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Climate change and geotechnical design in permafrost and frozen ground

Changement climatique et conception géotechnique dans le pergélisol et les sols gelés

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ABSTRACT: Climate change is predicted to strongly affect the northern hemisphere over the coming decades. The continuous warming trend observed in Svalbard since the 1980s are creating concerns related to the stability and durability of existing infrastructure on permafrost and uncertainties related to the design of new structures and infrastructure in the region. An increase in ground temperatures in permafrost regions may reduce the bearing capacity and increase settlement rates and subsidence of foundations, and stability of natural and engineered slopes. This paper provides a summary of our current knowledge related to the effect of climate change on foundations and foundation design in northern areas subjected to seasonal frost and permafrost. A methodology is suggested that takes climate change scenarios into consideration in foundation design. The sensitivity of particular structures and foundations vary from small or negliglible to considerable.

RÉSUMÉ: Les changements climatiques devraient affecter fortement l'hémisphère nord au cours des prochaines décennies. La tendance au réchauffement continu observée à Svalbard depuis les années 1980 suscite des inquiétudes quant à la stabilité et à la durabilité des infrastructures existantes sur le pergélisol et aux incertitudes liées à la conception de nouvelles structures et infrastructures dans la région. Une augmentation de la température du sol dans les régions de pergélisol pourrait réduire la capacité portante, augmenter les taux de tassement et l'affaissement des fondations, ainsi que la stabilité des pentes naturelles et aménagées. Ce document résume nos connaissances actuelles sur les effets du changement climatique sur les fondations et leur conception dans les zones nord exposées au gel et au pergélisol. Une méthodologie est proposée qui prend en compte les scénarios de changement climatique dans la conception des fondations. La sensibilité de certaines structures et fondations varie de petite ou négligeable à considérable.

Keywords: Climate change, foundations, permafrost, frozen soils

1 INTRODUCTION

Climate change is predicted to strongly affect the northern hemisphere over the coming decades (IPCC, 2014; Instanes et al.,). The continuous warming trend observed in Svalbard since the 1980s are creating concerns related to the stability and durability of existing infrastructure on permafrost and uncertainties related to the design of new structures and infrastructure in the region. An increase in ground temperatures in permafrost regions may reduce the bearing capacity and increase settlement rates and subsidence of foundations, and stability of natural and engineered slopes. The conventional design of foundations and structures in the Svalbard region is based on the priciple of maintaining the frozen ground thermal regime during the service life time of the structure. The heat from the buildings are prevented from penetrating into the ground and warming up, or at worst, melt the permafrost. This is achieved by allowing an open crawl space between the heated structure and the ground surface. In this manner the air temperature between the warmed structure and the ground surface should be equal to the ambient air temperature. Usually the building or structure is elevated above the ground surface on piled foundations, shallow foundations or footings. Water and drain pipes to and from the building are insulated and secured under the insulated floor. In this way, it can be avoided that the heat from the building warms up the foundation soils and change the thermal regime of the underlying permafrost. Direct foundations on embankments using insulated slab on ground and an artifical cooling systems, have also been widely used in Svalbard over the last 30 years (Rongved and Instanes, 2012). Due to the rapid climate warming in the Svalbard region, it is necessary to assess the long-term consequences of observed climate change and future climate scenarios for existing and new buildings and structures. This knowledge can be used in the planning of new infrastructure projects and in maintenance of existing buildings. This article focuses on factors considered critical in relation to predicted climate change, especially related to increased temperature and rainfall. The review is based on Instanes Consulting Engineers more than 50 years experience in design of foundations on permafrost in Longyearbyen and Svalbard, and ongoing projects related to climate change and effects on permafrost and foundations on permafrost.

Figure 1. Longyearbyen, Svalbard (N78°13’ E15°39’). Map from the Norwegian Polar Institute, www.toposvalbard.no

2 OBSERVED CLIMATE CHANGE IN SVALBARD

The mean annual air temperature in Longyearbyen has increased approximately 3 °C since year 1900. Figure 2 shows the observed mean annual air temperatures for Longyearbyen 1912-2018 (the mean annual air temperature for 2018 is an estimate based on 10 months of observations). It can be observed from the figure that the 30-year mean has increased from a minimum of -6.7 °C to approximately -3.9 °C in 2018. It should be noted that the meteorological ‘normal temperature’ coincides with the observed minimum temperature in the observations period. During the last 20 years the increase in air temperatures is related to the decrase in sea ice extent in and around the Svalbard archipelago, and the largest increase in air temperatures is therefore observed during the winter months.

