Report

Climate Change Impacts on Foundation Settlements of Selected Cultural Heritage Structures

PCCH-Arctic Report Nr.4

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Report No:

2025:00369 - Unrestricted

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KEYWORDS
Climate change
Cultural heritage
Foundation settlements

VERSION
1.0

DATE
2025-03-28

AUTHOR(S)
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CLIENT(S)
Research Council of Norway

CLIENT'S REFERENCE
Agnes Aune

PROJECT NO.
102024999

NO. OF PAGES
33

SUMMARY
This report assesses the impact of climate change on the foundation settlements of selected cultural heritage structures in Longyearbyen and Ny-Ålesund, Svalbard. Utilizing climate projections from the Norwegian Meteorological Institute, the study evaluates potential foundation instability driven by permafrost degradation. The analysis focuses on thaw settlement, caused by melting ice-rich soils, and creep settlement, the gradual deformation of soil under load, particularly relevant for foundations in frozen ground. By examining various foundation types (shallow, pile, surface) across different structures, the report provides insights into the long-term stability challenges posed by rising temperatures and increasing active layer thickness. The findings aim to inform strategies for mitigating climate change impacts on these valuable heritage sites.

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REPORT NO.	ISBN	CLASSIFICATION	CLASSIFICATION THIS PAGE
2025:00369	978-82-14-07475-8	Unrestricted	Unrestricted

COMPANY WITH MANAGEMENT SYSTEM CERTIFIED BY DNV
ISO 9001 • ISO 14001
ISO 45001

Document history

VERSION	DATE	VERSION DESCRIPTION
1.0	2025-03-28	First version of report

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APPENDICES

N/A

1 Introduction

Evaluating foundation settlement for selected cultural heritage structures due to the impacts of climate change is of paramount importance. This report specifically aims to assess potential settlement issues that could emerge as a result of shifting climatic conditions, with a particular emphasis on structures located in Longyearbyen and Ny-Ålesund.

Climate change introduces considerable risks to the stability and integrity of foundations, particularly in regions characterized by permafrost. As global temperatures continue to rise, the consequent thawing of permafrost has the potential to induce ground subsidence, thereby compromising the structural integrity of buildings. This report employs climate projections provided by the Norwegian Meteorological Institute (MET) to thoroughly analyze both historical data and anticipated future scenarios, thus offering a detailed and comprehensive understanding of potential climate-driven impacts on foundation stability.

The methodology applied in this study includes assessments of both thaw settlement and creep settlement. Thaw settlement is triggered by the melting of ice-rich soils, leading to a decrease in soil volume and subsequent ground subsidence. Conversely, creep settlement involves the gradual deformation of soil subjected to continuous stress over extended periods, an issue particularly significant for pile foundations embedded in frozen soil conditions.

By investigating settlement behaviors across various foundation types and soil conditions, this study seeks to generate valuable insights into the long-term stability prospects of cultural heritage structures. The outcomes of this research will aid in the formulation of effective strategies designed to mitigate the detrimental impacts of climate change on these historically significant and valuable structures.

2 Climate projections and ground thermal regime

The climate projections presented in this report are produced within PCCH-Arctic project by 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.

