REVIEW

# BUILDING STABILITY ON PERMAFROST IN VORKUTA, RUSSIA

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ABSTRACT. The Infrastructure stability on permafrost is currently an important topic as the Arctic countries are developing climate change adaptation and mitigation programs. Assessing the sustainability of infrastructure facilities (especially in urban environments) is a difficult task as it depends on many parameters. This article discusses the city of Vorkuta, which is located in the northwest of Russia. This city differs from many others built on permafrost because most of buildings were built according to Principle II (The Active Method) of construction on permafrost with thawing soil prior to construction. Assessments of the engineering and geocryological conditions, basic principles of construction in the city, and reasons for building failures, were carried out within this study. The research is based on publications, open data about buildings, and visual observations in Vorkuta. About 800 buildings are in use in Vorkuta in 2020 (43% of what it was 50 years ago). According to the analysis, about 800 houses have been demolished or disconnected from utility lines over the past 50 years (about 250 of these are still standing, pending demolition). Since 1994, the construction of new residential buildings has almost stopped. Therefore, buildings that have been in use for over 50 years will account for 90% of the total residential housing stock by 2040. The effects of climate change in the city will depend primarily on the principle of construction employed and on the geocryological conditions of the district. Buildings constructed according to Principle I (The Passive Method) were found to be more vulnerable due to a decrease in permafrost bearing capacity. The impact of increasing air temperature on some of the buildings built on bedrock (the central part of the city) and some built on thawing soil will be minimal, as other factors are more significant.

KEYWORDS: Vorkuta, permafrost, Arctic cities, urban infrastructure, foundation, climate change

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## INTRODUCTION

Permafrost covers 21 million km$^2$. This accounts for 22% of the Northern Hemisphere's exposed land area (Obu et al. 2019). There are 1162 permafrost settlements with a total of 5 million inhabitants. Most of these settlements are relatively small (with a median size of 622 inhabitants), but 123 of them had a population of over 5000 inhabitants in 2017. Eighty-five percent of these large permafrost settlements are located in the Russian Arctic. These Russian settlements are mostly located on continuous permafrost, except for in a few regions (the Komi and Nenets regions), where settlements are located in zones of sporadic and discontinuous permafrost. The majority of settlements in the Arctic are in continuous permafrost zones (Ramage et al. 2021).

The major factor of infrastructure accidents in permafrost regions is the change of the soil temperature regime, which may be caused by natural or anthropogenic factors. Several studies focused on the assessment of the climate change impact on permafrost, including (Nelson et al. 2001; Romanovsky et al. 2010; Aalto et al. 2018; Vasiliev et al. 2020). Near-surface permafrost in the Arctic warmed by over 0.5°C between 2009 and 2017 (Biskaborn 2019), leading to changes in the stability of infrastructure, on which Arctic inhabitants are directly dependent.

Cities on permafrost (especially in the Russian Arctic) are very complex systems, which combine natural and technical sites. A city is a center of concentrated anthropogenic impact on the natural environment, covering a large area. The consequences of this negative impact depend both on natural conditions (climatic, geocryological) and on the intensity of the anthropogenic impact, which leads to a significant change in the natural conditions. Geocryological conditions are a set of permafrost characteristics that affect the construction and use of infrastructure facilities. These characteristics include the distribution of permafrost, composition and properties of frozen soil (the physical, mechanical and thermal properties), mean annual ground temperature, morphology and genesis of taliks, composition, properties and depth of the active layer, and also geocryological processes. Cities in the Arctic develop their own special microclimate: their radiation balance, air temperature and humidity, wind conditions and precipitation, along with the spatial distribution of these characteristics, are changing (Khrustalev et al. 2011). As a result, there is a significant transformation of geocryological conditions and change in the thermal state of the environment. Moreover, each city has its characteristics that must be taken into account. A series of works is devoted to urban infrastructure in the Arctic (Khrustalev and Davidova 2007;

Grebenets et al. 2012; Streletskiy et al. 2012b; Melvin et al. 2017; Shiklomanov et al. 2017; Hjort et al. 2018; Streletskiy et al. 2019; Shiklomanov et al. 2019).

