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RELIABILITY OF BASEMENTS AND STRUCTURES IN CRYOLITHOZONE

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THE METHOD OF SELECTING PROJECT SOLUTIONS FOR LAYING THE LINEAR PART OF OIL PIPELINE IN PERMAFROST

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The proposed methodology for selecting optimal design solutions for oil pipeline laying in the permafrost zone is based on probabilistic approach to predicting thermal and mechanical interactions between a buried pipeline and frozen soils. It allows choosing the optimal pipeline routing, laying techniques and design parameters, in keeping with the principle of minimum initial investment and loss contingency.

Permafrost zone, oil pipeline, reliability function, risk function, cost of risk, total present value, cots-based engineering-geocryological map, pipeline laying technique, oil pipeline route

INTRODUCTION

Most studies of pipeline facilities in the permafrost zone currently seeking to ensure the reliability of pipeline transport and its safe operations (which involves designing and introducing geotechnical monitoring systems, developing software and computational systems for predicting parameters of pipeline facilities [*Surikov, 2016*]; application of and managing natural hazard monitoring systems), include analysis of hazardous geological processes for the purpose of their systematization and risk analysis, as well as preventive measures against their adverse implications [*Golofast et al., 2016; Lobodenko and Fedorenko, 2016*]. Specifically, in the context of permafrost, the widely used base soils thermal stabilization method allows to preserve soils in the frozen state during the entire operating life of a structure [*Lobodenko, 2016*]. Nevertheless, this method is in equal measure unreliable, especially in the zone of sporadic or warm permafrost distribution, inasmuch as the applicable heat stabilizers depend on climate conditions. The main task in designing pipeline facilities is to ensure unfailing operation of trunk pipelines under the complex natural and climatic conditions [*Golofast et al., 2016; Surikov, 2016*].

The proposed here estimation of the pipeline system reliability at the pre-project stage by choosing the optimal design solutions for laying oil-pipeline in the permafrost zone is based on the probabilistic-statistical approach to predicting thermal and mechanical interactions between oil pipeline and frozen soil bases, i.e., with permafrost-affected soils. Experience makes it plain that during the operations of oil trunk pipelines oil spill accidents taking place in Russia constitute 0.013–0.015 (accidents fraction) per 1000 km per a year [*Nechval, 2005*], which means that mishaps occur annually. In general, the two main reasons for them tend to be basically reduced to violation of requirements of technological conditions and/or disregard of geological (geocryological) conditions.

Technological conditions are subject to recovery in the course of repairs, which cannot be said about the geological and especially geocryological conditions, being beyond restoration, and given the vast areas (within the entire permafrost distribution region of a geocryological map), the accidents often result in the pipeline route transfer to a safe distance. This imposes higher requirements for the trunk oil pipelines safety and reliability in the permafrost zone. The permafrost soils quality (bearing capacity and deformability) is known to be dictated by their temperature, which is determined by the interplay of climatic factors. The safety of engineering structures on permafrost soils, as probability of maintaining their strength, is therefore a climate-dependent value varying in space and time.

The trunk pipelines – frozen bases interaction processes (above-ground and on-ground laying) and the enclosing environment (underground laying) are classified as random processes whose prediction is impossible using the existing deterministic approaches. Reliability of trunk oil pipelines in the permafrost zone can be estimated at the pre-design stage only from the perspective of the probability-statistical approach, which means giving up the old deterministic methods for calculating thermal and mechanical interactions between the pipeline and the environment, in favor of the novel probabilistic-statistical methods enabling risks assessment, which is to various extents provided for in the project, and allowing to opt for those not entailing disastrous economic and ecological losses.

The choice of optimal design solutions for construction trunk oil pipelines in the areas of permafrost distribution includes:

– selection of the optimal pipeline route;

– the choice of the pipeline laying methods with the optimal design parameters, e.g., the pile foundation depth for above-ground laying or the thickness of thermal insulation in case of burying pipelines in permafrost.

Selection of the pipeline route and its laying method are carried out based on the problem solution optimization, as search for a minimum of the sum total of the present value of the "oil pipeline – environment geotechnical" system, consisting of the initial cost and cost of risk, which is the cost equivalent of the geotechnical system safety, for each region in the engineering geocryological map with an area projected for oil pipeline construction. The engineering-geocryological map with the indicated pipeline laying costs (cost-based engineering-geocryological map) underlies the design-solution. Its scale is dependent on the design stage and varies from 1:10 000 to 1:100 000. This map is generated by linear programming methods for determining optimal routing which is associated with the lowest total present value, and provides for defining the optimal technique for a pipeline laying along it.

Therefore, to provide a scientifically substantiated selection of the optimal design solutions for pipeline construction under the permafrost conditions it is necessary to be equipped with: 1. Methods for determining the reliability function, risk function, cost of risk and total present value. 2. Methods for constructing a cost-based engineering-geocryological map. 3. Methods for selecting the optimal route and optimal technique for oil pipeline projection on this map.

Methods for estimation of the system reliability function, cost of risk, and total present value

Determination of the reliability function. Analytical expression of the reliability function:

$$P(t)=\begin{bmatrix}\nu_i(\tau)\le\nu_i^{lim}(\tau),\ i=1,2,...,n\\ 0\le\tau\le t\end{bmatrix}, \qquad (1)$$

where $P(t)$ is reliability function; t is the time interval for which the reliability function; $\nu_i(\tau)$ is i-th coordinate of the process in quality space (loads received by a structure) at the moment of time τ; $\nu_i^{lim}(\tau)$ is i-th coordinate of the boundary of region of admissible states (the maximum loads that can be received by the structure without its failure) at time τ; n is the number of the quality space coordinates (limiting conditions for calculating strength and stability).

