Climate change and possible impact on Arctic infrastructure

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ABSTRACT: There are increased concerns related to the impact of a possible global climatic change on Arctic infrastructure. Especially important is how the climatic scenarios may change (increase) the environmental loads the structures are designed for. This may cause increased risk of damage to infrastructure and threat to human lives. In addition, future infrastructure design in the Arctic may be directly affected by climate change. In order to evaluate the impact of climatic change on Arctic infrastructure, the author is of the opinion that climate change has to be treated in a similar manner to environmental loads. This means that the climatic scenarios must have a probability of occurrence or “likelihood” connected to the prediction. In this presentation the existing engineering design procedures for Arctic infrastructure are briefly presented, and the climatic scenario input data needed for infrastructure impact studies is discussed.

1 INTRODUCTION

The average global surface temperature is projected to increase from 1.4 to 5.8°C between 1990 and 2100. Warming at higher latitudes of the Northern hemisphere may be greater than the global average (IPCC 2001).

Several authors have addressed the issue of the possible effect of climate warming on infrastructure and engineering structures in permafrost regions (Nixon 1990a, b, Ladanyi 1995, 1996, Ladanyi et al. 1996, Lunardini 2001, Khrustalev 2000, 2001). In the continuous permafrost zone, climate warming may increase active layer depth and permafrost temperature. In the discontinuous permafrost zone, in some cases, the permafrost has a temperature close to 0°C and is already in a state close to melting. Further warming may be extremely serious (Ladanyi 1995).

Several authors report that indications of climate change are already evident in the Arctic such as increased active layer thickness, warming permafrost, increased mass movements, thawing of ground ice, coastal erosion and damage to infrastructure and engineering structures in permafrost regions (Osterkamp & Romanovsky 1999, Khrustalev 2000, 2001).

For structures on permafrost, it is often difficult to differentiate between the effect of possible climate warming and other factors that may affect a structure on permafrost such as:

- Site conditions being different to the assumed design site conditions.
- Design of the structure did not take into account appropriate load conditions, active layer thickness and permafrost temperature.
- Contractor did not carry out the construction according to the design.
- Maintenance programme was not carried out according to plan.

- Structure is not used according to design assumptions.

In order to evaluate the impact of climatic change on Arctic infrastructure, the author is of the opinion that climate change has to be treated in a similar manner to environmental loads. This means that for impact studies, the climatic scenarios must have a probability of occurrence or “likelihood” connected to the prediction.

Engineering design for Arctic infrastructure includes in general:

i) Probability analysis of the loads that the structure will be subjected to during its lifetime.
ii) Evaluations of how these loads affect the structure at different levels of risk.

Environmental loads for Arctic civil engineering structures are typically ocean waves and currents, wind, precipitation, ice loads and earthquakes. The magnitude of an environmental load is a function of the probability of occurrence.

Figure 1. Damage to structure in Pyramid, Svalbard. Climate warming or maintenance problem?
In the case of foundations on permafrost, the “load” can be associated with the maximum active layer thickness (thaw depth) and maximum permafrost temperature that the foundation soils will experience during the lifetime of the structure. Based on historical meteorological records and climate change scenarios, it is possible to develop probability of occurrence for such a “load”.

In this presentation the existing engineering design procedures for foundations in permafrost regions are briefly presented, and the climatic scenario input data needed for infrastructure impact studies discussed.

2 DESIGN PROCEDURES FOR FOUNDATIONS IN PERMAFROST REGIONS

The strength and deformation characteristics of frozen soils are dependent on soil type, temperature, density, ice content, unfrozen water content, salinity, stress state and strain rate. Thawing of the frozen soil, or an increase of the temperature of the frozen soil, may lead to deteriorating strength and deformation characteristics, potentially accelerated settlements and possible foundation failure.

Design of foundations in permafrost regions must, therefore, always include an evaluation of the maximum active layer thickness and permafrost temperature that the foundation soils will experience during the life-time of the structure. The initial and long-term bearing capacity of the foundation can then be determined.

The air thawing index (ATI) is a useful parameter to determine the “magnitude” of the thawing season and will be defined in the following as an environmental load. ATI is defined as the integral of the sinusoidal air temperature variation during one year for T > 0°C (the air freezing index, AFI, is defined as the integral of the sinusoidal air temperature variation during one year for T < 0°C).

