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Pipeline shore crossing approaches in Arctic conditions

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Abstract. The development of the Arctic region will entail the construction of new infrastructure, in particular, subsea pipelines. Considering the lack of actual field practice, ecosystem vulnerability and lack of common Arctic international standards, their development will be a big challenge, in particular, in the shore crossing zone. The design and construction of pipelines in the shore crossing area require a special approach that takes into account environmental and technological aspects of development. This work is aimed at analysing and determining environmental and technological factors influencing the design of offshore pipelines in the Arctic coastline. The paper presents theoretical and analytical work and the research is applied to a specific case study (pipelines from the Leningraskoye field to shore), through engineering calculations. Currently, there are five Arctic projects with shore transition areas for which trenching has been implemented. In order to determine the best shore crossing approach, it is important to consider the following environmental conditions: ice encroachment; ice ridges; shoreline erosion; permafrost thawing. Environmental characteristics should predetermine the choice of approach. Among three existing methods: trenching, tunnelling and horizontal directional drilling (HDD), the micro-tunnelling method is recommended for the Leningradskoye field in combination with a cofferdam corridor to protect the buried pipe from waves and ice in the nearshore area. In order to protect the surrounded permafrost from melting seasonal cooling-device is recommended to be used. The burial depth is determined to be more than 3.52 m in accordance with Force model calculations of ice ridges scouring depth. On the basis of research, the general choice-making diagram was proposed for Arctic shore crossing areas.

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 [1]. To meet the global demand for hydrocarbons, the development of unconventional resources and the exploration of new regions are becoming critical, including the Arctic offshore. 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 development of the Arctic region will entail the construction of new infrastructure, in particular, subsea pipelines. Considering the lack of actual field practice, ecosystem vulnerability and lack of common Arctic international standards, their development will represent technological and environmental challenges including the shore crossing zone. The aim of this work is to analyze the influence of physical environmental factors and climate change processes on the pipeline shore crossing methods.

2. Existing Practices in Arctic Pipeline Shore Crossing Areas

2.1. Existing Arctic projects

Several Arctic projects with shore crossing transitions exist nowadays. One of the best- known is the Northstar project in Alaska (Beaufort Sea), the first subsea pipeline constructed in the Arctic. The shore crossing part consists of a vertical 90-degree transition between the below-ground subsea pipelines and the above-ground onshore pipelines. Such transition results in deep excavation between the shoreline and the pipeline's daylight location.

The offshore production facility Ooguruk shore crossing design is similar to the one implemented in the Northstar project. Opposite to Northstar pipeline, a long-radius vertical transition was designed [3].

Another Alaskan project is Nikatichuq pipeline located at a depth of 3m offshore in the Beaufort Sea. 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 same techniques were also implemented for shore transition – with a vertical sweeping curve transition.

Another project located in the Arctic-like conditions is Sakhalin-I. In the shore crossing area, a cofferdam corridor with perpendicular wing walls was constructed in order to protect the trench and backfill soil from waves. One more Arctic project is Bovanenkovo – Ukhta pipeline, 67 km of which was laid offshore on the bottom of the Baydaratskaya Bay. The pipeline coastline transition area was constructed by trenching and backfilling. In the areas of the coast, a cofferdam corridor was made.

Thus, five subsea pipeline projects with shore crossing in the Arctic region (sub-Arctic for the Sakhalin I) were considered and analysed. The general information on these projects is presented in Figures 1-3 and Table 1.

Table 1. Pipeline shore crossing projects existing in the Arctic

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	-	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	-
Sakhalin I	Okhotsk Sea	15 m	Trenching	5 m	-	-	Trenching. Cofferdam corridor with wing walls	-
Bovanenkovo – Ukhta pipeline	Kara Sea	22-23 m	Trenching	-	12-13 m	20 m	Trenching. Cofferdam corridor	-

Figure 1. Beaufort Sea projects

Figure 2. Bovanenkovo-Ukhta pipeline

Figure 3. Sakhalin I

2.2. Methods of pipeline shore crossing

There exist three methods to design and construct pipelines in the shore crossing area: trenching, tunnelling and horizontal directional drilling (HDD). The method used for the above-mentioned projects is trenching which is based on the burial of pipelines in a trench and further, concrete or gravel covering can be used as well as pipeline strengthening or anchoring.

Tunnelling is based on building a tunnel initiated onshore and terminated at the seabed. The tunnel end should be at a depth where a pipeline is completely safe from scouring. For the onshore part, a vertical tunnel is required. Then pipes are placed inside the submerged tunnel lined with concrete. The tunnel gives protection role from water and permafrost thawing.

