Preprints.org

Article

Not peer-reviewed version

Substantiation of the Monitoring Network of Talik Zones in Urbanized Permafrost Areas Based on GPR Profiling Data (Aanadyr, Chukotka)

Oleg D. Tregubov * and Konstantin K. Uyagansky

Posted Date: 27 May 2024

doi: 10.20944/preprints202405.1722.v1

Keywords: Arctic urbanization, adaptation to climate change, GPR, permafrost monitoring.

Article

Substantiation of the Monitoring Network of Talik Zones in Urbanized Permafrost Areas Based on GPR Profiling Data (Aanadyr, Chukotka)

Oleg D. Tregubov [1,*] and Konstantin K. Uyagansky [2]

[1] Northeastern Integrated Research Institute of the Far Eastern Branch of the Russian Academy of Sciences, Anadyr, 689000
[2] Northeastern Integrated Research Institute of the Far Eastern Branch of the Russian Academy of Sciences, Anadyr, 689000, uyagansky@yandex.ru
* Correspondence: tregubov2@yandex.ru

Abstract: Modern climatic changes have an impact on the bearing capacity of permafrost soils at the base of the foundations of buildings and structures in the urbanized territories of the Arctic and Subarctic. The activation of cryogenic processes leads to the destruction of the infrastructure of human settlements and, as a result, to social, economic, environmental consequences for the population. Based on the results of geothermy of frozen and thawing soil, GPR profiling of the territory of the city of Anadyr, it was concluded that the main risks of permafrost degradation are associated with the spread of hydrogenic melt zones. Maps of soil temperature in imaginary cross-sectional with a depth of 3, 5 and 10 m were compiled; maps of the capacity of thawing soils and the permafrost aquifer; a map of zones of dangerous spread of exogenous cryogenic processes. A permafrost monitoring system in the territory of Anadyr has been substantiated, which will consist of an automated network of observations of soil temperature in 35 wells at the border and at the epicenter of 20 zones of dangerous development of exogenous cryogenic processes and 12 control GPR profiles at the intersection of linear hydrogenic taliks.

Keywords: Arctic urbanization; adaptation to climate change; GPR; permafrost monitoring

---

1. Introduction

The International circumpolar active layer (CALM) and permafrost temperature (GTN-P) monitoring systems in the natural landscapes of the Arctic and Subarctic have shown their effectiveness and viability. The results of the observations are in demand by analysts and researchers of the impact of climate warming on permafrost. At the same time, changes in the permafrost of settlements have been practically ignored by scientists. The ongoing researches, as well as long-term observations of permafrost parameters in cities, are not systematic. They are carried out by initiative groups of scientists without proper funding and a long-term perspective. It is believed that monitoring the state of permafrost in urban cities and towns is not directly related to fundamental science and is an applied research.

The purpose of this article is to substantiate new approaches to the organization of permafrost monitoring in urbanized areas. To do this, it is proposed to analyze the results of our work on the organization of a network of observations of dangerous exogenous cryogenic processes in Anadyr. An important part of the article is the analysis of recent publications devoted to the study of permafrost formation processes in anthropogenic landscapes, applied research methods, as well as the peculiarities of the impact of climate change on the urban environment in the cryolithozone. The introductory part of the work also presents a critical analysis of the existing approach to the organization and management of geotechnical monitoring of permafrost in populated areas. The description of the research object is given from the point of view of the suitability of Anadyr for the introduction and testing of new approaches to monitoring permafrost and assessing the impact of climate change on the urban environment. When describing dangerous ground warming zones identified by GPR profiling, remarks are made about their genesis, seasonal dynamics and evolution. The article concludes with the authors' proposals on the regulations for monitoring and the network for the placement of observation wells and control geophysical profiles in Anadyr.

2. Statement of Problem

About 5 million people live in 1,162 settlements in the circumpolar permafrost region. Of these, 3.3 million live in areas where there is active degradation of permafrost caused by climate warming [1–3]. The main threats to the population are breakage and permanent disruptions to the functioning of residential, energy and transport infrastructure. According to independent estimates in the Arctic and Subarctic, the loss of bearing capacity of building foundations, depending on the time of their construction and the rate of climate warming, is 12-40% [4,5]. Model calculations show that with the warming of permafrost from -4 to -1 oC in the 21st century, the loss of bearing capacity of pile foundations will reach 75% [3].

The restoration of infrastructure in the cryolithozone will require significant financial expenditures from the governments of circumpolar states [4,6]. At the same time, the existing forecast permafrost-climate models take little account of the specifics of the geocryological conditions of urbanized territories [4]. Therefore, it is difficult to plan the real amounts of material and financial costs necessary for the complete reconstruction of the infrastructure. Thus, the most optimal option at this stage of uncertainty is to adapt the existing infrastructure of populated areas to current climate changes [7]. To do this, it is necessary to establish a systematic monitoring of the permafrost conditions of cities and towns, focused on stopping the threats of expanding ground thawing zones, destruction of buildings, utilities and road surfaces [8].

Researchers of the influence of climate warming on the permafrost roof in natural landscapes, along with an increase in the thickness of the active layer, pay attention to the threat of subsidence of the Earth's surface associated with the melting of shallow underground ice [9,10]. The subsidence of the surface is a consequence of thermokarst, which is described in classical scientific works on geocryology and is extremely uneven in space [11,12]. In natural landscapes, the result of thermokarst on flat terrain is the formation of swamps and shallow lakes, and on mountain slopes - linear melting zones, which represent groundwater runoff routes. In addition to low-mountain landscapes, linear thermokarst is typical for marine and river terraces [13–18]. On the surface, taliks usually correspond to depressions and shallow ravines with drying streams [16,19]. The thickness of the subaerial and subaqual talic zones is usually 5-12 m, but can reach 18-20 m [4,14,15]. Infiltrating atmospheric precipitation, melt water from underground ice and condensation waters are the source of nutrition for the suprapermafrost waters of taliks [20]. The formation and runoff of condensation waters in the active layer of mountain-tundra landscapes of the cryolithozone is one of the main sources of nutrition for rivers and groundwater [21]. In the conditions of the rugged relief of the slopes and the mosaic structure of the cryolithological basis of the landscape, talic zones form a complex structure [4,17,18]. By changing the configuration of the boundaries, hydrogenic talic zones thaw out arrays of frozen soils, but not from the surface as with the radiation-convective effect of the atmosphere, but along the front of their expansion and deepening. Most populated areas in the Arctic and Subarctic are located on sea and river terraces, as well as on the slopes of low mountains.

In cities and towns, the situation with the formation and functioning of Talik zones is aggravated by a number of factors:

1. A general increase in the temperature of frozen soils and an increase in the power of the active layer due to disturbance of the soil and vegetation cover and the formation of a newly formed layer of "warm" permafrost in the soils of the filling of construction sites [22,23].

2. A general increase in the background temperature of the surface air layer (UNI)[1], salinization of soils and groundwater.

3. Increased freezing of the upper layers of permafrost in winter in places where snow is cleared on roads, sidewalks and squares [4].

4. Reducing the intensity of thawing of the active layer in the summer in the ventilated underground of buildings on pile foundations [24]. A decrease in the temperature of frozen soils in winter and the formation of an ice curtain around the perimeter of buildings that are equipped with thermostabilizers [25].

5. The formation of talik zones during the leveling of the urban terrain surface and the filling of ravines and swamps with soils.

6. An increase in the permafrost runoff of groundwater due to the formation and filtration of condensation waters in voids and dispersed soils of the active layer, as well as due to water leaks from engineering networks, wet cleaning of road surfaces in the summer.

[1] Urban Heat Island (UHI)

In such an environment, the expansion of existing and the formation of new talik zones in urbanized territories is the main threat of thawing of the frozen soil of the foundations of buildings and structures. The authors of the works [4,18,26] also came to such conclusions.

It is difficult to predict the development of talik zones in natural and anthropogenic landscapes using climate modeling. This is due to the fact that the dynamics of the hydrogenic talik with current climate changes is indirectly related through intermediate links of climatic and cryohydrogeological processes [1,14,16,18]. Therefore, in order to predict the impact of the dynamics of talic zones on the stability of foundations of buildings and structures, comprehensive monitoring of the physical and spatial characteristics of thawed and thawing grounds is necessary, followed by statistical modeling of dangerous exogenous cryogenic processes.

H.M. French talik refers to the unfrozen ground located between the layer of seasonal freezing and the upper surface of permafrost rocks [27]. In another definition, only thawed areas of permafrost surrounded by frozen grounds are classified as talic zones. Other definitions of taliks are also known, in which the authors focus on certain aspects of their formation or the physical parameters of thawed soil [28]. Therefore, it is necessary to clarify which taliks pose a threat to the infrastructure of populated areas and require monitoring.

1. The talik zone bounded by permafrost from below consisting of thawed or cooled plastically frozen soils with temperatures above the freezing point of soil loosely bound water (>Tbf). For soils of sandy-clay composition, the freezing point Tbf is usually in the range from -0.3 to -1.5 °C [29].

2. Buried unfrozen or thawed to temperatures of Tbf and above, the former frozen soil, which contains an excess of hygroscopic moisture, loosely bound and free water.

3. Subaerial talik zones, bounded at depth and along the flanks by permafrost and overlain atop by a layer of seasonal freezing. In plan and section, such taliks have the shape of a buried mulda.

4. Hydrogenic talic zones with groundwater aquifers having a feeding and unloading area, hydrostatic and cryogenic pressure.

As can be seen, the main property of talik zones, which pose a danger to the infrastructure of settlements, is their ability to transfer accumulated or incoming heat from the atmosphere to the surrounding permafrost soil in a convective-conductive way. Unfrozen soils, deep-lying cryopags, as well as the taliks of temporary artificial earth embankments do not pose a danger to the frozen soils of the base.

Significant advances in the study of morphology and electrophysical properties of soils of talik zones have been achieved using a complex of nearsurface geophysical methods [14,15,17,23,26,30,31]. It is important to note that even 20-15 years ago, nearsurface geophysics was used exclusively as an auxiliary method in conducting engineering surveys for construction and in geological exploration of mineral deposits [32–36]. In the last decade, geophysical methods have been increasingly used as independent ones, for which drilling of reference and test wells is an auxiliary method. The peculiarity of such studies in the cryolithozone is that they allow detecting signs of cryogenic processes (thawing and freezing, watering, thermokarst, frost heaving, solifluction, cryogenic salinization). In addition, it is possible to conduct repeated seasonal and interannual geophysical research in order to study the spatial and temporal dynamics of cryogenesis [26]. In the detailed study of nearsurface sections of the permafrost roof, tomographic geophysical methods have priority [23,26]. Subsurface georadolocation sounding methods (GPR) are used for in-line inspection of vast territories with the separation of thawed and frozen soils, underground ice and aquifers in the context of the boundaries [34,37,38]. In an urban environment, the use of individual electrical and seismoacoustic methods is limited by interference from reinforced concrete slabs of road surfaces, as well as the presence of various kinds of physical noise [30]. Therefore, the most optimal for surveying the territory of settlements is GPR profiling on a scale that allows you to identify and track in space a talic zone with a width of 5 m or more with a depth resolution of 0.25-0.5 m. This result can be achieved by combined GPR profiling with a sensing frequency of 150-400 MHz [30]. Together with GPR profiling, it is advisable to use drilling materials for reference and test wells, and data from measurements of soil temperature in them [22,38].

Currently, there are no unified ideas about the organization of monitoring the state of permafrost in cities and urban-type settlements in the cryolithozone. The most famous paradigm of engineering and geological monitoring was in the USSR. The essence of the paradigm is to continue measuring the temperature of the soil at the base of the foundations of buildings in the observation wells of construction monitoring by the decision of the building owner or by order of the supervisory state structures in the field of construction control [39]. In modern realities, this is the creation of an automated network of measurements of ground temperature on the basis of existing and newly drilled observation wells along the perimeter of buildings. The greatest success in creating such a geotechnical monitoring system was achieved in Salekhard [40]. What are the advantages, disadvantages and fundamental error of this

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 27 May 2024 doi:10.20944/preprints202405.1722.v1

approach? The advantage of this monitoring system is the availability of proven methods, equipment, measurement rules and interpretation of the data obtained. Among the disadvantages of the conservative approach to the organization of monitoring the state of permafrost in urbanized areas, we note:

1. The aggregate data of monitoring the soils of the foundations of individual buildings represent only a statistical assessment of the degradation of permafrost at the base of the foundations of buildings in the city and do not allow to establish the causes of thawing of permafrost. A time series of temperature measurements makes it possible to record the beginning of warming of the soils of an individual building and, accordingly, predict the timing of loss of the bearing capacity of the foundation, rather than prevent the beginning of permafrost degradation.