The conditions ensuring unfailing performance of the "oil pipeline–environment" system (Table 1) are indicated in the square brackets of expression (1). The value of the reliability function at the end of the geotechnical system operations is termed the system safety:

$$P = P(t_e),$$

where t_e is in-service time.

Table 1. **No-failure conditions of the "oil pipeline–environment" geotechnical system (compiled after [*Recommendations..., 1974; Tartakovskii, 1976; SP 36.13330.2012*])**

System	Subsystem	Quality preserving condition	Logical relation	Notations
Pipeline – environment	Above-ground pipeline–foundation	From pile foundation stability counter vertical forces	$F_u(\tau) > F(\tau)$	$F_u(\tau)$ – bearing capacity of pile at moment τ; $F(\tau)$ – pile loading at moment τ
		From pile foundation stability counter lateral forces	$Y(\tau) < Y_u$	$Y(\tau)$ – pile head vertical deviation at moment τ; Y_u – deviation limit
		From pile foundation stability counter frost-heave forces	$F_y(\tau) > F_n(\tau)$	$F_y(\tau)$ – forces preventing pile buckling, including loading at moment τ; $F_n(\tau)$ – frost-heave forces acting on the pile foundation at moment τ
	Buried pipeline–soil base	From pipe material strength	$\sigma_n(\tau) < \sigma_{lim}$	$\sigma_n(\tau)$ – longitudinal tension in pipeline at moment τ; σ_{lim} – limiting resistance of metal
		From pipe lengthwise stability	$F_{com}(\tau) < F_{lim}$	$F_{com}(\tau)$ – compressive axial force at moment τ; F_{lim} – limiting axial resistance of pipe
		From pipe floating up stability	$F_{akt}(\tau) < F_{pas}(\tau)$	$F_{akt}(\tau)$, $F_{pas}(\tau)$ – expulsive and retention forces at moment τ respectively
	On-ground pipeline–soil base	From pipe material strength	$\sigma_n(\tau) < \sigma_{lim}$	$\sigma_n(\tau)$ – longitudinal tension in pipeline at moment τ; σ_{lim} – limiting resistance of metal
		From pipe lengthwise stability	$F_{com}(\tau) < F_{lim}$	$F_{com}(\tau)$ – compressive axial force at moment τ; F_{lim} – limiting lengthwise resistance of pipe

Calculations of the reliability function consist of three stages.

Stage one: the selection of the quality space V (limiting conditions for unfailing operations of the structure), the space of input parameters U and the operator of system L_s.

Stage two: solution of the stochastic equation

$$v = L_s u,$$

where v is the element of space V; u is the element of space U; L_s is system operator.

Space U is understood to be the numerical values of natural and technogenic factors. L_s operator is the sequential algorithm for calculating thermal and mechanical pipeline – surrounding medium – soil base interactions.

Stage three: defining the reliability function as probability of preserving the system quality during a time interval from 0 to t_e, i.e., the probability of finding the system in the region of admissible states in this time interval.

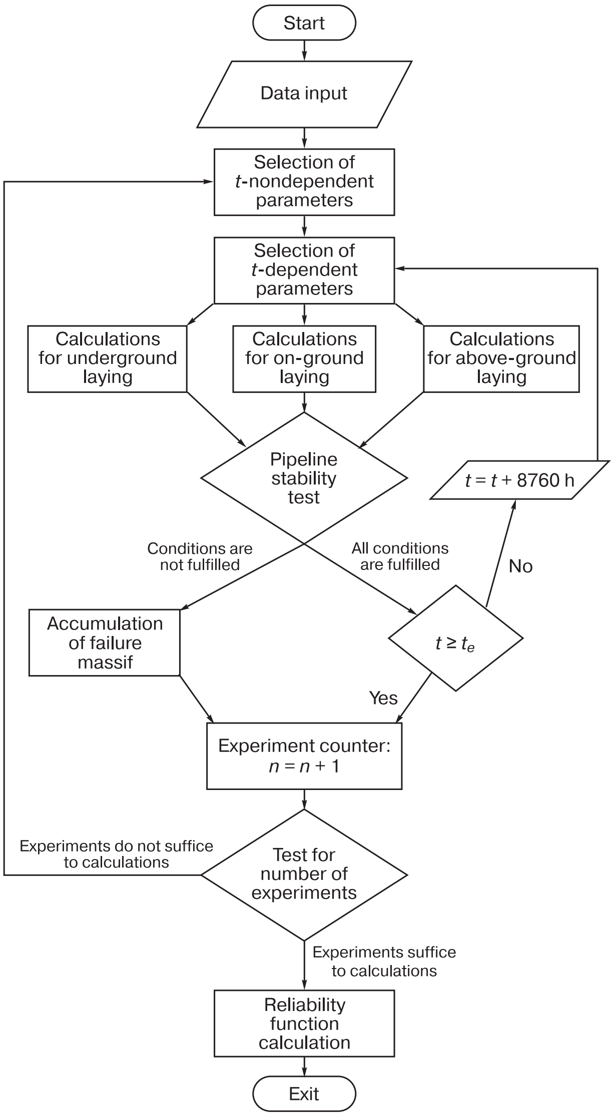


Fig. 1. Schematic algorithm for calculation of the reliability function.