Horizontal directional drilling's (HDD) main advantage is the ability to use the method for long distances and quite large pipe diameters (up to 56'') [4]. By choosing the direction, areas with permafrost thawing can be avoided. Advantages and disadvantages of all methods are presented in Table 2.

Table 2. Advantages and disadvantages of different shore crossing methods

	Trenching	Tunneling	HDD
Advantages	less expensive easy to construct	less environmental impact ability to choose direction very big diameters pipes works in all soil types	less environmental impact long distances and big diameter ability to choose the direction
Disadvantages	affect the environment limited distances and diameters limited by coast type	expensive technologically difficult	expensive limited by coast type

3. Arctic challenges for subsea pipeline installation and design

Arctic harsh conditions such as severe cold temperatures, permafrost, presence of ice, presence of ice ridges, and erosion of the coastline should be taken into account when designing a subsea pipeline.

3.1. Ice ride-ups and pile-ups

During the beginning of the winter and during the spring the shore crossing area is characterized by ice ride-up and pile-up, which are known as ice encroachment. According to [5], 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. The main factors that influence ice encroachment distance are wind stress, ice thickness and storm intensity. In [5] the encroachment distance (E) is calculated according to equation (1):

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

where h is a predicted pile-up elevation of the ice; l is the location of the peak of the ice encroachment, measured from the waterline; L is horizontal distance from the waterline to the elevation (at height H) of the land profile behind the shoreline; β is slope of the landward side of the ice rubble pile. 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 encroachment of the land behind the sloping shoreline is calculated according to equation (2):

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

Since ice encroachment can damage the onshore pipeline and shore infrastructure, it is important to keep the pipeline below the ground at this distance when designing and installing pipelines in the shore crossing area. The total *set-back distance of the above ground pipeline* components from the shoreline is the additive sum of the estimated shoreline erosion and the estimated ice encroachment distance [2].

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3.2. Ice Ridges and Ice Scouring

Ice ridges are ice features which were formed due to stress appearing within the ice when ice planes were colliding with each other under pressure. Ice ridges consist of two parts: above water part – «sail» made of small ice rubble accumulations; underwater part – «keel» which is formed as a chaotic conglomeration of broken ice. Typically, the height of the keel is four times bigger than the sail. The largest ridge to be recorded had a sail about 12 m and a keel of 45 m. Main drivers for ice ridges formation are winds and currents. In order to protect the pipeline, the correct burial depth should be determined. To calculate the gouge depth the Force model presented in [5], based on the assumption that friction forces depend on the gouging depth, is recommended (equation (3)):

$$F_{da} + F_{dw} + F_i - \mu F_{cy} - F_{cx} = 0 \qquad (3)$$

where F_{da} is the wind drag force; F_{dw} – current drag force; F_i is ice force; F_{cy} and F_{cx} are friction forces; μ is friction coefficient. This equation can be solved using computer programs, for example Maple.

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.

It is suggested in reference [5] that the force model discussed above is conservative. Further research may conclude on the needs for lesser trench depth values. Until documented values are given in state of art literature, however, conservative values must be used. For the case studied in Charter 4, a lesser value of gauge depth may not change the conclusion, as the erosion of the coast line is a mayor driver to define the trenching depth.

3.3. Coastline characteristics. Coastline erosion.

The sea coastline is one of the most dynamic parts of the Earth because in this area natural phenomenon are actively interacting with each other: hydraulic, lithological, atmospheric and biological. The Arctic region is characterized by a large scale of coastline erosion due to climatic conditions as well as the structural-geological profile (stretches of soft sediments). Low temperatures and lack of sun radiation cause prolonged interaction of the coast by sea ice and also contributes to the development of permafrost.

Erosion-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. The average speed of the Russian seacoast erosion is about 1.2 m / year according to [6].

