristics of the territory. One of the main parameters for the selection of the shoreline crossing method is the geotechnical characteristics of the offshore and coastal zones. To determine these characteristics, the morphogenetic map of the Kara Sea was used (AO «Roscartografia», National Atlas of the Arctic, 2017) [3] that is presented in Figure 24.

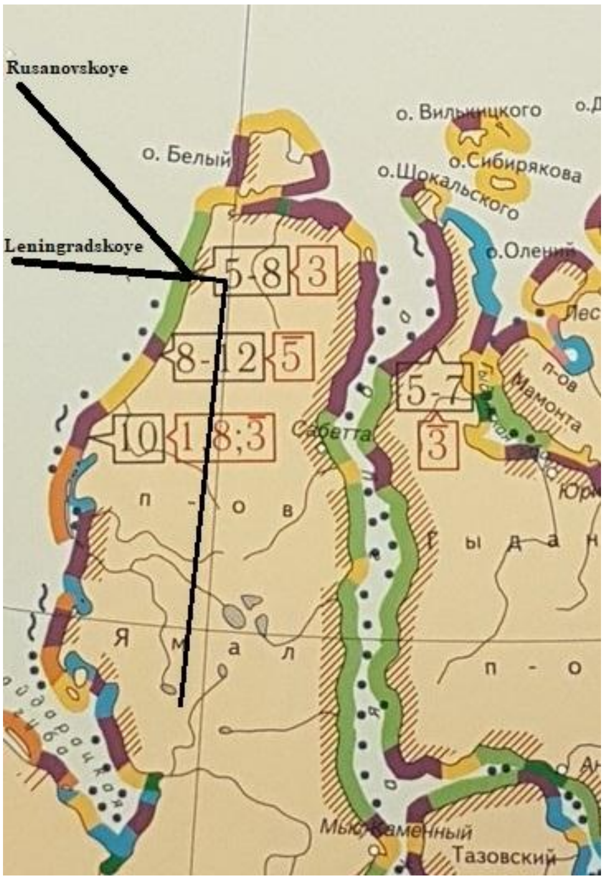


Figure 24 Morphogenetic map of the Kara Sea

As can be seen from the map the potential area for the shore crossing is composed by abrasive – accumulative sediments. The height of cliff is 5 – 8 m and the maximum abrasion rate is 3 m/year. According to the morphodynamic map of the Russian Arctic seas (AO “Roscartography” National Atlas of the Arctic, 2017) the area of shore crossing is located in the area of danger category with a shore erosion rate to be more than 3 m/year. The sea bed of the discovered area is also subjected to abrasion processes being formed by abrasive, thermos-abrasive and abrasive-accumulated structures. Therefore, the geotechnical conditions for the discovered area are not favorable and may be categorized as harsh conditions.

The northern part of the Yamal Peninsula is composed of the Lower-Upper Paleocene, Tibasalinsk Formation. The site is dominated by micaceous, silty clay. Up to 110 m, sands with aleurolite and clay interlayers are observed. The geological map of the studied area is presented in Figure 25.

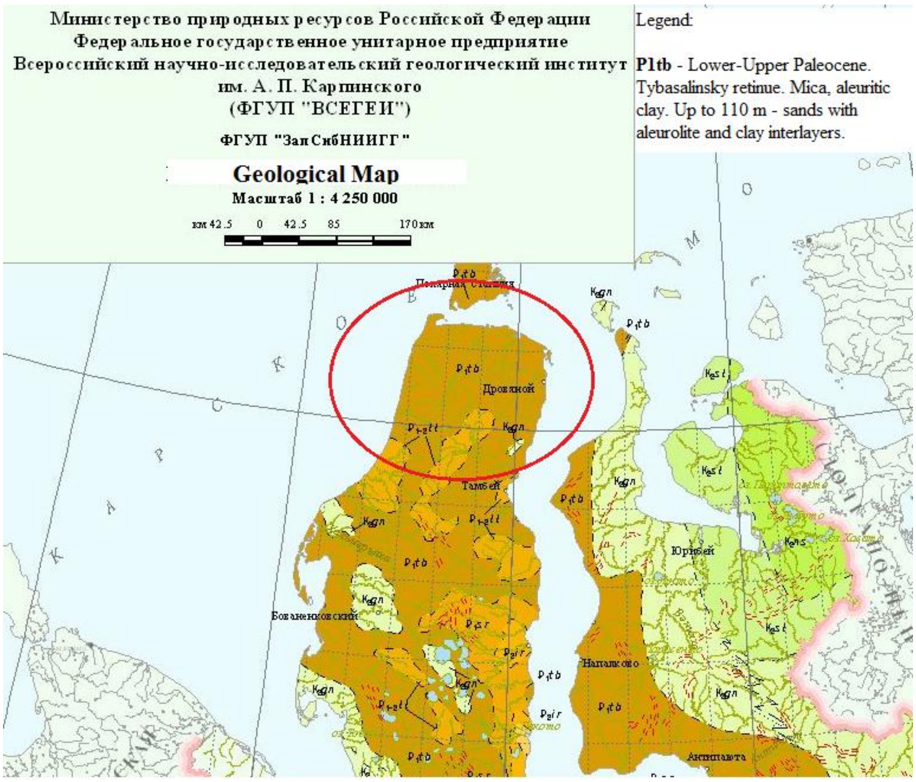


Figure 25 Geological Map of the Yamal Peninsula (http://www.vsegei.ru/ru/info/gisatlas/ufo/yamalo-nenetsky_ao/)

The Yamal Peninsula is covered with the permafrost with the thickness of 200 – 600 m and annual average temperature to be from -5 to -9 C°. According to the reports from Yamal governor the issue of permafrost melting is a critical for the region nowadays. The governor reported that the permafrost on the territory of the Yamal Peninsula in the YNAO thawed by 40 centimeters in 2017. [https://www.znak.com/2017-1201/vlasti_yanao_obespokoeny_tayaniem_vechnoy_merzloty_kotoraya_negativno_vliyaet_na_stroyki]. Therefore, it is crucial to design the shore crossing area so that all heat loss to be analyzed and taken into account. To avoid permafrost melting it is important to keep the temperature of pipeline/installation not above the permafrost temperature. The permafrost conditions are characterized by complex conditions.

The studied area is characterized by high cliff height. The existing projects described and analyzed in the Chapter 2 had a cliff height not more than 3 m. The high height of the cliff makes the design and installation of shore crossing area more complicated. The good example in the case of high cliff is the Langeland pipeline laid between Norway and UK being the longest submarine pipeline. The height of the cliff in this area reached up to 5 m and tunneling method was used in order to construct the transition area.

The Kara Sea is characterized by harsh ice conditions. The open water period lasts only 3 - 4 months and the sea is covered by solid first-year ice reaching the thickness up to 2 m from November to June. The most challenging aspect for pipeline design in the Arctic conditions is the presence of ice ridges.