The third, final stage in determining the reliability function appears the most difficult. There are two possible ways of implementing it – numerical and analytical.

The former, known as the Monte Carlo method [*Ermakov, 1975*], consists in statistical modeling of the system behavior under exerted random (i.e. stochastic) effects, and the random changes occurring in it.

For its implementation, one needs only to construct a deterministic description of the transformation of elements u into elements v and repeat it m times (several hundreds, and sometimes thousands of times), recording the system failures in each test, if any occur. The reliability function is then defined as the complement one of the quotient by dividing the total number of failures over time t by the total number of tests. One of the advantages of the Monte Carlo method is its low sensitivity to the system complexity, and that it can be realized in case of both one-dimensional and multidimensional quality spaces. Its disadvantage is the extremely costly computer time (the method is fully computer-implemented) and complexity of its results analyses.

The latter approach (analytical) is implemented through the involvement of failures known from the model reliability theory, given a number of significant assumptions, whose error estimation is also made using numerical method. The numerical method is primarily described as the most universal.

The numerical method consists in multiple mathematical modeling of the process in the soil base – engineering structure – environment interactions (both thermal and mechanical), whereas the simulation is performed with different values of probabilistic parameters. Statistical estimate of the reliability function is based on the simulation results:

$$P_m(k) = 1 - \left(\sum_{i=1}^{k} n(i) \right) \Big/ m,$$

where $P_m(k)$ is statistical estimation of the reliability function; k is the number of years from the onset of the geotechnical system operations; $n(i)$ is failure number in i-th year; m is number of experiments.

The number of experiments depends on the specified error of computation and is connected to it by the relation

$$m = 0.01 \frac{P}{(1-P)\Delta^2},$$

where Δ is the specified computational accuracy; P is target probability (reliability).

The program algorithm scheme is shown in Fig. 1. For finding the pipeline stability (core of the program) at each stage in time, we calculated thermal and mechanical interaction between structure and the environment, and tested the limiting conditions listed in Table 1; in the event of the system failure, the experiment is interrupted to follow by the failure recording with indication of the time step during which it occurred. Otherwise, the experiment proceeds to the next time step. The command to continue the computation arrives at the core from the cycle time, located immediately behind the core. Here, the number of taken steps is counted and the time-dependent parameters selection is performed at each step. If the number of taken steps corresponds to the length of operating period, the experiment is terminated, to form a new one. This process performs a cycle external to the cycle time, which pools and counts the number of the implemented experiments and selects the time-independent parameters for each new experiment. The program terminates the work, once the number of experiments corresponds to the specified accuracy of calculations. The emerging failure does not interrupt the program run, rather it only indicates that the experiment was unsuccessful, and that a new experiment should be started, while the failure counter receives one (score). After the cyclic operations (execution of the program) are completed, the program processes the fault counter and estimates the reliability function, finalizing therewith the program work.

The cycle including the selection of parameters that are not time-dependent results in the construction of a geological section with selection of soils characteristics. Given that thicknesses of lithological layers and all numerical values of soils characteristics are believed to obey the uniform distribution law, their selection is performed using a pseudo-random rav number. This number obeys the uniform distribution law and is calculated by a special program. The value of soil characteristics and layer thickness is derived from the sample by the number of sample which coincides with the rav number. Time-varying parameters are selected during the cycle time, for example, the air temperature. Given that the time-varying parameters are believed to obey the normal distribution law, they are selected using the pseudo-random number norm calculated by the special program. This number obeys the normal distribution law, has a mathematical expectation of zero, and a variance of one. The value of the selected parameter is derived using formula

$$u = \mathrm{M}_u + \mathrm{norm} \cdot \sigma_u,$$

where u is the value of selected parameter; M_u, σ_u is mathematical expectation (mean of distribution) of the parameter and its mean-square deviation.

Some technical parameters, such as the spacing between seasonally operating ground cooling systems (GCSs), the pile foundation depth for the above-ground pipeline or thermal resistance of the pipe (circular) insulation of buried pipeline, exert especially strong impacts on the geotechnical system safety, and can be equally helpful in directing its alterations.

Therefore, we call these parameters “controls” and use them to modify the system’s safety at our discretion. In this context, the system performance prediction is activated, which means that having the instrument for calculating the reliability function, it is possible not only to ascertain the acceptability of the design solution, but also to manage it, achieving optimum safety and reliability. On the one hand, the higher the reliability, the higher the initial cost C_0 of the system; on the other hand, it lessens the material damage caused by the system failure probability before its operating period ends. This damage is termed cost of risk C_R and depends on the reliability function. There emerges an optimization problem, whose solution results in finding optimal reliability:

$$C = C_0 + C_R \to \min. \tag{2}$$

Solution of equation (2) is illustrated by a diagram in Fig. 2.

Determination of risk function and estimation of risk cost. The potential risk of structures failure is inversely proportional to their reliability. The higher the reliability, the lesser the unsafety, or, conversely, the geotechnical system failure probability, which is commonly called risk, and the dependence of the failure probability on time is the risk function, which is related to the reliability function by a simple expression

$$R(t) = 1 - P(t). \tag{3}$$

The risk function (3) allows to assess the material damage that occurs when a geotechnical system fails [*Khrustalev and Pustovoit, 1988*]. This damage is called the cost of risk, which, in itself, is the cost equivalent of reliability.