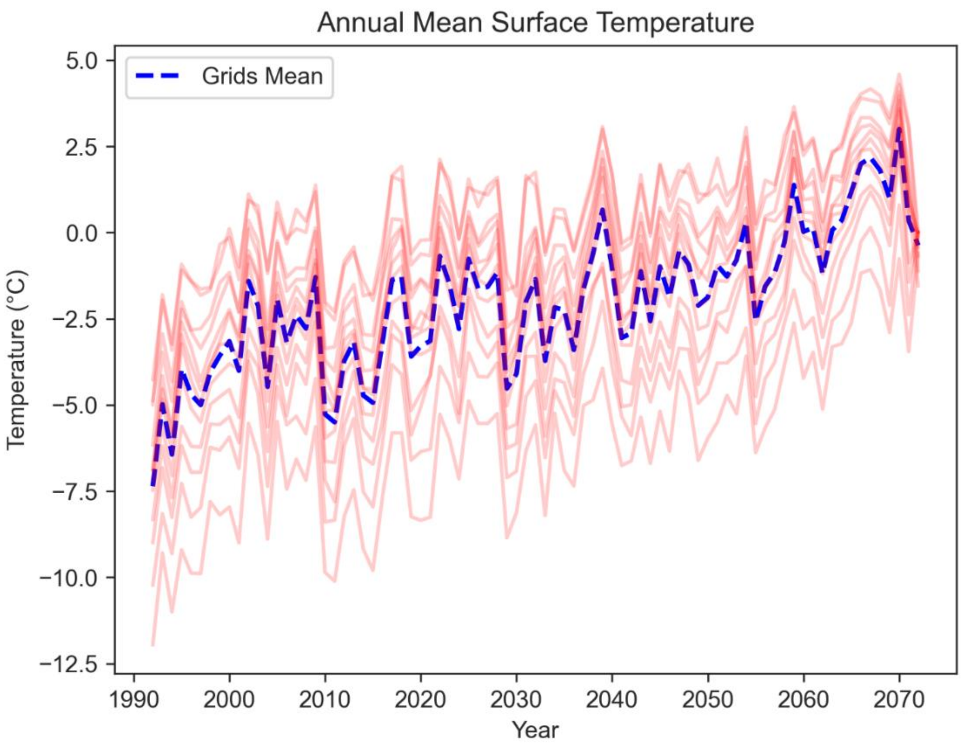

Figure 1: Historical and projected annual mean surface temperature in Longyearbyen.

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.

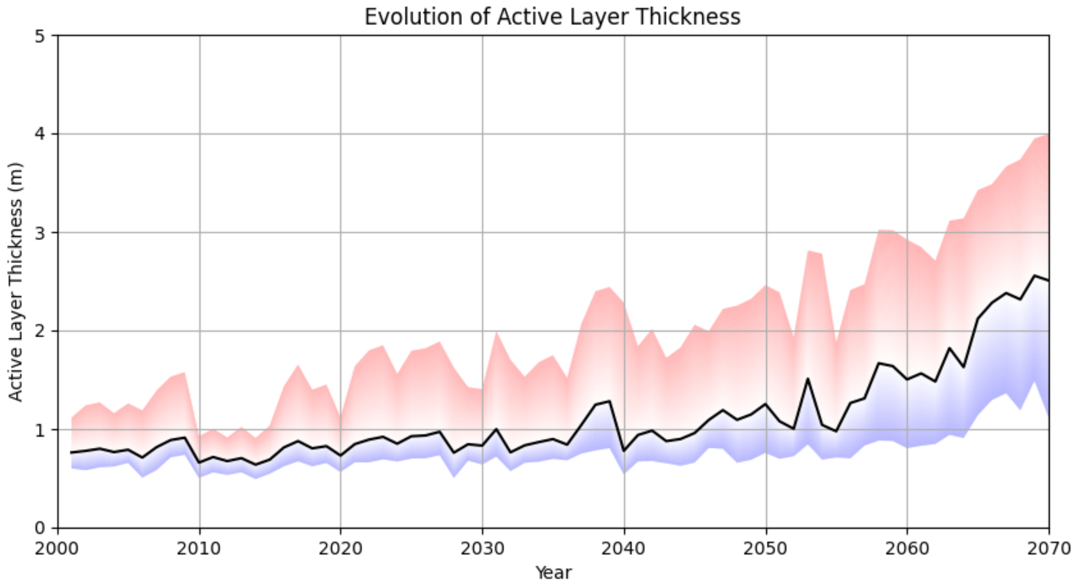

Figure 2: Evolution of active layer thickness in Longyearbyen.

