Arctic cities, permafrost and changing climatic conditions

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ABSTRACT
Climate change has resulted in permafrost degradation in numerous locations across the Arctic. The effects of climate change are exacerbated in areas of intensive human activity, particularly large industrial centers on permafrost. We used a combination of modeling techniques and field observations to evaluate how changes in climatic conditions have affected permafrost geotechnical properties in Russian large urban settlements such as Norilsk, Salekhard, Yakutsk, and Anadyr. The results show that there have been substantial decreases in foundation bearing capacity in all of these cities on permafrost from the 1970s to present. The projected changes under the six selected climate models show further decreases in foundation bearing capacity by the year 2050.

RÉSUMÉ
Les changements climatiques ont entraîné la dégradation du pergélisol dans plusieurs endroits à travers l'Arctique. Leurs effets sur le pergélisol sont exacerbés dans les zones d'activité humaine intensive, particulièrement dans les grands centres industriels. Une combinaison de techniques de modélisation et des observations de terrain ont permis d'évaluer comment les changements dans les conditions climatiques ont affecté les propriétés géotechniques du pergélisol dans les grandes agglomérations urbaines russes comme Noril'sk, Salekhard, Yakutsk, et Anadyr. Les résultats montrent qu'il y a eu des baisses substantielles de la capacité portante des fondations du pergélisol dans ces villes de 1970 à aujourd'hui . Les changements prévus pour six modèles climatiques sélectionnés montrent de nouvelles baisses de la capacité portante en 2050.

1 INTRODUCTION

Ongoing climate change has resulted in warming permafrost temperatures and increases in active-layer thickness in numerous locations across the Arctic (e.g. Romanovsky et al. 2010; Shiklomanov et al. 2012). The climatic impacts on the permafrost system are exacerbated in areas of intensive industrial development, where anthropogenic factors greatly amplify permafrost changes (Grebenets et al. 2012; Streletskiy et al. 2014). As a result, a combination of climate- and human-induced changes have led to accelerated deterioration of geotechnical environments and has created potentially dangerous conditions with respect to human infrastructure in large urban centres built on permafrost. This paper examines the past, present, and future state of permafrost geotechnical properties which reflect both climatic and anthropogenic impacts on the environment and have pronounced effects on urban landscapes.

2 DATA AND METHODS

Changes to the permafrost-geotechnical environment were evaluated using field observations and a quantitative methodology for assessing infrastructure stability in permafrost regions under climatic change. At the core of the methodology is the permafrost-geotechnical model which utilizes bearing capacity for a "standard foundation pile" embedded in permafrost as it is a primary variable for engineering assessments in permafrost-affected regions. The permafrost component of the model is based on the modified Kuryavtsev solution to the general Stefan problem of heat conduction with a moving phase boundary to estimate active layer thickness and permafrost temperature and accounts for the effects of snow cover, vegetation, and soil properties (such as texture, moisture, organic content, and ice content). This part of the model provides a sequential algorithm of temperature calculations at the bottom of each of the following layers: climate, snow, vegetation, organic layer, mineral soil. Permafrost temperature and thaw propagation are estimated using climatic variables (monthly air temperature and precipitation) and landscape conditions of the area (e.g., soil properties, presence of organic layers, and ground ice content). The characteristics of soil layer in frozen and unfrozen state are different depending on texture and soil moisture content. The detailed description, formulations, and parameterizations of the model can be found in Streletskiy et al. (2012a). The geotechnical part of the model is based on a set of formulations developed to estimate the bearing capacity of frozen soils for different common foundation types as a function of permafrost temperature and maximum annual thaw propagation (Streletskiy et al. 2012b). This part of the model utilizes procedures and parameterization taken from Construction Norms and Regulations (CNR 1990) to be consistent with the construction codes used in the U.S.S.R. and, later, in the

Russian Federation to build foundations in the permafrost regions.