2. The data of temperature observations do not reflect the dynamics of the permafrost conditions of the territory of the settlement as a whole, taking into account the open spaces of undeveloped areas. In essence, such monitoring is the control of the temperature of the "islands of cold permafrost" in the urban area. The measured temperatures at the base of the foundations without special filtration and disassembly are not suitable for spatial modeling of the permafrost conditions of the settlement as a whole.

3. Road infrastructure, energy networks, and centralized sewerage are outside the monitoring of permafrost conditions. The results of the observations do not provide the possibility of a long-term forecast of permafrost degradation with appropriate planning of preventive measures.

The fundamental error of the described approach to monitoring permafrost conditions is as follows. The main provisions of geotechnical construction and functional monitoring were developed in the twentieth century in the absence of significant trends in climate warming. The source of thawing of frozen soils at the base of the foundation was supposed to be the controlled building itself due to incorrect design or construction decisions, violations of the requirements for the operation of the building. In modern conditions, the source of warming in relation to the building is external. These are cryohydrogeological processes caused by the complex interaction of climate change and the infrastructure of the settlement. Accordingly, in our proposed concept, talik zones and the boundaries of their distribution are subject to control and geotemperature monitoring. Monitoring of soil temperature at the base of foundations remains a priority, but occupies the second level in the system of permafrost monitoring of urbanized territories. Such observations begin when the front of the thawing of frozen soils approaches the base of the foundation of the building.

Let's summarize the results of this section of the article. The problem of disruption of the infrastructure of settlements in the cryolithozone of the northern hemisphere due to climate warming is more urgent than ever. It is necessary to examine urbanized territories without delay in order to identify dangerous zones of development of exogenous cryogenic processes that pose a threat to the foundations of buildings and structures, followed by the organization of a temperature monitoring system and the boundaries of the spread of taliks. Existing approaches to geotechnical operational monitoring of buildings are not suitable for monitoring the territory of cities and towns as a whole, as they are focused on the safety of individual buildings and structures or their individual categories. Modern monitoring systems should be based on a landscape approach that takes into account the unity of lateral connections of cryohydrogeological processes affecting the bearing capacity of foundation soils. The most rational and effective method of mapping talik zones in urbanized territories is GPR profiling in combination with drilling of verification wells and measurements of soil temperature in the surveyed area. To promote the proposed approaches and methods, their coverage and open discussion are necessary.

3. Studied Object

Anadyr is the administrative, logistical and cultural center of the Chukotka autonomous district (Russia), located on the right bank of the Anadyr estuary, which belongs to the Bering Sea basin (Figure 1).

The city is located on the northeastern edge of the Anadyr lowland within the boundaries of the southern shrub tundra. In relief, the building area occupies the southern and eastern slopes of the mountain with the peaks of Verblygiy (116.5 m) and Alexandra (131.2 m). From the north, the city is bounded by the rocky cliffs of the Anadyr estuary, from the southeast by the floodplain of the Kazachka River. The permanent population of the city as of 2023 is 12,998 people. In summer, due to seasonal workers and tourists, the number of residents increases to 17 thousand people.

The climate of the Anadyr lowland is subarctic marine, turning in a northwesterly direction into temperate continental. Climatic conditions are formed under the influence of cyclones penetrating from the Bering and Okhotsk Seas, as well as anticyclones that come from the Arctic and northern Asia. The main indicators of climate and changes in their values in the XI century are shown in Table 1.

The city is located on the northeastern edge of the Anadyr lowland within the boundaries of the southern shrub tundra. In relief, the building area occupies the southern and eastern slopes of the mountain with the peaks of Verblygiy (116.5 m) and Alexandra (131.2 m). From the north, the city is bounded by the rocky cliffs of the Anadyr estuary, from the southeast by the floodplain of the Kazachka River. The permanent population of the city as of 2023 is 12,998 people. In summer, due to seasonal workers and tourists, the number of residents increases to 17 thousand people.

Figure 1. The city of Anadyr in a satellite image in the Beringian sector of the Arctic and in a photo from a UAV.

The climate of the Anadyr lowland is subarctic marine, turning in a northwesterly direction into temperate continental. Climatic conditions are formed under the influence of cyclones penetrating from the Bering and Okhotsk Seas, as well as anticyclones that come from the Arctic and northern Asia. The main indicators of climate and changes in their values in the XI century are shown in Table 1.

Table 1. Calculated climate indicators for the years 1960-1990 and 1991-2021 according to the observations of the Anadyr weather station.

Climate indicators	Average annual air temperature, °C	Average air temperature of the cold period (X-V), °C	Average air temperature of the warm period (VI-IX), °C	Annual precipitation, mm	Duration of the warm period, days
1990	-7.7	-15.2	7.2	312	124
2021	-6.2	-13.7	8.8	382	132
Changes in 30 years	+1.5	+1.5	+1.6	+70	+8

With an obvious warming of the climate and an increase in its humidity, it should be noted that the interannual fluctuations in the average annual air temperature reach 2 ° C, the interannual amplitude of precipitation is 200 mm, and the duration of the frost-free period varies by an average of 5 days.

Anadyr is located in a zone of continuous permafrost distribution. The thickness of permafrost rocks is 100-120 m. The temperature of permafrost in undisturbed conditions varies from -5 to -2 °C depending on the relief and age of frozen ground. The depth of seasonal thawing in the tundra landscapes of the Anadyr lowland varies between 0.45-0.65 m. Over the past 25 years, it has increased by 30% [41]. In floodplains and on mountain slopes, the thickness of the active layer is 1-1.5 m.

The urban development is located on the terraced slopes of the mountain (Figure 2). The uplands are volcanic-tectonic protrusions of sedimentary and volcanic rocks of Late Cretaceous, Paleogene and Neogene ages. These are siltstones, andesites and basalts. Along with the rocks of intrusions and lavas, fragile tuffs and breccias of various genesis are often found in geological sections. Glacial, lacustrine, and marine Late Pleistocene deposits are found by

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 27 May 2024 doi:10.20944/preprints202405.1722.v1

drilling in depressions and deep cuts to the Quaternary volcanic buried relief. The upper part of the geological section is composed of deluvial-colluvial, solifluction and proluvial-alluvial deposits.

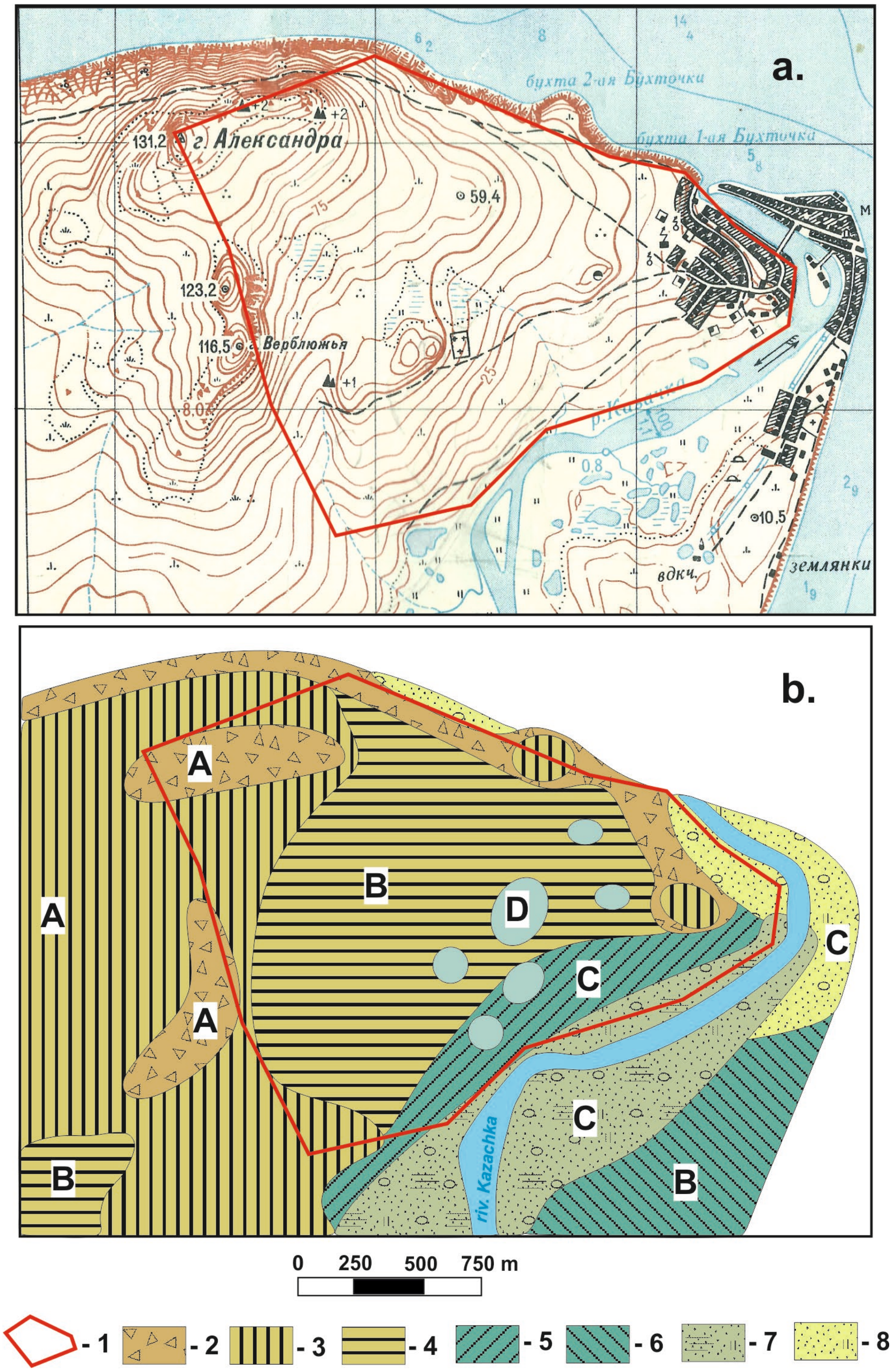


Figure 2. Geomorphologic and permafrost-hydrogeological conditions of the territory of Anadyr before construction: a - fragment of a topographic map on a scale of 1:25000 (1953); b - scheme of permafrost-hydrogeological zoning [42]. 1- modern territory of the city, 2 - igneous rocks of basic and medium composition, 3 - deluvial-colluvial and deluvial-solifluction deposits,4 - glacial and water-glacial deposits, 5 - marine sediments of the Late Pleistocene, 6 - marine and continental deposits of the Holocene, 7 - modern alluvial deposits, 8 - modern marine sediments. Groundwater: A - seasonal near-surface waters with atmospheric nutrition, B - permanent aquifer with atmospheric-groundwater replenishment, C - permanent aquifer with groundwater nutrition, D - suprapermafrost groundwater of stagnant type.

The modern territory of Anadyr was mostly built up in the 80s and 90s of the last century. The pre-construction relief was characterized by the presence of high moor, ravines (tributaries of the Kazachka River), altiplanation terraces and watersheds (Figure 2a). Currently, this surface is buried by a layer of technogenic soil with a thickness of 1 to 15 m. The results of engineering surveys for construction were summarized in the permafrost-hydrogeological zoning scheme of 1991 (See Figure 2b). The authors identified four hydrogeological zones that differ in the conditions of feeding and runoff of suprapermafrost waters [42]. This diagram shows engineering and geological areas that differ in the geological structure of permafrost sections (See Figure 2b).

The temperature of the frozen ground before the start of construction at a depth of 10 m varied from -4.4 – (-3.8) ° C in the upper part of the mountain slope to -2.6 ° C at the mountain foot. At the bottom of the gorges, the temperature of frozen soils reached -1.5 °C. In general, the builders noted a relatively low ice content of dispersed soils (up to 40%) with a wide variety of types of underground ice: lenses and layers of segregation ice; vein ice in cracks of rocks; buried reformed ice wedges in lake and marine sediments. In 1985-1990, 4 talik zones of natural and man-made genesis were discovered and surveyed using geophysical methods (VES) and drilling. Two 5-storey buildings built in a passive way (I principle of construction on permafrost) were recognized as emergency and demolished.