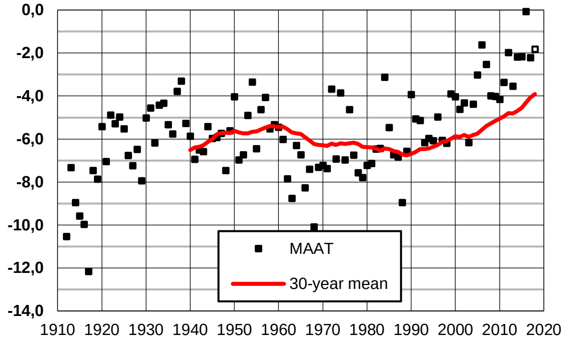

Figure 2. Mean annual air temperature (°C)

The increase in winter air temperatures during the last decades has also caused an increase in rain events during the winter months (November to April). However, there is only a slight increase in mean annual precipitation at Svalbard airport from 189 mm in 2006 to 200 mm in 2018, see Figure 3.

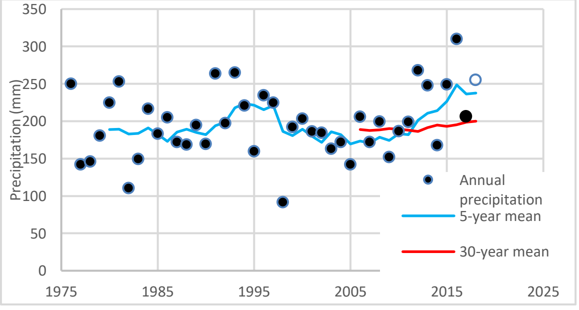

Figure 3. mean annual precipitation at Svalbard airport, 1976-2018

The strong increase in air temperatures has not caused a similar increase in extreme precipitation events. Figure 4 show the extreme 24-hour precipitation events during the period 1950-2018. It should be noted that 20 mm and 40 mm in 24 hours are equal to approximately 10 % and 20 % of the mean annual precipitation, respectively, and is therfore considered ‘extreme. The maximum observed 24-hour precipitation for Longyearbyen is 43.2 mm August 5, 1981. This event initiated several debris flows in the Longyear valley. Similar landslide activity was observed on July 11, 1972 (31.2 mm) and November 8, 2016 (41.7 mm).

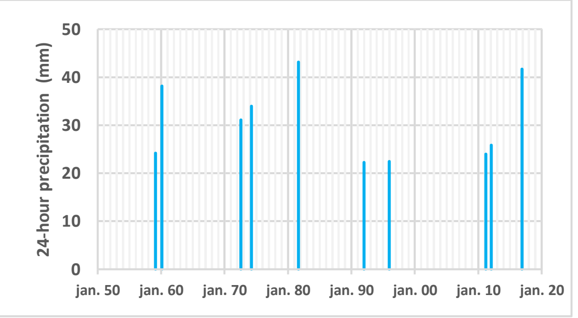

Figure 4. Extreme precipitation events 1950-2018 (mm/24 hours)

3 PREDICTED CLIMATE CHANGE IN SVALBARD

Future climate scenarios for Longyearbyen has been estimated based on various climate scenarios from the Intergovernmental Panel on Climate Change (IPCC, 2014). The scenarios are predictions of the increase of radiative forcing by year 2100 compared to pre-industrial levels. This is expressed as the so called *Representative Concentration pathways (RCPs)*. For this study three RCPs has been chosen for the prediction of future climate in Longyearbyen: i) Worst case scenario (RCP8.5), ii) Medium scenario (RCP4.5) and iii) Best scenario (RCP2.6). Table 1 presents a summary of the three climate scnearios for Longyearbyen compared to the observational period 1971-2000.

Table 1. Observed and estimated air temperatures for Longyearbyen

	Observed 1971-2000	**2071-2100 (best)**	**2071-2100 (medium)**	**2071-2100 (worst)**
Year	-5.9	-2.3	+0.6	+3.3
Winter	-14.0	-8.3	-4.9	-0.6
Spring	-9.6	-5.9	-2.9	+0.1
Summer	+4.5	+5.6	+7.1	+8.5
Autumn	-4.7	+0.5	+2.0	+4.7

The mean annual air temperature is predicted to increase 3.6 °C, 6.5 °C and 9.2 °C for the best, medium and worst scenarios, respectively. The associated increase in annual precipitation is predicted to increase 20 %, 30 % and 40 % for the three scenarios, respectively, compared to the 1971-2000 mean annual precipitation of approximately 190 mm.

