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Report

Evaluation of Foundation Settlements for Selected Cultural Heritage Structures under Climate Change Impacts

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SUMMARY
The report evaluates foundation settlement of selected cultural heritage structures in Longyearbyen and Ny-Ålesund under climate change conditions. Using climate projections from the Norwegian Meteorological Institute, the evaluation analyzes how warming temperatures affect active layer thickness and permafrost degradation through 2070. The methodology examines both thaw settlement from seasonal thawing and creep settlement from soil deformation under sustained loads. For the UNIS Guest House (pile foundation), Cableway Post Nr. 6 (shallow foundation), and House London 1 (shallow foundation), projected settlements increase significantly towards 2070, with thaw settlements generally exceeding creep settlements in magnitude. The progressive settlements may threaten long-term structural integrity. The findings highlight the need for site-specific soil investigations and potential adaptation measures to preserve these valuable cultural heritage structures in a warming climate.

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APPENDICES

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1 Introduction

This report is part of the PermaRICH project, funded by Fram Centre (KLD statsbudsjettet kap. 1474 Fram – Nordområdesenter for klima- og miljøforskning, post 70) and led by Line Rouyet at NORCE.

The evaluation of foundation settlement for selected modern infrastructure and cultural heritage structures under the impacts of climate change is essential. This report aims to assess the potential settlement issues that may arise due to changing climatic conditions, particularly focusing on structures located in Longyearbyen and Ny-Ålesund.

Climate change poses significant risks to the stability of foundations, especially in regions with permafrost. As temperatures rise, the thawing of permafrost can lead to ground subsidence, affecting the structural integrity of buildings. This report utilizes climate projections from the Norwegian Meteorological Institute to analyze historical data and future scenarios, providing a comprehensive understanding of the potential impacts on foundation stability.

The methodology involves evaluating both thaw settlement and creep settlement. Thaw settlement occurs when ice-rich soils melt, leading to a reduction in soil volume and subsequent ground subsidence. Creep settlement refers to the gradual deformation of soil under constant stress over time, which is particularly relevant for pile foundations in frozen soil conditions.

By examining the settlement behaviour of different types of foundations in different soil conditions, this study aims to provide insights into the long-term stability of modern infrastructure and cultural heritage structures. The findings will help in developing strategies to mitigate the adverse effects of climate change on these structures.

2 Climate projections and ground thermal regime

The climate projections presented in this report are obtained from the Norwegian Meteorological Institute. The projections cover a comprehensive time span, capturing both historical data and future scenarios extending into the mid-21st century and beyond. The temperature data are used to calculate the evolution of the active layer thicknesses and permafrost temperatures using analytical and numerical approaches; only the results are presented here.

2.1 Longyearbyen

Historical and projected temperature data for Longyearbyen was obtained from the Norwegian Meteorological Institute. The dataset includes information for a 3 by 4 grid, covering a total of 12 grid points across the region. The projected changes in the annual mean surface temperature were analysed using this data. To provide a comprehensive overview, the temperature plot, as shown in Figure 1, displays the data for each individual grid point. Additionally, the plot includes an average temperature trend line, which represents the mean temperature values calculated across all 12 grid points, offering a clearer depiction of the overall trend in surface temperature changes over time.

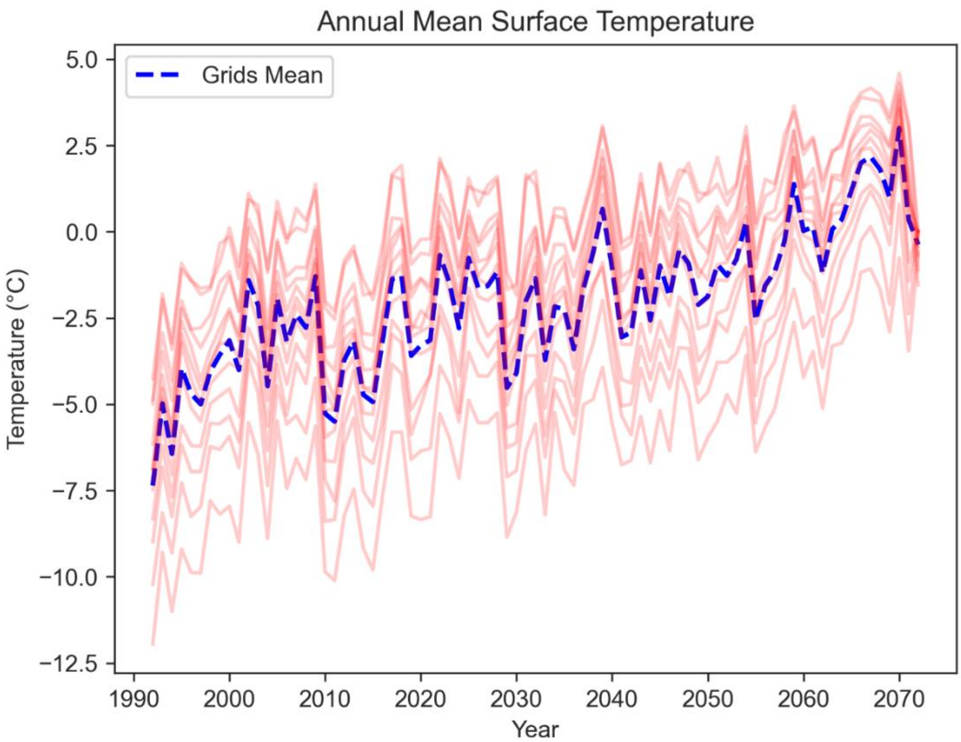

Figure 1: Historical and projected annual mean surface temperature in Longyearbyen.

The data was used to evaluate the evolution of the active layer thickness and the permafrost temperature in the Longyearbyen region. The active layer thickness, which refers to the uppermost layer of soil that thaws and freezes annually, is shown in Figure 2. The active layer thicknesses were estimated based on numerical simulations in Temp/W; (Bekele, Y., Sinitsyn, A., 2024). The plot displays the changes in active layer thickness over time, highlighting a gradual increase that becomes more pronounced in the latter half of the century. The shaded regions in the plot represent variability across the dataset, providing an understanding of the uncertainty or spread in the projections.

Similarly, Figure 3 illustrates the evolution of permafrost temperature, averaged for depths ranging between 5.0- and 20.0-meters based on simulation results. The plot reveals a consistent warming trend, with permafrost temperatures becoming warmer over the years, signalling ongoing permafrost degradation. Together, these figures provide a detailed view of how climate change is expected to impact the active layer and permafrost in the region, underscoring the need for further study and mitigation efforts.

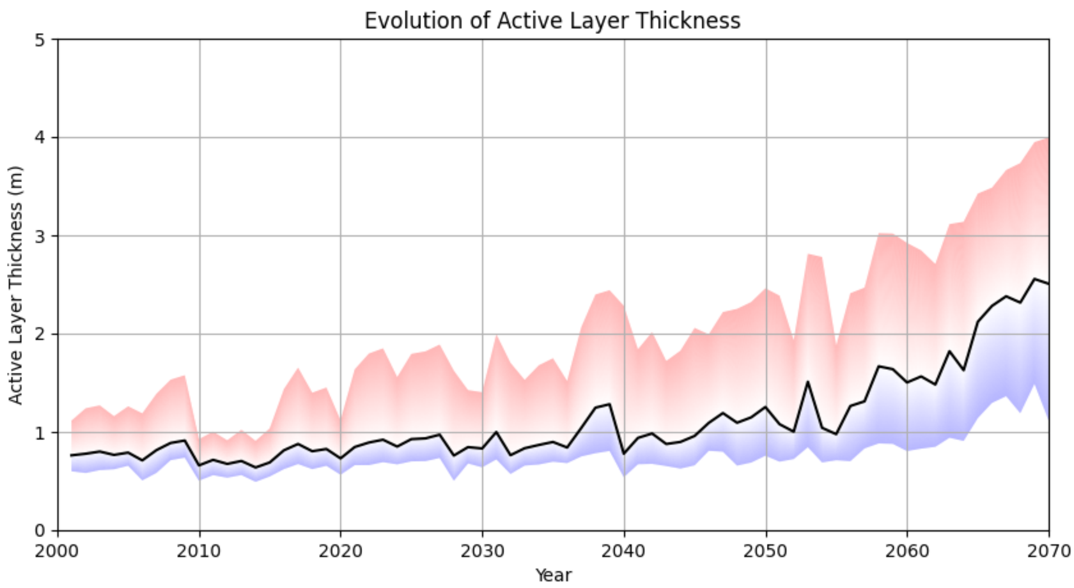

Figure 2: Evolution of active layer thickness in Longyearbyen.