In 2003-2007, a large-scale reconstruction of the urban infrastructure was carried out. Utility networks, road surfaces of streets and courtyards have been replaced, dilapidated buildings have been demolished, ventilated basements of buildings on pile foundations have been cleared. The practice of weekly cleaning of Anadyr from snow with the removal of solid precipitation outside the city limits has been established. The foundations of deformed buildings were reinforced with metal ties and equipped with thermostabilizers. The measures taken had a positive impact on the stabilization of permafrost conditions even during intense climate warming (1998-2007). According to the materials of engineering surveys of these years, the power of the active layer in the open space from the building has stabilized within 1.2-1.4 m. But already in 2018, there was an increase in the number of deformations on roads and concrete surfaces under buildings on pile foundations as well as in adjacent territories (Figure 3a). The number of icing field has increased; the time and place of their formation have changed (Figure 3b). All this pointed to the result of the influence of climate warming on the activation of thermokarst and the expansion of the boundaries of talik zones.

Currently, the area of the city is 3.45 km2. The residential area covers 1.4 km2, the territory occupied by a power plant, construction, agricultural enterprises, as well as warehouses for various purposes in the northern and southern parts of the city accounts for 1.2 km2. The rest of the territory is waste ground. There are 223 residential and administrative buildings in the city, built with preservation of permafrost, on a pile foundation with ventilated underground. Of these, 155 buildings (70%) have 5 floors. There are 19 buildings equipped with thermostabilizers. Of the 172 observation wells preserved from construction geotechnical monitoring, 14 are flooded with water, 54 are filled with ice[2]. According to ground subsidence and temperature measurements in wells, it is known about permafrost thawing under 17 buildings. The total number of seasonal icing field with an area of 75-4500 m2 is unstable and varies from 4-6 to 12-18. Subsidence of soil and concrete coverings is confined to the underground of buildings, roadsides and roadways and sidewalks.

[2] The requirements for observation wells in the cryolithozone in force in the USSR did not provide for mandatory sealing of the casing base. Even a single thawing of frozen soils at the bottom leads to the filling of open wells with pressurized groundwater.

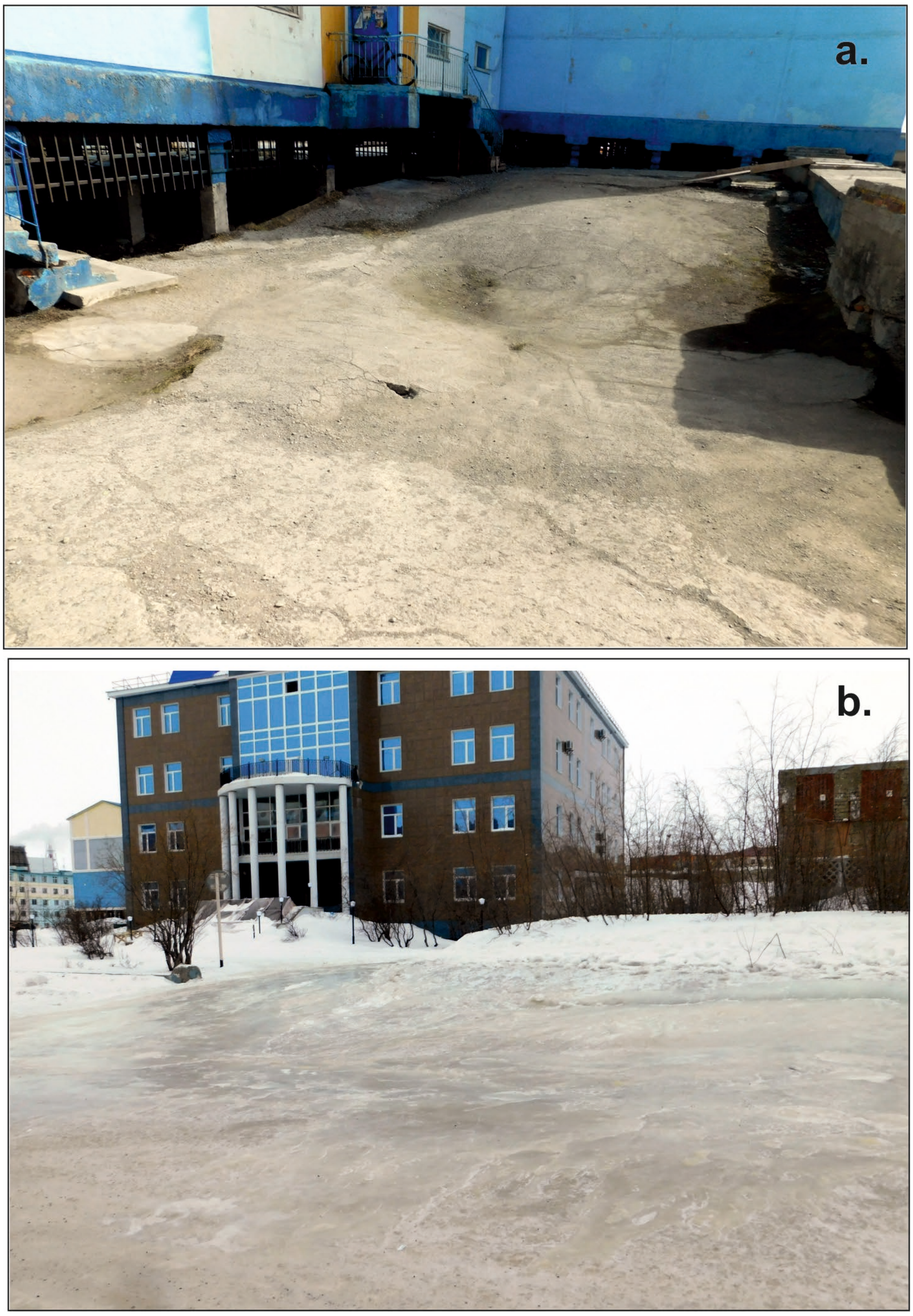


Figure 3. Demonstration of cryogenic processes on the territory of Anadyr: a - thermokarst subsidence (1.2 m) of concrete pavement; b - groundwater icing.

According to the landscape position, relief, infrastructure, nature and degree of impact of climate change on permafrost, Anadyr is an ideal object for the implementation and testing of a monitoring system for urbanized territories. Using the example of Anadyr, it is obvious that in conditions of a warming climate, permafrost geotechnical monitoring, which relies on monitoring the thermal effects of talik zones external to the foundations of buildings, will be the most effective. The active spatial and temperature dynamics of the talik zones of the city will make it possible to develop monitoring technologies, interpret data and forecast changes in permafrost conditions in a short period of time.

4. Research Methods

The main research methods were GPR subsurface sounding and geothermy of the upper permafrost layers. The physical foundations of the methods are described in the specialized literature [43,44]. The application of geophysical

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 27 May 2024 doi:10.20944/preprints202405.1722.v1

methods in engineering geology is regulated by documents [32,37]. When planning geophysical research, we took into account the methodological developments of the use of ground-penetrating radar in the cryolithozone, which researchers share in scientific articles [17,22,23,26,30,31,34,36,37,45].

However, in the selection of equipment, in the selection of parameters for GPR sounding and area survey, we were primarily guided by our own experience of geophysical work in Chukotka within the framework of engineering surveys and scientific research. The most fully applied methodological techniques are reflected in the work [46]. The adopted approach is based on the rejection of drafting cross sections with the display of exclusively electrophysical properties of the medium. The reason for this is the well-known dependence of the values of electrophysical parameters on the current physical properties of the sections (temperature, ice content and ground moisture) and uncertainty in the geological interpretation of the layers. The concept we have chosen is based on the use of reference geological and geophysical sections in the interpretation of radarograms, compiled using well columns and temperature measurements in them, definitions of ice content and ground moisture [46]. The number of reference sections used is determined by the geological and geocryological diversity of the mapped area. Subsequently, the results of the interpretation of radarograms are selectively certified by control wells.

The studies were conducted between October 2021 and April 2024. Oko-2 and Oko-3 radars with antenna blocks at frequencies of 400 and 250/700 MHz were used for GPR profiling. The main frequency of the probe was 250 MHz. An antenna unit with a frequency of 400 MHz was used as an additional one when profiling the boundaries of taliks in hard-to-reach places. The technical specifications of the devices can be found on the manufacturer's page [47]. In the conditions of the permafrost of Anadyr, when probing sites in the autumn-winter period, the devices demonstrate the following capabilities:

- 400 MHz - maximum detection depth 9-11 m, resolution 0.15-0.25 m;
- 250 MHz - maximum detection depth of 17-20 m, resolution 0.3-0.5 m.

GPR profiling was carried out in continuous mode, with a step of 300 mm, with a dielectric constant of the medium (Ɛ) 8, with an accumulation of 16 and a sweep of 200. The length of the profiles from 50 to 150 m, the number of trails from 1000 to 3000, was determined in advance depending on the conditions of the building of the territory. An important part of the work was the planning of profiles in order to evenly cover the area with GPR sensing points. The density of the city's development made it possible to provide details corresponding to the scale of geophysical work 1:10000 (720 points/km2).

The primary processing of radar images was carried out using the GeoScan32 program (2023.01.27.728) [48]. The processing of radarograms included:

1. Transformation the hardware length of the profile to its true length, setting the depth scale to zero, adjusting the profile gain in depth.
2. Filtering of re-reflected waves and air interference. Hyperbola refinement of the dielectric constant of soils, as well as the velocity of reflected waves along the length and depth of the GPR sensing profile.

Within the framework of the tasks of this work, the hypsometric position of the beginning and end of the profiles has not been determined. After initial processing, the radarograms were interpreted by highlighting and clarifying the physical characteristics of the layers, the boundaries of which were drawn along the axes of in-phase and along the bands of a sharp change in the wave pattern. 5 reference geological and geophysical sections were used in the interpretation of radar images. To make a map of the distribution of talik zones within the city, the following boundaries were identified on geological and geophysical sections: the sole of the seasonal thawing-freezing layer; the roof of the permafrost layer. If there are signs of groundwater spreading, the boundaries of the suprapermafrost aquifer and its thickness were determined. The rest of the information available on the radarograms was not used in this study. It should be noted that the upper part of the geological and geophysical sections (permafrost roof) is rather monotonous in its physical properties and genesis (Figure 4). The active layer with a thickness of 1.5 to 4 m, is replaced with a depth in cutting by thawed and plastically frozen sandy-clay soil with a thickness of 0.5 to 6 m. Frozen sandy-clay and gravelly ground lie beneath them. Frozen bedrock lies at the base of the sections at depths from 3 to 20 m from the surface. Aquifers are fixed in the thawed soil of the active layer, in thawed sandy-clay deposits, including on the border of permafrost ground.

Further, the numerical values of the section parameters (depth and thickness of the layers) were taken manually, which were entered into a spreadsheet. The rejection of automatic data reading and the formation of spreadsheets, spatial modeling provided by the GeoScan32 program is due to the large size of the data array and the inevitable errors associated with the omission of anomalies or, conversely, their excessive detail. In manual mode, each profile was analyzed individually: small in width (up to 5 m.) anomalies – ignored; the wide and deep anomalies – digitized in

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 27 May 2024 doi:10.20944/preprints202405.1722.v1

more detail. The matrix of the spreadsheet included columns with the number of the sounding profile, the rectangular coordinates of its location (X, Y), the values of the thickness of the seasonal thawing layer, the depth of the permafrost roof and the thickness of the permafrost aquifer.