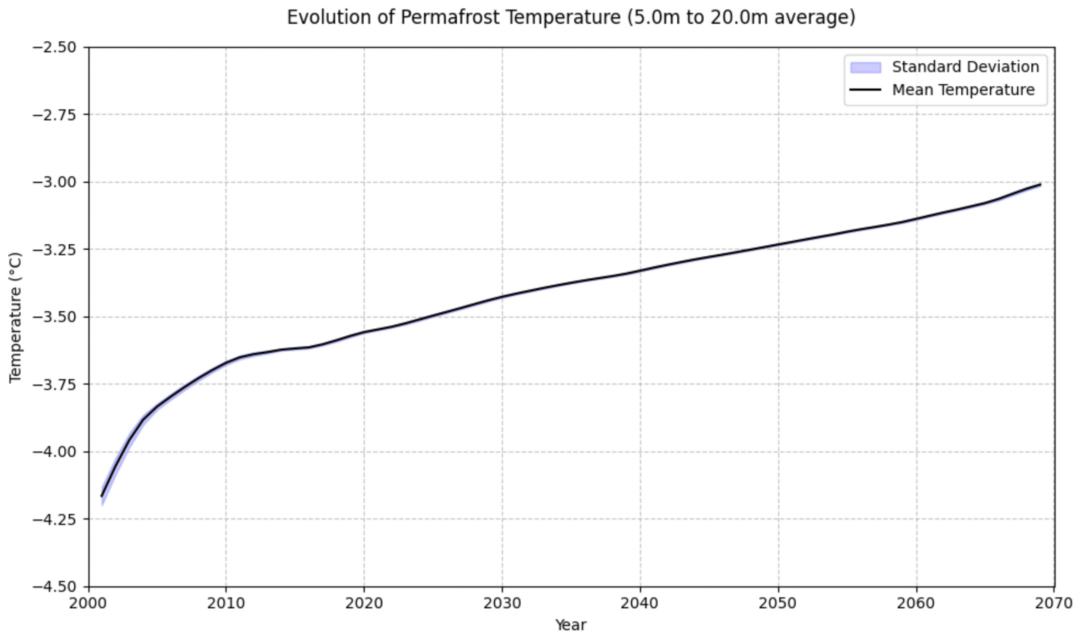

Figure 3: Evolution of average permafrost temperature in Longyearbyen.

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.