This work focused on Vorkuta, as one of the largest Arctic cities built on permafrost (with a population of 73,100 in 2020). Vorkuta is located in the European part of Russia. It was founded in 1930 as a GULAG mining camp and experienced intensive urban development between the 1960s and 1990s (Barenberg 2014). The region of Vorkuta is unique because, within a small area of the city, there is a wide variety of geological and geocryological conditions as well as economic activities (from coal mining to agricultural facilities). Practically all known methods of construction on permafrost can be found in the city.

The infrastructure of Vorkuta consists of buildings, underground, surface, and above-ground utility lines, roads and parking lots, pedestrian paths, green spaces, and parks. Contact areas of these elements with the ground surface form places with heat sources and temperature sinks. The sources of heat include the areas occupied by buildings built according to Principle II, underground utility lines, and green spaces (they accumulate snow and have a warming effect on permafrost). Temperature sinks (cold spots) include the areas occupied by buildings built according to Principle I, roads, parking lots, and any other surfaces where snow cover is removed. The temperature regime of soils can be affected by changing the structure of urban space. For example, this could be a change in the density of buildings, roads, the ratio of areas subject to technical reclamation (drainage, backfilling with sand, landscaping, snow removal). The density of buildings in the residential part of Vorkuta varies from 13 to 24% (Khrustalev et al. 2011).

The transport system consists of roads, railway lines, and an airport. The length of highways throughout the region is 120 km, and in the central part of Vorkuta it is 70 km. There is no road connection between Vorkuta and any other cities, it is connected with the center of Russia by the railway line Vorkuta - Kotlas -Moscow and with Western Siberia by the railway line Vorkuta -Labytnangi. Transport infrastructure is not considered in this research. It is necessary to take into account another set of permafrost parameters to assess the stability of transport infrastructure (Isaev et al. 2020).

Recently, there have been many assessments of the climate change impact on infrastructure (Khrustalev and Davidova 2007; Streletskiy et al. 2012a; Hjort et al. 2018). For example, according to one modelling study, Vorkuta is a high-risk infrastructure hazard area in the Russian Arctic (Hjort et al. 2018). However, most of the models do not consider the complex integral impact of all factors (geocryological conditions, features of the territory, principles of construction), which may lead to an incorrect interpretation of modelling results.

This paper discusses the role of permafrost conditions in the urban development of Vorkuta, the basic methods of construction, the reasons for infrastructure failure, and the impact of climate change on building stability.

## STUDY AREA

Vorkuta is located in the Ural region of the Bolshezemelskaya tundra, which is characterised by a gentle hilly plain with average elevations of 50–180 m. The climate is determined by the location of the region in the subarctic with low solar radiation in winter, the proximity to the northern seas, and intense westerly air mass transfer. The frost-free period is about 70 days, and winter lasts about eight months. The average air temperature is -5.53°C. An important factor of the temperature regime of frozen soils is snow cover (Isaev et al. 2020). The duration of the period with a stable snow cover is about 200 days. The average thickness of the snow cover is 62 cm; in urban areas it is 88 cm. In winter, some parts of the territory are exposed to snowdrifts, the thickness of which, in some places, can reach over 3.0 m.

Geological structure of the Vorkuta region includes deposits of the Devonian, Carboniferous, Permian, and Quaternary ages. Carbonate sediments (dolomites, limestones, and marbles) represent Carboniferous and Devonian deposits. Terrigenous sediments (conglomerates, sandstones, siltstones, mudstones, and coals) represent Permian deposits. These Paleozoic and Mesozoic rocks are covered by Quaternary sediments (Geocryology 1986).

The thickness of the Quaternary sediments cover varies from several meters up to 80-120 meters. It is uneven in thickness and complex in structure (Geocryology 1986). Genetically, Quaternary sediments are subdivided into four main types: diluvial, upper moraine, fluvioglacial, and lower moraine. There are some water-logged areas in the Vorkuta region, which contain lacustrine-boggy sediments and peat (Markizov 1991).

Silty clays with gravel mainly represent diluvial sediments, the amount of which increases with depth. The thickness of the cover-diluvial formations most often ranges from 0.5 to 1 m, going up to 3 m on the slopes, and 5 m at the bottom of the slopes.

Silty clays are characterized by a high content of clay particles (45–55%) and water content (25 - 30%). Silty clays and loams mainly represent the soils of the upper moraine. The content of clay particles is 35 to 45%, gravel – up to 10%. The water content is close to the liquid limit.

Fluvioglacial sands are usually water-saturated in the thawed state. Because of their high infiltration capacity, these deposits often contain groundwater.