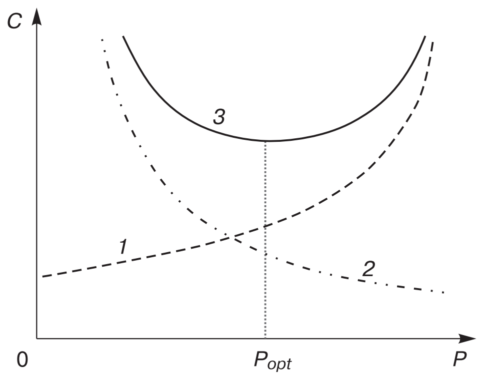


Fig. 2. Graphical determination of optimal reliability.

1 – initial cost (C_0); *2* – cost of risk (C_R); *3* – total present value ($C_0 + C_R$).
C – cost; P – reliability; P_{opt} – optimal reliability.

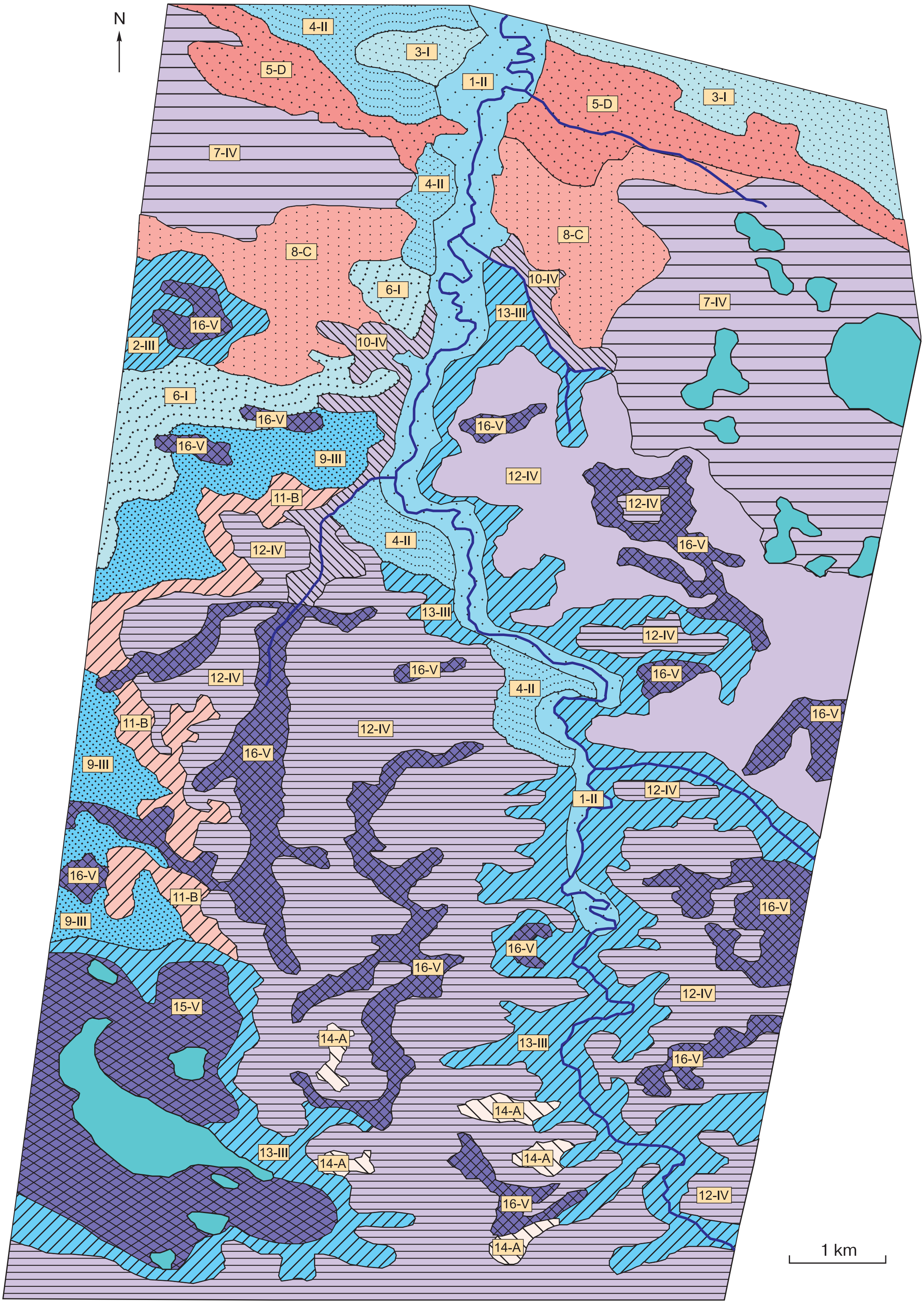


Fig. 3. An example of cost-based engineering-geocryological map.

