The problem of the sustainability of Svalbard infrastructure under changes of climate and permafrost conditions

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ABSTRACT

The Svalbard archipelago stands out particularly in the context of the global climate change in the Arctic region. The air temperature in Longyearbyen increased by 0.1°C per year over the past 30 years. With the current trends, we can predict an increase in air temperature by 3...4°C by 2080-2100. Rise in air temperature leads to warming of the permafrost. The current trend of permafrost temperature growth is 0.06...0.15°C per year. Such trends of change in climatic characteristics and permafrost parameters pose a great danger to infrastructure on the archipelago. We observe changes in the engineering and geocryological characteristics of frozen soils when they are getting warmer. Its bearing capacity decreases, as well as the forces of frost heaving. A complex of hazardous exogenous processes (first of all, cryogenic) that threaten the stability of the infrastructure are becoming more active. It results in increase of the rate of coastal erosion of the shores, in increase of avalanche activity. Changes in permafrost conditions and deformations of infrastructure facilities recorded in the archipelago are amplified by an anthropogenic factor: heat release from buildings, disturbance of natural covers, changes in the flow paths of surface and ground waters and etc.

KEY WORDS: Svalbard, infrastructure, permafrost, climate change, hazardous processes

INTRODUCTION

Currently, the issue of the sustainability of infrastructure in the Arctic is acute (Grebenets et al., 2012). This is due to the trends towards an increase in outdoor air temperatures and subsequent changes in permafrost conditions recorded in the northern regions. These changes negatively affect the engineering and geological parameters of frozen soils: the bearing capacity decreases, the soil settles, and the tangential forces of frost heaving increase (Iurov & Grebenets, 2019). In addition, there is an activation of hazardous exogenous processes for the infrastructure: thermokarst, thermal erosion, thermal abrasion, slope processes, etc. It is important to note that the Svalbard archipelago is a kind of "world leader" in the field of global warming. Extremely high trends were recorded here for an increase in air and frozen ground temperatures (NCCS, 2019). The role of anthropogenic impact is also extremely high in changing permafrost conditions and activation of exogenous processes. Heat release from buildings and structures, changes in the flow paths of surface and ground waters, disturbance of natural covers can radically change the engineering and geological properties of frozen soils.

The aim of this work is to assess threats to the stability of infrastructure in the Svalbard archipelago in the context of changes in climatic and permafrost conditions. The study analyzed the processes and features that pose the greatest danger to various infrastructure facilities in Svalbard; the changes in the engineering and geocryological characteristics of soils, caused by climatic trends, have been evaluated. Special focus is paid to the state of transport infrastructure facilities, especially linear facilities (roads, pipelines, etc.). Such structures are the most vulnerable due to their continuity and great length. These features do not allow bypassing areas with "bad" geocryological conditions during the construction of roads, pipelines and other similar facilities.

CLIMATE AND PERMAFROST CHANGES IN SVALBARD

In recent decades, Svalbard has recorded extremely high rates of climate change. The increase in outdoor temperature since the 1970s for the archipelago has been estimated at 0.8°C per decade (Van Pelt et al, 2016). The largest increase in temperature is observed in the northern part of Svalbard (on average about 1.3°C per decade), while in the southern part of the archipelago, the trends towards temperature increase are noticeably lower (about 0.45°C per decade) (Van Pelt et al, 2016). In the largest population center, Longyearbyen. The trend for an increase in air temperature in Longyearbyen over the past 30 years has been 0.101°C per year (NCCS, 2019). It is important to note that changes in air temperature occur extremely irregularly over the seasons. This corresponds with the general trend for the Arctic - warming in winter exceeds the increase in summer temperatures by approximately 4 times (Bintanja & van der Linden, 2013). The observed average increase in winter temperatures across the archipelago is 1.6°C per decade, summer temperatures are increasing by only 0.2°C per decade (Van Pelt et al, 2016). The linear trend in the growth of winter temperatures from 1971 to 2017. was 1.67°C per decade for Longyearbyen, the trend of an increase in summer temperatures was 0.47°C per decade (NCCS, 2019). According to various models, air temperatures will continue to rise in Svalbard in the coming decades. For example, the calculations in the NCCS report based on the CCLM model with the most negative climate scenario RCP8.5 suggest an increase in the average annual air temperature in Longyearbyen by 6.5°C by 2071-2100. If such changes do occur, then the average annual air temperature in this area (currently -5.9°C) will take the positive values (NCCS, 2019). Other models also indicate a significant increase in air temperature in the near future. For example, in the work of F. Nelson, the temperature rise by 2050 is estimated at 2.5°C (Nelson et al., 2002)