The work by Zubakin G.K et.al (2008) has analyzed and gathered the statistic for the ice ridges concentration that showed the maximum value during second half of winter. The typical ice ridge concentration for Kara Sea is about 20 %. Another feature that appears in the Kara Sea is «stamukhas» - grounded hummocks causing the ice gouging. In the Razhev Master thesis (2016) it is noted that Kara sea is also characterized by the presence of icebergs in the Rusanovskoye field area is high while in Leningradskoye is low. However, according to different research presented in Razhev master thesis it was concluded that it is necessary to protect subsea equipment in the water depths less than 80 m. The geometric parameters of the ice ridges observed in the Kara Sea were presented in work by Zubakin G.K et.al (2008) and are present in the Table 4.

Table 4 Geometric parameters of ice ridges

Parameter	Ridge length	Sail width	Sail height	Keel depth	Keel width	Ridge thickness	Keel / sail ratio
Min, m	24	7	1,5	6,0	21	7,7	3,0
Average, m	61	19	3,2	11,5	50	13,3	3,8
Max, m	95	34	4,5	15,7	72	19,8	6,7

According to presented analysis it can be concluded that the shore crossing area is located in the area of harsh environmental and geotechnical conditions. During the design and installation of pipeline it is important to take into account the type of the shore that is intent to coastline erosion; the presence and temperature of permafrost tended to melt with high rate; high height of cliff and presence of ice ridges in the nearshore area.

4.2. The Choice of the Method of Access to the Pipeline. Construction Technology

According to the Chapter 2 there are exist three kinds of shore crossing methods, while only trenching method was used for the Arctic projects.

The coast of the Yamal Peninsula is characterized by clay and sandy sediments, therefore, the coast is not rocky. The absence of rocky sediments allows the use of all three methods: trench, tunneling and horizontal directional drilling (HDD). However, the clays that make up the coastal territory are micaceous and silty, which characterizes them as structurally unstable, therefore, during the construction of the shore crossings it is necessary to create additional supports. In this case, the tunneling method seems to be the most stable compared to the trench and HHD, since it will be possible to build a protective stable structure. The use of microtunneling will also help to protect the pipeline from scouring by ice ridges in the coastal zone. Thus, in the case of an unstable high cliff, the tunneling method will be the most optimal (Prokopenko I.A., 2008).

The tunneling method is a complicated and expensive method. This technology was applied at the intersection of the coastline in Isington by the Langeled pipeline with a diameter of 44" and a length of 1,200 km, from Nyuhamna in Norway to Ecington in the UK. Among other advantages, tunneling methods provides the least environmental impact. The microtunneling method, which is widespread in the Russian Federation, is described in TSN 40-303-2003 “Trenchless laying of communications using microtunnel penetration complexes and the reconstruction of pipelines using special equipment”. The cycle of the shoreline crossing construction by tunneling method is presented in Figure 26.

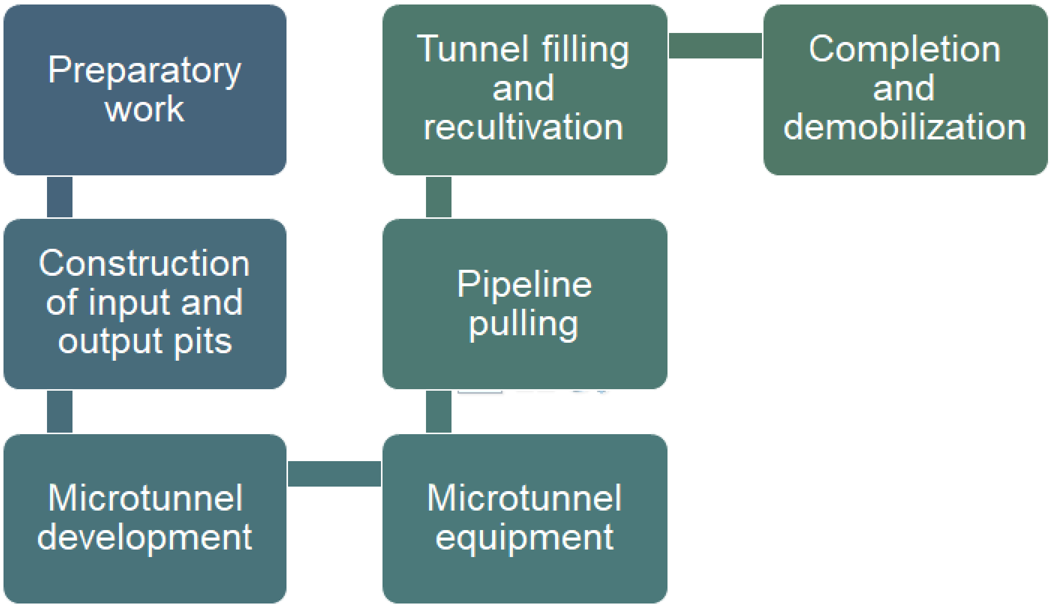


Figure 26 Cycle of tunnel construction

Due to the difficult engineering and geological conditions, it is proposed to use a shield penetration method for laying a tunnel, which involves the use of a special mechanized tunnel-boring machine (TBM).

Preparatory work. Construction of Tunnel. To lay a pipeline in a tunnel, it is necessary to build two shafts / mines: the starting one and the receiving one. The dimensions of the shafts should be set in accordance with the size of the working body. Before construction, the construction site of the starting shaft must be secured with rubble, and the soil in the places where the crane and other heavy equipment are placed should be compacted. Between the starting and the receiving shaft, it is necessary to provide permanent two-way radio communication.

Next, in the shaft, it is needed to install a press frame with powerful jacks and install a tunnel shield. The main jacking station with hydraulic drive must be placed in the starting shaft and fastened. Next is the installation of the working cutting body and the first section of the shield, then they are lowered into the shaft with a crane. A crushing chamber is located behind the cutting body; in working condition, this chamber is filled with bentonite [http://www.ingestroy.ru/view/document/mikrotunnelirovanie/]

The jack moves the shield in the ground by the amount of entry, equal to its length. Next, it is needed to put a pipe forcing, after which the process repeats. For the construction of the tunnel, it is necessary to use water that is supplied to the working body area by the feed pump from the sump located on the surface. After treatment, water is fed back to the sump, where it precipitates (Prokopenko I.A., 2008). Precipitated soil must be removed. The accuracy of penetration is carried out by a computer control complex using a laser shield system. By changing the size of the tunnel shield, it is possible to lay underground microtunnels of different diameters from 250 mm to 3000 mm. An example of a tunnel scheme is shown in Figure 27 and Figure 28.