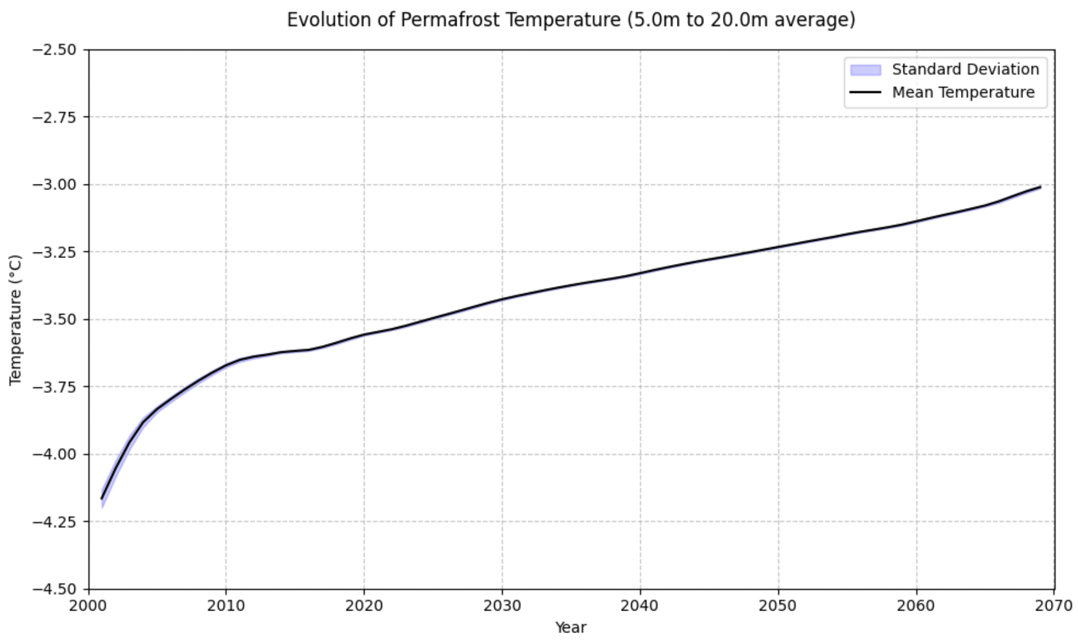

Figure 3: Evolution of average permafrost temperature in Longyearbyen.

2.2 Ny-Ålesund

Similarly, for Ny-Ålesund, the annual mean surface temperature projections are analysed based on both historical data and future projections. As with Longyearbyen, the temperature plot (as shown in Figure 4) displays individual grid temperatures along with the mean trend line for the grids.

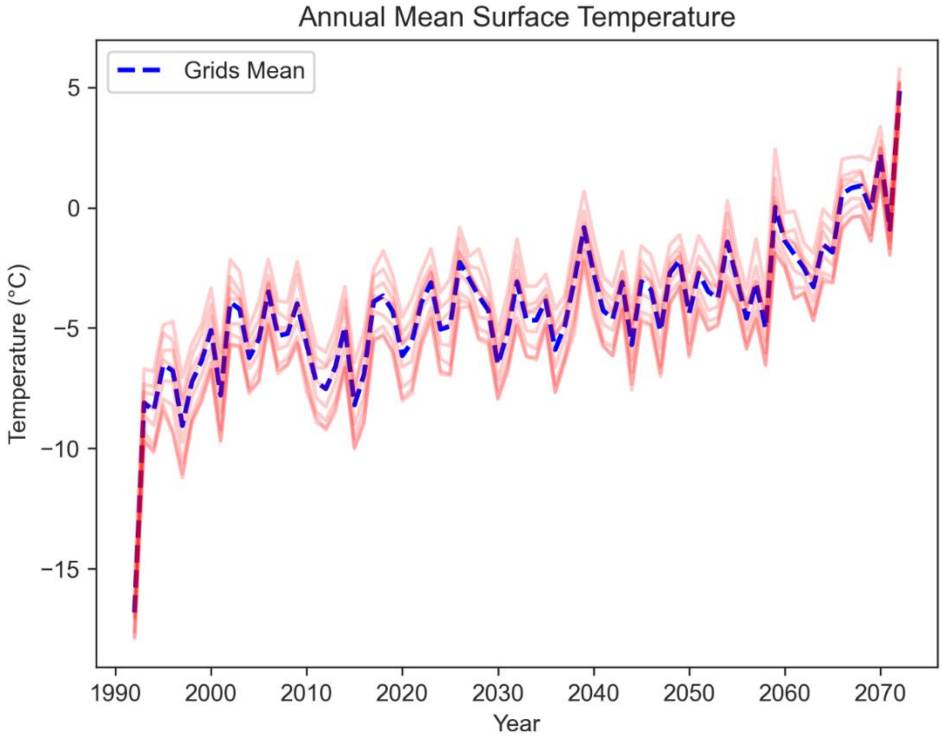

Figure 4: Historical and projected annual mean surface temperature in Ny-Ålesund.

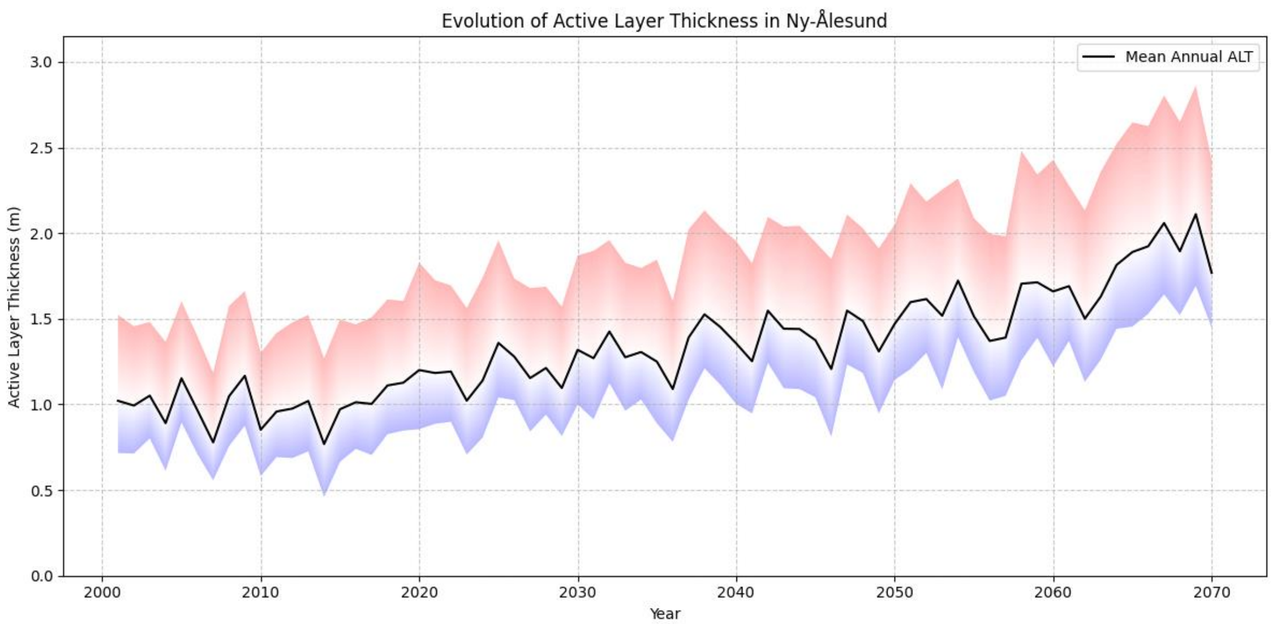

Figure 5: Evolution of active layer thickness in Ny-Ålesund.

In a similar way, the temperature projections were used to estimate the evolution of the active layer thickness in Ny-Ålesund and the result is shown in Figure 5. The evolution is presented including uncertainty ranges corresponding to uncertainties in the project temperatures.

Figure 6 presents the estimate evolution of the average permafrost temperature in Ny-Ålesund. The initial permafrost temperature is assumed to be -5°C and the projected value are obtained by a simple analytical estimation gradually adjusting it each year toward the average air temperature, considering that the ground responds slowly to temperature changes. The data indicates a general warming trend, with permafrost temperature rising from about -5°C in the early 2000s to nearly -3.0°C by 2070, suggesting significant permafrost degradation over time.