Average monthly temperatures and precipitation from weather stations located in or in close proximity to the urban centers were used for the climatic forcing in the permafrost-geotechnical model. These climate variables were used to evaluate historical changes in permafrost temperature, active-layer thickness, and bearing capacity. The following six CMIP5 global climate models (GCMs) were selected based on their ability to reproduce observed temperature trends in the Russian Arctic (Anisimov et al. 2013) and to evaluate future trends in permafrost-geotechnical parameters: 1) CanESM2 (CanESM) - Canadian Earth Systems Model 2, 2) CSIRO-Mk-3.6 (CSIRO) - Commonwealth Scientific and Industrial Research Organization Mark 3.6, 3) HadGEM2-ES (HadGEM) Hadley Centre Global Environment Model Version 2 – Earth System, 4) GFDL-CM3 (GFDL) Geophysical Fluid Dynamics Laboratory Climate Model Version 3, 5) IPSL-CM5A-LR (IPSL) for Institute Pierre Simon Laplace – Climate Model 5A – Low Resolution, and 6) NorESM1-M (NorESM) Norwegian Earth System Model version 1-M. The prognostic experiments ran from 2006-2300 under the RCP8.5 scenario, meaning that the radiative forcing at the top of the troposphere will increase by 8.5 W/m^2 by the year 2100. RCP8.5 represents the “worst case” climatic scenario.

Soil properties, such as texture, moisture, peat, and ice content can be highly variable within relatively small areas and are generally unknown. We have used a compendium of several characteristic soil types, and ground ice contents ranging from high to low representative of soil properties within each urban area. Snow depth is difficult to approximate in urban environments, as wind tunnels caused by buildings and snow removal results in snow depths deviating greatly from those observed under natural conditions reported by weather stations. Foundations of buildings are usually protected from snow, however, snow commonly accumulates along the sides of buildings. To assess the effect of snow redistribution on permafrost conditions, two extreme cases were included: one with no snow and another with 0.6 m of snow accumulation by the end of winter. As a result, for the foundation bearing capacity calculations, observation- and/or GCM–derived atmospheric conditions of a particular year (or period) were used as the climatic forcing while variable landscape parameters were represented by a range of possible snow redistribution scenarios, soil properties, and ground ice contents. A combination of landscape conditions for each year resulted in an array of 18 modeled results, which were averaged to produce a characteristic, settlement-specific value for foundation bearing capacity for each time period.

Changes in permafrost-geotechnical parameters were assessed relative to reference points corresponding to different construction periods. The Construction Norms and Regulations (CNR 1990) were followed to evaluate initial permafrost-geotechnical parameters which required the use of 30-year climatic norms for assessing geocryological-engineering (e.g. bearing capacity) conditions of the territory prior to construction. For example, construction in 1975 would have used 1945-1975 reference climatology data. Likewise, a construction in 2005 would have relied on reference climatology from 1975-2005.

The decade between 1965 and 1975 (further referred to as 1970) was selected as an initial reference period, since a large number of structures were built during this time. Ten-year reference periods were used to reduce computation demands from the model. Climatic, permafrost and geotechnical parameters were calculated for 10-year periods corresponding to the present (1995-2005 (2000)), near-future (2015-2025 (2020)), and mid-century (2045-2055 (2050)), as well as their relative changes relative to the initial 1970 reference period.

3 RESULTS AND DISCUSSION

3.1. Regional changes

3.1.1. Climatic characteristics

The Russian Arctic is warming significantly faster than global average rate. The mean annual temperature anomaly reached 0.8°C in last decade relative to the reference period. The latest warming trend initiated in the West and proceeded eastward. The rapid warming started in 1970 in the Salekhard region, followed by Norilsk in 1975, and Yakutsk in 1982. This warming trend plateaued around 1990 in all of the regions. The only region that follows a different pattern is Chukotka where modern warming started in 1970, but currently continues at a reduced rate. The annual amount of precipitation has not changed significantly in all of the discussed regions except for in the Yamalo-Nenets Autonomous Okrug where annual precipitation has increased by 10% over the 1985 – 1995.

