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PROPERTIES OF FROZEN GROUND AND ICE

VERIFICATION OF THE ACCURACY OF THE MODEL FOR PREDICTING STRENGTH OF SEDIMENTARY ROCKS OF SOUTHERN YAKUTIA BASED ON GEOMETRIC ELECTROMAGNETIC INDUCTION SOUNDING

L.G. Neradovskii

Melnikov Permafrost Institute, Siberian Branch of the Russian Academy of Sciences,
Merzlotnaya St. 36, Yakutsk, 677010 Russia

E-mail: L031950N@ya.ru

This article discusses the results of retrospective verification of the strength prediction model for saturated rocks of southern Yakutia. The model was developed for the geotechnical conditions of the city of Neryungri. The input data for the model consisted of the decay rate coefficients of the harmonic field of a vertical magnetic dipole measured at a 1.125 MHz frequency using the geometric electromagnetic induction sounding method. The error of model predictions was close to the allowable error of ±20% for average laboratory estimates of rock sample strength and ranged from ±16.8 to ±33.5% for different site conditions with a probability of about 70%. The total error of the model at this probability is 27.2% with maximum outliers overestimating the laboratory strength of weak rocks by 120.5% or underestimating the strength of strong rocks by 86.8%. The model predictions were more accurate (errors of 22.8 and 21.9%) for the rock masses composed predominantly of moderately strong (15–50 MPa) and strong (50–120 MPa) rocks. The statistical results indicate that the model is regionally representative and can be applied in the areas of warm and cold permafrost sedimentary rocks of southern Yakutia for rapid, cost-effective terrain evaluation by rock strength.

Keywords: *model for Neryungri City, sedimentary rocks, rock mass and laboratory samples, saturated rock strength, geometric sounding, remote electromagnetic inductive sounding, verification, error.*

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To my unforgettable teacher and mentor, Doctor of Geological and Mineralogical Sciences, Professor, Academician of the Russian Academy of Natural Sciences, Head of the Department of Geophysics of the Geological Exploration Faculty of the Irkutsk Polytechnic Institute G.S. Vakhromeev

INTRODUCTION

The development and application of geophysical models for predicting the values of geological characteristics was given paramount information and economic importance in the last century both in Russia and abroad. The basic principles for creating physical-geological models (PGM) were laid down in the 60–70s of the last century in geology [*Vakhromeev, Davydenko, 1987*]. In developing the idea, theory and methodological issues of practical application of forecast models, along with G.S. Vakhromeev and his students, many scientists of our country contributed. Among them: F.M. Goltsman, V.N. Strakhov, A.G. Tarkhov, V.S. Yakupov, V.P. Melnikov, B.M. Sedov, V.I. Dzhurik, A.A. Nikitin, A.D. Frolov, A.M. Epinatyeva, Yu.I. Blokh and other scientists. It is especially worth noting the contribution of the employees of the Hydroproject institutes named after S.Ya. Zhuk (Moscow) and the Scientific Research Institute of Hydraulic Engineering named after B.G. Vedeneev (St. Petersburg) in the development of models for seismic prediction of the mechanical properties of rocky-semi-rocky foundations of designed hydraulic structures in the North-East of the Russia, as well as in the Asian and Caucasian republics of the former USSR.

In a systematized and generalized form, the results of research from the designated institutes are reflected in the recommendations [*Recommendations..., 1981; Recommendations..., 1985*], as well as in the monograph [*Voronkov, 2009*]. There are other important publications, but they are less known and accessible to the modern reader, for example, monographs on solving predictive engineering-geological and geological exploration problems using seismoacoustic and other methods of geophysics [*Savich, Yashchenko, 1979; Grib, Samokhin, 1999; Syasko et al., 2004*].

Previously [*Neradovskii, 2022a*] a new PGM was considered, built using data from the remote inductive sounding (RIS) method for the engineering-geological conditions of the city of Neryungri. The model was created by using the classical probabilistic-statistical approach[1] to predict the average strength estimates of the sandstone massif, assuming the possibility of its transition under the influence of climatic and technogenic-anthropogenic factors from a frozen to a water-saturated state at the base of engineering structures in the city of Neryungri. For the sake of brevity, let's call this model the model of the city of Neryungri.

Unlike seismic models, which have long become standard for solving typical geomechanics problems, the Neryungri model uses a different petrophysical basis. Instead of the propagation velocities of longitudinal and transverse waves, the measure of attenuation of a steady-state harmonic high-frequency elliptically polarized field of a vertical magnetic dipole (hereinafter referred to as the HFVMD field) in the layer of annual heat turnover is studied.

The purpose of this article is to prove or refute the hypothesis about the regional status of the model of the city of Neryungri with the possibility of its application outside this city in other engineering and geological conditions. The achievement of the goal was obtained by summarizing the results of model verification at five sites in the areas of distribution of frozen sedimentary rocks in the permafrost zone of South Yakutia.

RESEARCH METHODOLOGY OF MODEL ERRORS

There are two verification methods: internal and external. The result of internal verification depends on the factual material on which the model is built. Therefore, in cases of a combination of favorable conditions, a false decision can be made about positive or negative verification of the model. If it is possible to confirm or refute the results of an experiment by additional verification or control drilling of boreholes or sinking pits, the method of external verification is used outside the boundaries of building models with other conditions for obtaining the actual material.