Legend

Geological structural zoning (layer: DISPERSIVE SOILS)

Region No.	Subsurface structure (thickness of layer, m)
1	Coarse and medium grained (1.5–5) sands underlain by sand-loam
2	Sand-loam (1–2) underlain by fine-grained and silty sands
3	Fine-grained and silty (2–3) sands underlain by coarse and medium-grained sands
4	Fine-grained and silty (2–5) sands underlain by clay-loam
5	Coarse and medium-grained (2–3) sands overlaying fine-grained and silty (3–5) sands; underlain by sand-loam
6	Fine-grained and silty (2–3) sands overlying sand-loams (1–2); underlain by clay-loam
7	Clay-loams (7–8) underlain by sand-loam
8	Fine-grained and silty (2–3) sands overlying sand-loams (1–2); underlain by clay-loam
9	Fine-grained and silty (2–3) sands overlying sand-loams (3–5); underlain by sands
10	Sand-loams (1–2) overlying fine and silty (2–3) sands; overlain by clay-loam
11	Sand-loams (2–3) overlying coarse- and medium-grained (1.5–2.5) sands; underlain by sand-loam
12	Clay-loams (2–10) overlying sand-loam (1–2); underlain by clay-loam
13	Sand-loams (1–2) overlying clay-loam (2–3); underlain by sand-loam
14	Sand-loams (1–2.5) overlying coarse- and medium-grained (0.5–1.5) sands; underlain by clay-loam
15	Peat (3–5) underlain by fine-grained and silty sands
16	Peat (1–3) underlain by fine and silty sands

Geocryological structural zoning (layer: GEOCRYOLOGY)

Area types with non-merging permafrost

Area index	Permafrost table depth, m
A	<3
B	3...5
C	5...8
D	8...12

Area types with merging permafrost

Area index	Average annual temperature, °C
I	>–0.5
II	–0.5...–1.0
III	–1.0...–2.0
IV	–2.0...–3.0
V	–3.0...–7.0

Additional notations

14-A Area index according to subsurface structure (14) and permafrost occurrence depth (A)

10-IV Area index according to subsurface structure (10) and soil temperature (IV)

Area boundaries

River

Lake

To define it, we agree that each failure of the system (its breakdown) corresponds to economic losses C_{ec} equal to the system repair costs, the costs of eliminating the environmental aftermaths and augmented by incidental damage caused by the system standstill during the repair works. These costs will be termed "the penalty function of time", inasmuch as they depend on time of the failure onset, and written in the form

$$c_f(t) = \begin{cases} C_{res} \big/ (1+E)^{t_{ref}}, & t_{ref} \le t_e, \\ 0, & t_{ref} > t_e, \end{cases}$$

where t_e is operating (in-service) period, yrs; t_{ref} is time of the failure onset, yr; E is norm reduction factor for expenditures occurring at different times; C_{res} is economic losses incurred due to the system failure.

As was already noted, the risk function is one complement to the reliability function. Then the density of the risk function, that is, the failure probability in the time interval from t to $t + dt$ will be equal to

$$p_f = \frac{dR(t)}{dt} = \frac{d[1 - P(t)]}{dt} = -P'(t),$$

when $P'(t)$ is the first-order derivative of the reliability function in time.

Knowing the risk function density and the penalty function, it is easy to calculate the mathematical expectation of the cost of failure whose value will be taken as the cost of risk:

$$C_R = \int_0^\infty c_f(t)p_f(t)dt = -\int_0^\infty c_f(t)P'(t)dt. \qquad (4)$$

Given that t is measured in years and the time step is assumed to be equal to one year, then formula (4) can be rewritten in the following finite-difference form:

$$C_R = \sum_{k=1}^{m} C_{res}(k)K(k)\mu(k),$$

$$\mu(k) = P(k-1) - P(k),$$

$$K(k) = 1/(1+E)^k,$$

where $\mu(k)$ is the risk function density in the k-th year; k is the year of the structure operations; $K(k)$ is coefficient for the time (duration) of failure.

For non-renewable systems, which include, as mentioned above, oil pipeline systems that failed due to changes in the permafrost-geological conditions (the disturbed cryogenic conditions cannot be restored), C_R is equal to the remaining value of the geotechnical system as of the time of failure onset, plus incidental damage costs associated with the termination of the system performance, and the costs of eliminating the environmental consequences of the accident, which can be expressed by the formula

$$C_R = C_0(1 - k/m + e_{res}),$$

where C_0 is initial cost of the geotechnical system; e_{res} is the economic responsibility coefficient equal to the incidental damage costs to the initial cost ratio; k is the year of the structure's operations.

Estimation of total present value. The total present value is the sum total of the two components – the initial cost of the geotechnical system, i.e., its estimated construction costs, and the cost of risk, which is the costs of eliminating aftermaths of the accident which may arise in the course of the geotechnical system operations during its in-service life, reduced to a unified time (the time of commencement of the structure operations).

Given that time is measured in years, and the time step is equal to one year, then the formula for the total present value can be represented in the finite-difference form

$$C = C_0\left[1 + \sum_{k=1}^{m}(1 - k/m + e_{res})K(k)\mu(k)\right].$$

It should be noted that the coefficient of economic responsibility is made up of the sums of the coefficients of different items of recovery costs, which include costs of the system repair and the environment recovery, including repairing the damage to vegetation, soils, wildlife, etc.

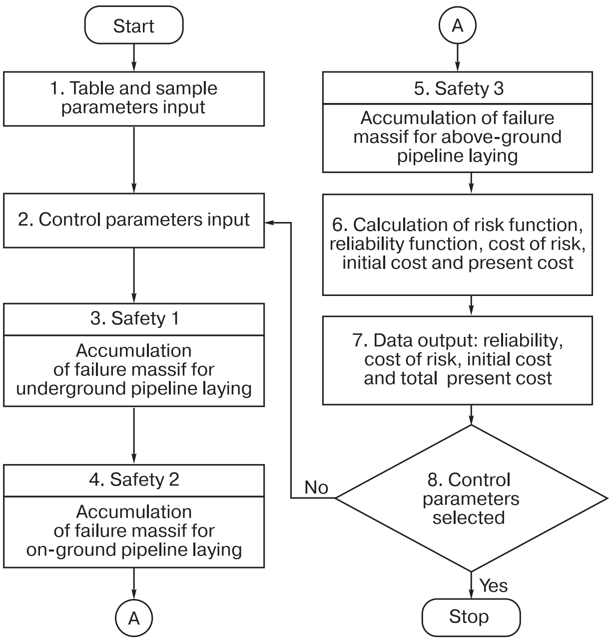


Fig. 4. A general scheme for the algorithm.