Projected changes in annual and seasonal anomalies follow the same pattern in all of the regions. According to the model ensemble selected for analysis, the mean annual temperature anomaly is expected to reach +4.1°C in Salekhard and Norilsk, +3.7°C in Yakutsk and +4.0°C by the middle of the XXI century under the RCP8.5 scenario relative to 1960-1990. Maximum changes are expected to occur in the fall and winter, with less warming during the summer and spring seasons. The three models ranked the highest for reproducing observed trends predicted higher warming values. Meanwhile global climate models project linear temperature trends. However, observational data shows signs of stepwise changes from one stationary regime to another. Precipitation projections are much more uncertain, as the annual precipitation anomaly at the middle of the XXI century ranges from +20 to +150 mm depending on the model.

3.1.2. Permafrost characteristics and foundation bearing capacity

The observed and projected increases in air temperature and winter precipitation have important implications for the permafrost thermal regime. Climate-induced increases in permafrost temperature and ALT lower foundations' bearing capacities. According to the Russian Construction Rules and Regulations, safety coefficients implemented in permafrost engineering designs to account for climatic variability and change are relatively low. For mass-produced residential mid-rise buildings on permafrost the construction designs from the 1960s and 1970s rarely accounted for more than a 35% reduction in foundation bearing capacity. The climate-induced decrease in foundation bearing capacity below safety coefficients can undermine the structural stability of buildings' foundations and can be, at least partially, attributed to widespread deformations found in Arctic settlements on permafrost (Streletskiy et al. 2012). Due to space limitations the presented analysis and results are focused predominantly on the city of Norilsk, Russia, which is the largest industrialized urban center on permafrost. The Norilsk region is characterized by severe climate, forest-tundra vegetation, and continuous permafrost (Figure 1). The Norilsk industrial complex consists of highly concentrated open and underground mining operations, and an array of pre-processing and smelting facilities, highly developed transportation infrastructure, and a very densely populated urban core. While the projected changes in climate characteristics for Norilsk are similar to those for Salekhard, Yakutsk, and Anadyr the corresponding increases in permafrost temperatures and ALT has lead to non-linear decreases in bearing capacities depending on initial permafrost conditions in each city. For example, Salekhard is located on warm permafrost that is near the melting point, while Norilsk is located on relatively cold permafrost. Therefore, the same change in projected temperature will lead to greater deterioration of foundation bearing capacity in Salekhard relative to Norilsk.

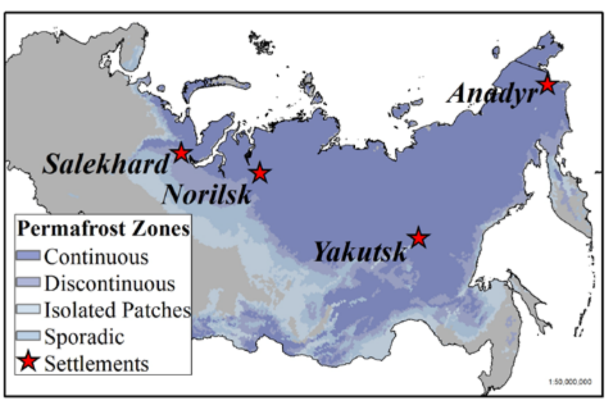

Figure 1. Map showing the geographic locations of the four cities discussed in this paper. The blue shades show permafrost areas. Grey areas show no permafrost.

3.2. Urban centers on permafrost: Norilsk

3.2.1. General characteristics

The current population of the City of Norilsk is about 178,000 people and is projected to increase slightly over the next decade. Unlike many other Arctic urban centers based non-traditional activities which rely largely on temporary shift-workers, the city of Norilsk has a substantial permanent population. Although 72% of the total labor force is employed by the Polar Division of Norilsk Nickel, Mining and Metallurgy Company there are also significant non-primary employment sectors such as government, education, transportation, and service. The city is also characterized by relatively low population turn-over. Only about 13,000 people (or less than 10%) are replaced annually indicating that a majority of the population has a permanent residency in the city requiring significant housing stock. However, only 2 new residential buildings have been constructed in the city since 2002 and very few built in the last twenty years. Difficult engineering conditions related to the severe climatic conditions, presence of ice-rich permafrost, and human-induced intensification of cryogenic processes make construction expensive and problematic. Residential buildings are typically designed for less than a 50-year lifespan in the Arctic and the majority of these buildings were constructed prior to the 1980s. Almost 50 nine- and five-story buildings built in 1960s-80s were recently disassembled (Grebenets et al., 2012). Presently about 300 structures in Norilsk have significant deformations due to changes to the permafrost-geotechnical environment. More than 100 residential mid-rise buildings are in a state of structural failure yet are still occupied by approximately 5,000 families. The deterioration of infrastructure in Norilsk has resulted in an acute local housing crisis.