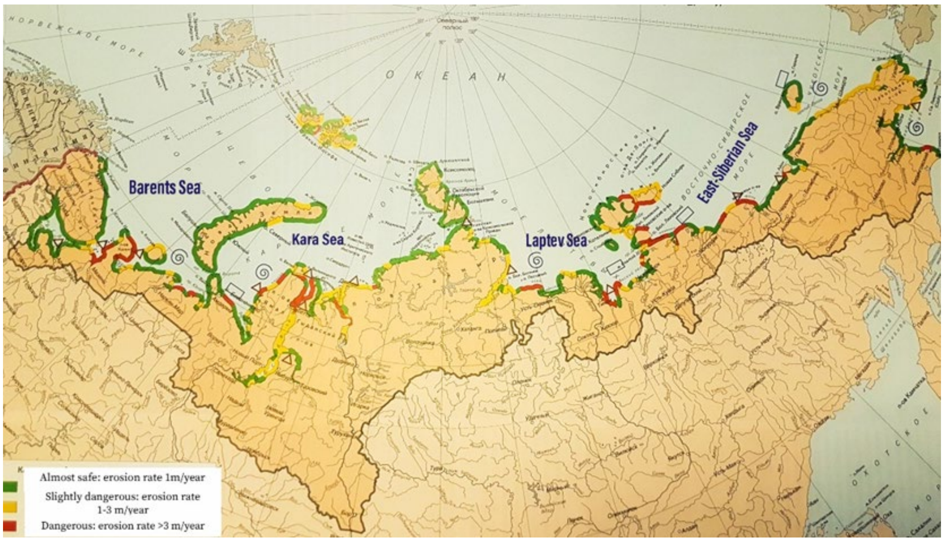

Figure 4. Morpho-dynamic map of the Russian Arctic seas [6].

The practically safe category with respect to coastal erosion (58% of the total length, green colour in Figure 4) is typical for the Arctic coast of Russia, 28% is of the second category - slightly dangerous and about 14% of the coastline is of the dangerous category (red colour in Figure 4).

Heat transfer from pipelines can also affect the shoreline erosion. When the pipeline is operating, its temperature is higher than the surrounding temperature, which leads to soil temperature increase. This process changes the bearing properties of the permafrost. As the temperature rises, the permafrost begins to melt, and the entire load carrying capacity is transferred to deeper soils. To calculate the soil thermal resistance for a single buried uninsulated pipeline the following equations (4-5) [7] are considered:

$$R_s = \frac{\ln\left\{\left(\frac{d}{r_{op}}\right) + \left[\left(\frac{d}{r_{op}}\right)^2 - 1\right]^{\frac{1}{2}}\right\}}{2\pi k_s}; \left(\frac{d}{r_{op}} > 2\right) \tag{4}$$

$$R_s = \frac{\ln\left(\frac{d}{r_{op}}\right)}{2\pi k_s}; \left(\frac{d}{r_{op}} > 4\right) \tag{5}$$

Where:

- R_S is thermal resistance of soil, $(\mathrm{m} \cdot \mathrm{K})/\mathrm{W}$;
- d – burial depth to centreline of the pipe, m;
- r_{op} – outer radius of pipe, m;
- k_s – Thermal conductivity of soil, $\mathrm{W}/(\mathrm{m} \cdot \mathrm{K})$.

3.4. The Effect of Climate Change on the Arctic Environment.

Due to effects of permafrost melting and soil settlement, as caused by the current world climate change, coastline erosion is accelerating. According to [8] mathematical modelling 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 «active layer». With the development of climate warming in the coming century, we should expect an increase in the degree of coastal processes. With raising water temperature, the rate of thermal abrasion and the intensity of coastline destruction will increase. In addition, climate warming will lead to a decrease in the ice cover of the Arctic seas, an increase in the duration of the ice-free period, increased winds and wind surges and increased storm activity, which will intensify the physical effects of waves on the shores and intensify the overall process of their erosion and destruction.

4. Choice of shore crossing approach method with example on Leningradskoye field

The Leningradskoye field located in the Kara Sea, close to the Yamal Peninsula, was chosen as a practical case for the analysis of a subsea pipeline shore crossing case. The initial gas reserves are estimated at 3.0 trillion m^3 [9]. One of the field development concepts introduced by Gazprom was the use of subsea production systems with the laying of subsea pipelines to a shore gas processing plant. [9]

4.1. 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. Abrasive – accumulative sediments compose the potential area. The height of cliff is 5 – 8 m and the maximum abrasion rate is 3 m/year - danger category red. The seabed of the studied area is also subjected to abrasion processes. The northern part of the Yamal Peninsula is composed of the Lower-Upper Paleocene, Tibasalinsk formation dominated by micaceous, silty clay. Sands with aleurolite and clay interlayers are observed to a depth up to 110 m [6].

The Yamal Peninsula is covered with permafrost with the thickness of 200 – 600 m and the annual average temperature is from -5 to -9 C°. According to 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 cm in 2017 [10].