For design purposes, the design air thawing index is commonly defined as (Andersland & Anderson 1978, Andersland & Ladanyi 1994):

- the average air thawing index for the three warmest summers in the latest 30 years of record,
- the warmest summer in the latest 10 years of record if 30 years of record are not available.

To give design air freezing indices with varying probability of occurrence, engineering practice in Norway (related to frost protection) is based on statistical analysis of historical meteorological data (NTNF & PRA 1976). A similar approach can be used for air thawing indices in permafrost areas, see Table 1.

ATI2 is approximately equal to the 30-year mean value of the air thawing index. The average air thawing index for the three warmest summers in the latest 30 year of record usually lies somewhere between ATI20 and ATI50. The magnitude of thawing to be used in the design is dependent on the type of foundation/structure and the consequences of differential settlements or failure. For road embankments, it is common to use ATI2 to ATI10, for buildings ATI50 to ATI100, while for more sensitive structures like power plants and oil or gas pipelines, higher ATIs should be considered.

For thermal analysis using advanced methods such as finite element models, the design air thawing index is usually represented by a time series or a sine curve, with a combination of an average winter (AFI2) and design summer. Maximum thaw depth and permafrost temperature is usually caused by a combination of warm winter(s) and summer(s). Combinations of warm winters (low air freezing index) and warm summers (high air thawing index) should, therefore, also be considered.

3 DESIGN PROCEDURES UNDER CLIMATE CHANGE SCENARIOS

Paoli & Riseborough (1998) present a thorough investigation of climate change impact on permafrost engineering design based on a change (increase) in the average temperature. The consequences of failure and climate change sensitivity of engineering projects are evaluated through a screening process. The method provides a prototype for systematically considering the issue of climate change effects on Arctic infrastructure.

Khrustalev (2000) recommends, based on observations from Yakutsk, Russia, comparison of meteorological data series before 1970 to those after 1970 to take into account recent climate change. In this approach, it is assumed that temperature variation before 1970 (1830–1970) is caused by natural factors only, while the temperature increase after 1970 can be assumed to give a linear trend that can be extrapolated into the future.

An alternative approach is to use the output from general circulation models (GCMs) to construct artificial air temperature time series for given locations from 2000–2100. This data can be used to investigate how the probability of occurrence of air thawing or

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Table 1. Design air thawing index (ATI).

<table>
<thead>
<tr>
<th>Magnitude of thawing</th>
<th>Probability of occurrence in one single year</th>
<th>Predicted number of occurrences</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATI2</td>
<td>50%</td>
<td>1:2</td>
</tr>
<tr>
<td>ATI10</td>
<td>10%</td>
<td>1:10</td>
</tr>
<tr>
<td>ATI20</td>
<td>5%</td>
<td>1:20</td>
</tr>
<tr>
<td>ATI100</td>
<td>1%</td>
<td>1:100</td>
</tr>
<tr>
<td>ATI1000</td>
<td>0.1%</td>
<td>1:1000</td>
</tr>
<tr>
<td>ATI10000</td>
<td>0.01%</td>
<td>1:10000</td>
</tr>
</tbody>
</table>
freezing index changes with time and climate scenario (Instanes & Mjureke 2002).

Longyearbyen, Svalbard (78°25’N, 15°47’E) is used as an example of this approach. Preliminary analyses have shown that similar trends to those presented below, are prevalent for other permafrost areas such as Siberia, Alaska and Northern Canada (Instanes & Mjureke 2002).

Figures 2 and 3 show calculated air thawing and freezing index in the time period 1912 to 2100 respectively based on:

i) Meteorological records from 1912 to 2001 (continuous bold line).

ii) Predicted mean monthly air temperatures 2000 to 2050 based on empirical downscaling of the results from the Max-Planck-Institute’s ENCHAM4 GCM (Hanssen-Bauer et al. 2000) (continuous line).

iii) Average of the predicted mean monthly air temperature 2000 to 2100 of four GCMs (CCC1 from the Canadian Climate Center, GFDL from Geophysical Fluid Dynamics Laboratory, HadCM3 from Hadley Climate Centre, CSM from NCAR Climate System Model) using the IPCC B2 emission scenario (ACIA 2001, IPCC 2001) (dotted line).