3.2.2. Climatic characteristics

The climate of Norilsk is characterized by severe cold winters and relatively warm, but short, summers. The mean annual temperature between 1980 and 2010 was -8.5^{o}C and the total precipitation was 465 mm, the majority of which was snow. Mean air temperature during the coldest month (January) was -26.8^{o}C, and during the warmest month (July) was +14.2^{o}C. Between the 1970s and 2010s, mean annual air temperature and precipitation increased by 1.4^{o}C and 10 mm, respectively (Figure 2).

According to the six models used in this study, the mean annual air temperature in Norilsk increased by 1.3^{o}C from 1970 to 2000, which is in agreement with the observational trend from the Norilsk weather station. HadGEM, IPSL, and GFDL represented the observed temperature trend best. According to these three models, temperature increases of 4 and 6^{o}C are expected relative to 1970 by 2020 and 2050 respectively under the RCP8.5 forcing (Figure 3). There is a large uncertainty in snow cover representation across the models, with IPSL predicting a 40 cm increase and HadGEM showing a 30 cm decrease. According to these three models, snow cover is predicted to increase slightly by the middle of the century.

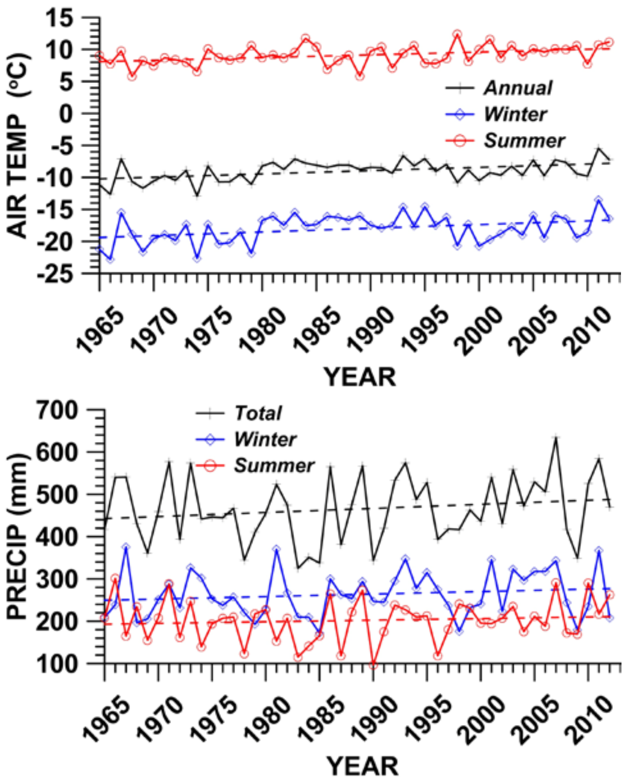

Figure 2. Mean annual, winter and summer temperature and precipitation observed by Norilsk weather station.

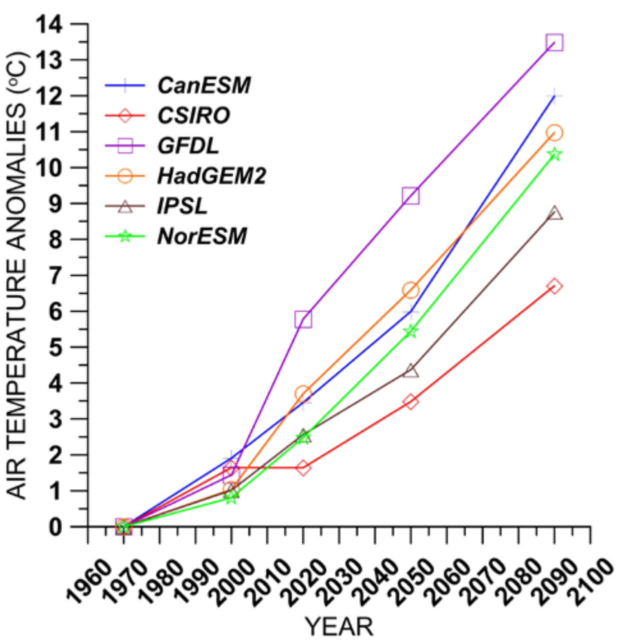

Figure 3. Mean annual air temperature anomalies in Norilsk area relative to the reference decade of 1970s using six climate models.