Common to all sites of the verification of the model of the city of Neryungri was the use of engineering geological elements (EGE)[2]. A method for using EGE to solve the problem of classifying geological bodies was proposed by N.V. Kolomenskii and I.S. Komarov [*Kolomenskii, 1956*]. Thanks to the knowledge of EGE, it was possible to correctly compare point laboratory estimates of the strength of rock samples with volumetric estimates of the strength of the rock mass obtained using the RIS method. In solving the scaling problem, point estimates of the strength of rock samples partly acquired three-dimensional properties due to classification according to a set of standard (average) indicators of the composition, state, and properties of sedimentary rock masses[3].

The actual material for verifying the model of the city of Neryungri was a set of laboratory data and the RIS method that was uniform in content and comparable in depth to the study of sedimentary rocks. Laboratory data consisted of average values of R_c – temporary uniaxial compressive strength in air-dry and water-saturated states of sedimentary rock samples [*GOST 21135.2–84, 1984*]. The samples were prepared from rock monoliths taken from borehole cores at different depths [*Levkovich, 1989*].

RIS method data were obtained in the vicinity of boreholes using SEMZ equipment [*Lebedev et al., 1991*]. The measurement technique using SEMZ equipment and mathematical processing of measurement results are described in [*Neradovskii, 2022a*]. The study of the strength of sedimentary rocks was carried out at a frequency of 1.125 MHz in a spacing band[4] from 5–10 to 30–100 m. At this frequency and the effective values of the electrophysical characteristics[5], estimated from the palettes of V.F. Lebedev [*Lebedev et al., 1991*], adjusting the spacing of the receiving and transmitting antennas provided the depth[6] of study of rock strength comparable to drilling operations.

In addition to the first verification site, in the remaining sites the initial data for the modified version

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[1] Using methods of correlation and regression analysis.

[2] EGEs are the result of complex painstaking intellectual work of geological engineers. Theoretically, the approach using EGE is based on a difficult-to-understand method of pattern recognition [*Vapnik, Chervonenkis, 1974*], which, in many practical variants, is widely used in all areas of geophysics when solving classification problems, for example, using currently neural networks, i.e. principles of artificial intelligence.

[3] These indicators combine and organize individual values of geological characteristics that are scattered and variable in depth and area into group most probable values with a given reliability of their determination in laboratory conditions.

[4] The distance between the antenna emitting the primary HFVMD field and the antenna receiving the total primary and secondary field formed in the sedimentary rock mass.

[5] Electrical resistance and the real part of the complex relative dielectric constant. These characteristics were assessed based on the results of measurements of all components of the elliptically polarized field of the HFVMD not at all, but only at some points of the RIS, evenly distributed over a sparse observation network over the area of the verification sites.

[6] The effective penetration depth of the elliptically polarized HFVMD field into the sedimentary rock mass was assessed according to a graph borrowed from the work of V.S. Titlinov and R.B. Zhuravleva [*1995*].

of the Neryungri model [*Neradovskii, 2022b*] were the group values of the coefficient *k*, which were determined in the vicinity of the boreholes in 2–4 azimuths. The values of the coefficient *k* correctly identified the measure of attenuation of the HFVMD field in the transition zone of the reduced distance[7] by reducing the values of the vertical component of the HFVMD field depending on the spacing of the receiving and transmitting antennas. The monotonically nonlinear process of reduction of this component of the HFVMD field when applied to the studied frozen strata of heterogeneous and anisotropic sedimentary rocks was correctly described by a power function. The values of the coefficient *k* were equal to the values of the power function exponent. These values were automatically determined by approximating with a power function the graphs of the absolute magnitudes of the vertical component of the HFVMD field, plotted depending on the spacing of the receiving and transmitting antennas.

ENGINEERING GEOLOGICAL CONDITIONS

This article discusses the features of the verification sites of the model of the city of Neryungri, helping the reader to understand the natural environment in which the model errors were studied.

First Verification Site

The results of internal verification of the model of the city of Neryungri was published [*Neradovskii, 2022a,b, 2023c*]. The site is located in the central part of the city of Neryungri, where 218 boreholes were drilled to a depth of 10–15 m in the late 1980s. Testing for the strength of the sedimentary rock mass using drill holes, followed by a laboratory assessment of rock monoliths with average R_c values, was done at a depth of 7–17 m. According to RIS data, the depth of rock strength study was 6–18 m.

According to the data of Neryungristroyizyskaniya LLC and a generalization of the results of regional studies [*Kudryavtsev, 1975; Zhelinsky et al., 1976; Zhelinsky, 1980; Grib, Samokhin, 1999*] the dominant lithotype in the thickness of Mesozoic coal-bearing sedimentary rocks in the city of Neryungri and South Yakutia was sandstone. In addition, there is one more feature inherent in the permafrost zone of Southern Yakutia. This is the heterogeneity and high variability of the strength of sandstone, decompressed by tectonic processes with the formation of a complex system of crushing and fracturing [*Mokshantsev et al., 1964; Buldovich et al., 1976*]. These processes were superimposed on the processes of cryogenesis [*Shesternev, 2001*], as a result of which isolated patches of permafrost an intermittent island cryolithozone was formed in South Yakutia. Its structure, power and temperature are regulated by climate, landscape and geomorphology of the area [*Kudryavtsev, 1975*], as well as intraterrestrial heat flows [*Zheleznyak, 2015*]. The permafrost thickness in the watershed areas of Southern Yakutia is predominantly 20–50 m. The mean annual temperature at a depth of 10–20 m is close to 0°C. In the city of Neryungri, according to thermometry data from survey boreholes in areas of permafrost degradation with the appearance of thawed sandstones[8], the temperature at a depth of 10 m varied from 0.0 to 6.5°C. In places where permafrost was preserved, its thickness was 13–18 m, and the average annual temperature at a depth of 10 m varied from –0.1 to –0.4°C.