To measure the temperature in the wells, 4-channel devices for automatic registration of U12 temperature values from the Hobo Offset manufacturer were used. This logger data (U12) has proven itself well in monitoring the temperature of the permafrost roof within the framework of the international CALM and GTN-P programs. The accuracy of temperature measurements is hundredths of a degree Celsius. During the work, 4 devices were used. In accordance with the depth of the observation wells and the length of the casing heads, the devices were equipped with cables[3] 7.5, 10, 11.5 and 20 m long. The temperature sensors were located at intervals of 1.2, 1.5, 3 and 5 m. The algorithm of operation was adopted as follows:

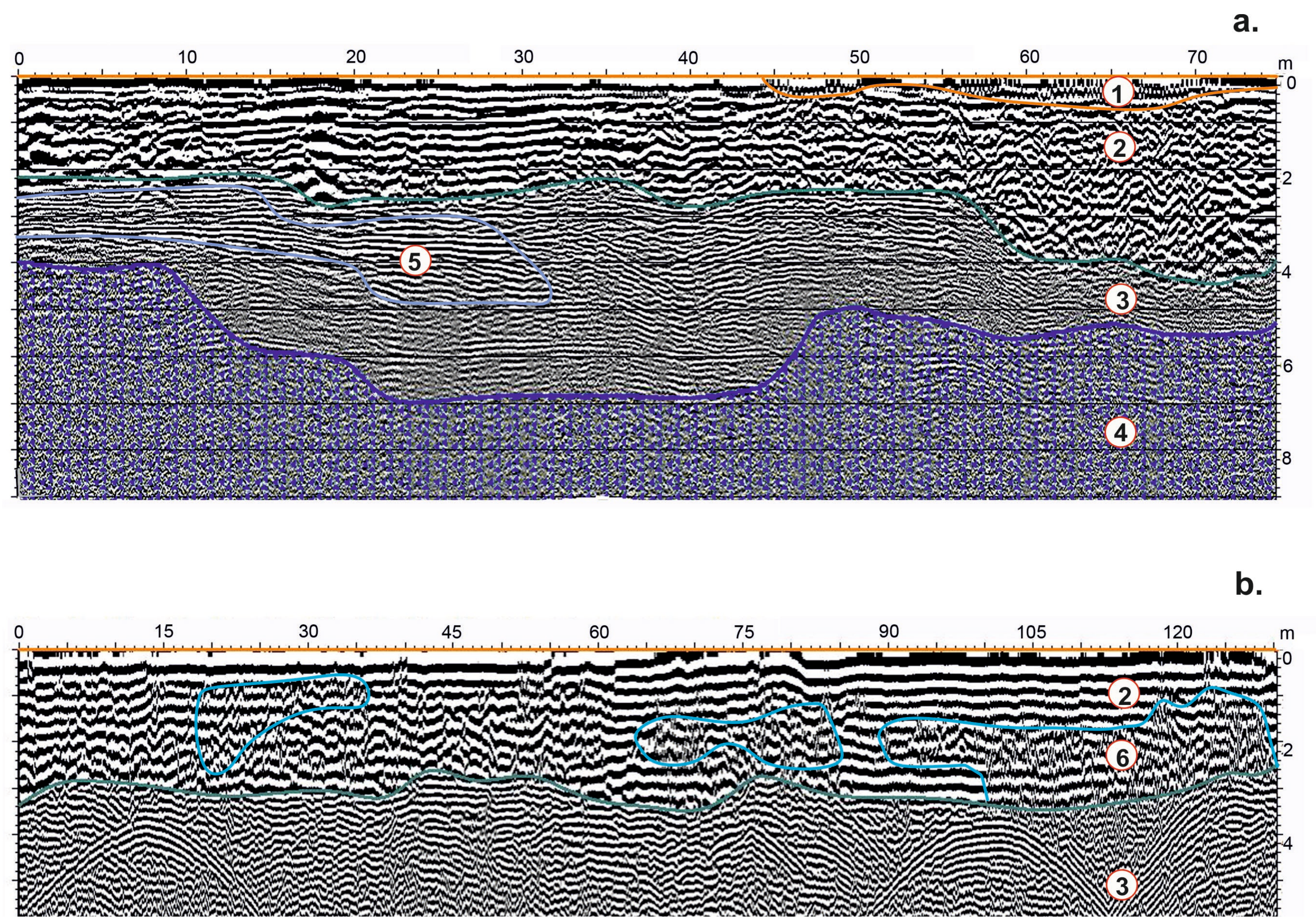
1. The condition of the well, depth and suitability for measurements were determined in advance. A catalog of wells suitable for measurements (86 in total) was compiled, indicating the address of their location and depth. Wells with a depth of less than 5 m, as well as those located inside the underground of buildings or near thermosiphons, were rejected.

2. In November, under favorable weather conditions, at the beginning of the working day, logger programs were launched in temperature registration mode after 1 minute. Thermistor chains of different lengths were installed in wells of the appropriate depth for measurements for 20-30 minutes (temperature stabilization time). The field log recorded the time of installation and removal of the logger from each well.

3. At the end of the working day, the recording was stopped, the data was saved in a file with the appropriate date and time. Then, in accordance with the records of the measurement time in the log, the temperature of the ground at the appropriate depth was determined. The measured parameters were entered into a spreadsheet. After the end of the measurements, the measurement data was recalculated in accordance with the temperature gradient for depths of 3, 5 and 10 m.

[3] Thermistor chain

 doi:10.20944/preprints202405.1722.v1



Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 27 May 2024 doi:10.20944/preprints202405.1722.v1

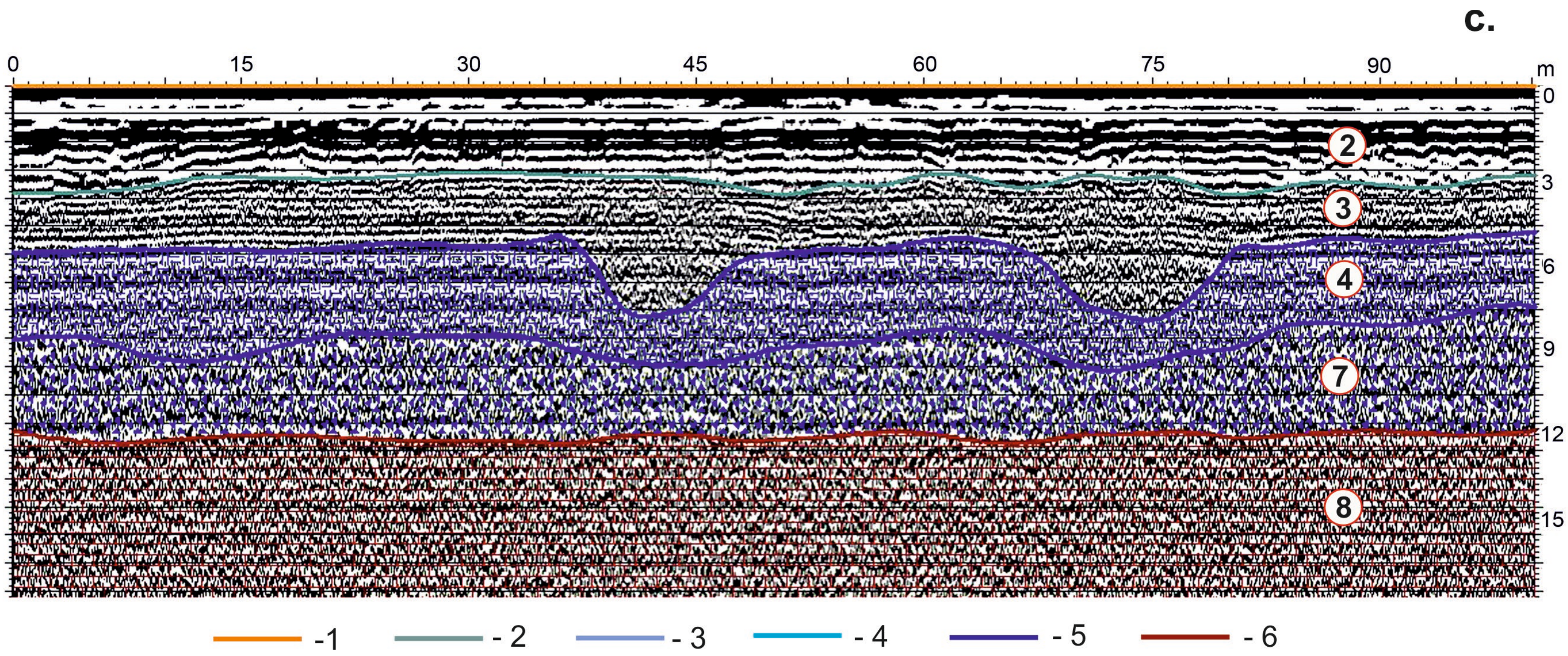


Figure 4. Typical examples of recognition of radargrams GPR profiling: a - section with subsidence and residual permafrost in a seasonally thawed layer (AB 400 MHz); b - section with groundwater in the active layer (AB 400 MHz); c - section along the side of the talic zone (AB 250 MHz). Boundaries in section: 1 - surface earth, 2 - soles of the seasonal thawing layer (freezing), 3 - lenses of residual frozen soils; 4 - aquifer in the active layer; 5 - roofs of frozen soils of various compositions; 6 - frozen rocks. Figures in circles: 1 - subsidence of reinforced concrete slabs in the active layer (ε = 3-4)[4]; 2 - technogenic soil in the active layer (ε = 4-6) ; 3 - thawed and plastically frozen watered sandy-clay deposits (ε = 16-18); 4 - frozen icy (20-40%) sandy-clay deposits (ε = 9); 5 - frozen strongly icy (>40%) sandy-clay soil (ε = 8); 6 - aquiferous gravelly-sandy technogenic soils (ε = 8-11); 7 - frozen strongly icy (>40%) gravelly deposits (ε = 8); 8 - frozen basalts and andesites (ε = 9).

[4] ε - Dielectric constant

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 27 May 2024 doi:10.20944/preprints202405.1722.v1

The result of processing geothermal data was a spreadsheet in which well numbers, rectangular coordinates (X, Y) and soil temperature values as of November for depths of 3, 5 and 10 m were indicated in columns. An important problem of geothermal research has become the uneven distribution of observation wells over the area of the city. For this reason, the southern outskirts of Anadyr (about 20% of the area) were excluded from the general territory of geothermal research. The density of observation points within the boundaries of spatial modeling of ground temperature was about 32 wells / km2, which corresponds to the scale of work of 1:25000.Spatial modeling of GPR profiling and geothermy data was carried out using the Surfer 12.8.1009 program. The spreadsheets were loaded into the program and processed using the Kriging method. The results of spatial modeling were presented in the form diagrams of isoclines for values corresponding parameters.

The revealed spatial anomalies of the thawing grounds capacity were successfully verified by drilling 6 wells. The correctness of the selection of criteria for hazardous talic zones and approaches to the interpretation of radarograms is confirmed by the results of measurements of soil temperature in verification and observation geothermal wells. In talik zones, the depth of seasonal freezing (thawing) reaches a maximum of 4-4.5 m. Below are thawed soils with a capacity of 2-3 m, cooled plastically frozen soils lie in the depth range of 7-10 m (Figure 5 a, b).

In the background conditions of permafrost preservation, the depth of seasonal thawing is 1.8-2 m. Starting from a depth of 3 m, frozen soils lie in the section (Figure 5 d).

On contact with the talic zone, the depth of seasonal thawing increases to 3 m. In the depth range of 4-6 m, the soil cools to -2.2 ° C only by the end of the winter period, and then the soil temperature rises to -1.45 ° C, which corresponds to a plastic-frozen state (Figure 5c).

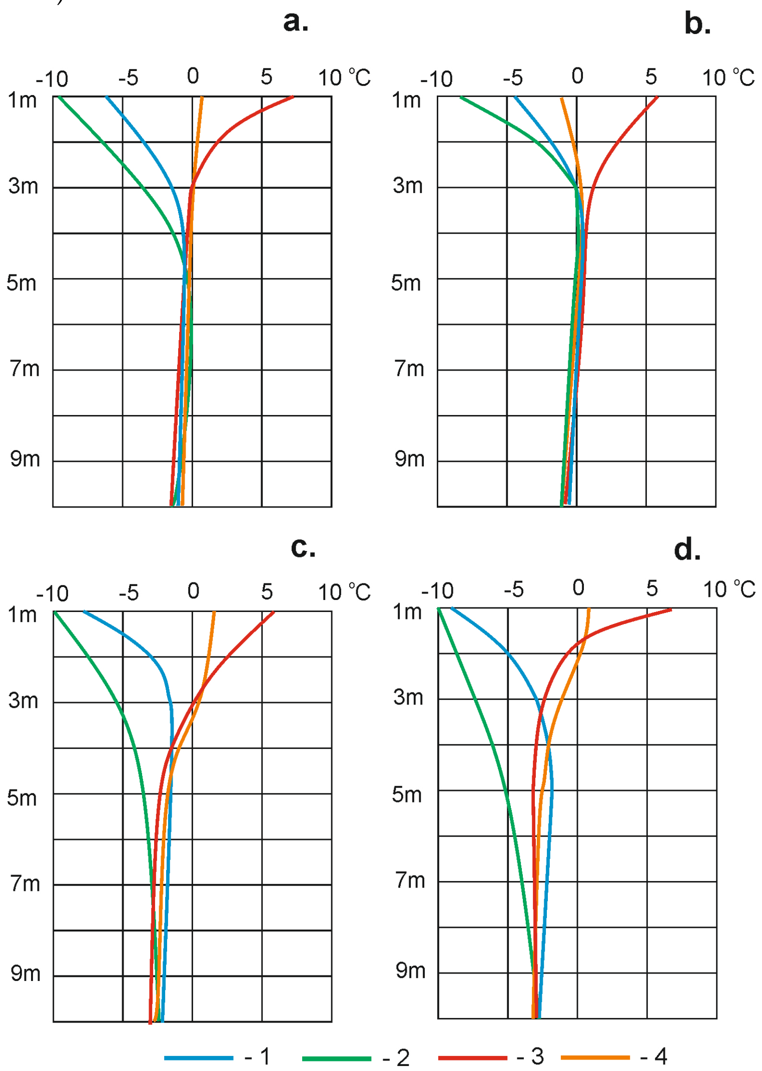


Figure 5. Seasonal soil temperatures measured in 2023-2024 in verification wells in the city of Anadyr: a - the marginal part of the talik zone, b - the center of the talik zone, c - outside the talik zone, d - on the border of the talik zone. Symbols: 1 - January, 2 - April, 3 - July, 4 - October.