3.2.3. Permafrost temperature and active layer thickness

The area is characterized by continuous permafrost. Permafrost temperatures measured at 10 m depth in Norilsk have varied from -7 to -0.5^{o}C prior to major construction in the 1960s to -2.5 to 0.5^{o}C in 2000s. Snow accumulation in residential yards, excessive heat from the underground utility lines, leaking and broken water and sewage pipes, have contributed to the permafrost warming, and in some cases, the development of taliks. The combined influence of climatic and environmental factors with the technogenic influences on the ground thermal regime has resulted in a highly heterogeneous permafrost temperature field in the city. For example, in some parts of the city permafrost temperature has increased by 3-5^{o}C relative to 1940s, while other sites demonstrate less pronounced changes (Figure 4).

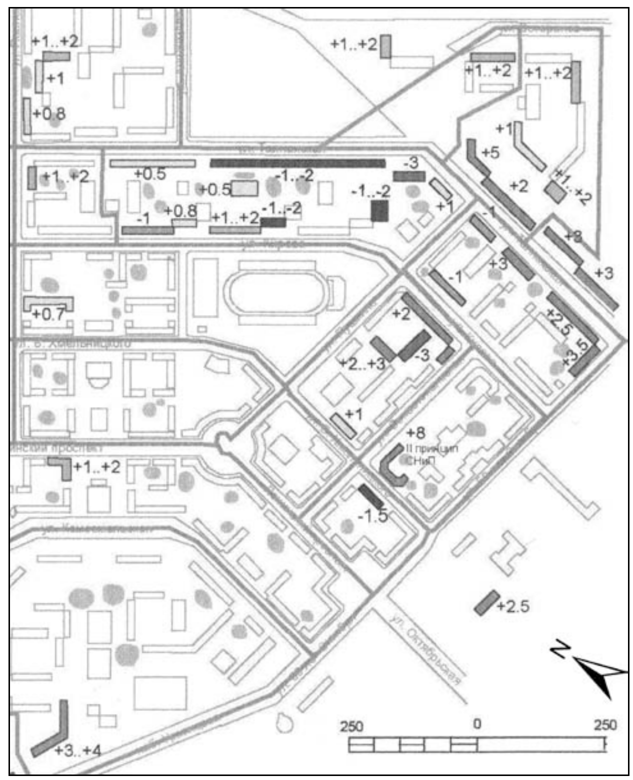

Figure 4. Map showing ground temperature change at 10 m depth from 1940 to 2006, measured in a series of monitoring boreholes of the old part of Norilsk city (after Grebenets et al., 2012). Grey dots represent location of snow piles.

The ALT data are available only for 2005-2013 from the Circumpolar Active Layer Monitoring (CALM) site R32 outside of Talnakh, located in the vicinity of Norilsk in an undisturbed typical tundra landscape. The mean ALT over the observation period was 0.92 m (0.81 - 1.03 m). The permafrost modeling forced by six GCM-produced climate scenarios resulted in average 2000s ALT of 1.00 m which agrees well with the observational data. Analysis of model produced changes in ALT indicate that ALT values from the 2000s were on average 0.13 m thicker than those in

1970s and that the ALT is projected to increase by an additional 0.4 m by 2020 (Figure 5).

Moreover, the climate forcing in the permafrost model produced by two out of the six GCMs resulted in the development of a residual thaw layer above the permafrost by the year 2050. The remaining four models project a 1.8 m average increase in ALT by the year 2050 relative to 1970. All models, except CSIRO, show near-surface permafrost disappearing by the end of the century. According to CSIRO, low temperature permafrost will persist throughout the century even under the strongest forcing scenario (Figure 5).