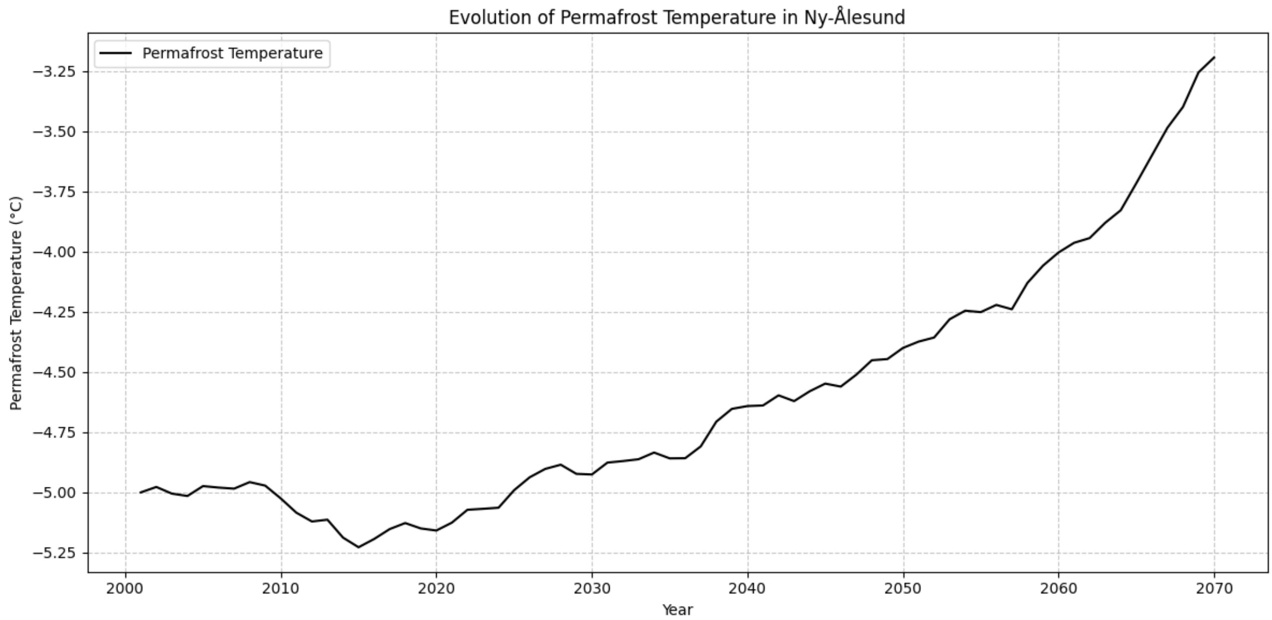

Figure 6: Evolution of average permafrost temperature in Ny-Ålesund.

The active layer thicknesses for Ny-Ålesund are estimated based on analytical approaches. The permafrost temperatures are predicted based on observations from thermal simulation for Longyearbyen and using data interpolation to obtain rough estimates. The estimates for both the active layer thicknesses and permafrost temperatures are considered to be conservative.

3 Structures selected for case study

This chapter provides an overview of the structures chosen for analysis in this study, focusing on their foundation types, dimensions, estimated loads, and the prevailing soil conditions at their respective sites. The selected structures represent a diverse range of designs and foundation systems, allowing for a comprehensive evaluation of their performance in permafrost conditions. The structures were selected from both Longyearbyen and Ny-Ålesund.

3.1 Structures in Longyearbyen

UNIS Guest House and Cableway Post Nr. 6 on Line 6 are the structures in Longyearbyen selected for analysis in this study.

Figure 7 and Figure 8 show pictures of the UNIS Guest House as seen from the outside and the pile foundations supporting the structure, respectively. The UNIS Guest House is a two-story building with a rectangular layout, ca. 14 m x 68 m. The building's foundation consists of timber piles supporting the structure above ground level. This design allows for proper ventilation and minimizes the thermal disturbance to the underlying permafrost. The timber piles are integrated with horizontal bracing elements to provide additional stability. Figure 9 shows a picture of Cableway Post Nr. 6 on Line 6.

Figure 7: UNIS Guest House, Longyearbyen. Picture: © Anatoly Sinitsyn/SINTEF AS.

Figure 8: Pile foundation of UNIS Guest House, Longyearbyen. Picture: © Anatoly Sinitsyn/SINTEF AS.

Figure 9: Cableway Post Nr. 6 on Line 6. Picture: © Anatoly Sinitsyn/SINTEF AS.

Table 1 presents the foundation types, their dimensions, the estimated loads and soil conditions at the site for the UNIS Guest House and Cableway Post Nr. 6 on Line 6.

Table 1: Structures in Longyearbyen selected for analysis.

Object	Foundation type	Dimension	Load on foundation	Soil properties
UNIS Guest House	Pile foundation (ca. 150 friction piles)	L* = 9 m, D = 0.25 m (assumption)	V = 61 kN**	Unspecified
Cableway Post Nr. 6, Line 6	Shallow foundation, embedded 2 m in permafrost.	B x L = 5.9 m x 0.3 m (2 wooden strips) (Pasquini, 2023)	Small cableway post, q = 16 kPa (Based on loads from (Pasquini, 2023)	Unspecified

L=Length, D=Diameter, V=Axial load on pile, B=Breadth, W=Width

*Length embedded in the ground (otherwise the building is elevated above ground)

**The load is estimated based on simple calculations for dead and live loads of a two-storey house and assuming a load factors of 1.5.

3.2 Structures in Ny-Ålesund

The structure from Ny-Ålesund that is selected for case study is the London 1 house, a picture of which is shown in Figure 10. House London 1 is a single-storey wooden residential structures supported by surface foundations. House has an approximate footprint of 8.5 m by 4 m, with 12 individual foundation pads measuring ca. 30 cm x 30 cm; see Table 2.

Figure 10: House London 1, Ny-Ålesund. Picture: © Anatoly Sinitsyn/SINTEF AS.

Table 2: Structures in Ny-Ålesund selected for analysis.

Object	Foundation type	Dimension	Load on foundation	Soil properties
London 1	Surface foundation	One-storey house, ca. 8.5 m x 4 m Foundation: B x L = 30 cm x 30 cm; 12-piece foundations per house	120 kPa*	Ice-rich permafrost (assumed)

*The load is estimated based on simple calculations for dead and live loads of a one-storey house.

4 Settlement evaluation methodology

Settlement under climate change conditions in permafrost regions involves two primary mechanisms: thaw settlement and creep settlement. These mechanisms represent the dominant processes affecting ground stability in permafrost regions under warming conditions. While conventional settlement types such as elastic deformation and primary consolidation also occur (particularly in the active layer), their magnitude is typically negligible compared to thaw and creep effects in permafrost environments.

4.1 Thaw settlements

Thaw settlement in permafrost regions results from the melting of ice-rich soils, leading to ground subsidence. This process is particularly critical in areas experiencing climate warming, where previously stable frozen ground begins to thaw. The mechanism involves not only the phase change of ice to water but also the subsequent reorganization of the soil structure as the ice matrix that previously provided structural support transforms into a liquid state.

Andersland & Ladanyi (2003) provide a method for estimating thaw settlement by considering the reduction in soil volume as ice turns to water and drains away. Their approach has been widely validated in field conditions and provides a reliable basis for settlement predictions. The settlement, s_t, can be estimated based on the depth of thaw, initial ice content, and soil properties using the following relationship:

$$u_t = H \cdot \frac{\Delta V}{V}$$

where H = Depth of newly thawed soil

$\frac{\Delta V}{V}$ = Volumetric reduction upon thaw

For practical engineering applications and preliminary assessments, the thaw settlement can be approximated by considering the characteristic 9% volume change that occurs during the ice-to-water phase transition, combined with the soil porosity. This simplified approach yields:

$$u_t = 0.09 \cdot n \cdot H$$

where n = Porosity

This approximation assumes a 9% expansion/contraction of ice during freezing/thawing, which is typical for most subsurface conditions. The accuracy of this approximation depends on the initial ice content distribution, ground temperature regime, and specific soil properties of the site under investigation. For critical infrastructure projects, site-specific testing and more detailed analysis may be required to refine these calculations.

4.2 Creep settlement of foundations

4.2.1 Pile foundations

Pile creep settlement analysis is essential for understanding the long-term behavior of piles in frozen soil conditions, particularly under sustained loads. This analysis is based on the work of Andersland & Ladanyi (2003) in Frozen Ground Engineering and the research by Weaver & Morgenstern (1981), which provide critical insights into creep mechanisms in frozen soils. This section explores the time- and temperature-dependent creep behavior of friction piles in ice-rich and ice-poor soils, as well as the settlement rate of end-bearing piles in these conditions.

Friction piles in ice-rich soils
Friction piles are foundational elements commonly used in geotechnical engineering to support structures by transferring loads to deeper soil layers. In ice-rich soils, which contain a significant amount of ground ice, the behavior of these piles under sustained loads is influenced by the unique properties of the frozen soil matrix.