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 27 May 2024 doi:10.20944/preprints202405.1722.v1

5. Research Results

Geothermic studies, due to the low density and uneven distribution of observation wells over the city area, and the fact that most of them were confined to the perimeter of buildings, had a reconnaissance character. The result of spatial modeling of soil temperature in wells ground temperature fields constructed for imaginary cross-sections at a depth of 3, 5 and 10 m from the surface (Figure 6).

The deepest cross-section shows the general trends in the temperature of permafrost within the boundaries of the urban landscape. The lowest temperatures, in the range of -2.5 - (-3.5) °C, were recorded in the northwestern and northeastern outskirts of the city, as well as in the eastern half of residential area. The general trend of increasing soil temperature at a depth of 10 m to -0.5 ° C has a southerly direction. This is somewhat different from the geotemperature pattern of the 90s, when the soil temperature increased from northwest to southeast: from -4.4 to -1.5 °C. Obviously, these changes are largely related to the formation of a layer of man-made soils during construction, and in fact a layer of newly formed frozen soils frozen in modern times. This is confirmed by the fact that cold anomalies tend to areas where rocky soils andesites and basalts lie close to the surface, and the thickness of man-made soils is minimal. Simultaneously with technogenic changes in the structure of the permafrost roof, climate warming led to an increase in seasonal thawing and the thickness of the annual temperature turnover layer from 10-12 m to 12-16 m.

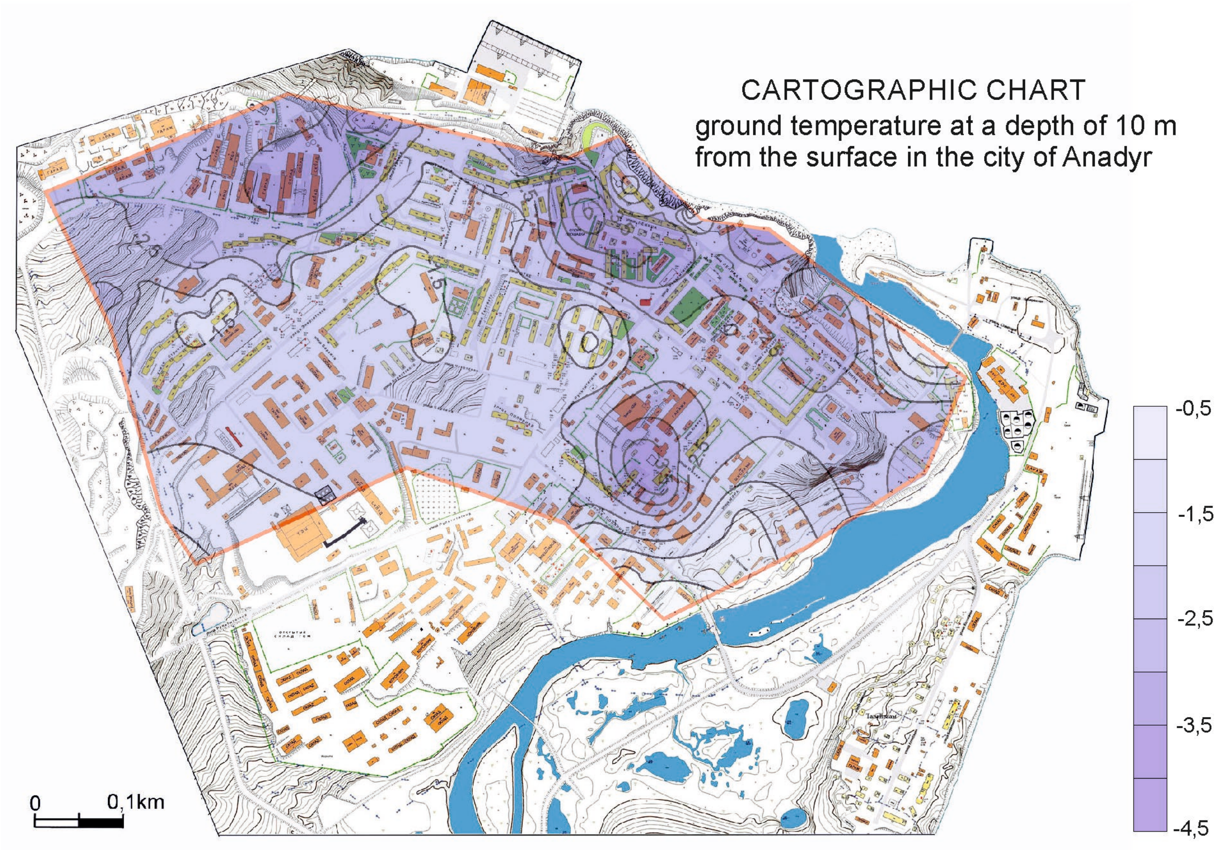
The most extensive positive anomaly, limited by the isotherm of -1.5 ° C, is confined to the floodplain of the Kazachka River and the buried bed of the left tributary (Figure 6a). It is divided by rocky ground with a temperature of -3 ° C. The same anomaly in size and sign is located in the western part of the studied territory. It was detected in areas with heavy dumping of man-made soils (6-15 m). Point anomalies in the central part of urban development on the surface correspond to modern subsidence of soil and concrete coatings.

The temperature field of soils at a depth of 5 m generally follows the contours of anomalies of a 10-meter cross-section, but differs in higher temperature values: from -3.5 to 1.5 °C. At the same time, as expected, with a decrease in the depth of the slice, cold anomalies are localized, and warm anomalies in the city center expand and complicate their morphology (Figure 6b).

The temperature field closest to the surface of the 3-meter cross-section reflects the dynamics of modern cryogenic processes. The soil temperature varies from -2 to positive 2 degrees Celsius. The isotherm of -0.5°C in relief runs along the middle part of the slope of the southern exposure. There are no spatial trends in soil temperature changes within the contour of residential area. Here, against the general background with a temperature of -0.5 ° C, there are quite large anomalies with ground temperature in the range from -1.2 to - 2.0 ° C. In the north-east of the city, such an anomaly is confined to the basement sea terrace. On the northwestern outskirts of the city and in its center, the contours of the anomalies of the city are recorded by shallow buried lava basalts. These patterns indicate that the permafrost roof is now cooling from below due to the better conductivity of cold in rocky soils from permafrost to the surface. The number of positive anomalies on the map has increased compared to the 5-meter cross-section. Local positive anomalies with temperatures above -0.5 °C grouped and formed chains down the slope or along streets oriented in the cross of the slope. The most contrasting positive temperature anomaly (up to 2 °C) corresponds to the buried bed of the left tributary of the Kazachka River.

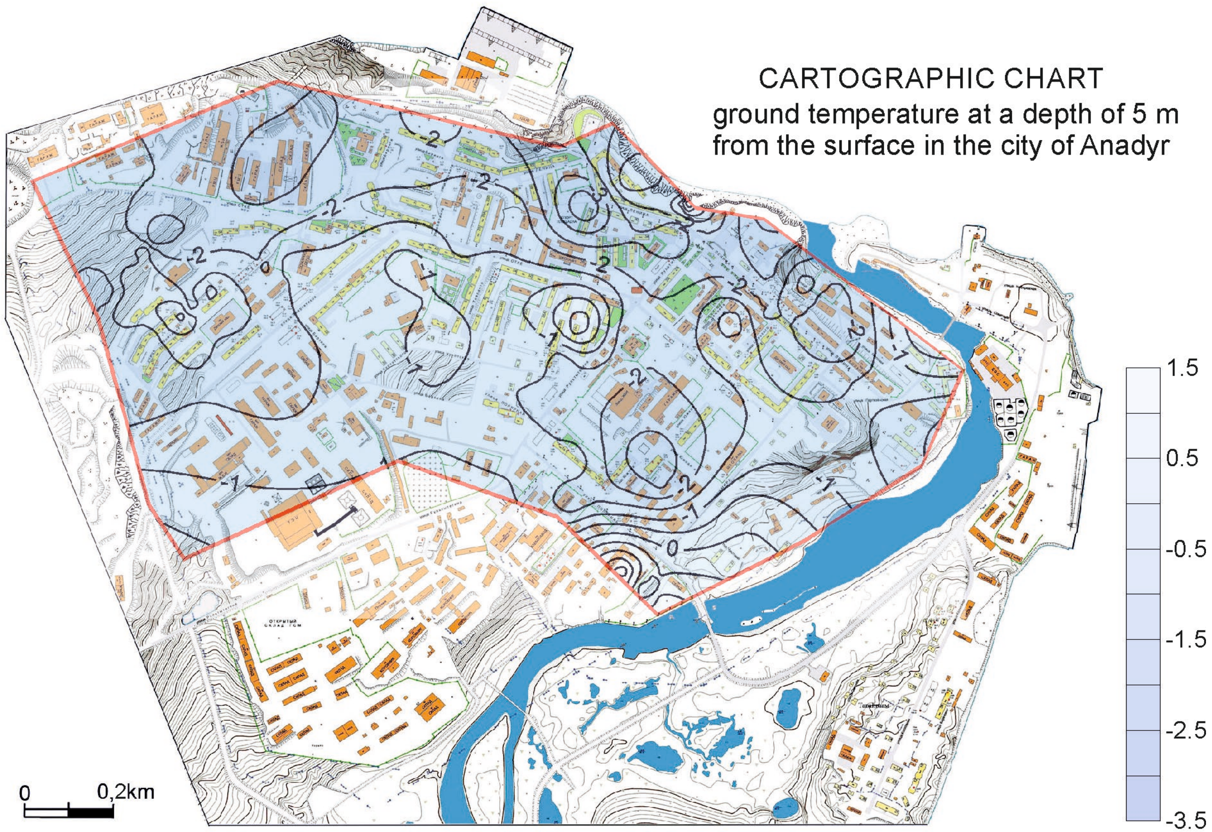
Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 27 May 2024 doi:10.20944/preprints202405.1722.v1

a.



 doi:10.20944/preprints202405.1722.v1

b.