The identity of the complex of natural conditions of the territory of the city of Neryungri and Southern Yakutia in the areas of distribution of coal-bearing sedimentary rocks is very important. It gives grounds to consider the territory of the city of Neryungri as a key area for its inclusion in the state network of long-term geocryological and geotechnical monitoring [*Melnikov et al., 2022*].

Second Verification Site

Unlike the first site, internal verification of the model of the city of Neryungri was done in a more complex way in one of the residential areas called “M” [*Neradovskii, 2023b; Neradovskii, Osmushkin, 2023*]. Based on the combination of favorable and unfavorable conditions for the operation of engineering structures, the “M” block is not much different from similar conditions in other city blocks. The complexity of solving the verification problem in quarter “M” was the comparison of geological and geophysical average R_c values determined with a very large time gap of 53 boreholes drilled along the perimeter of engineering structures. Laboratory average R_c values were obtained in 1984–1985 based on sandstone monoliths, most often taken at a depth of 5–10 m. Geophysical forecast estimates of average R_c values of a water-saturated sandstone massif were determined using a modified version of the model for the city of Neryungri in 2017–2018 at depths from 5–7 to 14 m.

As for the verification problem itself, it was correctly solved by eliminating the systematic difference between laboratory and geophysical series of strength values. This simple operation was performed several times until the stage of equiprobable local deviation towards an increase or decrease in individual geophysical strength values relative to laboratory values.

Third Verification Site

In this area, an external verification of the model of the city of Neryungri was made [*Neradovskii, 2023c*]. The site is located in the north of South

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[7] The product of the spacing of receiving and transmitting antennas by the module of the complex wave number.

[8] At construction sites with destroyed soil and vegetation cover.

Yakutia, 421 km from the city of Neryungri on the border with the continuous permafrost zone of Central Yakutia along the AYAM highway between the Amga station and the Bolotny crossing. The length of the section is 52 km. The site is located on the right, kurum-covered, gentle slope of the Modut river valley. The presence of kurums complicated but did not prevent the work of the RIS method. The ability to work on kurums makes the RIS method indispensable[9] when studying the strength of sedimentary rocks using probabilistic forecast models and, in particular, the model of the city of Neryungri.

Drilling and geophysical work was carried out in 1993–1995 not throughout the entire site, but selectively in places where the construction of excavations, culverts, bridge crossings, etc. was planned. The total length of the section for solving the problem of verifying the model of the city of Neryungri was 4.3 km.

According to JSC Mosgiprotrans[10], the rocky-semi-rocky foundation of engineering structures at the third site of verification of the model of the city of Neryungri was a frozen dolomite massif with a low temperature. The massif lies under a thick layer of colluvium–eluvium and is in a highly fractured state with the cracks everywhere filled with clayey material. The thickness and composition of colluvium–eluvium, as well as the strength of the dolomite massif, varied greatly along the axis of the AYAM route. With an average value of 8.0 m, the thickness of the colluvium–eluvium layer varied from 2.1 to 23.4 m. However, in most cases (72%) the thickness of the colluvium–eluvium did not exceed 10 m.

According to borehole thermometry data, the average annual temperature of the dolomite massif at a depth of 10–15 m varied from –0.8 to –4.8°C with an average value of –3.4°C.

Fourth Verification Site

In fourth area, the model of the city of Neryungri was verified in 1990–1991 at Kurgellyakh station [*Neradovskii, 2023c*]. According to the data of drilling 25 boreholes to a depth of 10–15 m, the soil foundation of the station is composed of Lower Cambrian carbonate rocks of the Olekma Formation in the form of interlayering of dolomites with limestones. On top of the rocks are covered with a layer of Quaternary and ancient deluvial-eluvial deposits. Quaternary deposits have a thickness of 0.4–2.1 m. They are widespread and composed of loam with the inclusion of gruss and gravel of sedimentary rocks. Ancient deposits of the Cenozoic or Paleozoic age consist of bright red, yellow clays and are distributed within the boundaries of tectonic zones of crushing and fracturing of the sedimentary rock massif. Most often, the thickness of the clay layer is 1.6–2.8 m. However, adjacent to tectonic zones and in the zones themselves, the thickness increases to 4.5–8.6 m or more, as at the points of two boreholes, where clays of the ancient weathering crust extend to depths of 24.6 and 17.4 m. Testing for the strength of sedimentary rocks was carried out during drilling operations in the depth range of 0.8–11 m. Most often, monoliths were selected from borehole cores at a depth of 6–11 m. Using the RIS method, rock strength has been studied in the depth range of 6–12 m.

Fifth Verification Site

In fifth area, testing of the model of the city of Neryungri has been completed [*Neradovskii, 2023d*]. The site is located at the AYAM Olen railway station, 682 km north of the city of Neryungri. The station site is located on the Leno-Aldan plateau on the slope of the valley of the Hoyos-Ordoh stream, the right tributary of the river Lutenga. The absolute elevations of the relief at the station location vary from 320 to 340 m.