There is also a decrease in the duration of the winter period in Svalbard in addition to changes in temperature indicators,. According to observations at the meteorological station at Longyearbyen Airport, the average cold season from 1971 to 2000 was 240 days. However, the NCCS projected that the cold season will be 96 days shorter by 2100 (NCCS, 2019).

Changes in climatic parameters have a negative impact on the state of permafrost. An increase in permafrost temperature has been recorded over the past 20 years in many northern regions: in Alaska, Canada, the Russian Arctic and, in particular, on the Spitsbergen archipelago (Romanovsky et al., 2017). The change in the climatic parameters of the winter period plays a particularly important role. An active increase in winter air temperatures, combined with a reduction in the cold season, does not allow frozen soils to gain a "cold reserve" in winter.

The key site for our research was the town of Longyearbyen, located in the coastal part of West Spitsbergen. Here, the permafrost is thinnest in the archipelago (about 100 m in the coastal valleys, in one of which the settlement is located) (Liestøl, 1977) and the highest temperature (Romanovsky et al., 2010). At the same time, the permafrost conditions in the study area are rather heterogeneous: the temperature at the level of zero annual fluctuations (at a depth of about 10-15 m) varies from -2.2° to -5.2°C (Instanes, 2016; NCCS, 2019). An increase in the temperature of frozen soils at a depth of zero annual fluctuations since 2008-2009. to 2016-2017 ranged from 0.4 ° to 0.5 ° C in Longyearbyen. The rate of temperature growth at the depth of 10 m for different sites ranges from 0.06 ° C to 0.15°C per year (NCCS, 2019). Modeling of permafrost temperature fields by 2071-2100 using the RCP8.5 scenario shows that by the end of the century, permafrost temperatures at depths of 5 and 10 m may approach 0°C.

METHODS

We calculated the main parameters of frozen soil under the further climate change towards warming. We calculated properties that are key importance for assessing the stability of linear transport systems: an increase of the active layer thickness, thaw settlement and an increase in frost heaving forces.

To calculate the thickness of the active layer (d_{th}) by 2050, the method proposed in SN 25.13330.2012 (Russian building rules) was used (1.1)

$$d_{th} = [\frac{(2\lambda_{th}(T_{th,c} - T_{bf})t_{th,c})}{q_l} + \left(\frac{Q}{2q_l}\right)^2]^{0.5} - \frac{Q}{2q_l} \quad (1.1)$$

$$Q = (0.25 - \frac{t_{th,c}}{t_l})(T_0 - T_{bf})k_m)\left(\lambda_f C_f t_{th,c}\right)^{0.5} \quad (1.2)$$

$$Q = L_y + (\frac{t_{th,c}}{t_2} - 0.1)(C_{th}\left(T_{th,c} - T_{bf}\right) - C_f\left(T_0 - T_{bf}\right)) \quad (1.3)$$

where:

T_{bf} – temperature of the beginning of soil freezing (°C)
$t_{th,c}$ – calculated period of positive temperatures (hours)
T_{bf} – calculated temperature of the soil surface in summer (°C)
t_1 = const = 3600 (h)
t_2 = const = 7500 (h)
T_0 – calculated average annual temperature of frozen ground (°C)
L_v – heat of thawing (freezing) of soil (Joule / m^3)

The tangential forces of frost heaving acting on the lateral surfaces of the basement in the active layer is calculated by the equation (2) (SN 25.13330.2012).

$$F_{кас.} = \tau_{fh} A_{fh} \quad (2),$$

where:

τ_{fh} – calculated specific tangential heaving force (kPa)
A_{fh} - area of the lateral surface of freezing of the foundation within the estimated depth of seasonal freezing-thawing of soils (m^2).