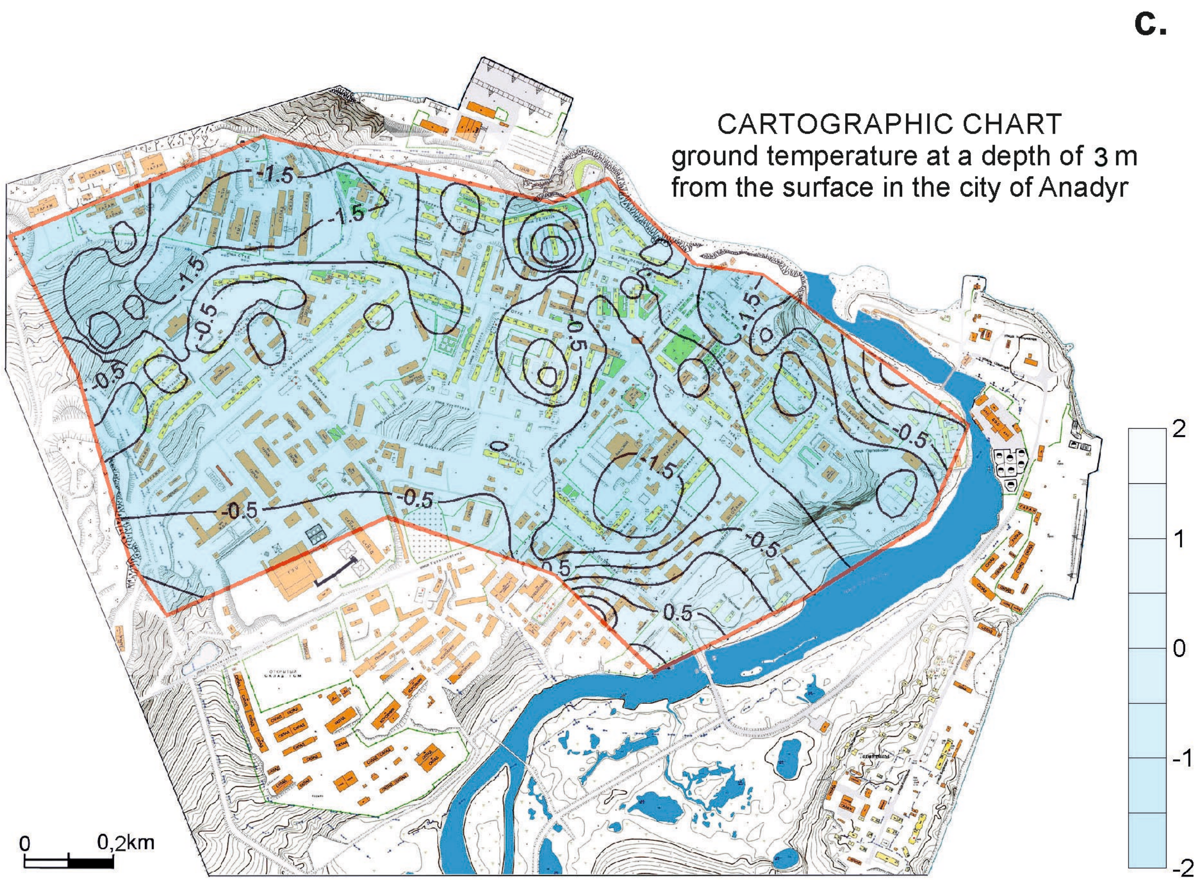


Figure 6. Replicas of soil temperature maps on the territory of the city of Anadyr for imaginary cross sections at a depth of: a – 10 m, b – 5 m, c – 3 m.

The main result of GPR profiling is the mapping of the depth of permafrost (Figure 7). The total capacity of seasonally thawed (seasonally frozen), thawed and cooled plastically frozen soils in the territory of Anadyr ranges from 2 to 18 m. The structure that isopachites form on the map is complex. The residential zone is divided, where the background for anomalies is the depth of permafrost 3-6 m, and the outskirts of the city in the south and northwest, for which the norm is the thickness of seasonally thawing and plastically frozen soils 6-10 m. In the most elevated part of the city, on vacant lots and in industrial zones, anomalies are extensive. Further down the slope, at the entrance to the residential area, wide anomalies are divided into many linear flows with inflations and bifurcations. Outside the residential area, in the lowest part of the city, the anomalies combine again and form a kind of plume. In the residential area, the anomalies are contrasting, in most cases they have linear outlines and are oriented downhill. The most contrasting and significant anomaly in the depth of permafrost is located within the boundaries of the production zone of the Anadyr power plant, where the capacity of man–made soils is 10-15 m. A significant part of linear, downhill-oriented anomalies are confined to streets and mainline utilities. The expansion of anomalies is recorded at the intersection of streets located in the cross of the slope. Bifurcation points are spatially correlated with groupings of storey buildings with ventilated pile foundations, as well as rocky ground lying near the surface. Modern subsidence's of soil and concrete coatings, as well as of icing field, are located on the periphery of the anomalies.

The most informative from the point of view of understanding the modern picture of exogenous cryogenic processes is a cartographic diagram of the total capacity of suprapermafrost waters in the active layer and the underlying thawed sandy-gravelly ground of talik zones (Figure 8).

It should be noted at once that in urban space the contours of anomalies of the depth of permafrost and the capacity of the horizon of permafrost waters rarely coincide. Usually, the power anomalies of the above-frozen waters are somewhat offset from the power anomalies of the thawed layer. The reason for this is the spread of waterproof clay deposits in the taliks, as well as the runoff of underground suprapermafrost waters. GPR profiling recorded the result of the summer-autumn redistribution, or rather the runoff of suprapermafrost waters. The contrasting pattern of anomalies indicates the active dynamics of permafrost waters.

As in the case of anomalies in the depth of the thawed layer, linear anomalies of suprapermafrost waters are confined to roads oriented in the direction by the slope of the terrain, active and buried ravines. In the northwestern outskirts of the city, a non-contrasting anomaly was recorded in an area with preserved natural soil and vegetation cover. The same non-contrasting anomalies were observed on the slope of the southern exposure with low-rise buildings. Most of the anomalies of the aquifer with a capacity of 2.5-3 m are located in areas with a thick layer of up to 6-12 m of gravelly soil on construction sites. This indicates the validity of our assumptions about the feeding of talik zones with condensation waters. Icing fields are confined to the periphery of anomalies or located in places of narrowing (pinching) of isopachites of permafrost waters.

6. Discussion

The patterns of distribution on the territory of Anadyr, the of soil temperature at various depths, the spatial dynamics of the capacities of thawing soils and suprapermafrost waters allow, taking into account the knowledge of geomorphology and the general patterns of the geological structure of the city, to make a number of reasonable assumptions.

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 27 May 2024 doi:10.20944/preprints202405.1722.v1

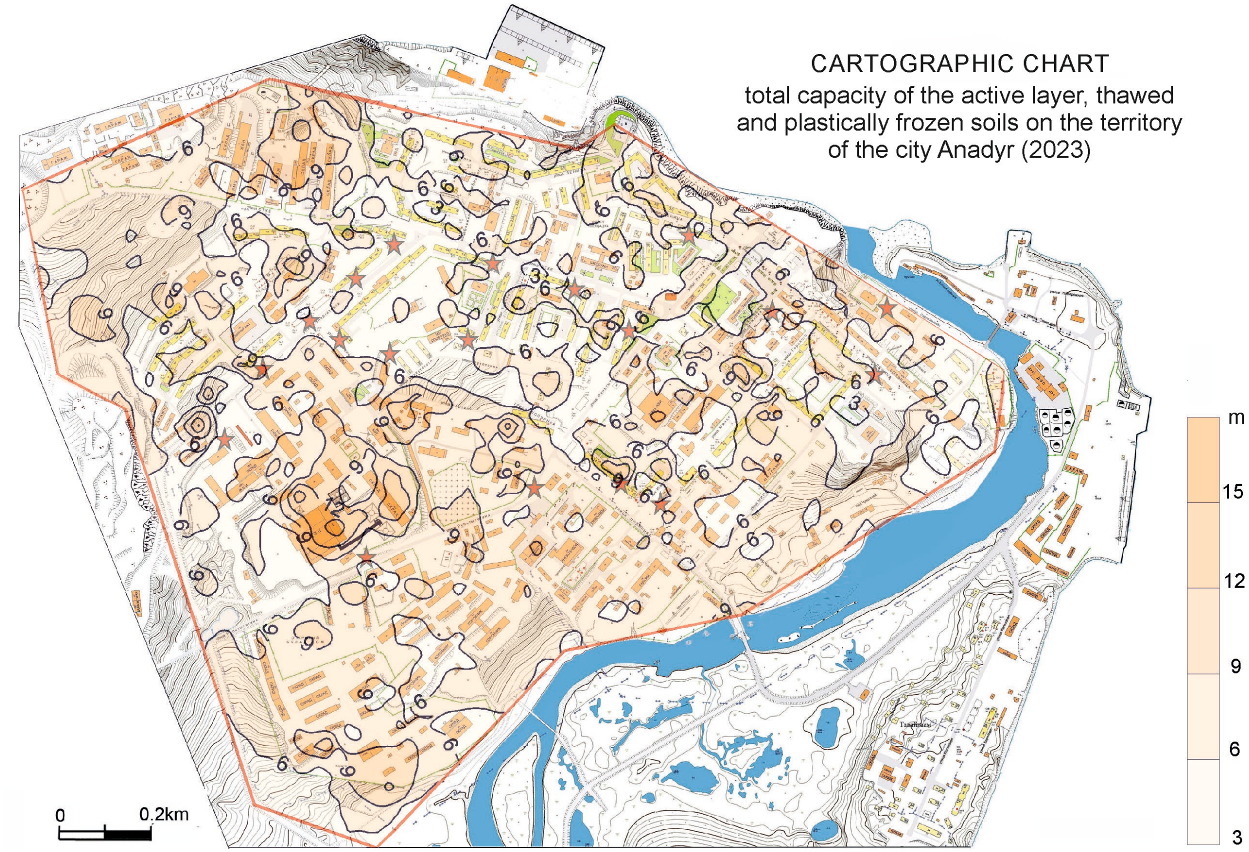


Figure 7. Replica of the cartographic diagram of the total capacity of the active layer, thawed and plastically frozen soils on the territory of the city of Anadyr (red asterisks indicate the places of subsidence of soil and concrete coatings).

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 27 May 2024 doi:10.20944/preprints202405.1722.v1

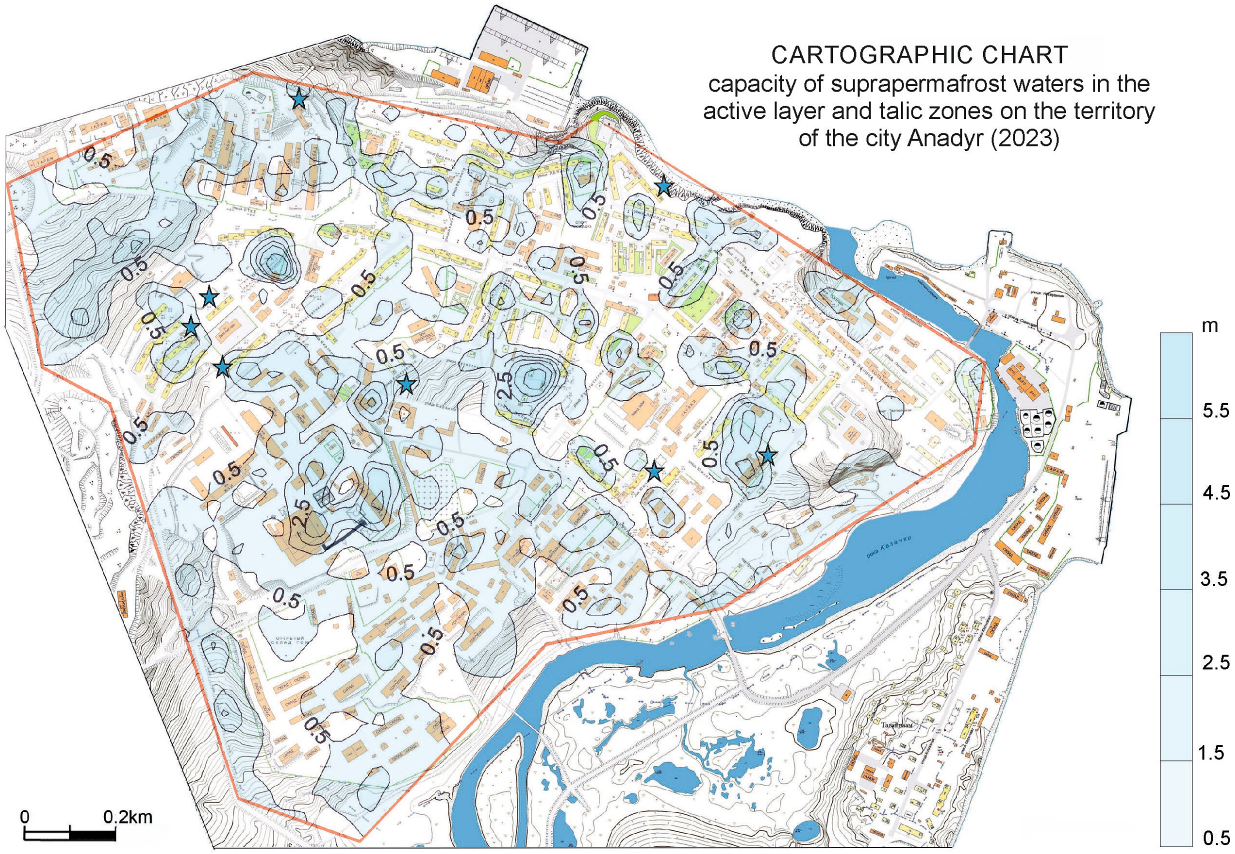


Figure 8. Replica of the cartographic diagram of the total capacity of the suprapermafrost waters in the city of Anadyr (blue asterisks mark the places of formation of groundwater icing fields).

 doi:10.20944/preprints202405.1722.v1

1. Zones of "cold" permafrost tend to be located in areas with low-power dumping of man-made soils and shallow occurrence of waterproof rocky rocks. Areal warming of the permafrost roof is observed on the southern slope of the built-up area, in areas of distribution in the geological section of marine and continental sediments. Local anomalies of "warm" permafrost are confined to buried streams and swamps.