Work using RIS and discrete ground penetrating radar methods was carried out at the station in the summer of 1989. Borehole drilling and pit excavation were carried out in the spring of 1990, taking into account geophysical data. Five of the 15 boreholes penetrated the top of the sedimentary rocks to a depth of 3–5 m.

According to V.M. Kalinin, V.S. Yakupov [*1989*] and M.N. Zheleznyak [*2015*], in the area of the Olen station, the cryolithozone has a continuous distribution to a depth of 200–300 m. According to borehole thermometry data, the temperature of frozen sedimentary rocks at a depth of 10–15 m varied from –1.3 to –2.3°C with an average value of –1.7°C.

The base of the engineering structures is composed of Lower Cambrian carbonate rocks in the form of interlayered limestones and dolomites, lying at a depth of 12–19 m. On top, the sedimentary rocks are covered with frozen Quaternary deposits of mixed genesis: alluvial, lacustrine-swamp and deluvial–eluvial. From above to a depth of 3–5 m, the composition of the sediments is clayey with alternation of clays, loams and sandy loams. Sands with lenses of gravel soils occur below at the boundary with sedimentary rocks. The thickness of Quaternary sediments naturally increases down the slope of the Hoyos-Ordoch stream valley.

Strength testing of the sedimentary rock mass was carried out during drilling operations at a depth of 14–18 m. Using the RIS method, the strength of the rock mass was studied to a depth of 10–19 m.

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[9] In comparison with methods of electrical tomography, transient processes and georadiolocation.

[10] 57 boreholes were drilled, but the verification of the Neryungri model was made using 37 boreholes, in which the depth of the dolomite massif did not exceed 10 m.

FINAL VERIFICATION RESULT

The actual material for the verification result was the errors of the Neryungri model, which characterize the degree of its accuracy in predicting the average strength of a water-saturated sandstone massif relative to laboratory data. GOST 21135.2–84 [*1984*] was adopted as the comparison standard. According to his requirements, when conducting mass laboratory experiments, errors in determining the average R_c values for six samples with a reliability of 80.0% should not exceed ±20.0%. As for the probabilistic-statistical analysis of errors in the model of the city of Neryungri, it was done using the "Stage" program [*Kulaichev, 2006*].

Let us first briefly consider, by way of statement, the particular errors of the model of the city of Neryungri for each of the five verification sites, and then the results of a detailed analysis of the general error for all sites. In addition, we present the result of an analysis of the dependence of model errors on the strength of sedimentary rocks obtained in the laboratory.

Partial errors presented in Table 1, represent the spread of individual values, estimated by the value of the standard deviation. This statistic, as is known, corresponds to the confidence probability of making probabilistic-statistical decisions equal to 68.2%. From Table 1, it follows that the accuracy of the model was often tested in the city of Neryungri, where the foundations of engineering structures are composed of frozen high-temperature sandstone. Here the spread of errors did not exceed ±30%. When checking the accuracy of the model outside the city of Neryungri, where frozen massifs of dolomite and limestone with different temperatures are common, the spread of errors did not exceed ±35%. With close partial errors, the overall average median error of the model in various engineering-geological conditions of its verification is ±27.8%.

Let us estimate the general error of the model of the city of Neryungri from the side of the probabilistic distribution of error values in the entire collected set of factual material (Fig. 1*a*). The summary histogram of this distribution indicates an equally probable spread of errors in one or another direction[11] near an almost zero value. A test using three criteria (Kolmogorov, Omega-square and Chi-square) refutes the null hypothesis that the distribution of errors corresponds to the Gaussian Law[12]. However, if three groups of anomalous errors, insignificant in terms of the number of definitions[13], are removed from the series of errors, then upon repeated testing, the null hypothesis is confirmed by all criteria. In this case, using the arithmetic mean zero error, you can find out the theoretical estimate of the mathematical expectation that corresponds to the unknown true value of the average error. That is, the error that is estimated from the general population of data consisting of an infinite number of definitions. In the case under consideration, this error with a confidence probability of 95.0% is within the interval ±2.37%. This means that in places where sedimentary rock strata are distributed, the average rock strength determined using the Neryungri model based on the total data set of the RIS method as a whole, for the work area or for individual survey areas, will practically not differ from laboratory data. The conclusion made acquires scientific significance when conducting regional studies using the well-known methodology of key areas[14], as well as in cases where the goal of scientific research is focused on the development of PGM of developed and subduing areas of the permafrost zone of Southern Yakutia.

As for the single errors of the Neryungri model, they vary in a wide range from −120.53 to 86.79%. Despite this, in 76.3% of cases the width of their spread is no more than ±30%. A detailed analysis of the sorted series of errors confirms the following. The percentage of model errors equal to laboratory errors

Table 1. **Summary of partial errors of the Neryungri city model**

Number	Name of the site	Verification type	Sedimentary rocks	Number of boreholes	Model error, %
1	The city of Neryungri	Internal	Sandstone	218	±27.8
2	Quarter "M" of the city of Neryungri	Internal	Sandstone	53	±30.1
3	Amga station-Bolotny crossing	External	Dolomite	37	±16.8
4	Kurgellyakh station	External	Dolomite, Limestone	25	±22.0
5	Olen station	External	Dolomite, Limestone	5	±33.6

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[11] In the direction of overestimation (error with a minus sign) or underestimation (error with a plus sign) of laboratory strength.

[12] This is the name of the law in the theory of errors. In general mathematical statistics, this fundamental law is called the Normal Law or the Law of Large Numbers.