To calculate thaw settlement of clay soil, we used equation 3

$$\delta = 1 - \rho_{df}(\frac{1}{\rho_s} + \frac{1}{\rho_w}\left(W_p + k_\partial I_p\right)) \quad (3)$$

where:
ρ_s – soil particle density (g/cm^3);
ρ_w – density of water (g/cm^3);
W_p – moisture at the rolling edge (%);
I_p – plasticity number
k_∂ – coefficient taking into account incomplete closure of pores in thawed soil

For the calculation, we used the trends in the growth of surface air temperature and permafrost temperature at the level of zero annual amolitudes, proposed by the NCCS (NCCS, 2019).

We used the method of ground-based laser scanning to study the deformations occurring at transport facilities in Longyearbyen. This method is quite useful for monitoring deformations that occur on linear objects such as roads and airfield runways. Such objects have a large extent and area, that makes impossible to use traditional geodetic methods to track vertical and horizontal movements of the surface of objects. We used a Riegl VZ-1000 laser scanner. It has fairly high measurement accuracy (about 5-8 mm). Measurement from one point allows to cover an area within a radius of 1000 m around the scan point. However, the effective shooting distance for our tasks is much lower: the use of scans with a scanning distance of more than 400 m is not effective. It is important to note that the prosess of scanning is quick, the shooting time is from 5 to 15 minutes from one point (it depends on the specified scanning settings). Such characteristics of the scanner can significantly reduce the time spent on surveying objects with a large area and length. As a result of scanning an object, we get a "cloud" of millions of points oriented in space. The scan result is a 3D terrain model oriented in space.

We used RISCANPro (www.riegl.com) and CloudCompare (www.danielgm.net) software to process the scanned data. This software provides a wide range of point cloud tools. The simplest tool is coloring in height. This tool allows us to determine the macrorelief of the surface of the object (irregularities with dimensions in the first meters). The weakness of the instrument is a low scale that does not allow to analyze small movements. The method of sections seems to be the most successful for the microrelief investigations of the objects. The average frequency of the location of points (7-10 points per 1 meter of surface) allows to track irregularities in size from the first centimeters. An automated comparison of scans at different times seems promising with the regular monitoring of objects for the occurrence of deformations. This procedure is possible in both programs and allows us to observe the appearance of irregularities with a resolution of 1 cm. Another method of detecting deformations on the surfaces of the objects under study is the calculation of the parameter of the geometric roughness of the surface. This method makes it possible to identify irregularities ranging in size from several millimeters to tens of centimeters.

RESULTS AND DISCUSSION

We created a forecast of the main engineering and geocryological parameters of frozen soils by 2050, on the basis of NCCS forecasts. It showed that the existing trends in climate change pose a significant threat to infrastructure facilities in Svalbard. The average calculated value of the increase of the active layer thickness in lithological conditions typical for Longyearbyen is15-17 cm, or 17-20% of current values. The result obtained correlates with the NCCA forecast of an increase in the depth of the active layer in the area of Longyearbyen by 1 m by 2100 (NCCA, 2019), as well as with other forecasts and models (Instanes, 2016).

An increase in the thickness of the active layer and an increase in the temperature permafrost will negatively affect the bearing capacity of frozen pile foundations, which are widely used in Svalbard. This is due to a decrease in the strength of freezing of frozen soil with the surface of piles, which occurs with an increase in temperature, and a decrease in the freezing surface size. We also forecast an increase in the tangential forces of frost heaving, acting on the pile foundations due to the growth of the active layer thickness.