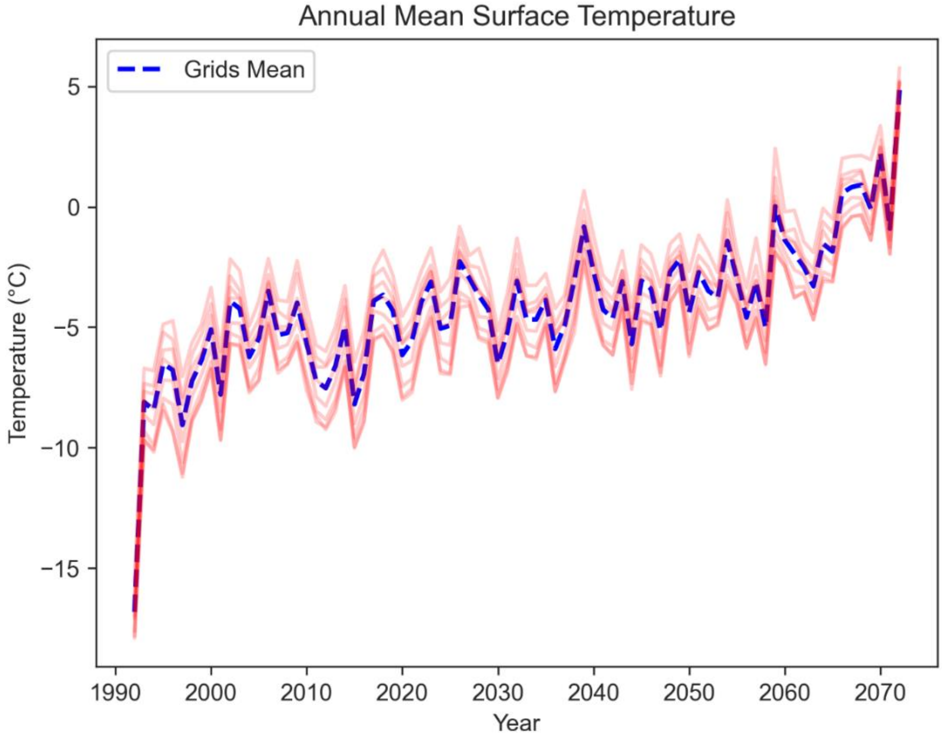

Figure 4: Historical and projected annual mean surface temperature in Ny-Ålesund.

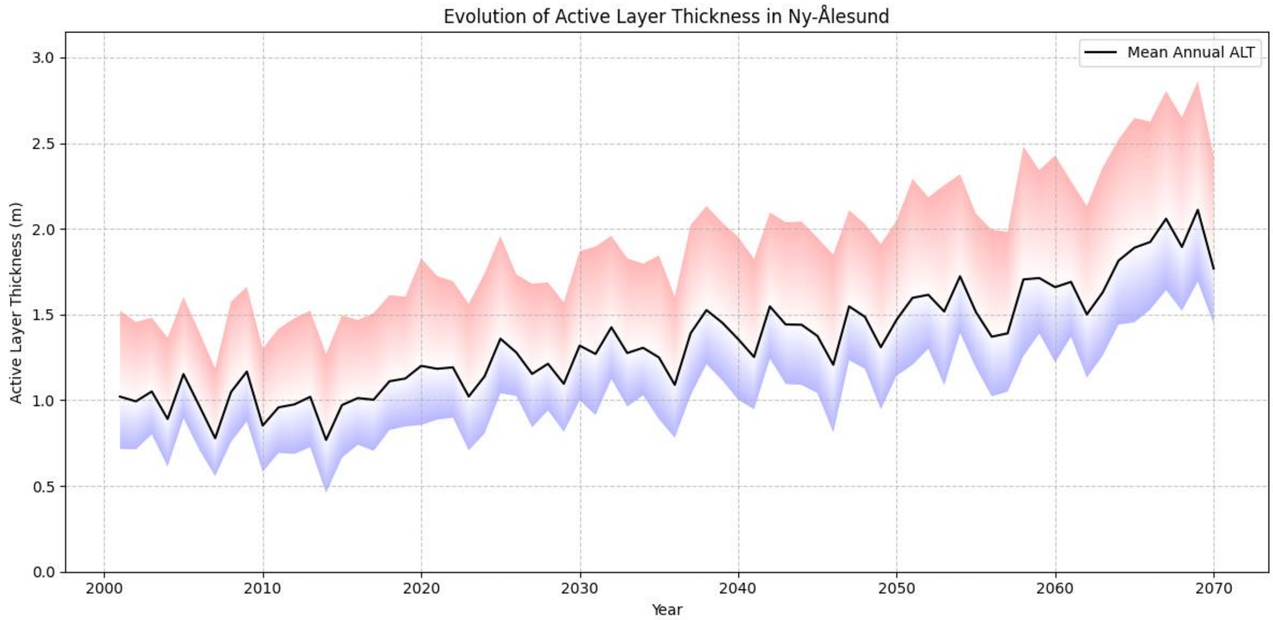

Figure 5: Evolution of active layer thickness in Ny-Ålesund.

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.