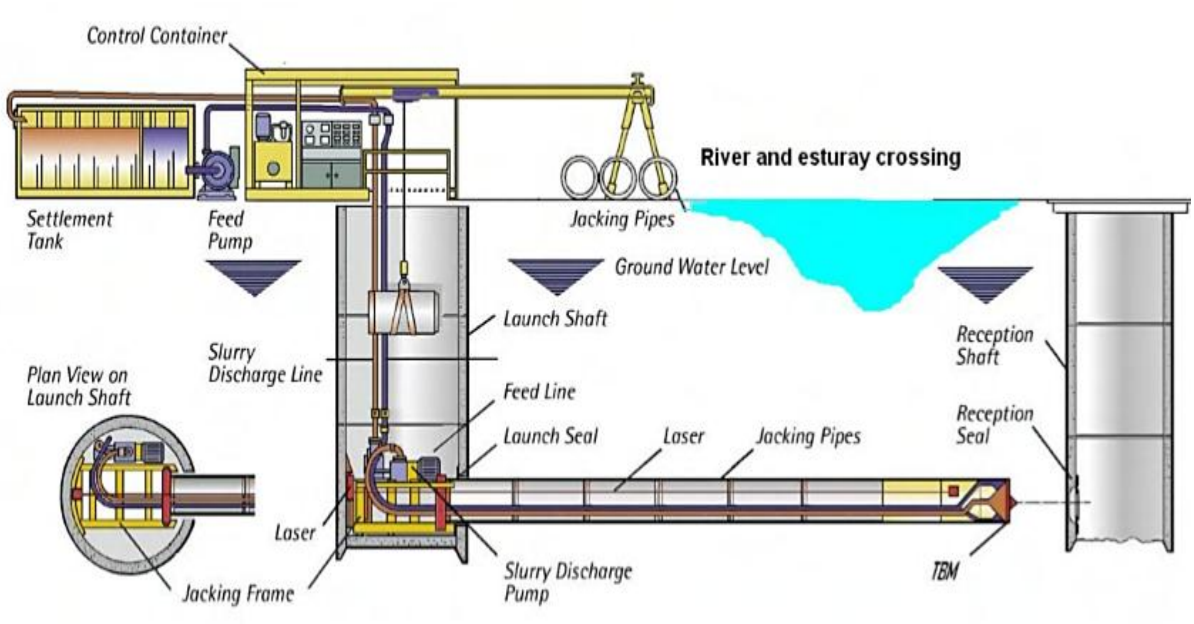
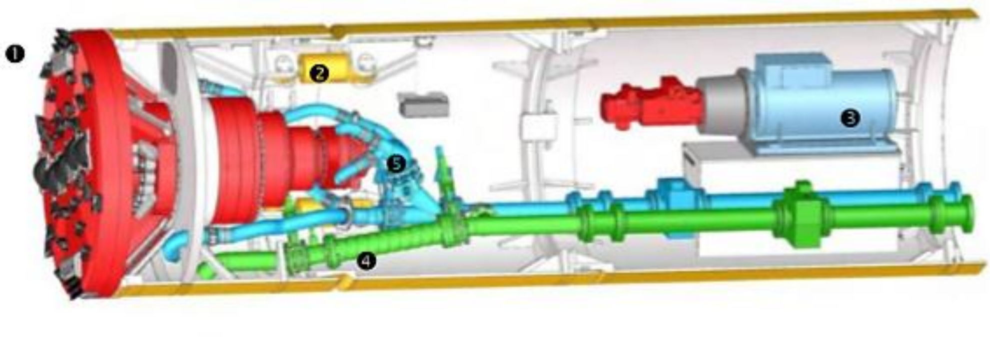


Figure 27 Scheme of Tunnel



❶ Cutting head ❷ Steering cylinder ❸ Drive unit ❹Removal pipe ❺ Feeding pipe

Figure 28 Working body scheme

The cutting body for laying the tunnel is covered with a special carbide metal and equipped with various tools developed, it should be selected in accordance with the soil characteristics. The most common among micro-passage complexes is Herrenknecht AG. The list of equipment of the complexes at the disposal of Russian contractors with licenses for the work is following:

- model ≪AVN-1500 (1600), manufactured by Herrenknecht-Germany;
- model "RVS-600AS", the company "Soltau" -Germany;
- model "RVS-250-A", the company "Soltau" -Germany [28].

In 2010, in Yakutsk, they used the model AVN-600, produced by Herrenknecht-Germany, for laying a tunnel for household needs in permafrost conditions (Figure 29)

Airlock personnel chambers are recommended to be installed behind the first shield section. They are necessary for conducting repair and maintenance work on the cutting body. In the last section of the shield it is necessary to install a telescopic station for the development of additional efforts at intermediate sites.

Figure 29 AVN-600, produced by Herrenknecht-Germany

On average, the duration of the installation of the test panel is from 30 to 50 days depending on the size and design of the shield, as well as on the organization of the delivery of individual components and elements into the chamber.

Installation and laying of the pipeline. Pipeline installation is carried out after the completion of the tunnel. After hydraulic testing and draining of water, the pipeline is laid on the trigger. The starting path for pulling the pipeline is located at the installation site and is equipped in accordance with the requirements. The schemes for installation and laying of oil pipelines in a tunnel are developed in the project with the definition of the method and sequence of installation, calculations of the strength and stability of the pipeline during construction.

When choosing an installation scheme, it is necessary to strive for the maximum length of the pipeline lugs for pulling, on the basis of the conditions of the terrain of areas adjacent to the tunnel, of lifting and traction means available to the construction company. The sequence of installation of pipelines is specified taking into account the scheme of their placement in the tunnel (Prokopenko I.A., 2008).

Starting path for pulling the pipeline should be equipped with roller bearings mounted directly on the axis of the pipeline on the planned base. When moving from the trigger to the tunnel, the pipeline must be supported by the pipe-laying crane.

The laying of pipelines in the tunnel is carried out by the method of pulling with a consistent increase of the whip at the installation site, adjacent to the tunnel. When dragging a pipeline, technical solutions are determined on the basis of its weight characteristics, the design of permanent and temporary supports and the length of the tunnel. To pull the pipeline into the tunnel from the starting pit, a trigger track is provided (Prokopenko I.A., 2008). From the receiving pit, there is a tensioning equipment for pulling the pipeline (traction winches). Guides are installed at the exit of the tunnel, which must withstand both vertical and horizontal loads.

This paper presents the calculation of the pulling force by SR 42-101-2003 General provisions for the design and construction of gas distribution systems of metal and polyethylene pipes [31].

For the calculation were taken some characteristics of the pipeline and the parameters of the tunnel (Table 5).

Table 5 Initial Pipeline Characteristics

Do	Pipeline Outer Diameter	1,02	m
l	Tunnel length	400	m
Δ	Pipeline Wall thickness	0,018	m
ρm	Pipeline Material Density	7850	kg/m3
ρi	Insulation density	975	kg/m3
Δi	Insulation material wall thickness	0,003	m
F	The coefficient of friction of the pipeline on the finishing of the tunnel	1	

E	Elastic modulus for steel	2,06 *1011	N
μ	The coefficient of friction of the pipeline on the ground	0,25	

The pull force P is defined as the sum of all types of resistance to pipeline movement in a tunnel:

$$P = \sum_{i=1}^{4} P_i = P_1 + P_2 + P_3 + P_4, \tag{28}$$

где:

P_1 – friction force from the weight of the pipeline (in the tunnel);

P_2 - additional friction forces from the support reactions;

P_3 - increased resistance to movement in the transition from straight to curved motion;

P_4 - friction force from the weight of the pipeline outside the tunnel.