Our calculations showed that the tangential forces of frost heaving will increase by 15-17% due to an increase of the active layer thickness. Such a significant increase in heaving forces can negatively affect the stability of relatively light timber residential buildings (a significant part of Longyearbyen's housing stock). It can lead to the development of uneven heaving deformations and damage to buildings together with a decrease in the freezing forces of pile foundations due to an increase in temperatures and a decrease in the freezing surface. The development of heaving is most dangerous for lightly loaded objects such as roads and pipelines. The key problem is the uneven development of the heaving process along the length of the structure of linear objects. This unevenness is due to the variability of permafrost-landscape conditions in the permafrost zone. The depths of seasonal thawing can differ by 1.5-2.0 times at relatively small distances (sometimes 1-2 m), with a permafrost-lithological diversity. The increase in frost heaving forces also differ significantly. The deformation of the object occur unevenly, which can lead to its complete destruction.

A laser scan of major streets in Longyearbyen (Fig.1) revealed numerous deformations caused by uneven thawing settlement. Technogenic impact plays a significant role. We recorded a number of cases of subsidence of roadsides and road surfaces, that were caused by anthropogenic flooding (Fig. 2). The depth of the subsidence is about 7-20 cm. Flooding occurs as a result of insufficient development of culverts under road embankments. The culverts are located slightly above the surface. It prevents the full flow of the spring snow melt. Utilities are laid through culverts, which prevent water flow and contribute to the formation of blockages from mineral particles and ice (Fig. 3). Stagnant water along the road embankments warm frozen soils at the base of the embankments and can cause the activation of the thermokarst process.