4 IMPACT OF PREDICTED CLIMATE CHANGE ON PERMAFROST AND FOUNDATION SOILS

4.1 Soil conditions in the Longyear valley

The soils in the Longyear valley is mainly composed of fluvial deposits of sand and gravel overlying marine clays and silts. The pore water salinity decreases from approximately 40 ppt near the coast line to 0 ppt at 50 meters above the sea level. The permafrost temperature close to the sea is approximately -4 °C, decreasing slightly up the valley. The soil contains pore ice, segregated ice and also buried glacial ice. Bedrock outcrops can be found on the valley slopes and the thickness of the sediments increase towards the middle of the valley. In the middle of the valley the depth to bedrock can be more than 100 metres. The slopes are subjected to risk of snow avalanches and land slides, while the middle bottom of the valley is subjected to flooding from the Longyear river. The harbour area is dominated by reclaimed land areas with various fill materials over marine silt and clay.

4.2 Ground thermal regime

Figure 5 shows the ground temperature profile for a 30 metre deep borehole on an undisturbed tundra site close to the University Centre in Svalbard, UNIS (coordinates N78°13.32 E15°39.91) at the National GeoTest Site Research Centre (NGTS) in Longyearbyen (L'Heureux et al., 2017). The borehole is located only 80 metres from the sea with an elevation of 3.5 m above sea level. The digital thermistor string was installed in the late summer of 2017, and has 30 temperature sensors at various depths logging ground temperatures every 6 hours. The ground temperatures reflect the air temperatures with exponential dampening with depth and a time lag. This means that the maximum thaw depth (active layer thickness) is observed on a later date than the maximum surface temperature. During the observational period, the surface temperature varies between -19.4 °C and +13.5 °C. At 5 m depth, the temperature variation is only from -2.7 °C to -3.4 °C, at 10 m depth from -2,1 °C to -3.9 °C, at 20 m depth from -3,9 °C to -4,3 °C and at 30 m depth the variation is between -3.8 °C to -4.0 °C. The maximum active layer thickness during the observational period is approximately 0.8 m.

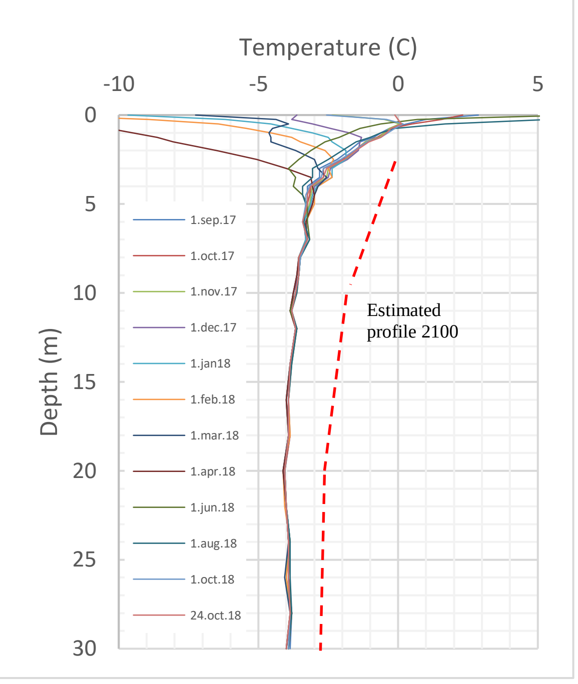

Figure 5. Ground temperature profile

The geothermal gradient in Svalbard is approximately 0.02 °C/m and a ground temperature of -4 °C at 20 metres depth indicate the the permafrost thickness can be up to approximately 200 m at this site.

In the engineering design of the first section of the University centre in Svalbard (UNIS) in 1994, the permafrost temperature at 10 metres depth was approximately -5 °C (Instanes and Instanes, 1999). This site is approximately 350 m west of the NGTS site, has a distance to the sea of 330 m with an elevation of 11 m above the sea level. The design ground temperature for the foundation design was set to -3.5 °C and a maximum active layer thickness of 2 m, with a service life time of 30 years. Figure 4 shows that the ground temperature in the area is now warmer than -5 °C, but still colder than -3.5 °C.

Geothermal analysis has been carried out in order to investigate the effect of climate warming on the ground temperature profile in Figure 4. The methodology for the analysis is described in Instanes (2016). Results for year 2100 from the geothermal analysis using the medium case scenario (RCP4.5) is included in Figure 4. It can be observed that the active layer thickness is predicted to increase from present value of approximately 1.0 m to 2.5 m, the temperature at 10 m depth increases from -3.6 °C to -1.9 °C, and at 20 m depth from -3.7 °C to -2.7 °C.

Even though the analysis show that the permafrost will not thaw within year 2100, it is expected that the increased temperatures will cause a reduction in bearing capacity and increased settlement rates for conventional foundation such as piles and footings. Future ground temperature increase must therefore be taken into account in future planning and engineering of new buildings and installations. It may be appropriate to consider longer piles and/or piles with a larger diameter than what is used today. There may also be an increased need for active foundation methods such as artificial cooling, especially for settlement sensitive structures or for structures with a service life span of more than 50 years. For areas with relative limited depth (less than 5 m) to bedrock, it may be appropriate to evaluate soil replacement or piles to bedrock.