For friction piles embedded in ice-rich soils, the steady-state creep behavior—which describes the constant rate of deformation over time under a sustained load—can be mathematically expressed using the following equation (Weaver & Morgenstern, 1981):

$$\frac{\dot{u}_c}{a} = \frac{3^{\frac{n+1}{2}}}{n-1} \cdot B \cdot \tau^n$$

where $\dot{u}_c$ = Pile settlement rate
a = Pile radius
τ = Average applied adfreeze load = Load / Effective shaft area
B, n = Creep constants depending on soil type

This equation illustrates that the settlement rate of a friction pile is directly related to the applied load and the soil's creep properties. The creep constants B and n are crucial as they encapsulate how different ice-rich soils respond to sustained loading. Accurate predictions help in designing foundations that mitigate excessive settlement, ensuring structural integrity and longevity.

The average applied adfreeze load can be estimated using

$$\tau = \frac{V}{2\pi \cdot a \cdot L_{eff}}$$

where V = Axial load on the pile
L_{eff} = Effective length of pile below -1°C

Friction piles in ice-poor soils
In contrast to ice-rich soils, ice-poor soils contain minimal ground ice and exhibit different mechanical behavior under load. The absence of significant ice content alters the soil's deformation characteristics, leading to what is known as damped creep behavior in friction piles.

For friction piles in ice-poor soils, the settlement over time is governed by the following relationship:

$$\frac{u_c}{a \cdot t^b} = \frac{3^{\frac{c+1}{2}}}{c-1} \cdot D \cdot \tau^c$$

where u_a = Pile settlement
t = Time elapsed after load application
τ = Average applied adfreeze load
D = Temperature function
$b,\ c$ = Creep constants depending on soil type

The presented equation captures the time-dependent settlement of friction piles in ice-poor soils, highlighting that settlement is not only a function of the applied load and pile geometry but also significantly influenced by the duration of loading and temperature conditions. The temperature function D integrates environmental factors, recognizing that warmer temperatures may reduce soil stiffness and accelerate settlement, while colder conditions might have the opposite effect. The creep constants b and c are vital for characterizing the soil's deformation behavior over time.

The temperature function can be expressed as

$$D = \left[\frac{1}{w \cdot (T+1)^k}\right]^c$$

where w, k = Constants dependent on soil type
T = Temperature below freezing

Alternative expression for friction piles
An alternative way for evaluating the axial settlement of a pile due to primary creep, according to Andersland & Ladanyi (2003), is given by:

$$u_c = \frac{3^{\frac{n+1}{2}}}{n-1} \cdot a \cdot \left(\frac{\tau}{\sigma_{cT}}\right)^n \cdot \left(\frac{\dot{\varepsilon}_c}{b}\right)^b \cdot t^b$$

where a = Pile radius, as defined earlier
τ = Average applied adfreeze load as defined in an earlier equation
σ_{cT} = Reference stress corresponding to an arbitrary reference strain
t = Time
$\dot{\varepsilon}_c$ = Arbitrary reference strain rate
b, n = Creep constants

The reference stress σ_{cT} is expressed as a function of temperature according to the following equation:

$$\sigma_{cT} = \sigma_{co} \cdot \left(1 + \frac{T}{T_c}\right)^w$$

where σ_{co} is the value of σ_{cT}, obtained in unconfined compression creep tests, extrapolated back to 1 °C and T_c is an arbitrary temperature, say 1 °C.

End-bearing piles in ice-rich soils
End-bearing piles are a fundamental type of deep foundation used to transfer structural loads directly to strong soil or rock layers beneath weaker surface soils. In ice-rich soils, which contain substantial ground ice, the performance and settlement behavior of end-bearing piles are influenced by the frozen soil properties and the interaction between the pile and the surrounding ice.

For end-bearing piles embedded in ice-rich soils, the settlement rate—the rate at which the pile sinks into the soil over time—depends primarily on the end-bearing pressure. This relationship is mathematically represented by the following expression:

$$\frac{\dot{u}_c}{a} = B \cdot \left(\frac{3}{2n} \cdot \sigma_E\right)^n$$

where $\dot{u}_c$ = Pile settlement rate
a = Pile radius
σ_E = End-bearing pressure
B, n = Creep constants depending on soil type

The provided equation highlights that the settlement rate of an end-bearing pile in ice-rich soils is a function of the end-bearing pressure and the soil's creep characteristics. The constants B and n encapsulate the soil's response to loading, where B influences the magnitude of settlement, and n determines the nonlinearity of the relationship between settlement rate and end-bearing pressure.

End-bearing piles in ice-poor soils

In contrast, ice-poor soils contain minimal or no ground ice, resulting in different mechanical behavior under loading conditions. For end-bearing piles in such soils, the settlement behavior is influenced by factors like soil consolidation, temperature variations, and the time-dependent nature of soil deformation.

The settlement rate for end-bearing piles in ice-poor soils can be described by:

$$\frac{u_c}{a \cdot t^b} = D \cdot \left(\frac{3}{2c} \cdot \sigma_E\right)^c$$

where u_c = Pile settlement
a = Pile radius
t = Time elapsed after load application
σ_E = End-bearing pressure
D = Temperature function
b, c = Creep constants depending on soil type

The equation for end-bearing piles in ice-poor soils incorporates both the applied load and the time over which the load is applied, reflecting the time-dependent settlement behavior of such soils.

While some of the pile creep equations presented above are not directly applicable to the cases analysed in this report, they are included to provide comprehensive theoretical background.

4.2.2 Shallow foundations

Shallow foundations, such as footings, are commonly employed to support structures by distributing loads directly to the near-surface soil layers. In cold regions characterized by active layers and permafrost, the behavior of shallow foundations under sustained loads is significantly influenced by temperature variations and the presence of frozen and thawed soil layers.

The creep settlement, u_c, for a uniformly loaded footing can be approximated by the following equation (Andersland & Ladanyi, 2003):

$$u_c = a \cdot I \cdot \left(\frac{q}{\sigma_{cT}}\right)^n \cdot \left(\frac{\dot{\varepsilon}_c}{b}\right)^b \cdot t^b$$

where a = Footing radius for circular footing or half width for other footings
I = Influence zone of the footing (different equations for different footings)
q = Uniformly distributed load on footing
σ_{cT} = Reference stress corresponding to an arbitrary reference strain
t = Time
$\dot{\varepsilon}_c$ = Arbitrary reference strain rate
b, n = Creep constants

The influence zone varies based on the type and geometry of the footing, representing the area of soil affected by the applied load. Different footing types (e.g., square, rectangular, circular) have distinct influence zones, each requiring specific equations to accurately model the soil-structure interaction.

For a circular footing

$$I = I_c = \left(\frac{3}{2n}\right)^n$$

For a strip footing

$$I = I_{st} = \left(\pi \cdot \frac{\sqrt{3}}{4}\right) \cdot \left(\frac{\sqrt{3}}{n}\right)^n \approx 1.36 \cdot \left(\frac{\sqrt{3}}{n}\right)^n$$

For a rectangular footing with width B and length L, the influence zone can be obtained by interpolation, and the resulting expression is given by

$$I = I_{st} \cdot \left[1 + \left(\frac{I_c}{I_{st}} - 1\right) \cdot \frac{B}{L}\right]$$

4.3 Total settlements

The total settlement for shallow foundations will be the sum of the thaw settlements and creep settlements, neglecting primary settlements in the active layer, i.e.

$$u = u_t + u_c$$

where u_t= thaw settlement
u_c= creep settlement

For pile foundations, the total settlement is typically different from that of shallow foundations due to the way loads are transferred to the ground and the depth at which piles interact with the soil. An increase in the thickness of the active layer causes deeper permafrost soils around pile foundations to increase in temperature. This reduces the soil's strength and stiffness, making it more susceptible to deformation under load. As a result, the creep settlement of piles increases because the piles are now interacting with a greater depth of weaker soil that deforms more readily over time. This effect is considered in the pile creep settlements by considering the relevant effective pile lengths and permafrost temperatures.

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5 Analysis and results

This chapter presents the outcomes of the settlement analyses conducted for the structures identified in Chapter 3. The analyses are based on the methodology discussed in Chapter 4, incorporating the effects of material properties and environmental condition. We first start by presenting the material parameters used in the analyses, as they form the basis for predicting settlements and ensuring the validity of the results. Following this, we present the settlement predictions for the structures located in Longyearbyen and Ny-Ålesund.

5.1 Material parameters

The material parameters assumed and used for settlement predictions are summarised below.

Porosity for thaw settlement evaluations

The porosity of silt soils typically ranges from approximately 35% to 50%, influenced by factors such as grain size distribution, compaction, and moisture content. In ice-rich silt, the presence of ice within the pore spaces can alter the overall porosity; however, specific values for ice-rich silt are not well-documented in the available literature. For the analyses presented in this report, a porosity value of 45% has been adopted.