The studied area is characterized by high cliff height that makes the design and installation of shore crossing area more complicated. A good example in the case of a high cliff is the Langeledd pipeline laid between Norway and UK being the world's longest submarine pipeline. The height of the cliff in the UK shore approach area reached up to 5 m and the tunnelling method was used 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 a thickness up to 2 m from November to June. The most challenging aspect for the pipeline design in the Arctic conditions is the presence of ice ridges. The geometric parameters of the ice ridges observed in the Kara Sea are present in Table 3 [9].

Table 3. Geometric parameters of ice ridges in the Kara Sea area

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 the above discussion, it can be concluded that the shore crossing area is located in an area of harsh environmental and geotechnical conditions. During the design and installation of pipelines it is important to take into account the type of shore condition which is susceptible to coastline erosion; the presence of soft soils; the temperature of the permafrost which tends to melt with high rate; the high height of cliff and the presence of ice ridges in the nearshore area.

4.2. Choice of shore crossing approach

The coast of the Yamal Peninsula is not rocky, however, characterized by clay and sandy sediments. The absence of rocky sediments allows the use of all three methods: trench, tunnelling 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. Moreover, the clay conditions will obstruct achieving the necessary trenching depth required due to the harsh ice conditions in the region. The short Kara Sea open water period also restricts the open operations of trenching. In this case, the tunnelling method seems to be the most stable compared to the trench and HDD, 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 tunnelling method will be the most optimal.

In order to protect the stability of pipeline in the nearshore zone, subsea rock installation over the pipeline is recommended to be applied in order to guarantee safe operations regardless of the dynamics of coastal seabed.

The tunnelling method, however, is a complicated and expensive method. This technology was applied at the intersection of the coastline by the Langeled pipeline in Isington (UK). 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".

In this paper, the pipe-in pipe method has not been considered due to very large costs of the pipe-in pipe concept. The method could, however, be considered as a protection method for pipelines in Arctic shorelines at least for the most exposed sections of the shore approaches due to the large strength capacity of the outer pipe against mechanical action. Note also that the concept prevents heat transfer from product into the permafrost, if proper insulation is selected.

4.3. Comparative analysis for the further design of the pipeline access to the shore

To determine further the method for the optimal design of the pipeline access to the shore, a comparative analysis was carried out with existing projects for pipeline existing in the Arctic, as well as the Langeled pipeline. The method used is the integrated assessment method based on the calculation of generalized estimates, taking into account estimates for all weighted criteria. The results of the comparative analysis are presented in Table 4.

Table 4. Comparative analysis (high values are favourable)

Project	5 –Cliff Height	4 –Coast erosion rate	3- Permafrost	2 – Ice Conditions	Total
The studied project	0,07	0,1	0,07	0,05	0,29
Langeled	0,07	0,16	0,29	0,24	0,76
Northstar	0,23	0,32	0,09	0,07	0,71
Oooguruk	0,14	0,32	0,09	0,07	0,62
Nikaitchuq	0,14	0,32	0,09	0,07	0,62
Sakhalin 1	0,14	0,16	0,29	0,07	0,66
Bovanenkovo-Ukhta	0,11	0,32	0,07	0,06	0,56

Integrated assessment ranking	0 – 0,2 Severe conditions	0,2 – 0,4 Difficult conditions	0,4 – 0,6 Normal conditions	0,6 – 0,8 Moderate conditions	0,8 – 1 Favorable condition

Thus, 4 comparison criteria were determined and presented in accordance with the importance for the selection and design of the pipeline access to the shore. 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.

As can be seen, Alaskan projects are located in more moderate conditions due to smaller cliff height and relatively small erosion rate. The conditions of the Langeled project also vary from the studied one due to the absence of permafrost and ice. However, the cliff height and erosion rate are similar to the studied projects. The conditions of the Bovanenkovo-Ukhta project are considered as normal for the Arctic Seas which is caused by the severe ice conditions and presence of permafrost.

Therefore, since all existing projects with pipeline shore crossing area are located in more favourable conditions it is important to integrate the different technologies in order to meet the severe conditions of the studied area.

4.4. Construction phases

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, and the soil in the places where the crane and other heavy equipment are placed should be compacted.

Next, in the shaft, it is needed to install a press frame with powerful jacks and install a tunnel shield. The jack moves the shield in the ground by an amount equal to its length. For the construction of the tunnel, it is necessary to use water that is supplied to the working body area by a feed pump located on the surface. After treatment, the water is fed back to the pump, where the soil must be removed [12]. 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 micro tunnels of different diameters from 250 mm to 3000 mm.