The friction force of the weight of the pipeline is calculated by the formula:

$$P_1 = q_w \times R \times (e^{f(l-l_i)/R} \times \cos\frac{l-l_i}{2\times R} - \cos\frac{2l-l_i}{2\times R}), \tag{29}$$

where:

q_w – linear weight of pipeline and insulation material, N / m^2;

R – the estimated radius of curvature of the tunnel, m;

l_i – current tunnel length, m;

The linear weight of the pipeline q_w is calculated by the formula

$$q_w = w_m \times \frac{\pi}{4} \times (D_o^4 - (D_o - 2\delta)^4) \tag{30}$$

where:

w_m – specific weight of pipeline material, N / m ^{3};

Pipeline weight q_{mp} according to formula (30):

$$qw = 7850 \times 9{,}8 \times \frac{\pi}{4} \times (1{,}020^2 - (1{,}020 - 2 * 0{,}018)^2) = 4356{,}8 N/m^2.$$

Similarly, the calculated weight of the insulation coating was calculated and amounted to q_w=45,9 N/m^2. Total weight is the sum of the pipeline and insulation material.: q_w=4356 +45,9 = 4402,7 N/м^2

The calculated radius of curvature of the tunnel is calculated by the formula

$$R=1200\times Do=1180{,}8 \text{ m} \tag{31}$$

The friction force P1, due to the weight of the pipeline, according to the formula (3.18) was P_1=110915,4 N.

Additional friction forces from P2 support reactions are determined by the formula:

$$P_2 = 0{,}5\times P_u \times (1+e^{f(l-l_i)/R}), \tag{32}$$

where: P_2 – friction forces from the support reactions that determine the bending of the pipeline, which is calculated by the formula:

$$P_2 = \frac{f\times\pi\times E}{16\times R\times B}\times(D_o^4 - D_i^4)\ , \tag{33}$$

where: B – support reaction arm, m, determined by the formula:

$$B=\sqrt{(R+D_o)^2-R^2} = 49{,}09\,\text{m} \tag{34}$$

The friction forces from the support reactions that determine the bending of the pipeline according to the formula (33):

$$P_2 = \frac{1\times\pi\times 2{,}06\times10^5}{16\times1180{,}8\times49{,}09}\times(1{,}020^4-0{,}984^4) \ \ =10106{,}7N.$$

Additional friction forces from P2 support reactions according to formula (35):

$$P_2 = 0{,}5\times10106{,}7\times(1+e^{1(400-375)/864}) = 10855{,}8N.$$

Increased resistance in the transition from straight to curved motion before leaving the pipeline from the tunnel P_3 is calculated by the formula

$$P_3 = \frac{\pi\times E}{128\times R^2}\times(D_o^4-D_i^4) \tag{36}$$

$$P_3 = \frac{\pi\times2{,}06\times10^{11}}{128\times1180{,}8^2}\times(1{,}020^4-0{,}984^4) = 52{,}52N.$$

The frictional force of the weight of the pipeline on the soil outside the tunnel P4 is determined by the formula:

$$P_4=\mu\times q_w\times l_i=27517{,}2N \tag{37}$$

The pull force P is determined by the formula (28):

$$P = 110915б4 + 10855{,}8 + 52{,}52 + 27517{,}2 = 2149341N.$$

4.3. Comparative Analysis for the Further Design of the Pipeline Access to the Shore

To determine further methods for designing the pipeline access to the shore, a comparative analysis was carried out with existing projects for pipeline exits in the Arctic, as well as the Langeled pipeline. The results of the comparative analysis are presented in Table 6.

Table 6 Comparative Analysis

5 - Favorable conditions	Project	5 –Cliff Height	4 –Coast erosion rate	3- Permafrost	2 – Ice Conditions	Total
4- Moderate conditions	Studied project	10	4	6	2	22
3- Normal conditions	Langeled	10	12	15	10	47
	Northstar	25	16	6	6	53
2- Difficult conditions	Угрук	20	16	6	6	48
	Nikaitchuq	20	16	6	6	48
1- Severe Conditions	Sakhalin 1	20	12	12	12	56
	Bovanenkovo-Ukhta (Baydaratskaya Bay)	15	16	6	4	41

Thus, 4 comparison criteria were determined and presented in accordance with the importance for the selection and design of pipeline access to the shore: the height of the cliff, the value of coastal erosion, permafrost and ice characteristics. Estimates for the criteria were also identified: maximum score 5 - favorable conditions. For the project under consideration, the main difficulties are the high values of coastal erosion and ice characteristics, which significantly distinguish the project from existing pipelines.

However, according to priority criteria: the height of the cliff and the values of coastal erosion, the most suitable project is the Langeled pipeline, which was also laid using the tunneling method. The method of laying a tunnel allows to pass all types of soils and set the desired trajectory.

An important aspect that distinguishes the project under consideration from the Langeled pipeline is the presence of permafrost on the project under consideration.

Thus, for designing a tunnel, it is necessary to apply permafrost protection practices. In Chapter 2, a formula was given for calculating the thermal resistance of the soil for a single buried uninsulated pipeline. In accordance with the formula, calculations were made of the thermal resistance of the soil for a single buried uninsulated pipeline and tunnel. The calculation results are shown in Figures 30 and 31.