5 CONSEQUENCES FOR EXISTING BUILDINGS AND STRUCTURES

5.1 Observed damage to structures

As can be seen from Figure 2, Longyearbyen has experienced a dramatic increase in air temperatures since the 1980-ies. Figure 4 shows that the ground temperature profile responds very slowly to the increase in air temperatures as long as the top layer remains undisturbed. The active layer thickness is still less than 1 m, and the permafrost temperature at depth approximately -4.0 °C. Construction work and excavations will alter the heat balance between the ground and atmosphere and in most cases cause warming and subsequent thaw of permafrost. In addtition, structures have a tendancy to accumulate snow during the winter months and poor drainage water during the thaw season. Snow accumulation insulates the ground and hinder heat to flow from the ground to the atmosphere durinng the cold winter months. Running water causes thermal erosion and ponded water will also transfer heat to the frozen ground. These factors also add to the problem of permafrost warming and thaw. It is a well known that disturbance and removal of the organic top layer and excavations in permafrost may cause an irreversible detrimental effect on the conservation of permafrost (Andersland and Ladanyi, 2004). There are numerous reports in the media about damage to foundations and structures in the settlements on Svalbard, presumeably caused by the observed climate warming. However, a more detailed engineering investigation, show that in all of the reported cases, the observed damage and failures are caused by disturbance of the permafrost by the construction work and/or the permanent structure. Very often removal of the organic layers and excavations without considerations for conservation of permafrost has taken place. In many cases the ventilated space under the completed buildings have been blocked, warm structures are placed directly on thaw sensitive ground, and drainage surface water runs freely along and under the structure. In all these cases, the damage and failure of foundations could have been avoided with proper planning, engineering design, construction and maintenance.

5.2 Planning for the future

In general, the bearing capacity of piled foundations in permafrost is a function of the adfreeze bond between the pile surface and the surrounding permafrost. If the pile is placed in a predrilled borehole, the bearing capacity of the pile is a function of the lowest value of adfreeze bond between the pile surface and backfill/slurry and the adfreeze bond between the backfill/slurry and the surrounding permafrost. The shear strength of the adfreeze bond is time and temperature dependent, and will decrease with increased temperatures. Piled foundations are, therefore, sensitive to ground temperature warming. On the other hand, shallow foundations such as plates and footings are not dependent on adfreeze bonding for the bearing capacity and may be a better foundation solution in a warming climate. Since the surface layers will be more affected by increase in surface temperatures, it may be necessary to increase the foundation depth. A minimum requirement is that the depth of the foundation is deeper than the predicted active layer thickness during the service life time of the structure.

Piled foundations have realtively lower costs, shorter installation time, and transfers the loads to deeper soil layers, compared to shallow foundations. By increasing the pile length and possibly the diameter or circumfrance of the pile, piles may also be used in a warmer climate than today. Wooden piles should, however, be avoided since rotting is already a problem for existing foundations using wooden piles. Using other (hollow) pile types (steel or possibly concrete) allows for future artificial cooling of the piles if needed. For buildings with long service lifetime (>50 years) or settlement sensitive structures, artificial cooling systems (Instanes B. Instanes A., 2008) or other types of active cooling will be necessary. However, artificial cooling systems has a requirement for electrical power during freeze-in and also for maintance of the design ground temperature, and is therfore more maintenance-intensive than for example piling. For areas with relatively shallow depth to bedrock, foundation methodologies known from non-permafrost areas can be considered. In the case of shallow depths to bedrock, replacement of soils or piles to bedrock should be considered.

As pointed out by Instanes et.al (2016), climate change may alter the amount and type of precipitation in the Arctic, its seasonal distribution, timing, and rate of snowmelt. It is important that municipalities in the Arctic develop a plan for handling drainage water, taken these changes into account. Risk assessment for flooding, snow avalanches and land slides must therfore also consider climate change scenarios in the evaluation of geohazards for the service lifetime of the structure.

6 CONCLUSIONS

Future development in Longyearbyen and Svalbard should preferably take place in areas that have limited risk of beeing subjected to snow avalanches, landslides and flooding. In addition, the locations should preferable have favourable soil conditions such as frictional soils without segregated ice. Unfortunately, there is very limited areas that fulfill these requirements in the present location of Longyearbyen.

The engineering design must also take into account a realistic service life time of the building and/or structure, and then assessing the probable warming of the permafrost during this service lifetime. A greater need for soil investigations must be implemented in the project, that includes ground temperature measurements prior to construction. As a part of the planning and engineering design, consideration must be given to allowable settlements and differential settlements during the service life of the building. The construction methods, selection of building materials, architectural solutions and the desired level of operation-/maintenance-cost of the foundation solution must also be considered.

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