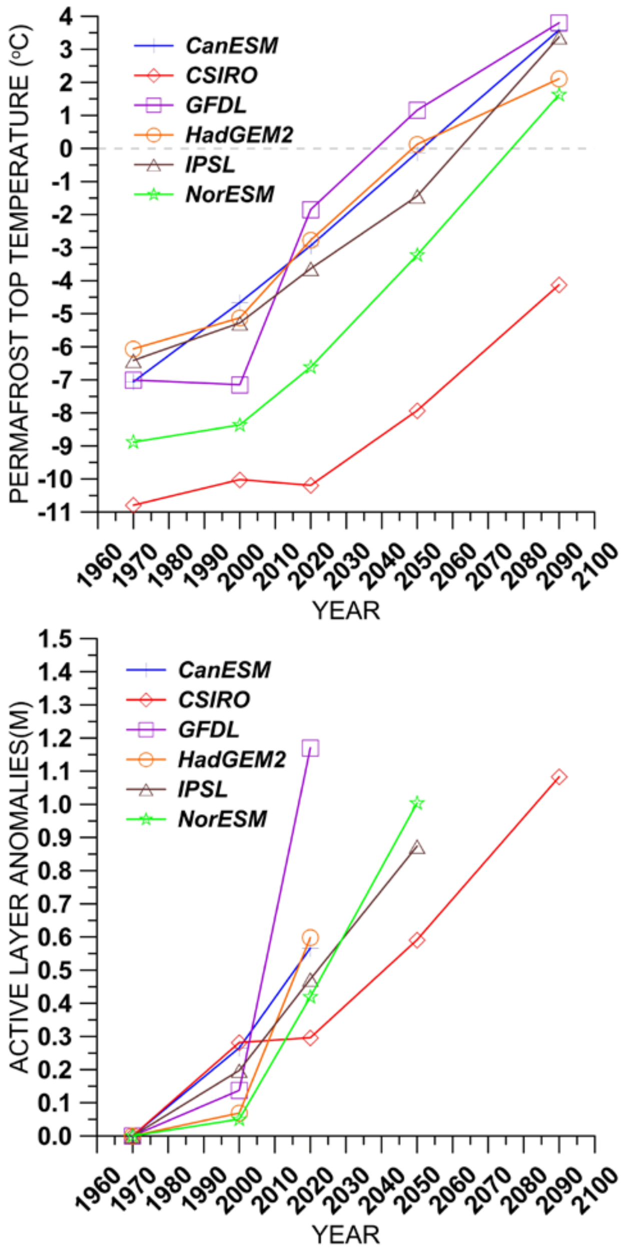

Figure 5. Permafrost temperature (TTOP) and active layer thickness (ALT) anomalies relative to decade of 1970s using six climate models.

3.2.4. Foundation bearing capacity

Changes in permafrost conditions described above are expected to result in an overall decrease in bearing capacity. Historical changes of foundation bearing capacity were estimated by the permafrost-geotechnical model forced by climate observations from the Norilsk meteorological station. Results show that for the buildings constructed around the 1960s, the decrease in bearing capacity was, on average, 15% depending on soil by 2013, while for those built around the 1970s and 1980s, there was 21% average decrease comparing with 2013 values. This indicates that structures built in the 1970s and 1980s are more prone to deformations due to the climate-induced reduction in bearing capacity compared to those constructed in 1960s.

The bearing capacity values obtained by modeled experiments forced by the six GCM-produced climates show a decrease by 10±9% from 1970 to 2000, which is similar to the 12% estimate obtained from using observational data as the climate forcing over the same time period. By 2020, bearing capacity is projected to be reduced by 37±22%, which is greater than the designed safety coefficients used in the construction for the majority of structures built in the late 1970-80s in the Norilsk area. With the extremely slow pace of new construction it is quite possible that many of the older structures still will be in place by 2050. Our assessment indicates that the ability of older foundations to support an effective structural load will decrease by two thirds (67±28% according to six GCM-produced climates) and will severely undermine the stability of buildings in Norilsk (Figure 6).