Creep material parameters

The creep parameters used for the settlement predictions are summarized in Table 3. Based on (Andersland & Ladanyi, 2003), creep parameters for different soil types are presented and the applicable soil types used are used for different structures in Longyearbyen and Ny-Ålesund.

Table 3: Creep material parameters used for settlement prediction for different soil types; (Andersland & Ladanyi, 2003).

Creep parameter	Value			Unit
	(Very) Ice-rich silt (soil)	Fine sand	Clay	
b	1.0	0.63	0.33	-
n	3.0	2.63	2.38	-
w	0.6 (0.37)	1.0	1.2	-
σ_{co}	0.071 (0.103)	0.16	0.17	MPa
$\dot{\varepsilon}_c$	10^{-5}	10^{-5}	10^{-5}	h^{-1}

5.2 Settlement predictions for structures in Longyearbyen

We start the settlement evaluation for structures in Longyearbyen by evaluating the thaw settlements. Figure 11 shows the evolution of thaw settlement in Longyearbyen from 2000 to 2070, based on the active layer thickness trends presented in Chapter 2 and using the methodology presented in Section 4.1. The thaw settlement remains relatively low and stable until around 2040, after which it begins to increase steadily, with a notable rise in both the mean value (black line) and the variability (shaded area). By 2070, the thaw settlement reaches values exceeding 10 cm in the upper bound case, reflecting the progressive thickening of the active layer over time. This increase indicates a direct relationship between the active layer thickness and the extent of thaw settlements in the region.

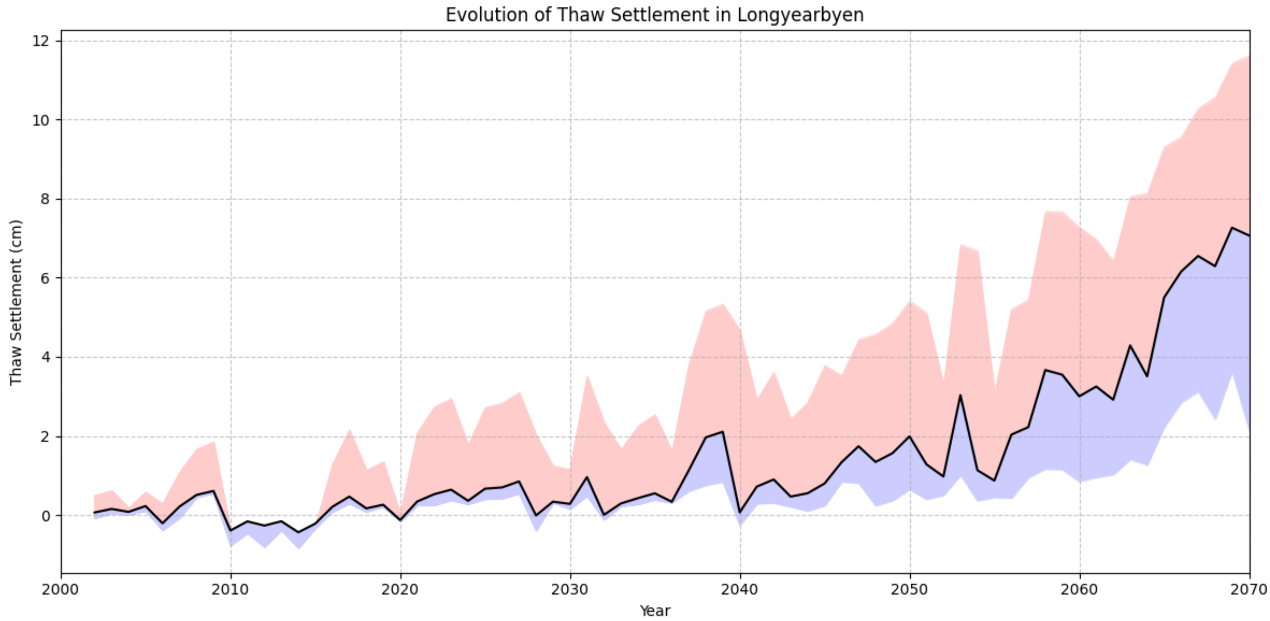

Figure 11: Predicted thaw settlements in Longyearbyen.

__UNIS Guest House__

The evolution of the active layer thicknesses in Chapter 2 and the thaw settlements presented in Figure 11 imply that the pile foundations of the UNIS Guest House will be affected such that the effective length of the piles, L_{eff}, reduces significantly. Thus, we first estimate the change in this effective length before calculating the expected creep settlements.

The effective pile length below -1 °C is calculated by adjusting the total pile length based on the active layer thickness and a factor accounting for the depth between 0 and -1 °C. This factor is assumed to be ca. 1.1 based on observations from numerical simulations. The total pile length below ground is reduced by the product of the active layer thickness and this factor. This calculation is performed for the mean active layer thickness, as well as the upper and lower bounds of the active layer thickness (mean plus standard deviation and mean minus standard deviation, respectively). The resulting effective lengths represent the pile length below -1 °C for different scenarios, accounting for variations in the active layer thickness. Figure 12 shows the evolution of the effective pile length for the pile foundations of the UNIS Guest House.

Based on the evolution of the effective pile length and the creep settlement calculation methodology in Chapter 4, we estimate the creep settlements of the pile foundations for the UNIS Guest House. Since the soil type is not clearly specified, the pile creep settlement calculations are performed for the three different soil types and creep parameters presented in Table 3. The pile creep settlement results for an ice-rich silt soil are shown in

Figure 13. Similarly, the pile creep settlement results when assuming the soil type to be fine sand are shown in Figure 14. Finally, the results when assuming a clayey soil type are presented in Figure 15. A comparison of the results shows that, in general, the expected pile creep settlements are very low compared to the thaw settlements. A cross comparison of the pile creep settlements shows that larger creep settlements are predicted for an ice-rich soil type, as expected, even though the settlement values are still very low. The results give an indication of the potential creep settlements that might occur for UNIS Guest House. A

detailed study considering the actual soil type (or soil types in a layered soil) is required for a more conclusive picture of the settlement predictions.

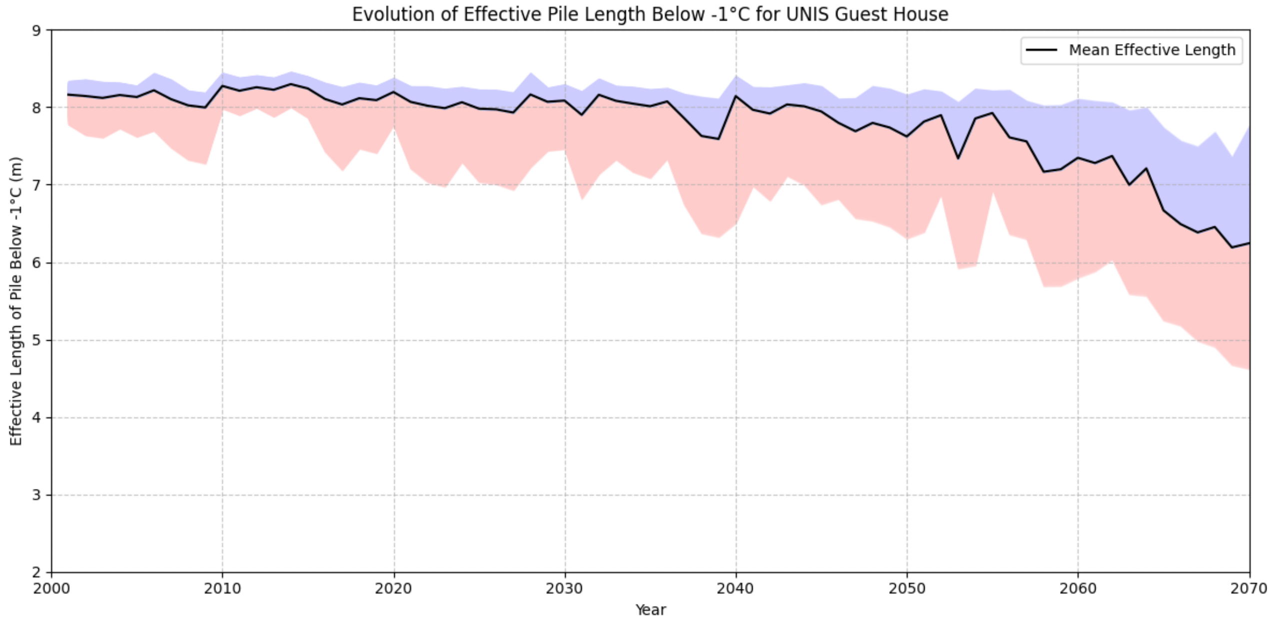

Figure 12: Evolution of effective pile length below -1°C for UNIS Guest House.