Silty clays and loams with inclusions of gravel represent the lower moraine. These soils are often frozen. The ice content in the upper part is 25–31% and decreases with depth.

Lacustrine-bog sediments consist mainly of silty clay and clay. They contain thick (up to 0.2-0.4 m and more) ice layers and ice lenses. After thawing, these sediments have a low bearing capacity.

Thaw subsidence of Quaternary sediments depends on the quantitative content of ice inclusions, their shape, and position within the ground. For example, the maximum thaw subsidence of diluvial sediments is 0.2-0.3 m/m, whereas for lacustrine-boggy sediments it is 0.7 m/m. The minimum subsidence is observed in sandy and gravel deposits with a massive cryogenic texture (less than 0.01 m).

The features of the relief, widespread presence of clay in the Quaternary sediments and the permafrost extent result in a high occurrence of swamps and lakes, mainly of thermokarst genesis.

Vorkuta belongs to the subzone of discontinuous high-temperature permafrost, which occupies up to 80-90% of the area (Geocryology 1986). The area contains many taliks of various genesis. The most common permafrost thickness is 40-80 m. The permafrost table is uneven, varying from several meters to 40 m. The smallest depth of the permafrost base is 15–20 m, the highest is 200 m. The mean annual ground temperature varies from -0.1 to -1.5 °C (rarely -2.0°C). The thickness of the active layer varies from 0.3 to 2.5 m. Unfrozen soils are found near the Vorkuta River (Khilimonyuk et al. 2011).

## METHODS

Several reported cases of collapsed buildings were evaluated to determine the reason for such incidents, and then fieldwork was carried out to determine whether faulty design, faulty maintenance, or both, caused the failure. The current state of buildings in Vorkuta was examined during fieldwork, with analyses of relevant scientific publications, official reports, and reports from the municipal authorities. Building observations were carried out as part of the field courses for master students, organized by the Geocryology Department of MSU. Master students, led by representatives of the geocryological service of the Komi Republic, studied the experience of construction and use of buildings in Vorkuta and carried out visual and instrumental surveys of the foundations. Building observations consisted of the following stages:

- Gathering of information about the history of the building;
- A visual inspection, during which the presence of structural defects and deformations of the building and its structures (deflections, rolls, bends, distortions, faults, etc.), features of nearby areas of the territory, vertical planning, organization of surface water drainage were determined;
- An instrumental inspection, which consisted of measuring the geometric parameters of buildings, determining the actual characteristics of building materials, and the parameters of cracks;
- Surveys of foundations, which included the excavation of pits near the foundations with a description of the soil and an examination of the condition of the foundation. Cracks in structures (transverse, longitudinal, inclined, etc.), bare reinforcement, concrete falls, areas of concrete with discoloration, and the most damaged areas of foundation structures were all recorded to assess the condition.

Based on a literature review and field research, the information on the engineering design of foundations in Vorkuta and the main reasons for urban infrastructure failure in the city was summarized.

## RESULTS AND DISCUSSION

## ENGINEERING DESIGN OF FOUNDATIONS

Practically all major methods of construction on permafrost (construction on bedrock, Principle I, Principle II) can be found in Vorkuta. The most common type of foundation is piling foundation (accounting for about 80% of the housing stock) (Eroshenko et al. 1979). In this section, the engineering design of foundations is considered in more detail.

### Construction on bedrock

In some areas of Vorkuta, bedrock is found at a depth of 1.5 to 5 meters. This is enough for the construction of pile or column foundations. Most of the buildings, built on bedrock, currently are in a stable state (Vorkuta thermal power station, city center, Northern and Leninsky districts).

### Principle I

A major task is to preserve the soil in the frozen state during the construction and lifespan of the structure. A crawlspace foundation is the most common foundation type in Vorkuta. Quarter 22 (comprising 2-storey wooden panel and stone buildings) was built in the 1950s according to Principle I. During the first 9 years of the use of buildings, the permafrost table rose due to clearing and removing snow from the streets (Khrustalev et al. 2011).

In Vorkuta, about 100 wooden one- and two-storey buildings were built on shallow foundations according to Principle I from 1950 to 1960 (Markizov 1991). Slag, gravel, natural sand-gravel mixture, burnt rock from mine waste heaps, and other local materials were used for backfilling (Romanenko et al. 1974).