2. The most contrasting anomalies by the capacity of thawed ground are located in a residential part of the city with dense buildings of apartment buildings, a network of utilities and roads. On the outskirts of cities with low-rise buildings and vacant lots, non-contrasting areal anomalies are widespread. The suprapermafrost waters are spatially correlated with the depth of ground melting. The anomalies of the capacity of suprapermafrost waters are most structured in terms of morphology and location in space.

3. The factors that determined the location of talik zones and have an impact on their development are divided into natural and man-made. Among the natural factors, geological, geomorphological and climatic are distinguished. The geological structure of the territory influences the configuration of taliks through the distribution of igneous and sedimentary rocks of various ages, temperatures and water permeability in the geological section. Чем древнее возраст четвертичных горных пород, тем ниже температура их промерзания. Geomorphological factors – this is the slope of the surface of the modern and buried relief, of the permafrost roof, as well as buried ravines and streams, swamps, sea and river terraces. The climatic factor is realized through different exposure of slopes in the absence of shading of the surface by tall buildings; through favorable conditions for air circulation in summer and preservation of snow cover in winter.

4. Among the technogenic factors influencing the formation and evolution of talik zones:

- power and conditions of filling the surface with gravelly soil;
- snow removal of roads, streets and courtyards;
- orientation in the space of main streets and utilities; location of buildings with ventilated foundation and thermostabilizers in the urban area.

5. Collectively, the anomalies of the power of thawing soils and suprapermafrost waters located in the area of elevated ground temperatures, naturally oriented in space, are grouped, and represent hydrogenic zones (20 zones) of dangerous development of exogenous cryogenic processes (Figure 9). These zones are dynamic, are influenced by climatic and man-made factors, have a alimentation area and unloading of ground waters. Along with them, there are relatively isolated and static anomalies of the thawed layer, the nature of which is due to the inherited development of natural taliks of stagnant waters, discovered even before the start of construction [42].

Our proposed permafrost monitoring system in the city of Anadyr will consist of an automated network of soil temperature observations in observation wells and 12 control geo-radar profiles in the strike zone and along the border of 20 zones of development of dangerous exogenous cryogenic processes (See Figure 9). The network is planned to consist of 35 observation wells with a depth of 10.5 m. Temperature recording at depths of 1, 3, 5 and 10 m will be performed every 6 hours. The measurement data will be automatically transmitted over the mobile communication to the central server. Next, the data is processed and presented in the form of graphs and charts. The control profiles are produced annually at the end of the warm season. The results of GPR of control profiles will be presented in the form of geological and geophysical sections. The permafrost monitoring system also includes visual observations of subsidence of ground and concrete coverings, the icing field of ground water.

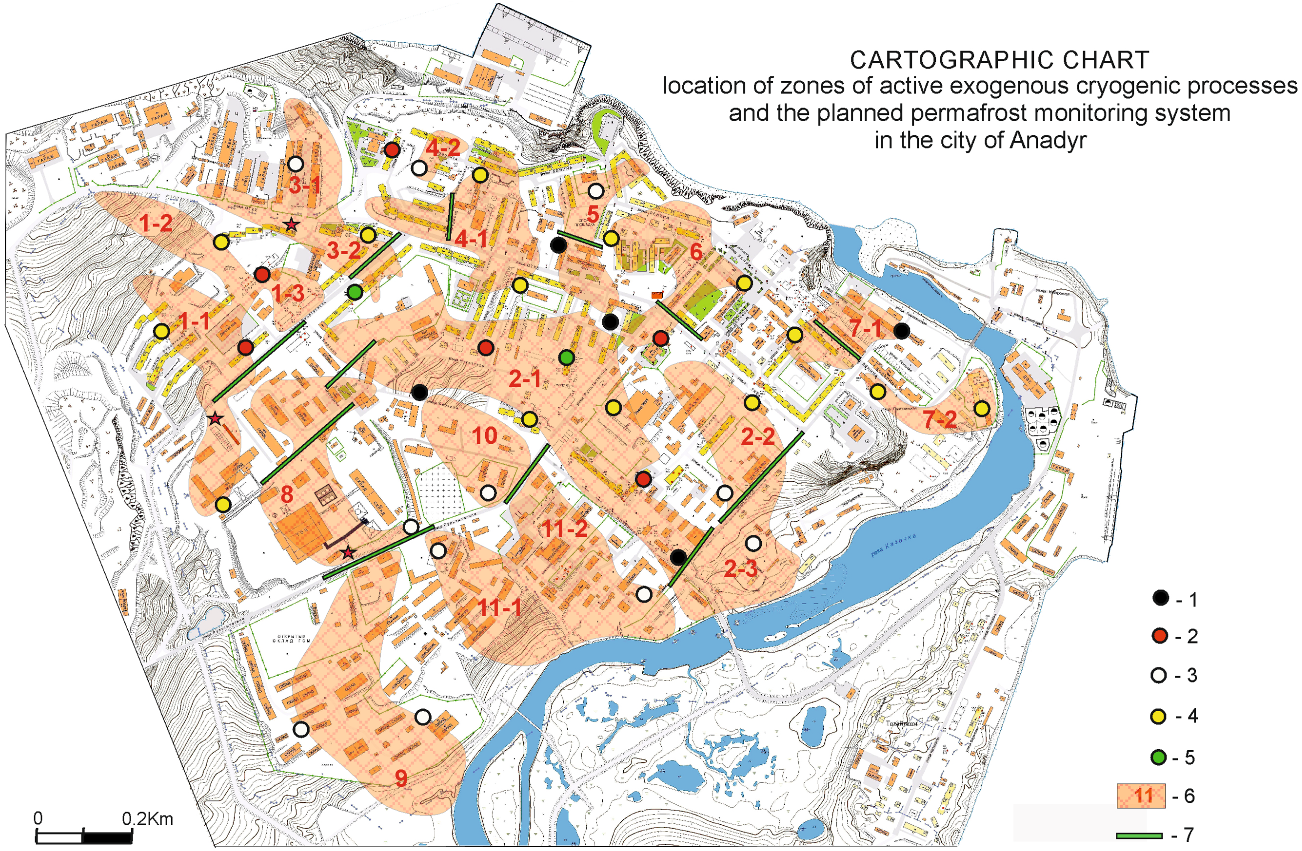


Figure 9. Replica of the schematic map of the zones of active exogenous cryogenic processes and the planned permafrost monitoring network in city of Anadyr Symbols: observation wells: 1 - verification for GPR profiling, 2 - the current experimental segment of the automated network, 3 - drilling is planned for 2025, 4 - previously drilled wells for construction monitoring, 5 - scientific monitoring of soil temperature; 6 - zones of dangerous exogenous cryogenic processes; 7 - GPR profiles of permafrost monitoring.

In 2023, an experimental segment of the automated soil temperature monitoring network was created and is operating, which consists of 6 wells and 24 sensors. The completion of the permafrost monitoring system and the start of systematic observations is planned for 2025-2026. The total cost of creating a permafrost monitoring system in the city of Anadyr will amount to $ 250,000. The annual cost of maintaining the monitoring system will be about $ 15,000. In the future, the system is expected to become more complex due to the formation of subsystems of industrial enterprises and individual residential neighborhoods in areas of dangerous development of negative processes.

Thus, in our reasoning, we returned to the beginning of the article, when we raised the question of what should be the system of permafrost geotechnical monitoring in the settlements of the cryolithozone. Based on the example of the research conducted in Anadyr, the answer is obvious. It is easier, more efficient and more cost-effective to control the dynamics of the development of 20 dangerous talik zones than the perimeter of the foundations of 223 residential and administrative buildings of the city. This conclusion is also based on the fact that building monitoring is aimed at passively protecting the foundation base from thawing, and monitoring of hazardous areas is focused on localizing the negative impact of the talik front on permafrost in the foundations of buildings and engineering structures. At the same time, the proposed monitoring system, which is important, covers roads, warm, electric and water supply communications of cite with observations.

Another important issue concerns the methods of monitoring the zones of development of dangerous exogenous cryogenic issues. The results of our research provide an answer to this question. Year-round and continuous, automatic monitoring of the ground temperature regime in the center and along the flanks of dangerous zones in combination with annual GPR profiling of taliks in order to control their geometric parameters in informative areas (See Figure 9). The algorithm of research aimed at substantiating and creating a system of permafrost monitoring of settlements is also clear: analysis of information about the geological structure, geomorphology, infrastructure of the settlement; measurements of soil temperature in existing or specially drilled wells, documentation of surface deformations; areal GPR profiling on a scale of at least 1:10000; computer spatial modeling of parameters of talik zones.

7. Conclusions

In our research, we have shown the relevance of the problem of creating a permafrost monitoring system in Arctic and Subarctic settlements. The main problems of choosing approaches to monitoring the degradation of permafrost in urbanized areas were identified. Using the example of the city of Anadyr, new approaches to substantiating the permafrost monitoring network were proposed and tested, technology, methods and sequence of work were described.

As a general conclusion of the work, it should be noted that, as part of adaptation to climate change, it is extremely necessary to quickly create a circumpolar system for monitoring permafrost degradation in urbanized areas. This system should be primarily focused on the safety of the population. Another task of permafrost monitoring is to ensure the functionality of the existing infrastructure of settlements during the transition period of permafrost-climatic transformation. For the cross-border dissemination and implementation of the urban permafrost monitoring system, an open discussion by the scientific community of the proposed approaches and methods, of the experience in creating local systems in specific climatic and technogenic conditions is necessary. This article is devoted to this.

Author Contributions: 1) Oleg D. Tregubov – project administration, conceptualization, methodology, writing – review and editing; 2) Konstantin K. Uyagansky – organization and conduct of geophysical work, discussion of the results of the researches.

Funding: The study was commissioned and financially supported by the autonomous non-profit organization "Chukotka Arctic Scientific Center"

Data Availability Statement: Databases of geophysical works are available with the permission of the customer of the work - the autonomous non-profit organization "Chukotka Arctic Scientific Center".