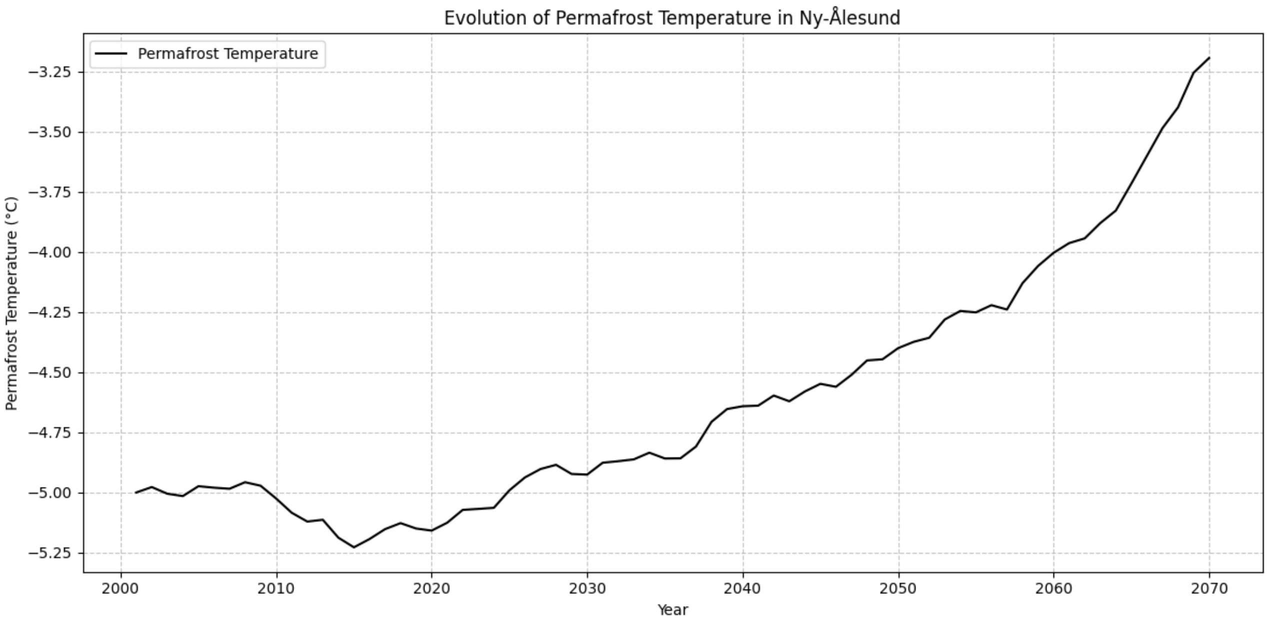

Figure 6: Evolution of average permafrost temperature in Ny-Ålesund.

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 section provides details of selected structures in Longyearbyen and Ny-Ålesund from the cultural heritage objects investigated in the PCCH-Arctic project. These include Cableway Posts Nr. 6 and 34 on Line 5-6, Cableway Post Nr. 32 on Line 3, Taubanesentralen, and Titankrana from Longyearbyen and Green Harbour House and Luftskipsmasta from Ny-Ålesund. These structures represent diverse foundation types and varying dimensions, which will enable detailed evaluation of their stability and performance under.

3.1 Structures in Longyearbyen

Cableway Posts Nr. 6 and Nr. 34 (Line 5-6), and Cableway Post Nr. 32 (Line 3)

Cableway Posts Nr. 6, Nr. 34 (Line 5-6), and Nr. 32 (Line 3) are supported by shallow foundation systems, assumed to be embedded 2 meters into permafrost, where additional pile foundations are considered for stabilization purposes. The shallow foundations are evaluated both as original construction solutions and for their potential restoration using pile foundations, providing important insights into the effectiveness of remedial measures in permafrost terrain. Dimensions and estimated loads follow criteria established by (Pasquini, 2023). Pictures of Cableway Posts Nr. 6 (Line 5-6), Nr. 34 (Line 5-6), and Nr. 32 (Line 3) are shown in Figure 7, Figure 8, and Figure 9, respectively.