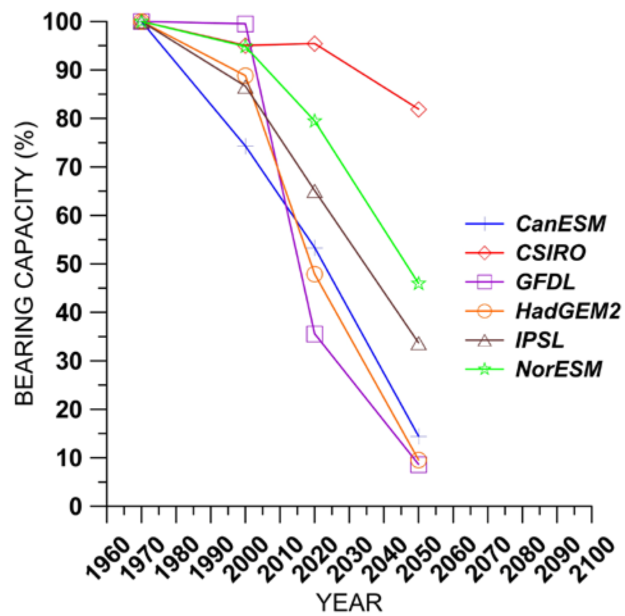

Figure 6. Relative changes of the foundation bearing capacity using six climate models. The decade of 1970s represents 100 percent. The changes shown on the graph result solely from changing climatic conditions and do not account for other technogenic or environmental factors potentially affecting ground thermal regime during a lifespan of the structures.

3.3. Other urban centers on permafrost

The three additional cities were chosen to represent large urban centers in various parts of the Russian Arctic (Figure 1). Salekhard is a growing oil-gas supported city located in Western Siberia. It is the capital of the Yamal-Nenets Autonomous Okrug (AO) with a population of 48,000. Yakutsk, the capital of the Sakha Republic, with a population of 293,000, is located in Central Siberia. Both Yakutsk and Salekhard utilize active and passive principles for construction on permafrost and it was not possible to estimate the number of people living in residential buildings built according to the passive principle on piling foundations. Anadyr, the port city and capital of Chukotka AO has a population of 14,000.

Application of permafrost-engineering model in conjunction with observation- and GCM-produced climate indicates that the percent of structures built according to the passive principle in the late 1960s and 1970s that experienced decreases in foundation bearing were as follows: 19% of buildings in Salekhard, 21% in Yakutsk, and 12% in Anadyr. The projected changes in foundation bearing capacity by mid-century have large uncertainties due to increased variability in the climate characteristics produced by the six GCMs. For example, the projected decreases in foundation bearing capacity by 2050 are within 30-40% using CSIRO and up to 90% using GFDL.

4. SUMMARY AND CONCLUSIONS

The economic development of Arctic industrial centers on permafrost mandates that housing be adequate to sustain the workforce residing in these centers. Foundation bearing capacity, which depends on permafrost properties, is used as a quantitative indicator of the ability of foundations to support their structural load. Permafrost properties are, in turn, affected by changes in climatic and environmental conditions and can be significantly altered by anthropogenic activities. As such, bearing capacity can be considered an important, indicator of permafrost changes in urban environments.

The combination of climate warming and human activity in urban areas has resulted in increased permafrost temperatures and decreased foundation bearing capacity. This trend is expected to continue in the future and urgent mitigation strategies need to be developed and implemented to maintain the structural integrity of infrastructure in many urban centers throughout the Arctic. According to the climate projections produced by six GCM models used in the analysis, 1.4 to 2.2^{o}C and 3.1 to 4.1^{o}C increases in near surface air temperature from the 1961-1990 normal are expected in the Russian Arctic by years 2020 and 2050 respectively. According to the majority of CMIP5 models, snow cover thickness is also expected to increase, as winter precipitation increases but there is substantial uncertainty related to this climate variable. These changes can lead to increased ground temperatures and thickening of the active layer resulting in decreased foundation bearing capacity throughout the Russian Arctic. The greatest changes are expected in West Siberia and Chukotka. While permafrost warming is more pronounced in northern permafrost regions, the settlements located at the southern fringes of permafrost regions are expected to experience higher decreases in foundation bearing capacity.

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