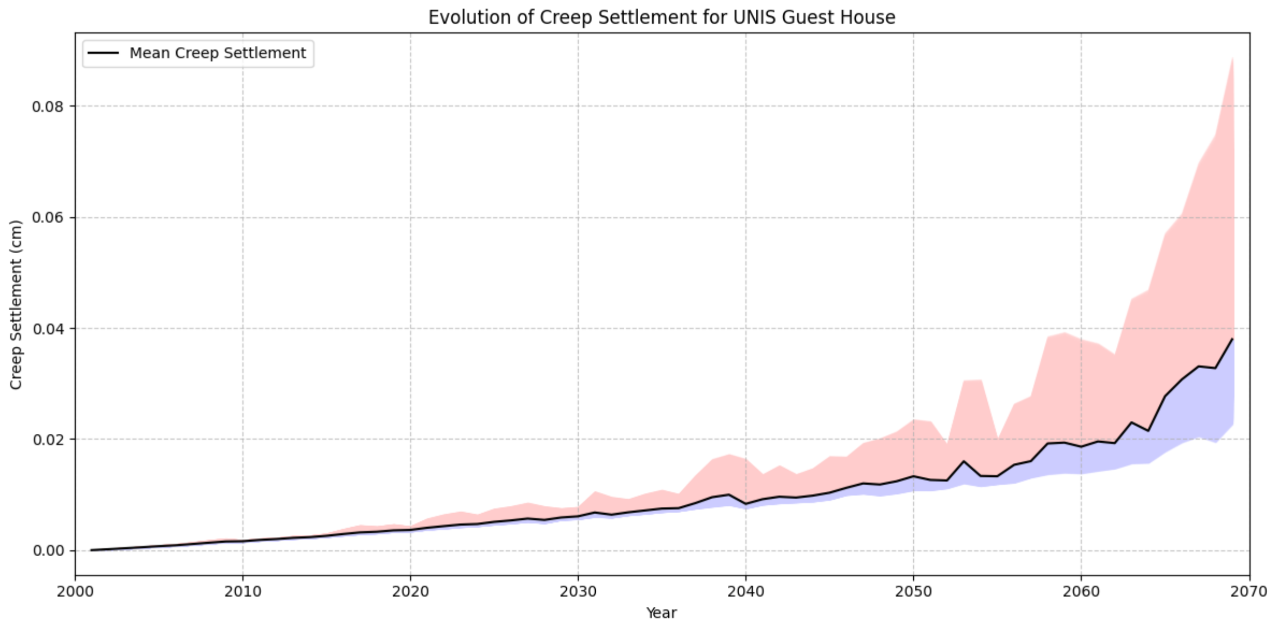

Figure 13: Evolution of pile creep settlement for UNIS Guest House assuming an ice-rich silt soil type.

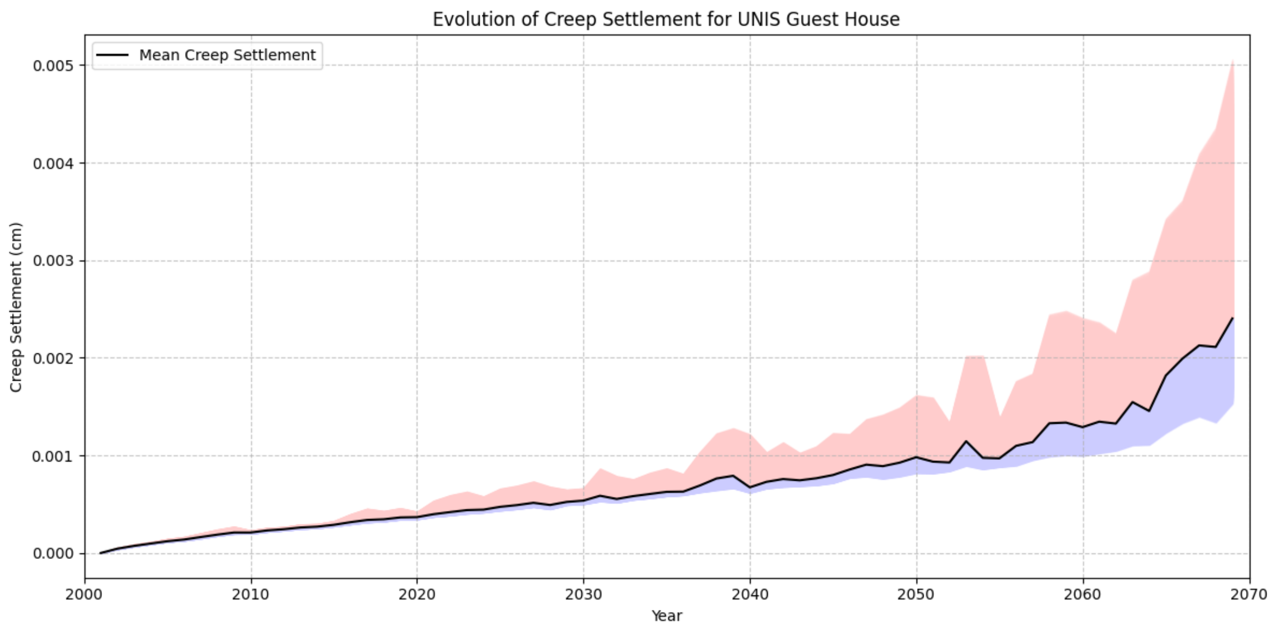

Figure 14: Evolution of pile creep settlement for UNIS Guest House assuming a fine sand soil type.

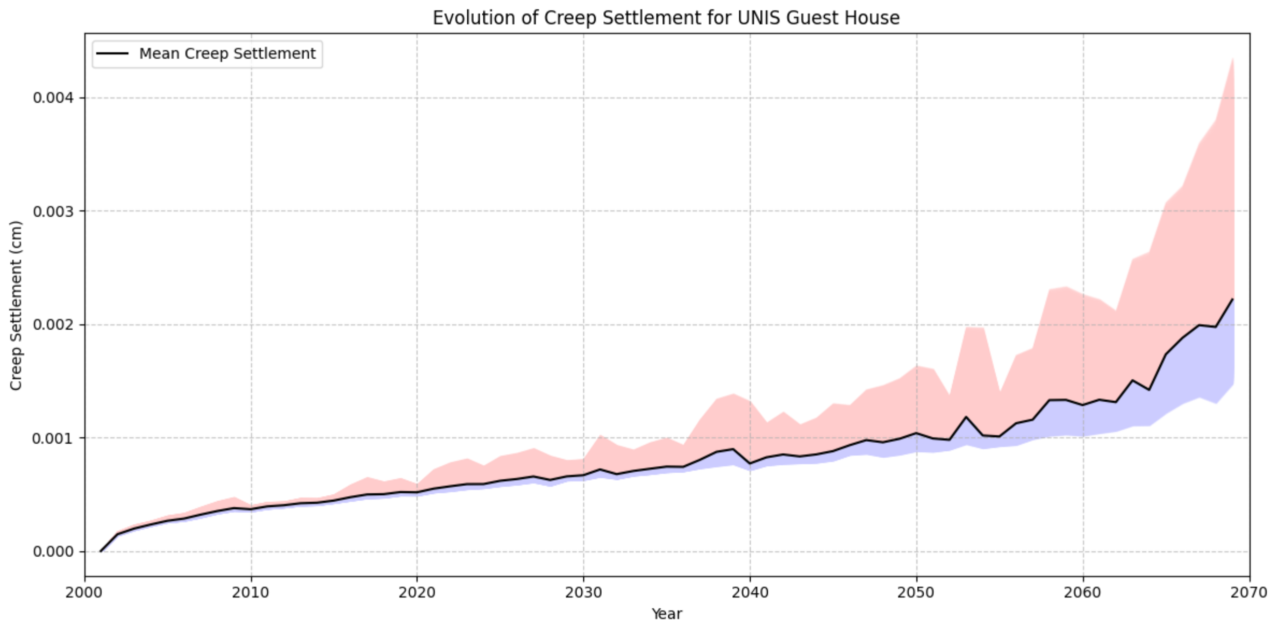

Figure 15: Evolution of pile creep settlement for UNIS Guest House assuming a clay soil type.

Cableway Post Nr. 6, Line 6

The foundation of Cableway Post Nr. 6, Line 6 features a shallow foundation which consists of two wooden strips with B x L = 5.9 m x 0.3 m. The total load on the foundations was estimated to be 16 kPa, according to (Pasquini, 2023). The thaw settlements calculated and presented in Figure 11 for Longyearbyen are considered applicable for this structure.