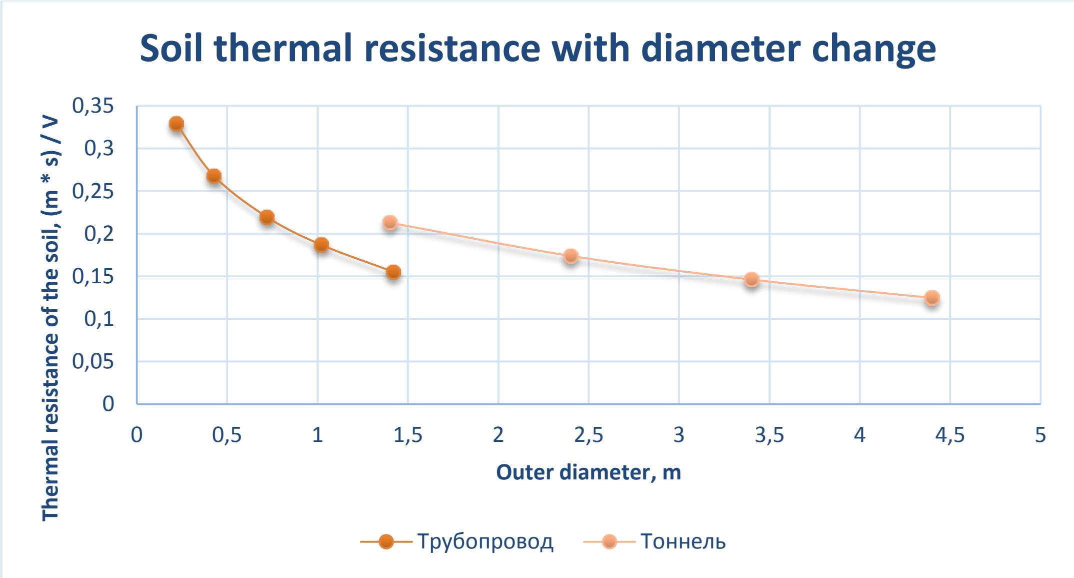


Figure 30 Soil thermal resistance vs diameter change

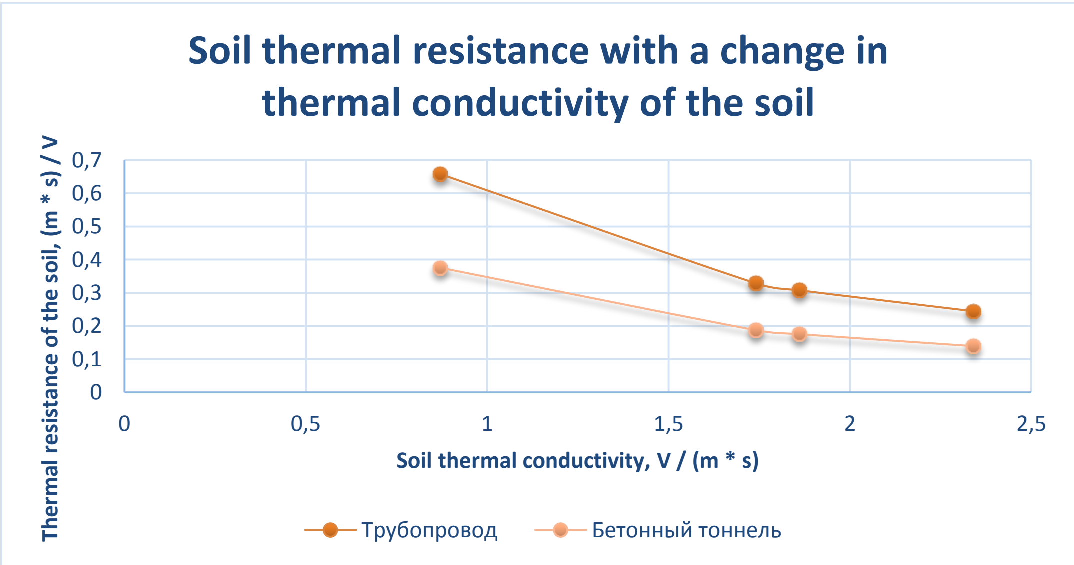


Figure 31 Soil thermal resistance vs soil thermal conductivity

Thus, from the calculations and the graphs presented it can be concluded that the thermal resistance is influenced by the composition of the soil, as well as the radius of the pipeline. With an increase in the thermal conductivity of the soil and its moisture content, the thermal resistance of the soil decreases. The project under consideration is located in the zone of wet soils and permafrost, which tends to melt in the summer. Also with an increase in the radius of the pipeline, the thermal resistance of the soil decreases.

Thus, when designing a tunnel, it is necessary to introduce technologies to prevent the melting of soils under structures. Today there are several systems: horizontal tubular systems of freezing and temperature stabilization of soils, vertical tubular systems of freezing and tubular seasonal cooling devices (SCD) to maintain the bearing capacity of the soil (Kolokolova N.A. and Harris N.A.)

The main company operating in the Russian market for temperature control of soil regimes is the enterprise NPO Fundamentstroyarkos LLC. Technical solutions of the company provide reliable freezing and the absence of thawing of the frozen ground under the structures (NPO Fundamentstroyarkos LLC).

The horizontal tubular system is a sealed heat transfer device that automatically acts in the winter due to gravity and a positive temperature difference between the ground and the outside air. The cooling tubes are located at the base of the structure. They are used to circulate refrigerant and freeze the soil. The condenser unit is located above the ground and is connected to the evaporative part (NPO Fundamentstroyarkos LLC). The scheme of the system is shown in Figure 32.

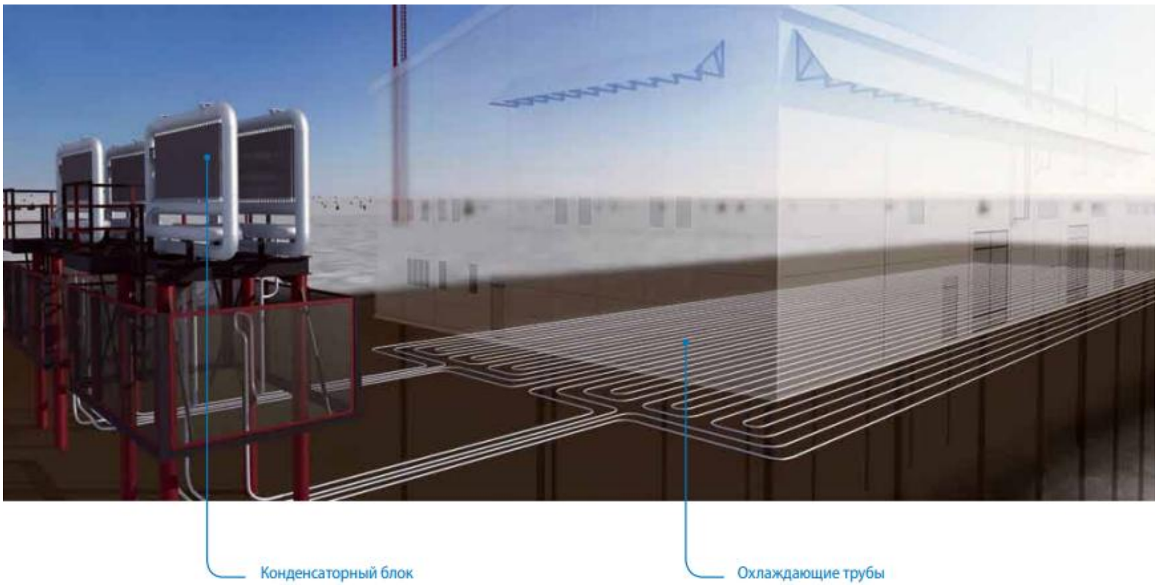


Figure 32 Horizontal tubular cooling system (NPO Fundamentstroyarkos LLC)

The vertical tubular system is an analogue of the horizontal system, reinforced with vertical pipes. Vertical pipes are placed at the required design points and connected to a condenser unit. The number of such pipes in one system is up to 30 pieces, depth is from 10 to 15 m. A feature of this system and horizontal system is the possibility of deep freezing of the soil in the most hard-to-reach places or places where the placement of above-ground elements is undesirable / impossible. All cooling elements are located below the surface of the earth. A condenser unit can be removed from a building for a distance of up to 100 meters (NPO Fundamentstroyarkos LLC).

The individual heat stabilizer is made in the form of a sealed one-piece welded structure of full factory readiness, charged with refrigerant, with the underground part of the evaporator and the above-ground condenser part. The heat stabilizer is installed vertically or at an angle of up to 45 degrees to the vertical in the immediate vicinity of the lower end of the piles in the foundations. The evaporative part of the heat stabilizer is in the ground and has a protective zinc coating (NPO Fundamentstroyarkos LLC).