### Principle II

Since 1970, most of the buildings in Vorkuta were built according to Principle II. This principle includes three major methods of foundation construction: adaptation of the building to uneven subsistence during thawing; preliminary thawing of the permafrost and stabilization of the permafrost's initial position.

The method of adapting a building to uneven subsidence during thawing is the oldest method of foundation construction in the North, which was used in the 1930-1950s. A survey of 94 buildings in Vorkuta showed that 29 of them were deformed within 5-10 years after they began to be used (Bondarev 1964). The average relative subsidence of the buildings was 0.25 m (for some buildings, up to 1 meter). Such large subsidence of the foundation is not possible to compensate for due to the destructive stresses that arise in it.

V.F. Zhukov (Zhukov 1958) proposed possibilities and outlined major conditions of using preliminary thawing of permafrost in 1958. Following that work, wide practical implementation of an alternative method of foundation construction began (Bondarev 1964). Calculations showed that to ensure the stability of buildings in Vorkuta, it is necessary to pre-thaw the permafrost to a depth of 18-31 m. But such a large pre-thawing depth also leads to enormous capital expenditures for preparing the foundation. This method became dominant in Vorkuta since 1970.

The method of stabilizing the permafrost's initial position was developed by the employees of the Gersevanov Research Institute of Bases and Underground Structures (which has a branch in Vorkuta) and engineers of Vorkutaugol (Khrustalev and Nikiforov 1990). This method was used when an unfrozen layer was detected below the active layer and the permafrost table. Frozen soils in this case are characterized by significant compressibility during thawing (over 0.02 m/m) and the foundations are located in a layer of thawed soil. The stabilization method relies on the fact that the permafrost table is stable all the time due to the alternating mode of operation of foundation ventilation. Alternating periods last 5-15 years with a negative average annual air temperature in the foundation (cold period) and 2-5 years with a positive average annual air temperature (warm period). It is necessary to consider frost heaving forces. A few 26-panel five-story buildings (1975–1978) were constructed in the settlement Vorgashor using this method. A modification of the stabilization method used cooling devices instead of ventilated foundations. Ten structures were built in 1980 using this modified method.

In Vorkuta, about 237 one- and two-story buildings were built on shallow foundations according to Principle II (Markizov 1991).

### Combination of Principle I and Principle II

This approach was used for Quarter 7 in the city center, where some houses were built according to Principle I, and others according to Principle II. This part of the city is characterized by an intense degradation of permafrost. The building density in this area is about 24% and there is a developed network of underground utility lines (heat pipelines, hot and cold water supply lines, sewerage).

High building density and significant thickness of snow cover led to the thawing of frozen soil near the buildings (Khrustalev et al. 2011). In addition, because of the deep thawing, infiltration of groundwater had increased, which further impacted the thermal regime as well. The cooling of soils only due to the presence of ventilated crawlspaces is insufficient to withstand the general changes in the permafrost conditions. The possibility of intensive thawing of frozen soils was not taken into account in this area, so most of these buildings were deformed. Buildings constructed according to Principle I have the greatest deformations. A similar situation was observed in the Railroad District of Vorkuta (Belotserkovskaya et al. 1989).

## HISTORY OF THE DEVELOPMENT OF VORKUTA

The history of Vorkuta began in 1921, when the first expedition, headed by Alexander Alekseevich Chernov started to study the Pechora region. A large Pechora coal deposit was discovered in 1924. In 1930, the Vorkuta coal deposit was discovered and the first coal was mined in 1934 (Strategy 2020). From 1934 to 1960, a railway, a thermal power station, 15 mines, woodworking and cement plant, residential and industrial buildings, along with roads in the city were built. Of 953 buildings constructed on permafrost soils in 1961, 856 were built without consideration of the frozen state of the ground (Bakalov 1964).

In 1960–1970, Vorkuta developed at a rapid pace: the volumes of coal production were constantly growing. Among the large new buildings of these years are the Khalmer-Yu, Yun-Yaga, and Vorgashorskaya mines, a dairy plant, a distillery, a poultry factory, and a garment factory. In 1977, there were 1.184 buildings in the Vorkuta region (Belotserkovskaya and Ponomarev 1985).

Vorkuta reached its greatest prosperity in the 1980s. In those years, the population reached 200 thousand people, while the production of cement and reinforced concrete structures in the city grew, and the volume of coal production increased significantly. About 100 thousand square meters of housing were commissioned annually (Barenberg 2014).