Since the soil type is not clearly specified, we again calculate the creep settlements assuming a very ice-rich soil type where the creep parameters presented in Table 3 apply, with the values in parentheses for the parameters w and σ_{co}, i.e. 0.37 and 0.103 MPa, respectively. The shallow foundation for Cableway Post Nr. 6, Line 6 is considered to be a strip footing and the influence zone required for creep settlement calculation is evaluated accordingly. The permafrost temperature we use in the creep settlement calculation is the average over a depth of 5 to 20 m, as obtained from numerical simulations. To include uncertainties in the creep settlement calculation, a load factor of ± 20% is considered. The calculated creep settlements are shown in Figure 16.

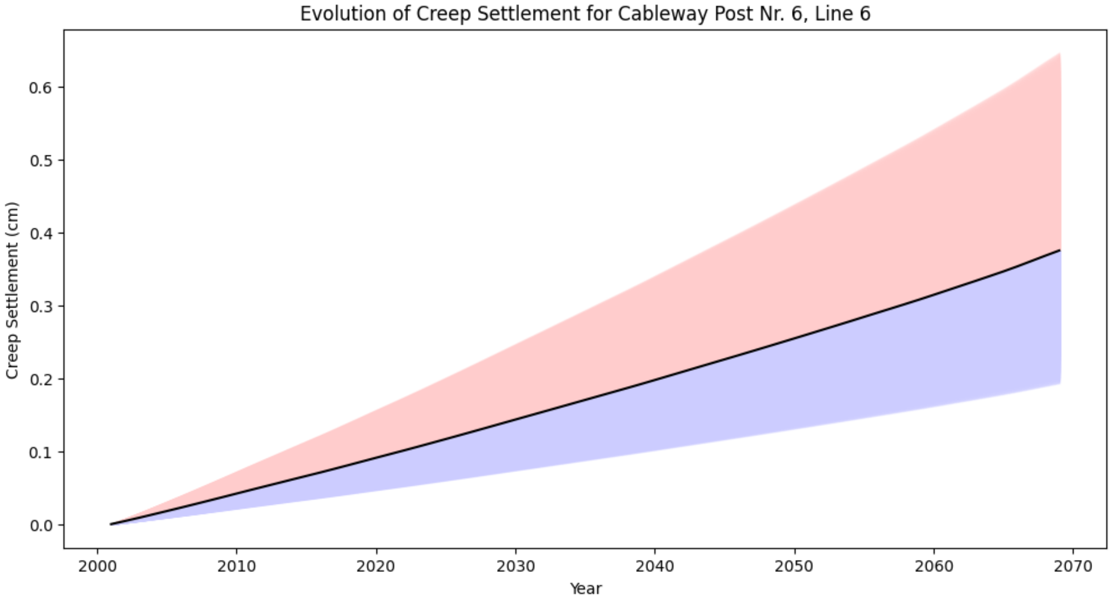

Figure 16: Evolution of creep settlement for Cableway Post Nr. 6, Line 6.

As described in the methodology chapter (Chapter 4), the total settlement for shallow foundations is the sum of the thaw and creep settlements. Figure 17 shows the evolution of the total settlement for Cableway Post Nr. 6, Line 6.

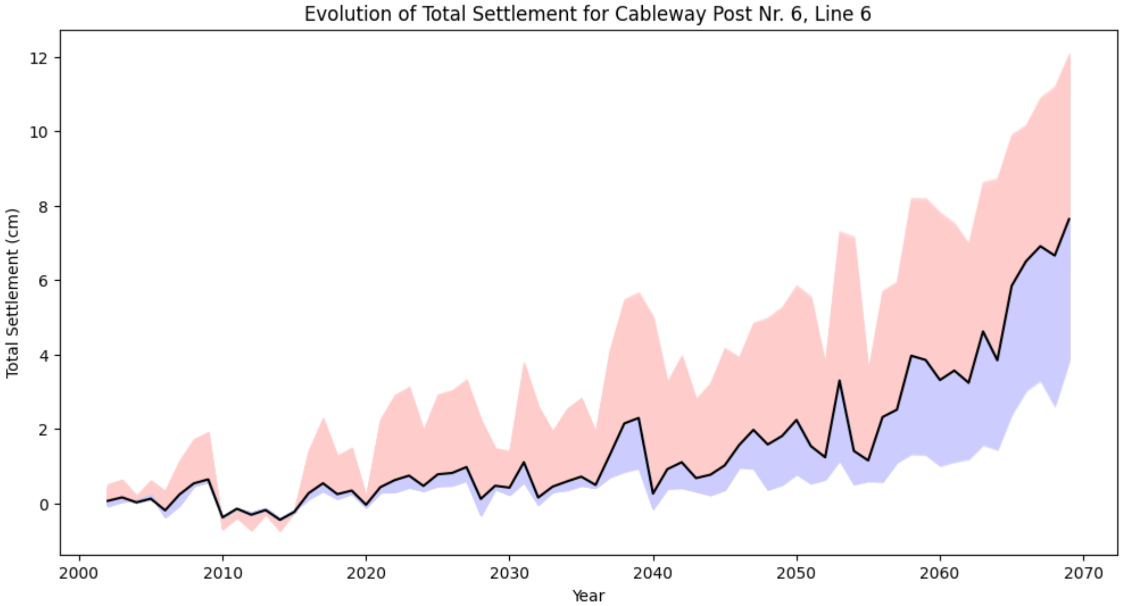

Figure 17: Evolution of total settlement for Cableway Post Nr. 6, Line 6.

5.3 Settlement predictions for structures in Ny-Ålesund

In a similar way as for the evaluations for Longyearbyen, we start the settlement evaluations in Ny-Ålesund with estimation of the thaw settlements. The thaw settlements, unlike for Longyearbyen, are based on analytical calculations as described in Chapter 2. The active layer thicknesses presented in Chapter 2 are used as a basis for the thaw settlement calculations, using the methodology presented in Chapter 3. The resulting thaw settlement predictions are shown in Figure 18. The predictions show that the thaw settlements could reach more than 5 cm by 2070. These results are then used as a basis to evaluate the total expected settlements of structure foundations in Ny-Ålesund

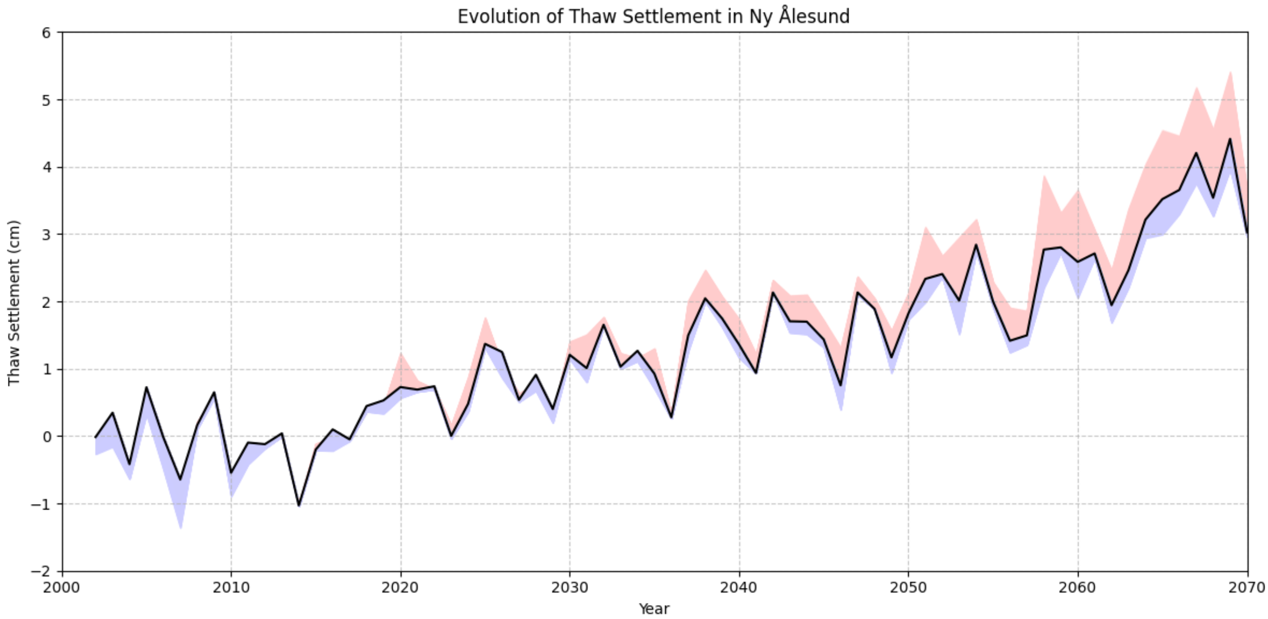

Figure 18: Predicted thaw settlements in Ny-Ålesund.