The deep seasonal cooling device (SCD) is a hermetic one-piece welded structure filled with coolant. Carbon dioxide is used as a coolant for deep sewing. It fills the entire frozen height of the SCD. Intensive circulation is provided through the use of special internal devices. The depth of the underground part, depending on the object of freezing, can reach 100 m. Deep-water control systems are designed to freeze and stabilize the temperature of dam soils, wellheads to ensure their operational reliability, highways, freezing local thawed zones. The scheme of the SCD is shown in Figure 33.

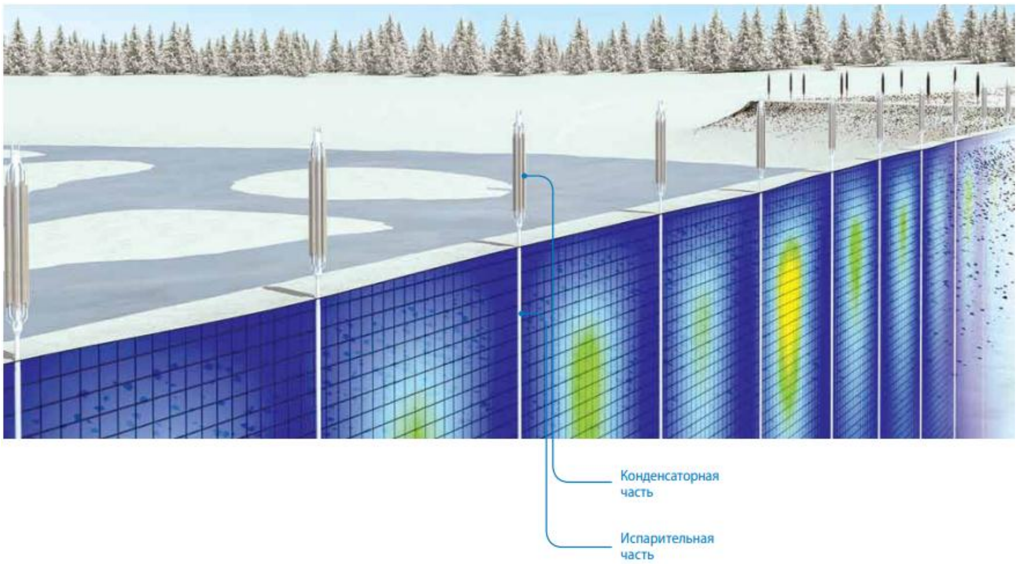


Figure 33 Scheme of Seasonal Cooling Device (NPO Fundamentstroyarkos LLC)

For the project under consideration, it is proposed to choose an SCD system to maintain the temperature of the soil. These devices may be installed along the entire length of the tunnel (NPO Fundamentstroyarkos LLC).

Another danger characteristic of the studied region is the presence of ice ridges and their scouring of the seabed, therefore, the sea part of the pipeline has been proposed to be buried in a trench. It is also proposed to build cofferdam for protection against waves, by analogy with the already existing projects described in Chapter 2.

To calculate the trench depth, we used the formula for ice ridge scouring depth calculation from Chapter 3 (formulas 5-24). The calculation was made for these characteristics of the Kara Sea and statistics on ice ridges in Maple. The calculation results are presented in Table 7.

Table 7 Results of Scouring Depth Calculation

Results of Calculations		
Wind drag force	402.58	κN
Current drag force	24501.9	κN
Weight	518340.9	κN
Buoyancy	532219.4	κN
Ice Force	0.024	κN
Ice ridge scouring depth	3.52	m

Thus, the required trench depth should be more than 3.52 m.

An analysis of the territory of the prospective project has shown that the tunneling method will be the most optimal method for getting the pipeline to shore. The main aspect of the choice of this method was the high value of the cliff height, as well as high rates of annual coastal erosion. Also, methods for protecting the surrounding soil from melting were reviewed and selected. For the coastal zone, it is proposed to lay the pipeline in a trench to avoid breakage of the pipeline with ice ridges. Also, to protect the coastal zone from erosion, it was proposed to use the cofferdam corridor. The approximate scheme of the studied project is presented in Figure 34.

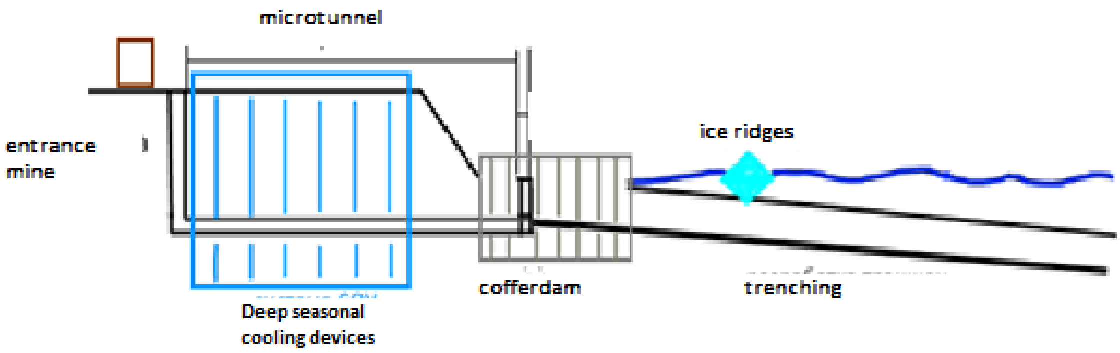


Figure 34 The approximate scheme of the project

The main advantages of the tunneling method are:

• ensuring the construction of pipelines without destructing the surface, which creates a safe environment during the work;

• works are conducted silently and surface vibrations are practically absent;

• completely eliminates manual labor during sinking and eliminates the presence of people in the face (the complex is managed by one operator from the control container located on the surface);

• the environment is not damaged during the work;

• ensuring high accuracy of the penetration path.

From the practical solution and analysis of the literature we can conclude that the choice of the method of access to the pipeline depends on many natural and climatic factors. So, among the climatic factors, the main influencing the choice of method will be the following:

- geological structure of the coastline;
- composition of the coastline soil;
- height of the cliff;
- location of relatively protected natural areas;
- coastal erosion rates;
- the presence of permafrost;
- ice conditions of the territory.

In accordance with the identified criteria, a diagram was drawn for the choice of the method of approaching the pipeline to the shore. The diagram is presented in Appendix 2.

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5. Environmental Impact Assessment. Risk Analysis

The environmental impact assessment of the offshore pipeline is necessary because of the multiplicity of the impact itself in different climatic conditions. The intersection of the offshore pipeline of the coastal zone especially affects the land environment of the coast and the marine environment of the coastal zone. Impact assessment should be carried out at all stages of the pipeline life cycle: pre-investment, investment and operational phases.