This paper presents the calculation of the pulling force according to SR 42-101-2003, “General provisions for the design and construction of gas distribution systems of metal and polyethylene pipes” [13]. For the calculation were taken some characteristics of the pipeline and the parameters of the tunnel (Table 5).

Table 5. Initial pipeline characteristics

Symbol	Description	Value	Unit
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/m^3
ρi	Insulation density	975	kg/m^3
Δi	Insulation material wall thickness	0,003	m
F	The coefficient of friction of the pipeline on the finishing of the tunnel	0,45	
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:

$$P = \sum_{i=1}^{4} P_i = P_1 + P_2 + P_3 + P_4, \tag{6}$$

Where 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 as in equation (7):

$$P_1 = q_w \times R \times (e^{f(l-l_i)/R} \times \cos\frac{l-l_i}{2\times R} - \cos\frac{2l-l_i}{2\times R}), \tag{7}$$

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 friction force P_1, due to the weight of the pipeline, according to equation (7) was P_1=204479 N.

Additional friction forces from P_2 support reactions are determined by the formula:

$$P_2 = 0{,}5 \times P_u \times (1 + e^{f(l-l_i)/R}), \tag{8}$$

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

$$Pu = \frac{f\times\pi\times E}{16\times R\times B} \times (D_o^4 - D_i^4)\ , \tag{9}$$

Additional friction forces from P_2 support reactions according to equation (8) is equal to be 43494N.

The increased resistance in the transition from straight to curved motion before leaving the pipeline from the tunnel P_3 is calculated by the equation:

$$P_3 = \frac{\pi\times E}{128\times R^2}\times(D_o^4 - D_i^4)$$
$$P_3 = \frac{\pi\times 2{,}06\times 10^{11}}{128\times 1224^2}\times(1{,}020^4 - 0{,}984^4) = 488{,}8N. \tag{10}$$

The frictional force of the weight of the pipeline on the soil outside the tunnel P_4 is determined by the equation (11):

$$P_4 = \mu \times q_w \times l_i = 108919{,}5N \tag{11}$$

The pull force P is determined by the equation (6):

$$P = 204479 + 43493{,}8 + 488{,}8 + 108919{,}5 = 357381{,}1 \text{ N}$$

Stresses that arise in the pipe during pull-in must satisfy the conditions of strength and deformability. The calculations showed that both of these conditions are satisfied. In accordance with the formulas, 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 5 and 6.

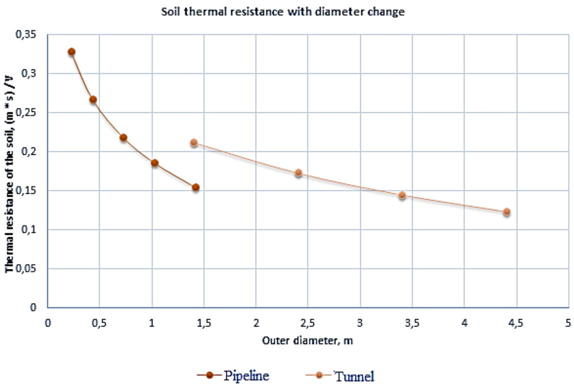

Figure 5. Soil thermal resistance vs diameter change

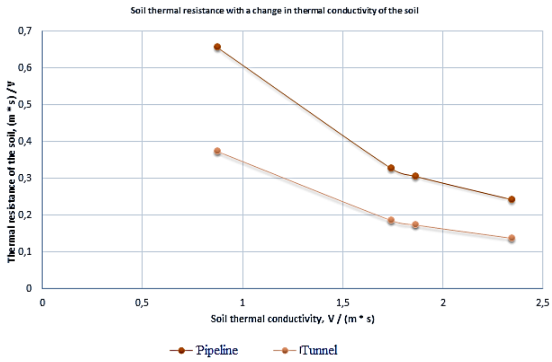

Figure 6. Soil thermal resistance vs soil thermal conductivity

Thus, from the calculations and the graphs 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 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. 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. 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 dangerous 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. Equation (3) linked with Maple software and data characteristics of the Kara Sea were used to calculate the scouring depth. The calculation results are presented in Table 6.

Table 6. Results of scouring depth calculation

	Values	Units
Wind drag force	402.58	kN
Current drag force	24501.9	kN
Weight	518340.9	kN
Buoyancy	532219.4	kN
Ice Force	0.024	kN
Ice ridge scouring depth	**3.52**	m

Therefore, the depth of the trench pipeline in the near shore area and further offshore territory should be not less than 3.52 m.