[13] Their share in the total body of factual material is 5.85%.

[14] It was proposed by the outstanding scientist V.A. Kudryavtsev.

(±20.0%) or close to them (±25.0%) is 59.8 and 68.9%, respectively. If we are guided by the use of statistics of one standard deviation, then with a probability of about 70% the spread of errors will be ±27.22% (Table 2). With any approach to error analysis, one should expect that in 7 out of 10 cases, the errors of the Neryungri model will differ from the laboratory error by 22.2–27.6%, i.e., no more than 30%.

To complete the analysis of errors in the Neryungri model, we will consider the issue regarding the dependence of errors on the strength of sedimentary rock samples determined in laboratory conditions. Let's solve this problem by grouping errors by categories of strength of water-saturated[15] rocky-semi-rocky soils [*GOST 25100–2020; 2020*]. An illustration of the variability of single errors shows their complex dependence on the strength of rock samples (Fig. 1*b*). This is not surprising, taking into account the dynamic natural conditions inherent in the complex permafrost zone of Southern Yakutia. The response of sedimentary rock masses to their high-frequency inductive excitation, expressed in different trends in error variability, is surprising. There are three such trends.

The first trend manifests itself in the form of the initial linear section of the error graph (Fig. 1*b*) with a minus sign, which means a systematic overestimation of the strength of rock samples according to the Neryungri model. The overstatement is small and averages 7.69%. However, in isolated cases it can reach more than one hundred percent. This feature is observed in places where rocks of low strength (less than 15 MPa) and low and low strength (3–5 and 1–3 MPa) occur. The share of such rocks that are unfavorable for the construction and operation of engineering structures is 12.0%.

The second trend with an equally probable overestimation and underestimation according to the model of the city of Neryungri of the strength of rock samples covers the most numerous rock massifs of the medium (15–50 MPa) and strong categories (50–120 MPa). The total share of such massifs favorable for the construction and operation of engineering structures is 78.9%.

The third trend manifests itself less noticeably at the end of the error graph (Fig. 1*b*) with the strength of rock samples being underestimated by up to 60 percent or more. There is a tendency in places where dense monolithic rock masses of a very strong category are distributed with R_c values of more than 120 MPa. The share of such breeds is minimal and amounts to 9.2%.

In a generalized form, the dynamics of single errors and their trends depending on the strength categories of artificially water-saturated laboratory samples of sedimentary rocks is shown in a bubble diagram (Fig. 2). Categorical statistics of the strength of rock samples and their errors according to the Neryungri model are presented in Table 2 and 3.

In an orderly form and taking into account tabular statistics, it becomes extremely clear that the difference between point and volumetric laboratory and geophysical estimates of the strength of sedimentary rocks in the studied parts of the permafrost zone of Southern Yakutia is far from the critical point beyond which the Neryungri model cannot be trusted.

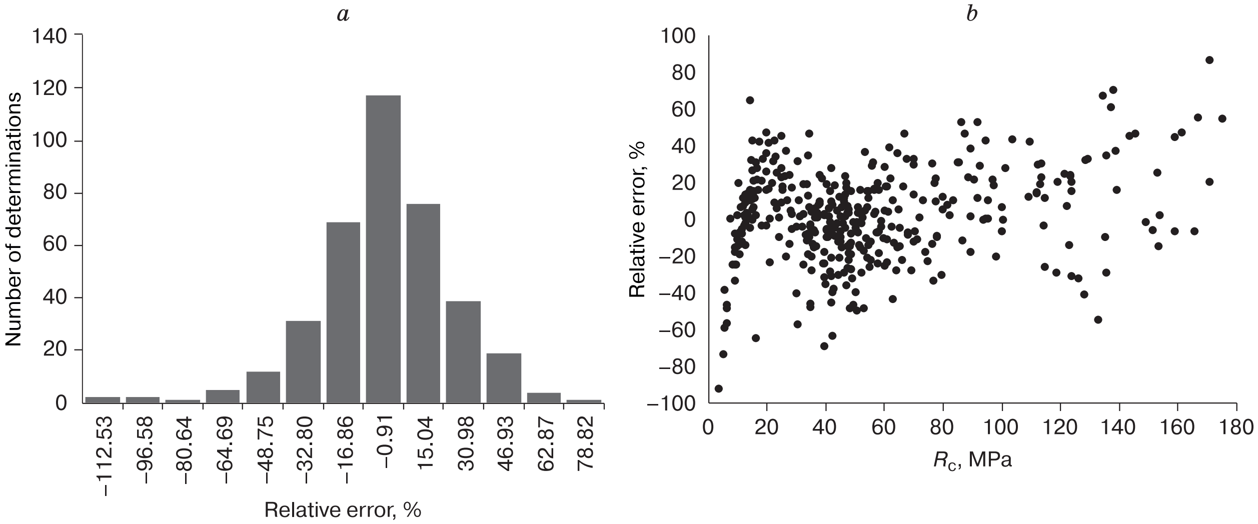

Fig. 1. Summary histogram of errors of the Neryungri model (*a*) and the field of scattering of errors depending on the strength (R_c) of water-saturated samples of sedimentary rocks (*b*).

Sample size – 393 determinations.

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[15] For the air-dry state, such categories are not provided in GOST 25100–2020 [*2020*].