Table 8 The degree of environmental impact during operations

Phase	Stages	Environmental Impact		
		No impact	Slightl Impact	Significant Impact
Preinvestment	Investment plan			
	Declaration of intent			
	Investment justification			
Investment	Design			
	Engineering survey			
	Conduct of negotiations			
	Contracting			
	Tenders			
	Building			
	Start-pad			
	Commissioning and commissioning			
Operational	Exploitation			
	Repair and overhaul			
	Reconstruction			
	Liquidation			

When designing, there is a danger of social damage, which may be related to the inconsistency of the parties and third parties - nature users about the characteristics of the pipeline and, in particular, its route. Therefore, the pipeline route and its design must be carried out in such a way as to minimize the intersection of water and land areas in order to minimize damage to the interests of third parties. The pipeline route must be laid at a distance from military grounds, areas of mining of mineral raw materials, as well as from specially protected natural territories. Moreover, it is necessary to minimize the intersection of pipelines with different cables and communication systems.

During survey work, noise may be caused by the effects of vessel engines. It is also possible the violation of the seabed during sampling and removal of small biological resources for subsequent analysis of the marine flora and fauna. Depending on the type of research and the means used, the zone of possible impact may vary from 1 to 500 m. When assessing the impact of noise on ecosystems, it should be taken into account that marine biota perceives sounds well in the frequency range up to about 500-600 Hz. Above these frequencies, its susceptibility drops rapidly. Frequencies in excess of 1.5-2.0 kHz are not actually perceived. Because of this, noises with a frequency of more than 1 kHz have practically no negative effect on marine biota (Prokopenko I.A., 2008).

Comparison of the spectra for the deep and shallow sea shows that at frequencies above 500 Hz, noise levels in coastal areas are 5-10 dB higher than in deep-water areas. The greatest impact on the environment is during the construction phase. When the pipeline is installed, the seabed area is alienated. During all construction processes: crushing, laying a trench, removing elevations, backfilling, dredging, the destruction of bentiferous communities occurs in the zone from 5 to 50 m in each direction from the center line of each string of a potential pipeline (Prokopenko I.A., 2008). Moreover, excavation work can cause sediment sedimentation, which will destroy habitat for marine flora and fauna. Hardening of sediments will also cause mixing of earlier sediments, which may contain contaminating elements. Dumping of the soil withdrawn during the development of a trench can have an effect similar to that which occurs during the laying of a trench.

Pipe-laying and additional vessels used in the construction of the pipeline line may have a noise and other disturbing effect on marine life. The work of the courts requires the temporary alienation of the water area in the construction area, which creates obstacles to shipping and fishing. The zone of influence of disturbance and noise from a water vessel for laying a pipeline is estimated to be approximately 1000 m around the vessel. Also during operations there is the possibility of collision of vessels, which, in the event of a fuel spill, would entail a significant negative impact on the marine environment.

During the construction of the pipeline in places of access to the coastal surface, there is a violation of the natural vegetation cover, soil, and there is a negative impact on animal populations (as a result of habitat destruction, as well as noise and disturbance factors). At the place of the pipeline exit, contamination of streams (flows) with eroded soil is possible (Prokopenko I.A., 2008).

Depending on the location of the subsea pipeline's access to the coast (open coast, bay, etc.), bathymetry, hydrographic conditions and lithology of bottom sediments, the zone of environmental impact is estimated to be in the range of 1000–2500 m (Prokopenko I.A., 2008). During the various tests possible discharge of water. There is the possibility of noise pollution for birds, recreation areas (beaches) and tourism. The estimated impact zone is about 500 meters (Prokopenko I.A., 2008).

During the period of operation, the impact on the environment is more prolonged, but less intense. The impact area from the installed pipeline, the intersection of pipelines or other installed underwater pipeline structures is estimated to be <100 m, but around the pipeline there is a safety zone (100 m in each direction) within which fishing is restricted (use of bottom trawls), shipping (anchorage) and some other activities.

Moreover, during operation of the pipeline it is possible to change the state of the soil. With increasing coastal erosion, the destruction of the soil occurs, which later may cause a loss of pipeline stability. This phenomenon is especially characteristic of the territories of the Arctic, in places where the pipeline lies in the permafrost zone, since during the summer period the soil permafrost cover tends to melt.

Another possible negative impact factor is the likelihood of emergency situations, of which the oil products spill the most damage when the pipeline is broken. Pipeline rupture can be caused by an inflection associated with a violation of the stability of the soil and the subsequent formation of free spans in the sea and land parts of the pipeline. When the pipeline ruptures, there is a release of produced products that are mixed with water. In the case of an oil spill, when mixed with water, emulsions are formed, the collection and cleaning of which can be a serious problem.

Construction work is associated with the maximum possible impact on the project as a whole: impacts on the bottom relief, aquatic environment and marine biota associated with the development and backfilling of the trench, as well as the development of quarries and drilling of wells with trenchless methods in small parts, dumping of soil, removal of soil; impact on terrestrial landscapes of the coast; emissions of pollutants into the atmosphere during the operation of marine engines, welding equipment, ground equipment; temporary alienation of the water area around pipelaying vessels; noises, vibrations. During the construction and operation of offshore pipelines there are many processes that cause a negative impact on the environment, so it is important to evaluate the possible risks during operations, as well as measures to prevent (Makarov C.B .; Shagarova L.B., 1997)

In GOST R 54505-2011 “Safety is functional. Risk management in railway transport” risk is defined as a combination of the probability (or frequency) of an undesirable event and the size of its consequences.

To assess the risks associated with the installation, operation and liquidation of the offshore pipeline in the intersection of the coastline, a method based on the use of a risk matrix was used. This method is a table of cells that displays a combination of the frequency of occurrence of an undesirable event and the severity of its consequences and allows informing decision makers about risk levels for the event in question (Belyaeva et. Al, 2005). The risk matrix allows you to determine the likelihood of a particular risk occurring, determine a possible hazard, and further develop measures to prevent or reduce the occurrence of risk (Novozhilov A.E., 2015).

When constructing a risk matrix, the categories of probability of occurrence (P) of risk from very high (6) to absolutely low (1) were first highlighted. Severity categories (S) from insignificant (1) to mortal (6) were also identified. Based on the data, a risk matrix was built (Table 9).

Table 9 Risk Matrix

			Severity (S)					
			Minor	Moderate	Serious	Very serious	Catastrophic	Disastrous
			1	2	3	4	5	6
Likelihood of occurrence (P)	V. Likely	6	6	12	18	24	30	36
	Likely	5	5	10	15	20	25	30
	Unlikely	4	4	8	12	16	20	24
	V. Unlikely	3	3	6	9	12	15	18
	E. Unlikely	2	2	4	6	8	10	12
	Remote	1	1	2	3	4	5	6

As can be seen from Table 9, the risks located in the zone shaded by green are acceptable risks. Risks located in the yellow shaded area are significant risks that need to be controlled to prevent these risks from falling into the critical area - shaded in red. In relation to these risks, appropriate measures should be taken to minimize their potential impact. These measures should be aimed at moving the risks into the yellow or green zones of the matrix.