It can be observed from Figure 2 that the air thawing index decreased from 1925 to 1970 (cooling summers) and increased from 1970 to 2002 (warming summers). The climate models show a significant increase during the next 100 years.

The historical maximum air thawing index for Longyearbyen is 615°C · days observed in 1990. This value is likely to be exceeded in 38% of the summers in the period 2000–2050, based on the empirical downscaling presented above. The extreme values exceed 800°C · days.

The results from GCMs in the period 2000–2050 show a cooling trend. Based on discussions with scientists providing the data, the author is of the opinion that this is probably due to misrepresentation of sea ice distribution in this region in the models. From 2060 to 2100, the GCMs show air thawing index greater than the historical maximum in approximately 50% of the summers. The extreme values are likely to exceed 900°C · days several times close to 2100.

It is also of interest to study the warming trend in the winter, since this will reduce heat loss from the ground during the winter months and directly influence thawing and warming of permafrost in the summer. It can be observed from Figure 3 that the air freezing index has decreased from 1912 to 1940 (warming winters), increased from 1940 to 1970 (cooling winters) and decreased from 1970 to 2002 (warming winters). However, the period from 1970 to 2002 is still not as warm as the period from 1925 to 1955. The climate models show a significant decrease in air freezing index (warming winters) during the next 100 years.

The historical minimum air freezing index for Longyearbyen is 1485°C · days, observed in 1954. Based on empirical downscaling, 26% of the winters are likely to be warmer than the historical minimum in the period 2000–2050. The extreme warm winter has an air freezing index below 1000°C · days. The results from GCMs in the period 2000–2050 shows a stable trend, but this is probably again due to misrepresentation of sea ice distribution in the models. From 2050 to 2100 the GCMs show air freezing index lower than the historical minimum in approximately 8% of the winters.

Figure 4 presents the design air thawing index for Longyearbyen for the period 1925–2050, based on historical meteorological data from 1912 to 2000 and the predicted mean monthly air temperatures from 2000 to 2050 based on empirical downscaling. The data is divided into 30-year series (1900–1930, 1910–1940, 1920–1950 and so on, ending with 2020–2050). Statistical parameters for each 30-year period
are calculated and the air thawing index associated with ATI20 and ATI100 are plotted in Figure 4, together with the 30-year mean, 10-year warmest and average of three warmest years in the 30-year period.

Table 2 summarises the change in design air thawing index and minimum air freezing index for Longyearbyen from 2000 to 2050.

It can be observed from Figure 4 and Table 2 that there is a substantial increase in design air thawing index in the period from 2000 to 2050. The 30-year mean (ATI2) increases from 450°C·days to approximately 618°C·days and the ATI100 increases from 616°C·days to 783°C·days. This means that the ATI2 in year 2050 will be equal to the present day ATI100 = 616°C·days and the historical present day maximum air thawing index.

It can also be observed from the figure that after approximately year 2005, the average of the three warmest summers in the last 30 years becomes more extreme than ATI100. This is due to the “shift” in climate between the observed data and modelled data.

4 DATA NEEDED FOR MORE ACCURATE PREDICTIONS

The climate scenarios still lack a probability of occurrence or “likelihood” connected to the prediction. The average global surface temperature increase of 1.4 to 5.8°C is dependent on emission scenarios and the climate model and it is, therefore, not a simple task to estimate the probability of occurrence for each model output. There are also uncertainties connected to application of the data to fixed locations, since the data output is an average over a greater area. The time series generated from GCMs is, therefore, not directly applicable to engineering design purposes, but gives an approximation of possible effects.

The output from the climate models is now available in a format that allows statistical analysis and “engineering judgement” to be applied to the data. However, the uncertainty related to the data is, as pointed out, high and more analysis is needed before the data presented in this paper can be used for design recommendations.