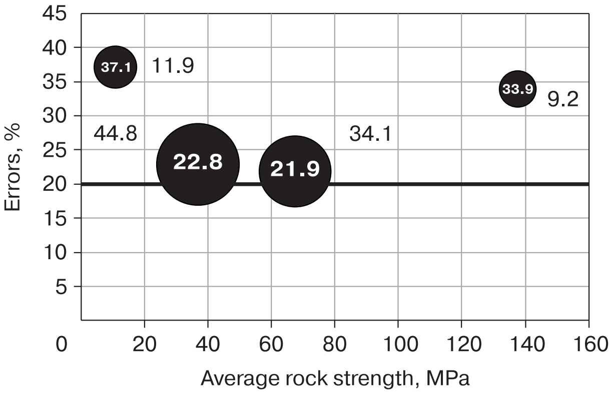

Fig. 2. Generalized proportional dynamics of errors of the Neryungri model depending on engineering-geological categories of strength of water-saturated samples of sedimentary rocks.

Solid line – permissible error level according to GOST 21135.2–84 [*1984*], equal to ±20%, provided that mass laboratory determinations of the strength of rocky and semi-rocky soil samples are carried out. Numbers in the circles indicate the spread of errors of the Neryungri model with a standard confidence probability of 68.2%, and the numbers near the circles indicate the share of errors in the total number of determinations.

When studying the most common sedimentary rocks of the medium strength category and the strong category with average R_c values equal to 15.20–36.81 and 56.70–73.54 MPa, the equally probable spread of errors in the second trend does not exceed 23.0%. The share of such small errors in the total number of determinations is 78.9%. In rare categories of weak and very strong sedimentary rocks with average R_c values equal to 6.30–11.01 and 123.60–141.81 MPa, there is an equally probable spread of errors in the Neryungri model within the limits of action of trends 1 and 3 after eliminating them systematic alternating background is ±37.12% and ±33.92%. The cumulative proportion of such increased errors is 21.1%.

The reason for the overestimation and underestimation according to the Neryungri model of the strength of sedimentary rock masses in the predicted water-saturated state in relation to the laboratory strength of rock samples in the same state lies in the combined action of the scale factor and the petrophysical factor. The first factor is of general importance and evaluates the strength of rocks at different scales. From the geological side, these are point estimates, and from the geophysics side, these are volumetric estimates. The scale factor always operates, but is especially intensified in extreme natural conditions, in the case under consideration – in the con-

Table 2. **Strength of water-saturated samples of sedimentary rocks of the cryolithozone of Southern Yakutia according to laboratory data**

Statistics	Strength of sedimentary rocks R_c, MPa				
	1	2	3	4	1–4
Arithmetic mean	10.20	35.00	73.54	141.81	54.95
Median mean	11.01	36.81	67.43	137.60	46.74
Modal mean	6.30	15.20	56.70	123.60	6.30
Standard deviation	3.37	10.55	19.65	16.37	37.90
Variation coefficient, %	33.00	30.10	26.70	11.90	69.00
Minimum	2.50	15.01	50.17	121.40	2.50
Maximum	14.78	49.65	119.30	175.20	175.20
Number of determinations	47	176	134	36	393

Note to Table 2 and 3: 1 – sedimentary rocks of low strength category with R_c less than 15 MPa; 2 – rocks of moderate strength category with R_c = 15–50 MPa; 3 – rocks of strong category with R_c = 50–120 MPa; 4 – rocks of very strong category with R_c > 120 MPa; 1–4 – strength in all categories.

Table 3. **Errors of the Neryungri model by categories of sedimentary rock strength in the predicted water-saturated state**

Statistics	Model errors, %				
	1	2	3	4	1–4
Arithmetic mean	–17.15	–0.63	3.87	17.95	0.45
Median mean	–7.69	1.38	3.80	21.98	1.91
Modal mean	n/a	15.60	–15.60	n/a	3.5
Standard deviation	±37.12	±22.85	±21.86	±33.92	±27.22
Minimum	–120.50	–69.12	–49.50	–55.08	–120.50
Maximum	64.33	47.00	52.80	86.80	86.79
Number of determinations	47	176	134	36	393

ditions of the distribution of weak and strong sedimentary rocks. The second factor is individual and is determined by the petrophysical and probabilistic-statistical (correlation, regression) features of the model of the city of Neryungri. They consist of a nonlinear dependence of the field attenuation measure HFVMD on the strength of rock masses [*Neradovskii, 2022a*]. In places where weak rocks with a strength below 15 MPa and strong rocks with a strength above 120 MPa occur, the measure of attenuation of the total primary and secondary fields HFVMD asymptotically approaches constant values of the coefficient *k*. This means that the induction effect that causes the HFVMD field to decay becomes so weak that it essentially loses its ability to respond to subtle changes in the strength of the sedimentary rock mass. In weak rocks such as loose marl, this is hampered by an excess of clayey material, which is located in the spaces between the consolidated remains of the block-cellular structure that have survived complete destruction. In hard rocks, on the contrary, there is a lack of clayey material, which is present fragmentarily in the fissure-vein structure.

As a result of the combined action of the noted factors, information uncertainty or duality in decision-making about the true strength of weak and strong rocks arises between survey data and the RIS method. In cases, where boreholes[16] penetrate weak rocks, their strength is tested without taking into account consolidated rock remains separated from each other. However, in the vicinity of such boreholes within a radius of 5 to 50–100 m, the model of the city of Neryungri takes into account the cumulative influence of rock remains that fell in varying quantities into the sphere of influence of the HFVMD field, which leads to an overestimation of rock strength by an average of –7.69 % (Table 3). If boreholes accidentally hit hard rocks, testing their strength is done without volumetric accounting of the clayey material. The Neryungri model takes into account the influence of all clayey material dispersed along thin hairline cracks. As a result, strength estimates are underestimated by 21.98% (Table 3), i.e. almost three times stronger than in the case of overestimation of strength.