The period from 1991 to 2006 turned out to be difficult and unstable years for the city. The political, economic, social crisis in the country also affected coal mining, and production began to decline. Most of the mines were closed and the population began to decline likewise (Shiklomanov et al. 2019).

In 2006, the municipal formation of the urban Vorkuta district was established, consisting of the city of Vorkuta and several settlements (Vorgashor, Eletsky, Zapolyarny, Komsomolsky, Meskashor, Mulda, Oktyabrsky, Promyshlenniy, Severny, Seida, Sivomaskinsky, Khanovei, and Yurshor). Most of the settlements were closed and abandoned (Shiklomanov et al. 2019). Since 2006, statistical processing of the socio-economic state of the city has been carried out, which was subsequently used for data processing.

The current state of the housing stock in Vorkuta is assessed using the online service of The Ministry of Construction, Housing and Utilities (https://dom.mingkh.ru/), which contains information about the housing stock in the Russian Federation, as well as statistics from 2006 to 2019 (Passport 2015; Passport 2020).

After the collapse of the USSR and the crisis in the mining industry, many residents left the city, moving to the southern regions of the country. The population of the city continues to decline annually, from 108.9 thousand (2006) to 73.1 thousand (2020) (Fig. 1).

This reduction in the number of people leads to the need to reduce the number of buildings since most of them are not used (Shiklomanov 2019). Thus, there is a constant reduction in the number of residential buildings in settlements. Compared to 2006, only 20% of the housing stock in the satellite settlements remains, whereas in Vorkuta it is still 80% (Fig. 1).

In 2020, about 800 residential buildings were in use in Vorkuta. There is no complete data for 41 houses, so further processing was carried out for 759 houses. Figure 2 shows the current state of the housing stock. 55% of the buildings have 5 floors, 15% have 2 floors, 12% have 3 floors, and the remaining 18% make up buildings with other numbers of floors - less than 5% each (Fig. 2).

According to Russian standards, buildings are expected to be used for 50 years (GOST 27751-2014). Thus, houses built before 1970 have been in use for more than this period. There are 43% of such buildings in Vorkuta. Every year the number of such buildings will increase and by 2040 it will reach 90% if the current trends continue.

Every year the number of buildings in a «critical» state increases (Passport 2020). It means a critical technical state of the building, characterized by its destruction or damage and deformations, which can cause loss of stability. As of January 1, 2019, 47 residential buildings were officially deemed critical and unusable. Thus, the number of critical houses in the city does not exceed 6%.

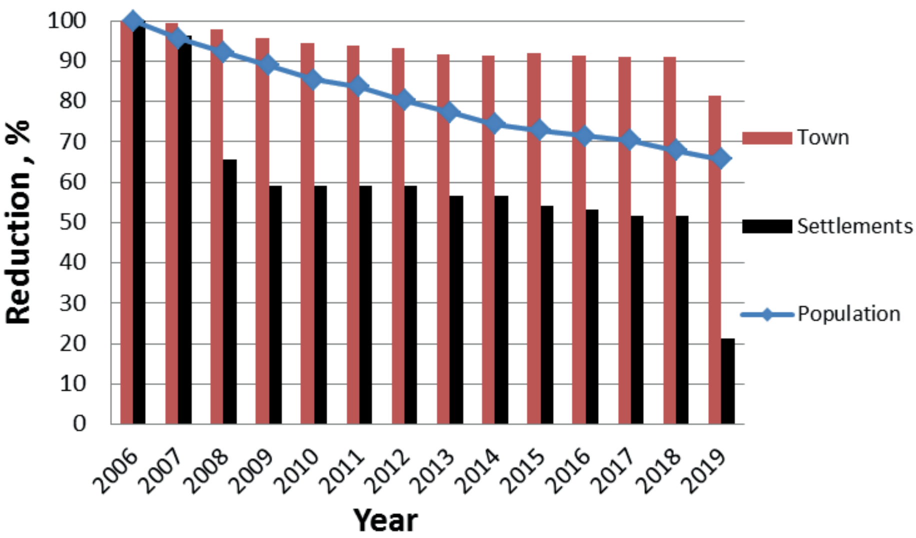


**Fig. 1. The reduction of total residential housing stock (in the city and satellite settlements) and population (total population in 2006 is taken as 100%)**

After resettlement of such buildings, it is necessary to demolish them and reclaim the territory. However, at present, these works are practically not carried out. The mayor of Vorkuta said in an interview that there are 155 abandoned buildings in the city (Interview 2020). It is almost 20% of the total residential housing stock. A special municipal program provides for the relocation of the population to the central part of Vorkuta to reduce the ineffective expenditures of the local budget for the maintenance of excess infrastructure (Strategy 2020). It includes the closure of several settlements and the disconnection of 47 buildings from utility lines. Over the four years of the program, 71 houses were disconnected from utilities, and 27 houses were demolished (Passport 2020).