Acknowledgments: Express our sincere gratitude to Vyacheslav V. Akinin and Vladimir V. Karpan for the administrative and organizational support of this study.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Rey, D. M., Walvoord, M. A., Minsley, B. J., Ebel, B. A., Voss, C. I., & Singha, K. Wildfire-initiated talik development exceeds current thaw projections: Observations and models from Alaska's continuous permafrost zone. *Geophysical Research Letters.* **2020**. 47 (15). [https://doi.org/ 10.1029/2020GL087565]
2. Ramage, J., Jungsberg, L., Wang, S. et al. Population living on permafrost in the Arctic. *Popul Enviro.* **2021**, 43, pp. 22-38. [https://doi.org/10.1007/s11111-020-00370-6h]
3. Hjort J, Karjalainen O, Aalto J, Westermann S, Romanovsky V.E, Nelson F.E, Etzelmüller B, Luoto M. Degrading permafrost puts Arctic infrastructure at risk by mid-century. *Nat Commun.* **2018**, 9(1):5147. [https://doi: 10.1038/s41467-018-07557-4.]
4. Grebenets, Valery, Dmitry Streletskiy, and Nikolay Shiklomanov. Geotechnical safety issues in the cities of Polar Regions. *Geography, Environment, Sustainability.* **2012**, *Volume* 5, No. 3, pp. 104-119. [https://doi: 10.15356/2071-9388_03v05_2012_08]
5. Pavel I. Kotov and Vanda Z. Khilimonyuk. Building Stability on Permafrost In Vorkuta, Russia. *Geography, Environment, Sustainability.* **2021**. *Volume* 14, No. 4, pp. 67-74. [https://doi.org/10.24057/2071-9388-2021-043]
6. Luis Suter, Dmitry Streletskiy & Nikolay Shiklomanov Assessment of the cost of climate change impacts on critical infrastructure in the circumpolar Arctic. Polar Geography. 2019. 42:4, p.267-286. [https://doi: 10.1080/1088937X.2019.1686082]
7. Shiklomanov, N. I., Streletskiy, D. A., Swales, T. B. & Kokorev, V. A. Climate change and stability of urban infrastructure in Russian permafrost regions: prognostic assessment based on GCM climate projections. *Geogr. Rev.* **2016**, No. 107, pp. 125-142. [https://doi: 10.1111/gere.12214]
8. Melnikov, Vladimir & Osipov, Victor & Brouchkov, A. & Badina, Svetlana & Sadurtdinov, Marat & Drozdov, Dmitry & Malkova, Galina & Zheleznyak, Mikhail & Zhdaneev, Oleg & Ostarkov, Nikolay & Osokin, Alexei & Sergeev, Dmitrii & Dubrovin, Vladimir & Kuznetsov, Mikhail & Frolov, Konstantin & Alekseev, Andrey & Fedorov, Roman. Past and Future of Permafrost Monitoring: Stability of Russian Energetic Infrastructure. *Energies*. **2022**, 15(9):3190. [https://doi: 15. 3190. 10.3390/en15093190].
9. O'Neill, H. Brendan & Smith, S. & Burn, C. & Duchesne, C. & Zhang, Y. Widespread Permafrost Degradation and Thaw Subsidence in Northwest Canada. *Journal of Geophysical Research: Earth Surface*. **2023**, 128, e2023JF007262 [https://doi: 10.1029/2023JF007262].
10. Wang, Ziyi & Xiao, Ming & Nicolsky, Dmitry & Romanovsky, Vladimir & McComb, Christopher & Farquharson, Louise. Arctic Coastal Hazard Assessment Considering Permafrost Thaw Subsidence, Coastal Erosion, and Flooding. *Environmental Research Letters*, **2023**, 18, 104003. [https://doi:10.1088/1748-9326/acf4ac]
11. Yershov E.D. Taliks and groundwater in the permafrost zone. In: Williams PJ, ed. General Geocryology. Studies in Polar Research. Cambridge University Press; UK. 1998, pp.388-406.
12. Jorgenson M.T. Thermokarst Terrains. In: John F. Shroder (Editor-in-chief), Giardino, R., and Harbor, J. (Volume Editors). Treatise on Geomorphology, Glacial and Periglacial Geomorphology, San Diego: Academic Press, USA. 2013. Volume 8, pp. 313-324. [http://dx.doi.org/10.1016/B978-0-12-374739-6.00215-3]
13. Popov S.V., Boronina A.S., Lebedeva L.S. The main factors in the formation of subaerial taliks on the example of the Shestakovka River basin (Central Yakutia), using a one-dimensional mathematical model. *Ice and Snow*, **2023**, No. 63 (4), pp.597-611. [https://doi: 10.31857/S2076673423040130]
14. Lebedeva L.S., Baishev N.E., Pavlova N.A., Efremov V.S., Ogonerov V.V.,Tarbeeva A.M. Ground temperature at the depth of zero annual amplitude in the area of suprapermafrost taliks in Central Yakutia . *Cryosphere of the Earth*, **2023**, *Volume* XXVII, No. 2, pp. 3-15. [elibrary_50823741_21686379.pdf]
15. Grib N.N., Kuznetsov P.Y., Syasko A.A.1, Kachaev A.V. How to determine dangerous engineering-geological events by geophysical methods. *Modern Problems of Science and Education*, **201,** 2:746. [https://doi: 10.17513/spno.129-22366]
16. Liu W, Fortier R, Molson J, Lemieux J-M. A conceptual model for talik dynamics and icing formation in a river floodplain in the continuous permafrost zone at Salluit, Nunavik (Quebec), Canada. *Permafrost and Periglac Process*, **2021**, No. 32(3), pp.468-483. [https://doi.org/10.1002/ppp.2111]

17. Vonder Mühll, D., Hauck, C., & Gubler, H. Mapping of mountain permafrost using geophysical methods. *Progress in Physical Geography: Earth and Environment*. **2002**, No. 26(4), pp. 643-660. [https://doi.org/10.1191/0309133302pp356ra]
18. Fortier, Philippe & Young, Nathan & Lemieux, Jean-Michel & Walvoord, Michelle & Fortier, Richard. (2023). Long-Term, High-Resolution Permafrost Monitoring Reveals Coupled Energy Balance and Hydrogeologic Controls on Talik Dynamics Near Umiujaq (Nunavik, Québec, Canada). *Water Resources Research*. **2023**, 59 (1), e2022WR032456. [https://doi.org/10.1029/2022WR032456]
19. Tarbeeva A.M., Tregubov O.D., Lebedeva L.S. Structure of the slope runoff network of the cryolithozone in the vicinity of Anadyr, *Geomorphology*, 2021, *Volume* 52, No. 1, pp. 109-120. [https://doi.org/10.31857/S0435428121010132]
20. Shepelev V.V. Suprapermafrost waters of the cryolithozone, Novosibirsk, Geo Publ. Russian, 2011, 169 p.
21. Tregubov O.D., Razzhivin V.Yu., Shamov V.V., Lebedeva L.S. The influence of the landscape structure of basins on the specific inter-soil flow of small rivers in the north and south of Chukotka. *Bulletin of the Moscow University. Series 5. Geography*. 2023. No. 1, pp. 107-118. [https://doi.org /10.55959/MSU0579-9414.5.78.1.9]
22. Yu, W., Guo, M., Chen, L., Lai, Y., Yi, X., & Xu, L. Influence of urbanization on permafrost: a case study from Mohe County, northernmost China. *The Cryosphere Discussions*. **2014**, No. 8, pp. 4327-4348. [https://doi:10.5194/tcd-8-4327-2014]
23. Tourei, A., Ji, X., Rocha dos Santos, G., Czarny, R., Rybakov, S., Wang, Z., et al. (2024). Mapping permafrost variability and degradation using seismic surface waves, electrical resistivity, and temperature sensing: A case study in Arctic Alaska. *Journal of Geophysical Research: Earth Surface*, **2024**, *Volume* 129, No. 3, e2023JF007352. [https://doi.org/10.31223/X5TD4H]
24. Perreault, P. & Shur, Y.. (2016). Seasonal Thermal Insulation to Mitigate Climate Change Impacts on Foundations in Permafrost Regions. *Cold Regions Science and Technology*, **2016**, *Volume* 132, pp. 7-18. [https://doi 10.1016/j.coldregions.2016.09.008]
25. Sakharov Igor. Modern approaches to the design of bases and foundations at permafrost zone sites with account for the effects of global warming. E3S Web of Conferences. 2023. 371, 02031. International Scientific Conference "Fundamental and Applied Scientific Research in the Development of Agriculture in the Far East" (AFE-2022). [https://doi.org/10.1051/e3sconf/202337102031]
26. Abdallah Basiru, Shishay T Kidanu, Sergei Rybakov, Nicholas Hasson, Moustapha Kebe, Emmanuel Osei Acheampong. Electrical Resistivity Tomography Investigation of Permafrost Conditions in a Thermokarst Site in Fairbanks, Alaska. AIMS *Geosciences*, **2024**, *Volume* 10(1), pp. 1-27. [https://doi: 10.3934/geosci.2024001]
27. French H.M. The periglacial environment. Longman; London, UK, 1976, 309 p. [https://doi.org/10.1017/S0016756800045131]
28. Mudrov, Yu. V. Permafrost phenomena in the cryolithozone of plains and mountains. General terms and definition. Illustrated encyclopedic reference. Moscow. Scientific World; Russia, 2000, 312 p.
29. Tsytovich, N. A. The Mechanics of Frozen Ground, McGraw-Hill; New York, USA, 1975 426 p. [https://doi.org/10.7202/1000294ar]
30. Zaplavnova, Anna & Olenchenko, Vladimir & Dergach, Petr & Fedin, K.V. & Osipova, Polina & Shein, Alexand. Approbation of seismic and electrical geophysical techniques complex for solving the permafrost monitoring problems on the pile-foundation building. *Russian Journal of Geophysical Technologies*, **2023**, No. 3, pp. 49-63. [https://doi: 10.18303/2619-1563-2022-3-49]
31. Wang, Y.; Fu, Z.; Lu, X.; Qin, S.; Wang, H.; Wang, X. Imaging of the Internal Structure of Permafrost in the Tibetan Plateau Using Ground Penetrating Radar. *Electronics*, **2020**, 9 (1): 56. [https://doi.org/10.3390/electronics9010056]
32. SP 11-105-97: Code of rules for engineering and geological surveys for construction. Part VI. Rules for the production of geophysical surveys. Gosstroi of Russia, PNIIIS; Moscow, Russia, 2004. 43 p.
33. Rossi M, Dal Cin M, Picotti S, Gei D, Isaev V.S., Pogorelov A.V., Gorshkov E.I., Sergeev D.O., Kotov P.I., Giorgi M. and Rainone M.L. Active Layer and Permafrost Investigations Using Geophysical and Geocryological Methods – A Case Study of the Khanovey Area, Near Vorkuta, in the NE European Russian Arctic. *Front. Earth Sci.* **2022**, 10:910078. [https://doi: 10.3389/feart.2022.91007]

34. Fedorova L. L., Kulyandin G. A., Prudetsky N. D. Determination of sites of thawed rocks in a permafrost massif according to GPR data. *Successes of modern Natural Science*, **2023**, No. 11, pp. 192-198. [https://doi: 10.17513/use 38163]
35. ASTM D4748-10. Standard Test Method for Determining the Thickness of Bound Pavement Layers Using Short-Pulse Radar. Washington, USA, 2010, 7 p. [https://www.astm.org/d4748-10.html]
36. Savvin D.V., Fedorova L.L., Soloviev E.E., 2018. Experience of GPR investigation at engineering-geological survey in Central Yakutia. *Engineering Survey*, **2018**, *Volume* XII, N. 7-8, pp. 92–100. [https://doi.org/10.25296/1997-8650-2018-12-7-8-92-100]
37. Portnyagina, V.V., Kulyandin, G.A., Budikina, M. E. Detection of underground utilities in the territory of old city buildings under asphalt concrete covering by GPR. *Eng. & Technol.*, **2023**, No. 16(3), pp. 307–315.
38. Shilin, A. A. Results of interpretation of georadiolocation studies of soil massifs in urban conditions. *Transport construction*, **2015**, No. 6, pp. 19-23. [http://znayugeo.ru/wp-content/uploads/2016/03/TS_06_05.pdf]
39. SP 305.1325800.2017. BUILDINGS AND STRUCTURES. Rules for conducting geotechnical monitoring during construction. Gosstroi Rossii, PNIIIS; Moscow, Russia, 2017. 61 p. [https://www.minstroyrf.gov.ru/docs/16046/]
40. Shein, Alexandr & Filimonov, Mikhail & Vaganova, N. & Leopold, Yaroslav. Development of an automated system for temperature monitoring of permofrost at the base of buildings in Salekhard. *Interexpo GEO-Siberia*. 2022. No. 2, pp. 328-333. [https://doi : 10.33764/2618-981X-2022-2-1-328-333]
41. Tregubov O.D., Uyagansky K.K., Nuteveket M.A. Monitoring of permafrost and climatic conditions of the Anadyr lowland // *Geography and natural resources*. **2020**, No. 2, pp. 143-152. [https://doi: 10.21782/GIPR0206-1619-2020-2(143-152)]
42. Stepanov R.V., Stepanova I.V. Permafrost-hydrogeological zoning of the city of Anadyr. In books Complex geocryological studies of Chukotka. Magadan: NEISRI FEB RAS, Russia. 1991. pp. 101-110
43. Everett, M.E. Near-Surface Applied Geophysics by Mark E. Everett; Cambridge University Press (CUP); Cambridge, UK, 2013, 403 p.
44. Ermakov, A.P.; Starovoitov, A.V. The use of the Ground Penetrating Radar (GPR) method in engineering-geological studies for the assessment of geological-cryological conditions. *Mosc. Univ. Geol. Bull*., **2010**, *Volume* 65, pp. 422-427.[https://doi: 10.3103/S0145875210060116]
45. Sudakova M.S., Sadurtdinov M.R., Tsarev A.M., Skvortsov A.G., Malkova G.V. Ground-Penetrating Radar for Studies of Peatlands in Permafrost . *Russian Geology and Geophysics*, 2019, Volume 60, No. 7, pp. 793–800. [https://doi:10.15372/RGG2019059]
46. Tregubov, O., Kraev, G., Maslakov, A. Hazards of activation of cryogenic processes in the arctic community: A geopenetrating radar study in Lorino, Chukotka, Russia. *Geosciences (Switzerland)*, **2020**, 10 (2):57. [https://doi 10.3390/geosciences10020057]
47. Geophysical Equipment & Survey. GEOTECH LLC. 2003-2022. https://geotechru.com; 19.05.2024.