London 1

As described earlier, the foundations for London 1 are rectangular surface footings, i.e. shallow foundations with dimensions and loads described in Table 2. The soil underneath the foundations is considered to be an ice-rich silt with creep parameters presented in Table 3. The creep settlements for London 1 are estimated based on the inputs from these tables. The permafrost temperature used in the calculations is as obtained in Figure 6. The influence zone of the footings is calculated based on the expression for a rectangular footing. To include uncertainties in the creep settlement calculation, a load factor of ± 20% is considered. The estimated creep settlements are presented in Figure 19. The total predicted settlement for London 1, as the sum of thaw and creep settlements, is presented in Figure 20.

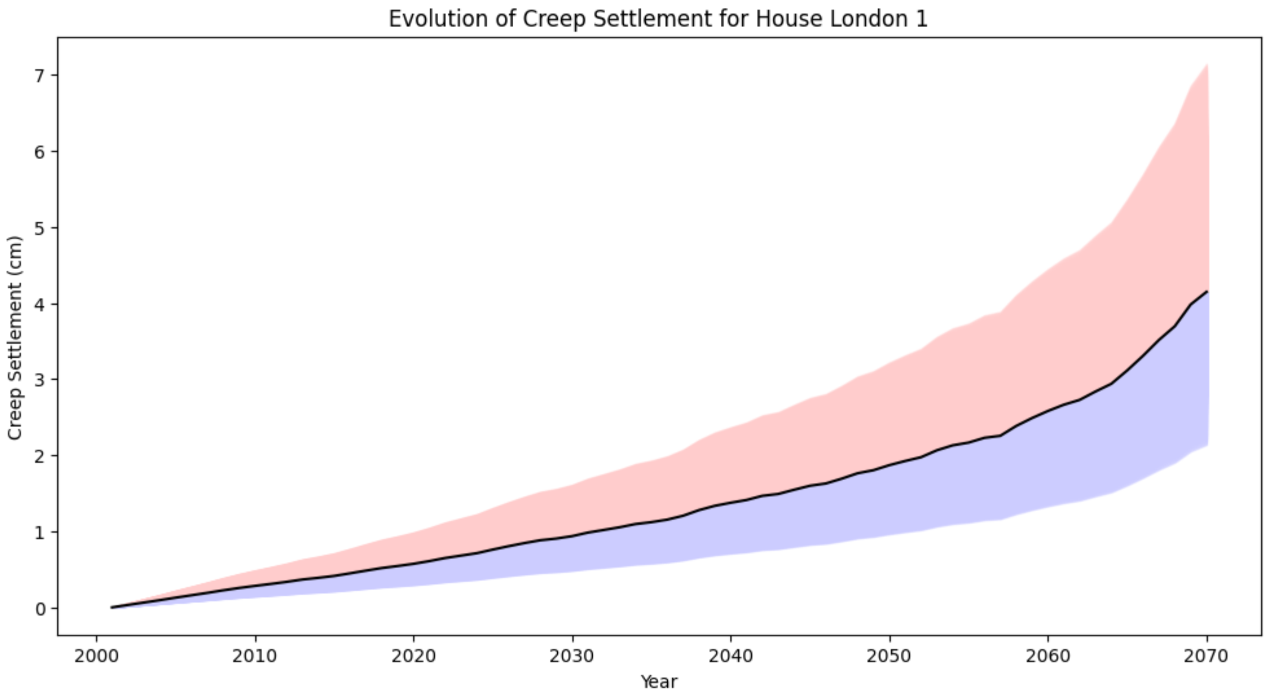

Figure 19: Evolution of creep settlement for London 1.

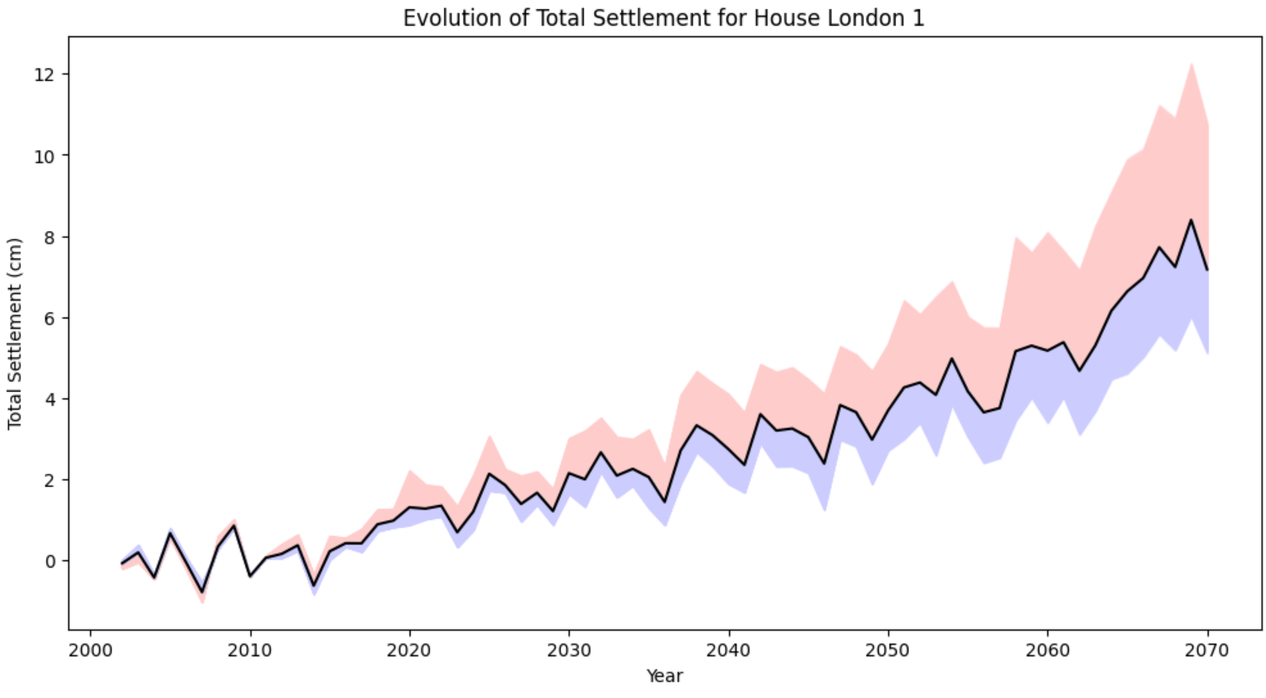

Figure 20: Evolution of total settlement for House London 1.

6 Summary and conclusions

This study has evaluated the potential settlement issues that may arise for selected cultural heritage structures in Longyearbyen and Ny-Ålesund due to climate change impacts on permafrost conditions. The analysis incorporates climate projections from the Norwegian Meteorological Institute, which indicate a consistent warming trend in both regions through 2070, with significant implications for active layer thickness and permafrost temperature.

The methodology employed in this study focused on two primary settlement mechanisms in permafrost regions: thaw settlement resulting from soil melting, and creep settlement due to the gradual deformation of frozen soil under sustained loading. Both mechanisms were analyzed for different foundation types, including pile foundations (UNIS Guest House) and shallow foundations (Cableway Post Nr. 6, Line 6 and House London 1).

The findings from the settlement predictions reveal several important trends. The active layer thickness in both Longyearbyen and Ny-Ålesund is expected to increase substantially by the latter half of the century, directly corresponding to increased thaw settlements.

For pile foundations such as those supporting the UNIS Guest House, the effective length below the critical temperature threshold is predicted to decrease over time, reducing the foundation's load-bearing capacity. While creep settlements for these pile foundations are relatively small compared to thaw settlements, they contribute to the overall settlement. The analysis shows that for shallow foundations, as in the Cableway Post Nr. 6 on Line 6 (Longyearbyen) and House London 1 (Ny-Ålesund), both creep and thaw settlements contribute significantly to the total projected settlements.

It is important to note that these predictions are based on generalized soil parameters and assumptions. For critical infrastructure and preservation planning, site-specific soil investigations should be conducted to determine actual soil conditions, ice content, and creep properties. Detailed evaluations based on site-specific soil conditions and material parameters would provide more accurate settlement predictions and allow for the development of appropriate mitigation strategies.

This study provides valuable insights into the potential impacts of climate change on cultural heritage structures in Arctic regions and underscores the importance of monitoring and potentially implementing adaptive measures to preserve these structures.

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