If we compare how the housing stock has changed over time, then the following stages can be distinguished. Until 1961, mainly two and three storey wooden houses were built. Currently, 163 such houses are still in use, i.e. only 17% of the total number of houses existed in 1961.

From 1964 to 1994, active construction of brick (and later panel) 5-story buildings began. Currently, 417 houses built before 1977 are in use, i.e. only 35% of the total number of houses. Thus, 800 houses have been demolished or disconnected from utility lines over the past 50 years.

It is also necessary to take into account the deterioration of utility lines. In 2018 and 2019, there was an increase in the number of accidents at sewerage facilities and heating pipelines. Furthermore, leaks and unaccounted water consumption increased from 28 to 62% (2006–2019). It will lead to a more rapid thawing of permafrost and the modification of cryogenic processes.

## THE MAIN REASONS OF INFRASTRUCTURE FAILURE

The analysis of infrastructure failure was carried out based on data from scientific publications of employees of the Gersevanov Research Institute of Bases and Underground Structures (Vorkuta branch), where systematic long-term observations of building stability were started (Bakalov 1964; Bondarev 1964; Belotserkovskaya and Ponomarev 1985; Belotserkovskaya et al. 1989). As a result, the following reasons can be distinguished.

1. Ignoring geocryological conditions, composition, and properties of frozen soils. During construction in the period 1930-1950, the depth of boreholes during engineering survey was 5-8 meters, in the 1960s and even at the beginning of the 1970s, it was increased to 10-12 m. The buildings were constructed according to Principle II without taking into account the high compressibility of soils during thawing below 10 meters depth, which led to significant and uneven settlement of soil during the building's use. Examples of buildings deformed for this reason are numerous.

The design and construction of the administrative building of construction department No. 6 (1970-72) was carried out without preliminary research. Although a solid reinforced concrete slab with rib beams was used as the foundation, the building experienced uneven settlement of soil and was later demolished in 1978 (Khrustalev et al. 2011). The railroad district of Vorkuta is one of the most complex areas. The upper part of the cross-section consists of ice-rich lacustrine-boggy soil (0.2-2.5 m thick) and diluvial sediments (1.0-4.5 m thick) with ice interlayers. The depth of foundation under each building was made the same, and adjacent foundations were located in both thawing and frozen soils since pre-construction preparation of the soil base was not considered in these projects (Belotserkovskaya et al. 1989). Ignoring the geocryological conditions and the compressibility of frozen soil after thawing led to the failure of some buildings.

2. Using two principles of construction in the same district. Sometimes a project was carried out when the facility was already in use, such as during the ground or underground laying of plumbing and heating networks in the immediate vicinity and even inside the contour of structures constructed according to Principle I. Such violations were very common for buildings constructed in the 1950s and 1960s, for example the city hospital, school, Krasnoarmeyskaya and Suvorov streets, and the railroad district. The principle of construction was independently selected for each building without considering the railroad district development as a whole (Belotserkovskaya et al. 1989).

3. Mistakes made during the construction processes. The most common and constantly occurring mistakes of construction technology are:
- waterlogging of foundation pits and construction sites;
- failure to perform adequate planning to provide a slope necessary for surface water runoff;
- allowing freezing of the thawed soil base during the construction processes;
- failure to design adequate ventilation of the foundation during the lifespan of structures.
- failure to ensure the design bearing capacity of piles due to under-loading of piles to design elevations.