Next, a list of possible risks was formed during the conduct of certain operations at different stages of the project. The main risks identified were the following: damage to the marine environment; violation of the state of the soil; noise pollution and the most dangerous oil spill transported during pipeline operation. After determining the main possible risks, the degree of probability of occurrence and the hazard assessment were determined for each of them. The degree of probability of occurrence is determined by calculating the probability of occurrence of risk during all operations. Due to the lack of statistical data, in this paper the likelihood of undesirable events was determined by experts (experts' assumptions). Similarly, the degree of risk of possible risk was determined, based on the environmental impact and safety of personnel. The risk analysis is presented in Appendix 1.

The degree of risk (R) and its location in the matrix was determined by multiplying the probability of occurrence by the degree of severity.

$$R = P * S \tag{38}$$

Thus, most of the risks were in the zone of significant risks. The only critical risk is harm to personnel, possible death during lifting operations and during laying of the pipeline. This risk may occur in case of equipment breakdown, loss of stability of the pipe-laying vessel or crane. This risk is critical and unacceptable and requires strict measures to prevent it. The risk of contamination of surface and groundwater was in the zone of acceptable risks due to their low probability of occurrence. The greatest degree of danger would entail a spill of petroleum products during the operation of the pipeline. For each risk, it is necessary to develop measures not only to reduce the likelihood of risk occurring, but also to reduce the degree of exposure.

For each of the risks, measures to prevent and mitigate it, including acceptable risks, were identified. The main measures that formed the basis for prevention measures for all possible risks were identified as follows:

- Permission to conduct operations in the specified zone;
- Competent and trained personnel;

• Operating and certified equipment;

• Continuous monitoring of the environment;

• Continuous monitoring of equipment.

Additional measures to reduce and prevent risks included: geotechnical testing; spill response measures; the use of thermal insulation material; regular inspection and repair of equipment at the operation stage.

Thus, when determining measures to reduce and prevent risks, all risks fell into the category of acceptable risks. A summary table of risk analysis during operations for the installation, operation and liquidation of the offshore pipeline in the intersection of the coastline is presented in Appendix 1.

According to the risk analysis the highest risks are associated with injuries and fatalies that might appear during the vessel operation in case of vessel crush or break down as well as during the pipeline overboarding and positioning on seabed that might bring the loss of vessel stability. The lowest risks were associated of subsurface water pollution and damage.

Therefore, in order to avoid and reduce these risks the reduction measures were developed: permit to work/operate (scope, equipments, personnel, risks and mitigation), competent and trained personnel, adequate and certified equipments, continuous monitoring

waste disposal procedure

geo-technical services

spill response

Thus, during the construction, operation and liquidation of the offshore pipeline in the zone of intersection of the coastline, all the Earth's envelopes are affected: the atmosphere (noise pollution), the lithosphere (soil disturbance), the hydrosphere (disturbance of marine habitats). The greatest negative impact occurs during the investment phase of the project during the construction of the pipeline. The paper also provides an analysis of possible risks during operations, identified acceptable, significant and catastrophic risks, and also developed measures to reduce and prevent risks.

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Conclusion

Master's thesis "Pipeline Shore Crossing Approach in the Arctic Conditions" is devoted to the study of methods for constructing transition zones in the Arctic conditions. The paper presents an overview of existing practices for building offshore pipelines coast crossing areas. 5 projects are reviewd and analyzed in the paper: Northstar, Uguruk, Nikaitchuq, Sakhalin 1 and the Bovanenkovo-Ukhta pipeline. In the Master's thesis a literary review and analysis of the applied technologies was carried out. According to the results of the analysis, it was concluded that the method of laying the pipeline in a trench was applied on all projects. Due to the harsh natural and climatic conditions, the projects used technologies to protect against damage from ice ridges, as well as from thawing permafrost.

The thesis also analyzes the climatic conditions that impede the design and the construction of the pipeline ashore zones. Issues of ice accumulation, formation of ice ridges, as well as coastal erosion are studied in detail. The paper analyzes the territories of the Russian Arctic seas and their susceptibility to coastal erosion. The paper also addressed the impact of climate change on coastal erosion.

In the master's thesis, possible solutions are given for choosing the shore crossing approach on the example of the Leningradskoye field, Kara Sea. According to the results of the analysis of the geological and hydrometeorological conditions a tunneling method was chosen. For this method the process of preparation and construction, as well as the choice of technologies to protect the pipeline from the harsh conditions of the Arctic region are described. On the basis of a practical example and data analysis, a chart was drawn up for selecting the shore crossing approach in the Arctic conditions.

The final part of the work is dedicated to environmental impact assessment at all stages of the project implementation. Based on the results of the analysis, it was concluded that the main negative environmental impact occurs during the construction and pipeline construction phase. The paper presents a risk analysis that displays possible risks, the degree of their danger, as well as measures to reduce them.

APPENDIX 1

Risk Analysis

Main activities	Main tasks	Major risks	Initial Risk P	Initial Risk S	Initial Risk R	Risk Reduction Measure(s)	Residual Risk P	Residual Risk S	Residual Risk R
Installation	Excavation	Noise, vibration and environmental pollution	6	2	12	Permit to work/operate (scope, equipments, personnel, risks and mitigation), competent and trained personnel, adequate and certified equipments, continuous monitoring	4	2	8
		Damage to subsurface stability	4	3	12	Same as 1 + geo-technical services	2	3	6
		Damage to permafrost	4	3	12	Same as 1 + geo-technical services + use of thermo-isolation materials	2	2	4
		Damage to subsurface water and pollution	2	4	8	Same as 1 + geo-technical services + waste disposal procedure	1	3	3
		Pollution of surface water (e.g. excavated soil disposal)	2	2	4	Same as 1 + geo-technical services + waste disposal procedure	1	1	1
	Pipeline preparation and loading onto vessel	Damage to equipments (e.g. pipeline) and facilities	6	3	18	Same as 1	2	3	6
		Injuries and fatalies	6	4	24	Same as 1	2	4	8
	Vessel operations	Damage to equipments (e.g. ice collision) and facilities	6	3	18	Same as 1	2	3	6
		Disturbance to marine environment	6	2	12	Same as 1	4	2	8
		Fuel spill	3	4	12	Same as 1 + spill response procedure	2	2	4
		Noise, vibration and environmental pollution	6	2	12	Same as 1	4	2	8
	Pipeline overboarding and positioning on seabed	Damage to equipments (e.g. pipeline) and facilities	6	3	18	Same as 1	2	3	6
		Injuries and fatalies	6	4	24	Same as 1	4	2	8
		Damage to seabed and marine environment	6	2	12	Same as 1	4	2	8
Exploitation	Oil / gas transportation	Spill (e.g. collision, errosion)	2	6	12	Regular inspection and maintenance, spill response	1	4	4

					procedure, use of safety valves			
		Loss of pipeline stability	3	3	9	Subsurface monitoring	2	3	6
	Inspection and maintenance	Similar to installation (excluding excavation)				See installation			

APPENDIX 2

Choice Making Diagram