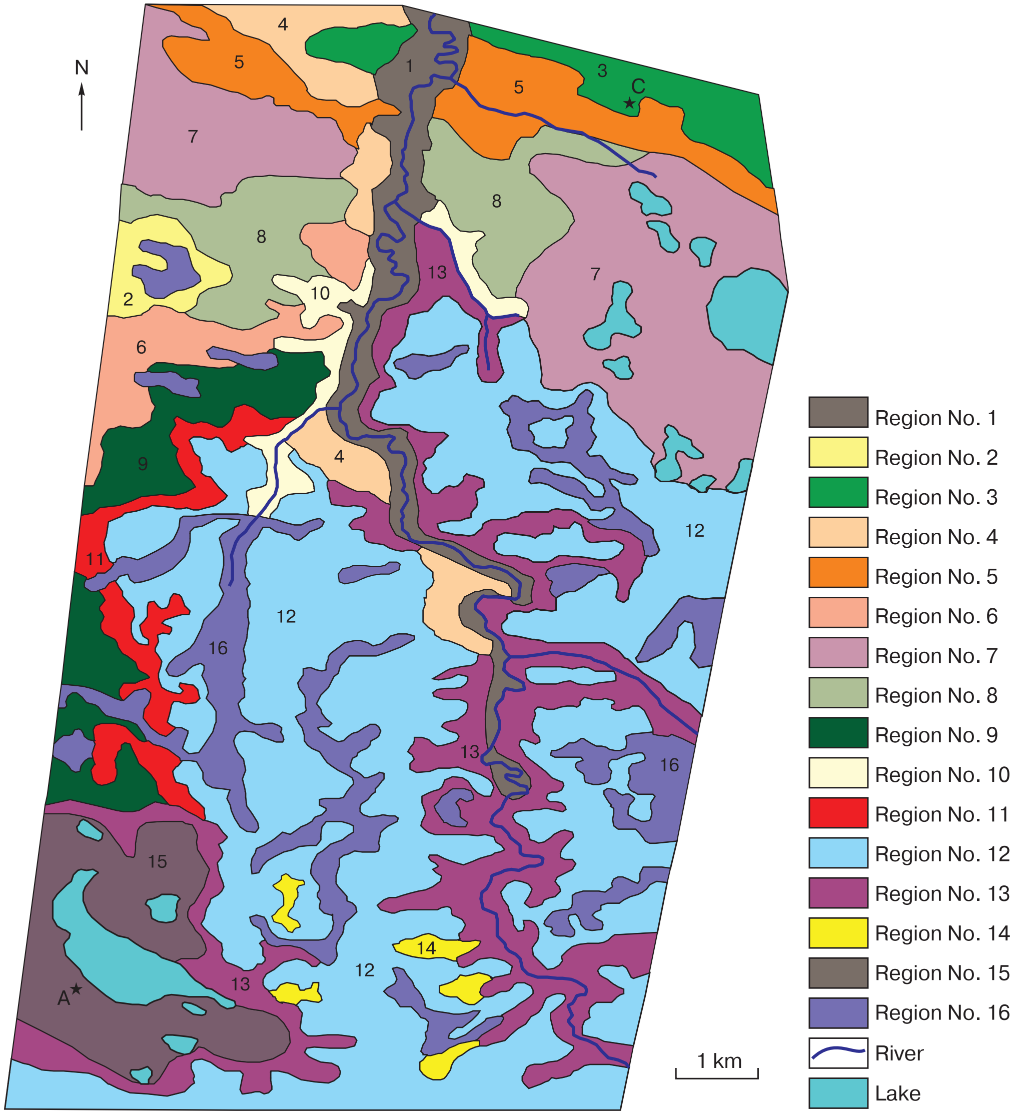
In calculations of failure massifs the operators Safety 1, 2, 3 use commonly known calculation methods set out in [*Recommendations..., 1974; Tartakovskii, 1976; Velli et al., 1977; Khrustalev, 2005; SP 36.13330.2012*].

Methodology for generating cost-based engineering-geocryological map

This is a special engineering-geocryological map, whose legend contains the minimal total present value of the "oil pipeline–environment" geotechnical system calculated for each of the mapped regions, with account of three known pipe-laying technologies (underground, on-ground, above-ground).

The engineering geocryological map is generated for the entire area of search for the optimal pipeline route, with the following group of layers applied: a) the depth of bedrock occurrence; b) the section of dispersed soils to a depth of 10–15 m (the layer includes water-physical, mechanical and thermophysical characteristics of the geological elements identified in the section); c) average annual temperature of permafrost soils with regard to merging permafrost type, or the occurrence depth of the top of permafrost soils with regard to non-merging type of permafrost.