4. Poor quality of construction materials. Northern climate combined with the possible effect of salt solutions

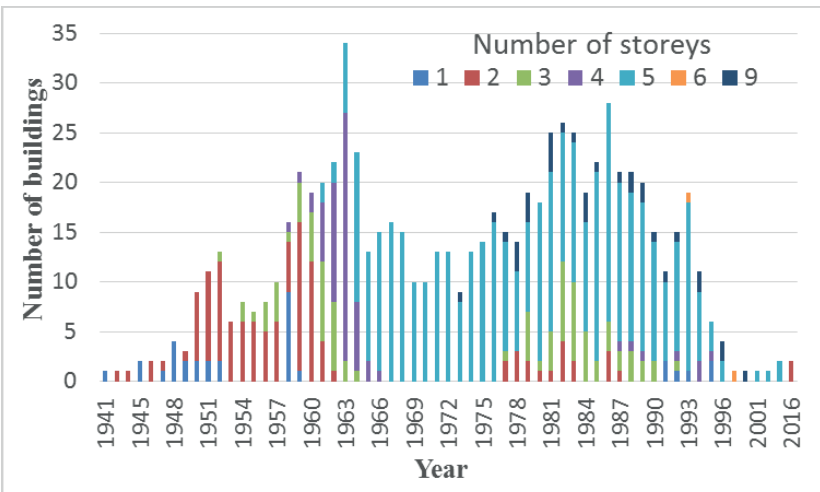


**Fig. 2. Breakdown of the current (2020) existing structures in Vorkuta, according to the year of construction (1941-2016) and the number of storeys. There are no 7- or 8-storey buildings**

in soils significantly intensify destructive processes in concrete, leading to a premature decrease in its strength (Grebenets et al. 2002; Grebenets and Ukhova 2008). When examining buildings in Vorkuta, wall panels were found with damage over the entire surface. Balcony slabs, canopies, and basement panels collapse very quickly under these conditions. After 2-3 years of use, almost all buildings showed traces of frost damage. A survey of Vorkuta foundations showed that up to 50% of columnar and pile foundations show signs of concrete damage in the form of cracks (20–30 cm long and more than 1 mm thick) after 10 years of use (Pantileenko 2016). The strongest concrete damage is observed in the active layer or above the surface. There is no concrete damage to the foundation below the active layer.

5. Improper building use. This can lead to changes in temperature and humidity conditions near the foundation. It is possible to subdivide improper building use into the following:

- the impact of water: repeated natural and technogenic flooding of the foundation, especially accumulation of chemically aggressive wastewater;
- improper use of the crawlspace foundation limiting ventilation;
- long-term heat sources near buildings constructed according to the first principle (hot water pipelines, coal ash dumps, waste heaps, rainwater pits).

## CLIMATE CHANGE IN THE VORKUTA REGION

Processing of the average annual air temperature at the Vorkuta meteorological station showed that from 1937 to 1998, temperatures did not change dramatically, but from 1998 to the present, a steady increase in air temperature has been observed (fig. 3).

Monitoring of the soil temperature began in Vorkuta at the beginning of the 1960s (Oberman 2008). The mean annual ground temperature in the western Russian Arctic has increased by 0.03 to 0.06°C/yr, and the permafrost table has lowered by up to 8 m in the discontinuous permafrost zone (Vasiliev et al. 2020). According to the observation data, the permafrost temperature near Vorkuta has increased by 0.02 °C to 0.68 °C/yr. The thickness of taliks has increased by 2 meters in some areas (Report 2019). Winter climatic parameters and thickness of the peat horizon of soils have a major impact on the active layer thickness in the Vorkuta region according to long-term active layer monitoring (over 17 years) (Kaverin et al. 2017).

Another factor that must be taken into account in the Vorkuta region is the influence of coal dust because it changes the radiation balance of the area. Snow melts in the city almost a month earlier than in natural conditions. The results of modelling in the northern part of Vorkuta (with ground temperatures of -1.5 to -2.0°C) showed only an insignificant influence of this factor. Snow pollution will have a stronger effect in the central part of Vorkuta, where the ground temperature is -0.5 °C (Khilimonyuk et al. 2011).

The effect of climate change on the stability of infrastructure will depend on the construction principle (Belotserkovskaya 1990). The least stable foundations, constructed according to Principle I will decrease their mechanical characteristics (Kotov and Stanilovskaya 2021) and bearing capacity (Streletskiy et al. 2012a) due to an increase of ground temperature. There is no official data about how many buildings were built according to Principle 1. However, according to our estimates, their number does not exceed 20% of the housing stock in Vorkuta.

Climate change will not have a significant effect on buildings constructed on bedrock. In this case, the stability of structures will depend only on the mechanical properties of the rock. The upper part of the rocks in Vorkuta has many cracks, therefore it has a low bearing capacity. It is also necessary to take into account the effect of tangential heaving forces on the stability of low-rise buildings.