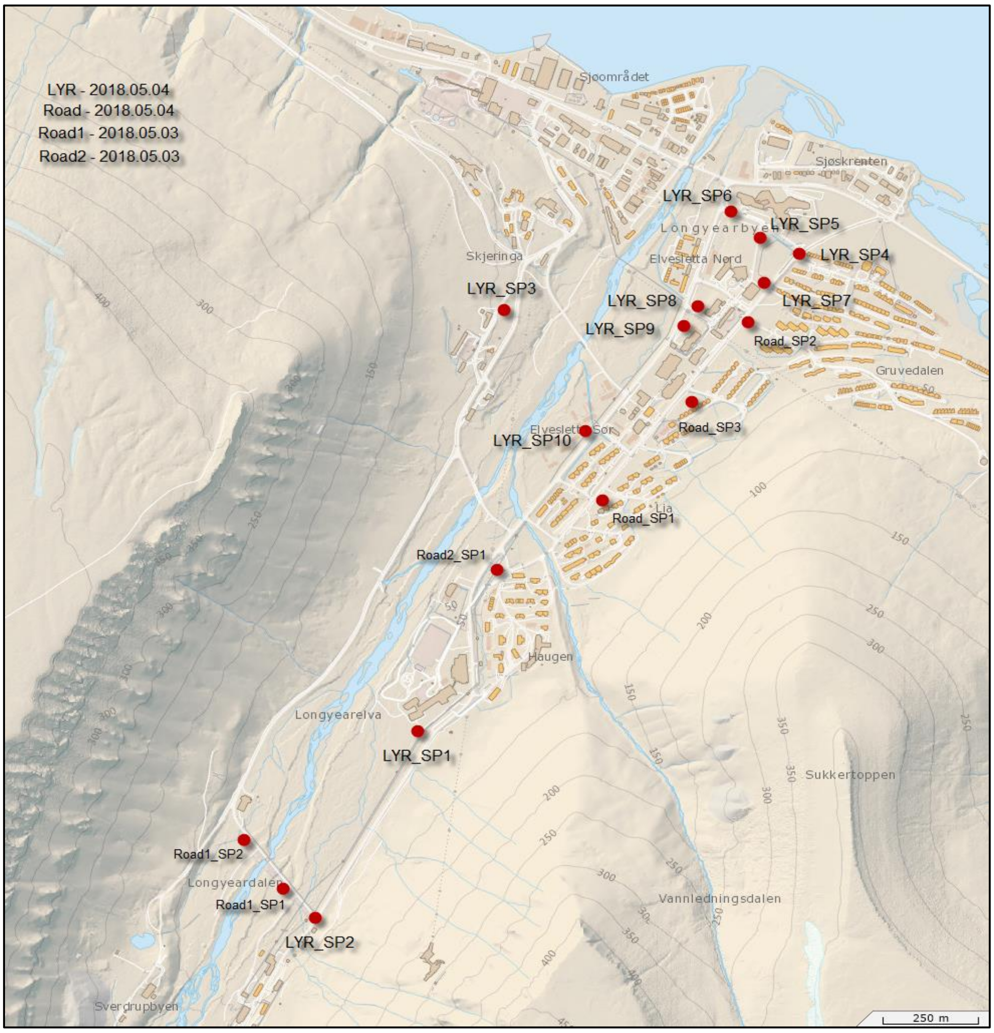

Figure 1. Location of scan positions (red dots) in Longyearbyen. (Map by toposvalbard.npolar.no)

Figure 2. Antropogenic flooding on the territory of Longyearbyen (photo by F.Iurov, May 2018)

Figure 3. Culvert and drainage trough in Longyearbyen (photo by F.Iurov, Oct. 2019)

A network of frost cracks on the surface of the runway at Longyearbyen Airport activated as a result of human activity. A network of frost cracks (Fig. 4B) was identified by visual inspection and laser scanning of the runway surface (Fig. 4A). The discovered polygons have a predominantly quadrangular shape with a side size of about 7-12 m. The reason for their formation was, hypothetically, overcooling of the runway soil base in winter, caused by the removal of snow from the surface. The amplitudes of changes in soil temperatures increase throughout the year, which leads to the activation of the process of frost cracking (Watanabe, 2013)