By superimposing the above layers, we obtain an engineering-geocryological map for complex evaluation of the target area. An example of such a map is shown in Fig. 3. Each of the regions, including water barriers (rivers, lakes), is then calculated according to the algorithm in Fig. 4. Calculation results with



Region No.	Underground laying		On-ground laying		Above-ground laying	
	P_{opt}, %	C_{opt}, monetary unit/LM	P_{opt}, %	C_{opt}, monetary unit/LM	P_{opt}, %	C_{opt}, monetary unit/LM
1	83	37 513	65	99 500	96	37 963
2	99	33 637	84	99 500	99	37 963
3	90	35 422	87	66 641	99	37 963
4	84	21 758	89	68 470	99	37 963
5	64	100 000	75	99 500	99	37 963
6	65	100 000	75	99 500	99	37 963
7	99	33 435	71	66 641	99	41 517
8	98	34 913	71	66 641	99	44 415
9	99	33 394	71	66 401	99	41 688
10	84	26 080	80	68 470	93	58 724
11	67	100 000	61	99 500	99	37 963
12	67	100 000	61	99 500	99	37 963
13	85	33 565	72	65 606	93	48 898
14	64	100 000	78	99 500	99	37 963
15	91	35 777	84	67 496	99	47 350
16	97	26 072	86	99 500	99	55 259
River	–	800 000	–	800 000	–	800 000

Fig. 5. Cost-based geological-geocryological map.

P_{opt}, C_{opt} – optimal reliability and optimal cost of pipe-line laying, respectively.

respect to the system reliability and total present value are reflected in the legend of the engineering-geocryological map, which is termed “cost-based engineering-geocryological map” (Fig. 5).

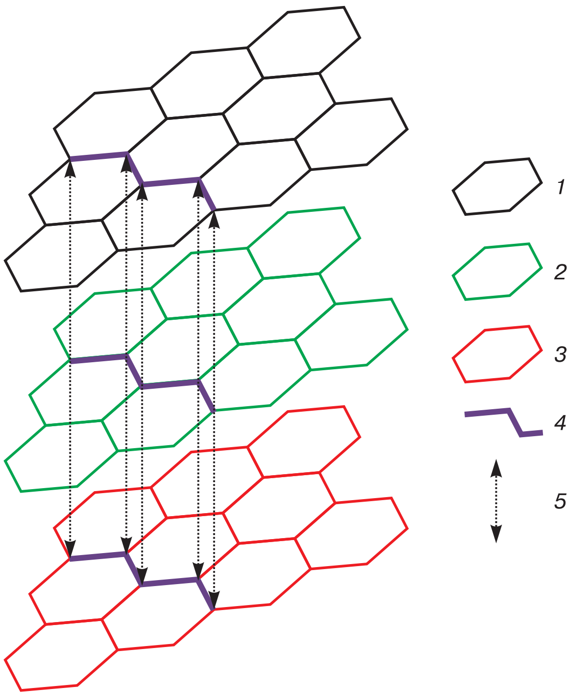


Fig. 6. Three-layer graph scheme.

1 – grid for above-ground laying; *2* – grid for on-ground laying; *3* – grid for underground laying; *4* – taxa boundary; *5* – additional edge with the change-over cost (transition from one laying technique to another).

Methodology for selecting optimal pipeline route and best-solution pipeline laying on the basis of the cost-based engineering-geocryological map

The optimal oil pipeline route between two control points on the cost-based map is determined by the linear programming method in automatic mode providing the calculation algorithm described below.

A three-layer grid (graph) consisting of vertices and edges with a length of 1 mm is superimposed on the cost-based map, while the regions’ boundaries are adjusted so that they pass along the grid edges (Fig. 6).

The cost of the region’s total present value is assigned to a mesh edge on each layer, which is multiplied by the edge length and divided by the map scale. The first layer of the grid reflects the cost of the underground laying, the second – on-ground, and the third – above-ground. The mesh vertices, located on the border between regions of individual layers, are connected with each other by the edges for the transitions from one laying technique to another; and are reduced to three change-over types: underground–on-ground, underground–above-ground, on-ground–above-ground. The cost values are assigned to the transition edges responsible for the change-over from one laying technique to another.

Further we build on the grids all possible continuous chains of edges including the junction edges connecting the control points with each other, with the total present value calculated for each chain, which these can count several hundred or thousands; the chain of edges corresponding to the lowest cost is taken as the optimal route.

Table 2. **Cost-related and design parameters of the optimal pipe-line route between control points A and B**

Number of region	Underground laying					Above-ground laying				
	P_{opt}, %	C_{opt}, monetary unit/LM	Pipe wall thickness, mm	Pipe insulation thickness, mm	Spacing between SCSs, m	P_{opt}, %	C_{opt}, monetary unit/LM	Pipe wall thickness, mm	Depth of pile embedment in soils, m	Spacing between pile supports, m
1	–	–	–	–	–	96	37 963	22	10.5	20
3	–	–	–	–	–	99	37 963	16	7	20
4	–	–	–	–	–	99	38 963	28	7	20
5	–	–	–	–	–	99	37 963	16	7	20
6	–	–	–	–	–	99	38 963	28	7	20
9	99	33 394	30	20	4	–	–	–	–	–
10	84	26 080	24	25	4	–	–	–	–	–
11	–	–	–	–	–	99	37 963	28	7	20
12	–	–	–	–	–	99	37 963	22	10	20
13	85	33 565	20	20	4	–	–	–	–	–
15	91	35 777	32	50	10	–	–	–	–	–
16	–	–	–	–	–	99	55 259	10	9	22
River	–	800 000	–	–	–	–	800 000	–	–	–

Note. P_{opt} – optimal reliability of pipeline laying; C_{opt} – optimal cost of pipeline laying; SCS – seasonal ground cooling system; LM – linear meter.