The stability of buildings constructed according to Principle II also depends on thermal influences and the thickness of thawing. The thawing depth for a typical 5-story residential building in Vorkuta is about 30 m. With climate warming, it is possible to assume an increase in soil temperature and even a decrease in the permafrost table. However, this effect will be very insignificant at depths greater than 42 m for Vorkuta (Khrustalev et al. 1993). Improper use can lead to much larger changes in soil temperature. The stability of buildings depends on thaw settlement. Thaw settlement calculations are performed using deformation characteristics (thawing and compressibility coefficients). These characteristics can be determined by field (hot stamp) and laboratory tests (compression and triaxial test) (Kotov et al. 2017; Kal'bergenov 2019). Deformation characteristics for different test methods can differ by several times in magnitude (Kotov et al. 2015). There are many factors influencing thaw settlement: the cryogenic structure, water/ice content, density, cryogenic texture, thawing conditions, and stresses. Therefore, thaw settlement varies widely. Indeed, settlement may not occur with increasing thawing depth due to the low compressibility of the soil (especially for sand and gravel).

Buildings constructed according to the method of stabilization of the permafrost's initial position have practically no thermal influence on each other. In addition, the buildings provide good snow and wind protection. This construction method is practically insensitive to climate change, which only affects the alternating mode of the needed ventilated foundation operation.

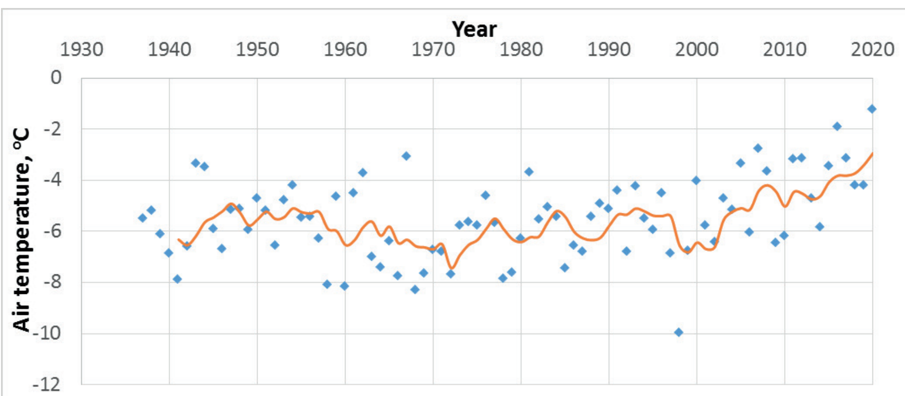


**Fig. 3. Annual mean of air temperature in Vorkuta (raw data (blue dots) and 5 years running mean (orange line))**

## CONCLUSIONS

This article describes various principles of construction in Vorkuta. According to the literature review and field observations, there are several reasons for infrastructure failure, which include ignoring the geocryological conditions, composition, and properties of soils; using two construction principles in the same city district; using poor-quality construction materials; mistakes made during the construction processes; and improper building use. Among those, improper building use is one of the major reasons.

The analysis of infrastructure stability in the context of climate change was carried out. Buildings constructed according to Principle I were found to be more vulnerable due to a decrease in foundations bearing capacity. The increasing temperature will not affect the stability of buildings built on bedrock (which depends on the mechanical properties of rock). Most of the buildings in the city were built according to Principle II, where the influence will depend on the method of construction and the thickness of thawing. There is no impact of climate change for two methods: the stabilization of the permafrost's initial position and the preliminary thawing of permafrost (if the thawing thickness was more than 42m). A slight increase in air temperature can accelerate thawing, but will not play a decisive role in comparison with the improper use of the infrastructure.

Currently, there is an unfavorable situation with residential buildings in Vorkuta due to the increasing share of housing stock being deemed critical (6% every year) and presence of several abandoned and unused buildings. About 800 buildings are in use in Vorkuta in 2020 (43% of what it was 50 years ago). According to the analysis, about 800 houses have been demolished or disconnected from utility lines over the past 50 years (about 250 of these are still standing, pending demolition). Since 1994, the construction of new residential buildings has almost stopped. Therefore, buildings that have been in use for over 50 years will account for 90% of the total residential housing stock by 2040.

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