An analysis of the territory of the prospective project has shown that the tunnelling 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. For the coastal zone, it is proposed to lay the pipeline in a trench to avoid damage of the pipeline due to ice ridges. Also, to protect the coastal zone from erosion, it was proposed to use a cofferdam corridor. The approximate scheme of the studied project is presented in Figure 7.

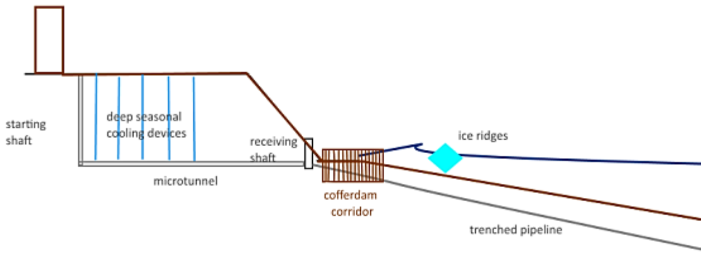

Figure 7. The approximate scheme of the project

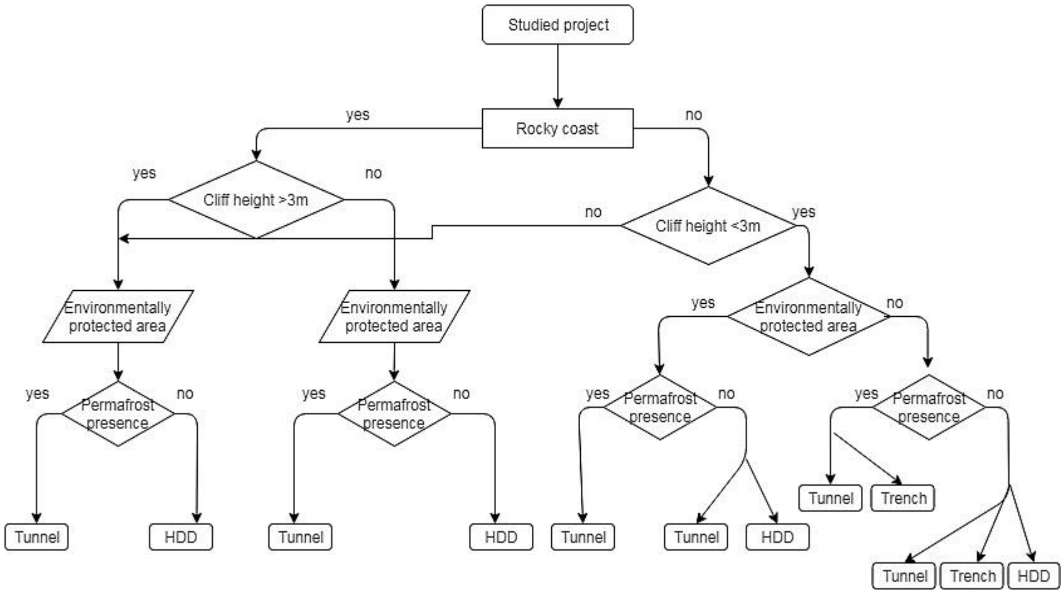

Figure 8. Decision making diagram

From a practical point of view 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 factors most influencing the choice of method will be the following: (1) geological structure of the coastline; (2) composition of the coastline soil; (3) height of the cliff; (4) location of relatively protected natural areas; (5) coastal erosion rates; (6) the presence of permafrost; (7) ice conditions of the territory. In accordance with the identified criteria, a shore crossing method decision making diagram was drawn (Figure 8).

5. Conclusions

1. Currently there are five Arctic projects with shore crossing areas, for all of which the trenching method was implemented.
2. In order to determine the best shore crossing approach, it is important to take into account following environmental conditions: ice encroachment; ice ridges; shoreline erosion; permafrost thawing. Environmental characteristics should predetermine the choice of shore transition method.
3. Micro-tunneling method was recommended to be used for the Leningradskoye field in

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combination with a cofferdam corridor to protect from waves and buried pipe in the nearshore area.

4. Calculations of soil resistance showed the decrease in case of tunnel diameter increase, therefore, in order to protect the surrounded permafrost from melting seasonal cooling devise is recommended to be used.
5. The burial depth is determined to be more than 3.52 in accordance with Force model calculations of ice ridges scouring depth.

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