In addition, there is a need for more accurate data on precipitation and frequency of extreme events; in this case extremely warm winters and summers. The only true test for the scenarios presented in this paper is evidence based on recent meteorological observations. As seen from Figure 2, the empirical downscaling predicts extreme air thawing indices to occur regularly after year 2000. This trend is not evident from the meteorological observations from Svalbard. Until such observations are made, it is not recommended to use the data directly for design purposes.

However, one such event has been observed in Canada, see Figure 5.

Figure 5 shows the historical air thawing index for Fort Smith, Canada (60°02′N, 112°00′W).

<table>
<thead>
<tr>
<th>Design ATI</th>
<th>2000</th>
<th>2010</th>
<th>2020</th>
<th>2030</th>
<th>2040</th>
<th>2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATI2</td>
<td>451</td>
<td>481</td>
<td>531</td>
<td>594</td>
<td>607</td>
<td>618</td>
</tr>
<tr>
<td>ATI20</td>
<td>568</td>
<td>597</td>
<td>648</td>
<td>711</td>
<td>723</td>
<td>735</td>
</tr>
<tr>
<td>ATI100</td>
<td>616</td>
<td>646</td>
<td>696</td>
<td>759</td>
<td>772</td>
<td>783</td>
</tr>
</tbody>
</table>

Table 2. Design air thawing indices (ATI) for Longyearbyen 2000 to 2050 in °C·days.
observations increases, the likelihood of such an event to be present in the data set also increases.

5 POSSIBLE IMPACT ON ARCTIC INFRASTRUCTURE

Several authors discuss the warming of permafrost and possible impact on Arctic infrastructure from global warming scenarios (Ladanyi 1995, Ladanyi et al. 1996, Bobov 1999, Smith 2000, Khrustalev 2001, Romanovsky & Osterkamp 2001). However, none of the authors present case histories showing climate warming acting as a trigger for extensive deformations or failure of foundations on permafrost. Discussions with engineers in Alaska, Canada and Russia confirm the assumption that climate warming so far cannot be directly associated with infrastructure damage. The heat flow between the ground and the atmosphere will be affected, most often in a negative way (warming of permafrost), by the construction activity and the structure itself (increased radiation and snow accumulation). In addition presence of taliks, cryopegs, saline permafrost, permafrost and surface water flows, ice inclusions, winter- and summertime precipitation can also potentially cause thermal instability of the foundations. In most cases, climate warming may act as an accelerator or catalyst for ongoing permafrost degradation associated with construction activity and existing infrastructure.

The design lifetime for structures in permafrost regions is typically 30–50 years. Within this timeframe, the structure should function according to design with normal maintenance costs. Total rehabilitation, demolition and replacement of old structures must be expected and are part of sensible infrastructure planning and engineering practice. The effect of climate change on arctic infrastructure is, as indicated above, difficult to quantify. Structural damage is often blamed on climate warming, when a thorough investigation and case history indicates human error or design lifetime being exceeded.

In continuous permafrost, it is believed that the climate scenarios do not pose an immediate threat to the infrastructure. This assumption is only valid if: (i) the correct permafrost engineering design procedures have been followed, and (ii) the infrastructure has not already been subjected to one of the factors mentioned in the introduction, or strains exceeding design values. Maintenance cost will probably increase compared to today’s situation, but it is possible to adjust Arctic infrastructure gradually to a warmer climate.

The predicted climate warming may have a serious effect on existing infrastructure on discontinuous permafrost. The permafrost is already in a state close to melting and further warming may be extremely serious (Ladanyi 1995). However, there is a lot of engineering experience dealing with discontinuous permafrost over the last 100 years. Human interaction and engineering construction very often leads to extensive thawing of both continuous and discontinuous permafrost. Techniques to remediate warming and thawing is already common practice in North America and Scandinavia (Andersland & Ladanyi 1994, Goering & Kumar 1996, Instanes 2000).

If the next 5 to 10 years shows evidence that the predictions and trends presented in this paper are correct, this will have a serious impact on the future design of engineering structures in permafrost areas.

However, engineering design should still be based on actual meteorological observations. The most important consequences of the predicted climate warming shown in this paper are:

- design air thawing (and freezing) index should be updated annually to account for observed variations in climate and climate change,
- remediation techniques should be considered such as artificial cooling of the foundation soils.

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REFERENCES