So, according to the results of verification of the model of the city of Neryungri, its errors in predicting estimates of the average strength of frozen sedimentary rock massifs in a water-saturated state are close to the errors allowed in laboratory estimates of the average strength of samples of rocky semi-rocky soils artificially saturated according to GOST 21135.2–84 [*1984*]. According to statistics, in most cases, i.e. with the reliability of solving the forecast problem equal to about 70%, the model errors barely exceed ±30%. With such accuracy, the model of the city of Neryungri is recommended to be used at all stages of engineering-geological surveys in areas of distribution of frozen strata of sedimentary rocks in order to zoning the built-up areas of Southern Yakutia according to the strength category of rocky semi-rocky soils.

CONCLUSION

Errors in the probabilistic assessment of the average strength of sedimentary rock masses in the predicted water-saturated state, studied at five verification sites of the Neryungri model, vary from ±16.8 to ±33.6% depending on the lithotype of sedimentary rocks and from ±21.9 to ±37.1% depending on the engineering-geological category of rock strength. In general, the average error rates with a probability of about 70% are equal to ±27.2 and ±30.1% and are close to the maximum permissible GOST 21135.2–84 [*1984*] laboratory error of ±20% in determining the average strength of samples of rocky semi-rocky water-saturated soils. This confirms the positive result of the representative verification of the model according to the following engineering-geological conditions for the construction and operation of engineering structures in the developed areas of the permafrost zone of Southern Yakutia:

1. Location – discontinuous island permafrost zone of Southern Yakutia and partly continuous on the border with the southern part of Central Yakutia.
2. The distance between verification sites is hundreds of kilometers.
3. Relief – terrain height 320–868 m.
4. Number of design and exploration boreholes – 338.
5. The depth of testing sedimentary rocks for strength is from 3–6 to 10–15 m.
6. The temperature of frozen sedimentary rocks in the lower part of the annual heat circulation layer at a depth of 10–15 m – from –0.1...–0.5 to –1.0... –4.0°C.
7. Lithotype of sedimentary rocks – sandstone, dolomite, limestone.
8. Depth of sedimentary rocks – from 2–3 m to 6–8 m or more.
9. Genesis and type of cover formations – Quaternary colluvium–eluvium, clayey eluvium of the ancient weathering crust, Quaternary dispersed sandy-clayey alluvial and lacustrine-marsh sediments.
10. Varieties of sedimentary rocks (rocky-semi-rocky) and the breadth of variability of their soil strength across all groups (from low to very strong).

The listed conditions are sufficient to prove the hypothesis about the regional status of the model of the city of Neryungri with the possibility of its application in areas of distribution of frozen sedimentary rocks of different temperatures at all stages of design and survey work in order to solve one of the

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[16] The location of boreholes is set by designers according to urban planning rules without prior knowledge of the geological structure of the engineering and construction survey areas, i.e., accidentally.

main problems of geomechanics in terms of zoning developed and subduing territories of the permafrost zone of Southern Yakutia according to the strength category of rocky-semi-rocky soils.

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References

Buldovich S.N., Melentiev V.S., Naumov M.S., Furikevich O.S., 1976. The role of recent faults in the formation of permafrost-hydrogeological conditions (an example of the Neryungri syncline of the Southern Yakutian Mesozoic Trough). *Merzlotn. Issled.* (Moscow, Moscow State Univ.) XV, p. 120–125. (in Russian)

GOST (State Standard) 21135.2–84. *Rocks. Methods for Determination of Axial Compression Strength.* Moscow, Izd. Standartov, 1984, 7 p. (in Russian)

GOST 25100–2020. *Soils. Classification.* Moscow, Standartinform, 2020, 38 p. (in Russian)

Grib N.N., Samokhin A.V., 1999. *Physico-Mechanical Properties of Coal-Bearing Rocks of the South Yakutian Basin.* Novosibirsk, Nauka, 240 p. (in Russian)

Kalinin V.M., Yakupov V.S., 1989. *Regional Patterns of Permafrost Behavior.* Yakutsk, Yakutsk Sci. Center, Siberian Branch of the USSR Acad. Sci., 144 p. (in Russian)

Kolomenskii N.V., 1956. *Engineering geology. Textbook for Geological Exploration Colleges.* Vol. 2, Part 2. Moscow, Gosgeolizdat, 320 p. (in Russian)

Kudryavtsev V.A.. (Ed.), 1975. *Southern Yakutia: Permafrost-Hydrogeological and Engineering-Geological Conditions of the Aldan Mining Region.* Moscow, Izd. Mosk. Gos. Univ., 444 p. (in Russian)

Kulaichev A.P., 2006. *Methods and Tools for Integrated Data Analysis.* Moscow, FORUM: INFRA-M, 512 p. (in Russian)

Lebedev V.F., Onushchenko V.I., Litvintseva L.M., 1991. *SEMZ system. A Methodological Guideline.* Krasnoyarsk, NPA Sibtsvetmetavtomatika, 83 p. (in Russian)

Levkovich A.I., 1989. *Methodology for Substantiation the Scope and Content of Engineering-Geological Surveys for Different Types of Industrial, Agricultural, and Residential Buildings and Structures on Permafrost with Consideration of Design Requirements.* Moscow, Gosstroy RSFSR, NPA Stroyizyskania, 173 p. (in Russian)

Melnikov V.P., Osipov V.I., Brouchkov A.V. et al., 2022. Development of geocryological monitoring of undisturbed and disturbed Russian permafrost areas on the basis of geotechnical monitoring systems of the energy industry. *Earth's Cryosphere* XXVI (4), 3–15.