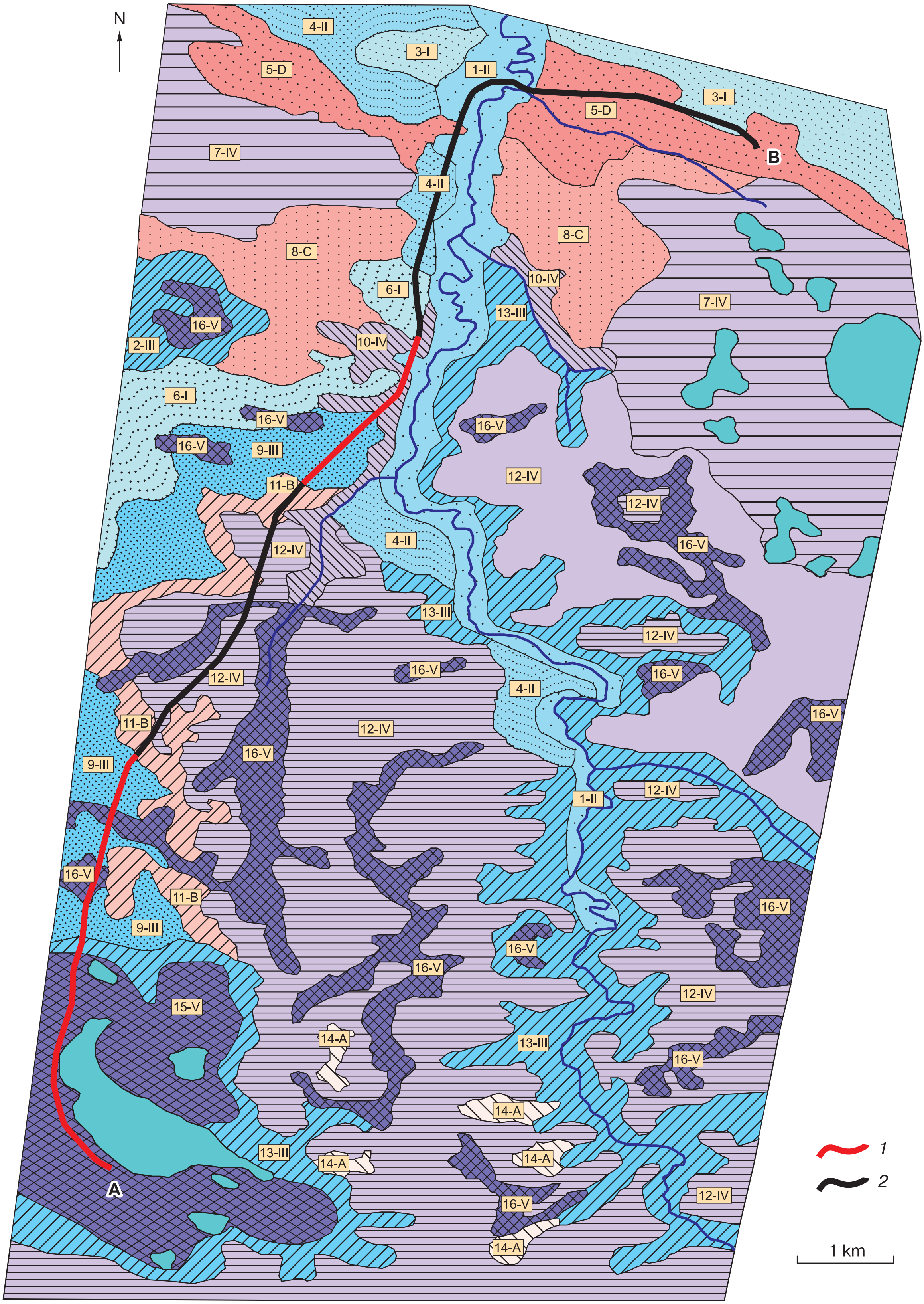


Fig. 7. Optimal pipeline route between control points A and B.

1 – underground laying; *2* – above-ground laying. Legend: cf. Legend for Fig. 3.

The optimal route is displayed on the map, with the fixed route segments aligned with a certain layer of the graph, allowing thereby to simultaneously display them on the map along with oil-pipeline laying techniques in various areas within the stretch of the optimal route.

Figure 7 provides an example of engineering-geocryological map which includes oil-pipeline route. Since the optimal pipeline laying technique is always rigidly connected with the calculated control parameters, the design parameters values are given as an attachment to the map (Table 2).

CONCLUSION

The proposed method for choosing best solutions for laying the linear part of oil pipeline in the permafrost-underlain area is unique, which is corroborated by its being based on the probabilistic-statistical approach to predicting the thermal and mechanical interactions between engineering structures and the environment. This approach considers the original natural and technogenic information as stochastic and allows taking into account its deviations from the nominal values in time and space, ensuring thereby evaluation of the pipeline system reliability as probability of its faultless operation during a given in-service time period. Accidents in the pipeline system are regarded by this approach as random events which have a monetary expression – the cost of risk, which is the cost equivalent of reliability. The attached cost of risk allows to evaluate the options for technical solutions at the pre-design stage in terms of their reliability rather along with the estimated costs, positioning thus this process to a new qualitative level. The economic effect from introducing the proposed methodology into production operations today can be assessed only qualitatively. It consists in increasing the reliability of the "oil pipeline–environment" geotechnical system, reducing the likelihood of accident risk and saving operating costs caused by unscheduled repairs.

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