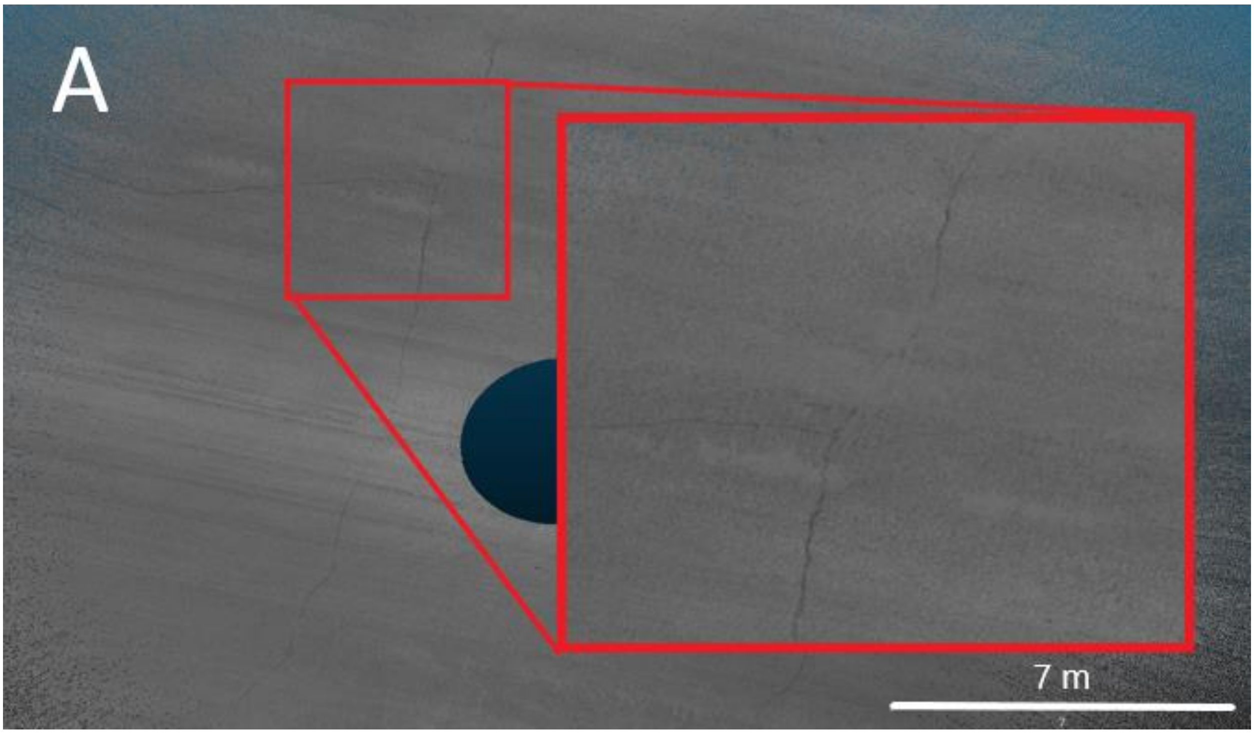

Figure 4A. Cracks on the surface of the runway of Svalbard airport on laser scan data

Figure 4B. Cracks on the surface of the runway of Svalbard airport (Photo by F. Iurov, Oct. 2019)

The mountainous nature of the area on Svalbard determines the abundance of slope processes. Existing trends in climate change can intensify it that also poses a threat to the existing infrastructure. An increase in the temperature of the upper horizons of permafrost and the thickness of the active layer is a lead factor for the formation of cryogenic landslides and solifluction (Fig. 4). The activation of these processes is associated with a decrease in the strength of frozen soils with an increase in temperature, an increase in their plasticity. An increase in avalanche activity is noted on Svalbard. Large avalanche destroyed 11 houses in December 2015. More than 20 people were affected (Indreiten & Svarstad, 2016). The next avalanche descended on the territory of the city on February 21, 2017 and destroyed two buildings. There is no proper engineering protection of infrastructure facilities in the vicinity of the city from the impact of avalanches.

Figure 4. «Drunk piles» on the site of destroyed old buildings (Photo by F. Iurov, Oct. 2019)

All settlements of the archipelago have a coastal location, which makes them especially vulnerable to the activation of thermal abrasion. The rate of abovementioned process increased significantly at the beginning of the 21st century: according to P. Zagorski (Zagorski et al., 2015), the rate of coastal retreat at all stations for the period 1991-2011 higher than in 1960-1990. The intensification of this process is growing rapidly due to a decrease in sea ice coverage in winter. It is also a consequence of an increase in winter temperatures and a reduction in the winter period. The thermal abrasion process poses a great threat to both the port infrastructure (which is in many ways a guarantee of the normal existence of villages on the archipelago) and to a number of roads along the coastline (Fig. 5).

Figure 5. Coastal erosion in Longyearbyen (photo by F. Iurov)

Erosion processes have intensified in Svalbard in recent years (Jaskólski et al., 2017). This is due to an increase in runoff from glaciers. Area and volumes of glaciers have been significantly decreasing in recent years. This trend is also associated with current climate warming trends. The development of erosion of permafrost sediments can pose a significant threat to infrastructure facilities in the region, especially, for bridges of linear facilities across watercourses.

CONCLUSIONS

Svalbard is rightfully considered the "world leader" in the field of global warming. Over the past decades, a significant increase in air and frozen ground temperatures has been recorded on the archipelago. Changes in permafrost conditions pose a significant threat to buildings and structures in the settlements of the archipelago. Similar trends are predicted in the future. We made the calculation of the main engineering and geocryological parameters to assess the sustainability of the infrastructure. According to our forecast, the thickness of the active layer will have increased by 17-20% by 2050. It will lead to an increase in the tangential forces of frost heaving (by 15-17%) and the activation of soil thaw settlement. Climatic changes lead to the activation of hazardous exogenous (mainly cryogenic) processes. This process is capable of deformations and destruction of infrastructure. Activation of "warm" cryogenic processes was noted. It is applicable to thermal abrasion, thermal erosion, and a number of slope processes. It is important to note that human activity is often the cause of changes in permafrost conditions and provokes the emergence of dangerous processes. Man-made flooding is an extremely good example of the rapid processes that lead to the road surface deformations in Longyearbyen.

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