Mokshantsev K.B., Gornshtein D.K., Gusev G.S. et al., 1964. *The Tectonic Structure of Yakut ASSR.* Moscow, Nauka, 240 p. (in Russian)

Neradovskii L.G., 2022a. A probabilistic model for predicting sands tone strength using electromagnetic induction sounding in the Southern Yakutian permafrost region: a case study in Neryungri. *Earth's Cryosphere* XXVI (6), 37–49.

Neradovskii L.G., 2022b. Assessment of the strength state of the rocky-semi-rocky foundation of engineering structures in the city of Neryungri in the permafrost zone of south Yakutia according to geophysical data (remote inductive sensing method). *Nedropolzovanie XXI Vek* 4 (96), 91–97 (in Russian)

Neradovskii L.G., 2023a. Approbation and verification outside the city of Neryungri of a probabilistic model for predicting the strength of sedimentary rocks. *Vestn. Evraziiskoi Nauki* **15** (4). https://esj.today/PDF/02NZVN423.pdf (in Russian)

Neradovskii L.G., 2023b. Internal verification of the accuracy of the probabilistic strength model of the rock-semi-rock foundation of engineering structures in one of the residential areas of Neryungri. *Vestn. Evraziiskoi Nauki* **15** (3). https://esj.today/PDF/21NZVN223.pdf (in Russian).

Neradovskii L.G., 2023c. Errors in average strength estimates of sedimentary rock masses in South Yakutia based on geometric induction sounding data. *Geoinformatika* 1, 48–62. DOI: 10.47148/1609-364X-2023-1-48-62. (in Russian)

Neradovskii L.G., 2023d. The accuracy of solution to the problem of forecasting the strength of sedimentary rocks by the method of remote inductive sounding in central Yakutia (Olen station). *Geofizika* 4, 50–57. (in Russian)

Neradovskii L.G., Osmushkin A.V., 2023. Retrospective analysis of the result of long-term change of sandstone strength in the built-up area of southern Yakutia (an example of District M in Neryungri). *Byull. Stroit. Tekhn.* 5 (1065), 14–17. (in Russian)

Recommendations for the Methodology of Developing Geophysical Schemes (Models) of Rock Masses in Concrete Dam Foundations. P 96-8, 1981. Leningrad, VNIIG, 113 p. (in Russian)

Recommendations for Studying the Static and Dynamic Characteristics of the Deformability of Rock Foundations of Hydraulic Structures in the Northern Construction-Climatic Zone (NCZ) Using Engineering Seismic Methods. P 19-85, 1985. Leningrad, VNIIG, 102 p. (in Russian)

Savich A.I., Yashchenko Z.G., 1979. *Study of Elastic and Deformation Properties of Rocks Using Seismoacoustic methods.* Moscow, Nedra, 214 p. (in Russian)

Shesternev D.M., 2001. *Cryosupergenesis and Geotechnical Properties of Permafrost.* Novosibirsk, Izd. Sib. Otd. Ross. Akad. Nauk, 266 p. (in Russian)

Syasko A.A., Grib N.N., Skomoroshko Yu.I., Nikitin V.M., 2004. *Technology of Geological and Geophysical Study of Coal Seam Outcrops in the Permafrost Zone.* Yakutsk, YaF GU SB RAS, 160 p. (in Russian)

The System for Medium-Frequency Electromagnetic Sounding (SEMZ). Technical Specification, 1991. Krasnoyarsk, NPO Sibtsvetmetavtomatika SSSR, 30 p. (in Russian)

Titlinov V.S., Zhuravleva R.B., 1995. *Technology for Distance Inductive Soundings.* Ekaterinburg, Nauka, 56 p. (in Russian)

Vakhromeev G.S., Davydenko Yu.A., 1987. *Modeling in Exploration Geophysics.* Moscow, Nedra, 1987, 192 p. (in Russian)

Vapnik V.N., Chervonenkis A.Ya., 1974. *Pattern Recognition Method.* Moscow, Nauka, 416 p. (in Russian)

Voronkov O.K., 2009. *Engineering Seismics in Permafrost Regions (Study of the Structure and Properties of Frozen and Thawed Rocks and Masses).* St. Petersburg, Vedneev VNIIG, 401 p. (in Russian)

Zheleznyak M.N., 2015. *Geothermal Field and Permafrost in the Southeast of Siberian Platform.* Novosibirsk, Nauka, 227 p. (in Russian)

Zhelinsky V.M., 1980. *Mesozoic Coal-Bearing Formation of Southern Yakutia.* Novosibirsk, Nauka, 119 p. (in Russian)

Zhelinsky V.M., Korobitsyna V.N., Karimova S.S., 1976. *Mesozoic Sediments and Genetic Types of Coal Seams in Southern Yakutia.* Novosibirsk, Nauka, 126 p. (in Russian)

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