Figure 7: Cableway Post Nr. 6, Line 5-6, Longyearbyen. Picture: © Anatoly Sinitsyn/SINTEF AS.

Figure 8: Cableway Post Nr. 34, Line 5-6, Longyearbyen. Picture: © Anatoly Sinitsyn/SINTEF AS.

Figure 9: Cableway Post Nr. 32, Line 3, Longyearbyen. Picture: © Anatoly Sinitsyn/SINTEF AS.

Taubanesentralen

The Taubanesentralen is assumed to be supported by a combination of shallow and deeper foundation systems. The evaluation for Taubanesentralen focuses particularly on terrain settlements, active layer thickness development, and permafrost temperature variations beneath and around the structure, as these parameters critically influence the stability and longevity of the presumably mixed foundation systems. A picture of Taubanesentralen is shown in Figure 10.

Figure 10: Taubanesentralen, Longyearbyen. Picture: © Anatoly Sinitsyn/SINTEF AS.

Titankrana

Titankrana, a historical crane structure, is primarily supported by a surface foundation system but is also presumed to have deeper foundations. Similar to Taubanesentralen, the structural assessment emphasizes terrain settlement, active layer thickness development, and permafrost temperature changes as key indicators of its foundation performance and stability. A picture of Titankrana is shown in Figure 11.

Figure 11: Titankrana, Longyearbyen. Picture: © Anatoly Sinitsyn/SINTEF AS.

Table 1 summarizes foundation details for the selected structures in Longyearbyen.

Table 1: Structures in Longyearbyen selected for analysis.

Object	Foundation type	Dimension	Load on foundation**	Soil properties
Cableway Post Nr. 6, Line 5-6	Shallow foundation*, embedded 2 m in permafrost. Future restoration using pile foundations: 4 piles, 10 m in permafrost, 0.25 m diameter	Big* Foundation base area = 2.16 m^2 (B x L = 0.225 m x 9.6 m)	80 kPa (172.9 kN)	Ice-rich permafrost (assumption)
Cableway Post Nr. 32, Line 3	Shallow foundation*, embedded 2 m in permafrost.	Medium* Foundation base area = 1.36 m^2 (B x L = 0.18 m x 7.6 m)	66.7 kPa (91.2 kN)	Ice-rich permafrost (assumption)

	Future restoration using pile foundations: 4 piles, 10 m in permafrost, 0.25 m diameter			
Cableway Post Nr. 34, Line 5-6	Shallow foundation, embedded 2 m in permafrost. Future restoration using pile foundations: 4 piles, 10 m in permafrost, 0.25 m diameter	Medium* Foundation base area = 1.36 m^2 (B x L = 0.18 m x 7.6 m)	66.7 kPa (91.2 kN)	Ice-rich permafrost (assumption)
Taubanesentralen¤	Presumably mix of shallow and deeper foundations.	-	-	Ice-rich permafrost (assumption)
Titankrana¤	Presumably mix of shallow and deeper foundations.	-	-	Ice-rich permafrost (assumption)

*Cableway posts are classified as Big, Medium or Small according to (Pasquini, 2023).
**The foundation loads are also according to estimates by (Pasquini, 2023).
¤For theses structures, the focus will be on evaluating active layer thicknesses and permafrost temperatures.

3.2 Structures in Ny-Ålesund

Green Harbour House

The Green Harbour House is a one-storey wooden building with an approximate footprint of 11 m by 4 m, supported by surface foundation system. Each surface foundation element comprises 5 logs by 6 logs, each log approximately 15 cm in diameter. A picture of the Green Harbour House is shown in Figure 12. The foundation remains of *Ny-London* are shown in Figure 13 and a similar foundation type is believed to be used for the Green Harbour House.

Figure 12: Green Harbour House, Ny-Ålesund. Picture: © Anatoly Sinitsyn/SINTEF AS.

Figure 13: Foundation remains in Ny-London (2021), similar foundation type is believed to be used at Green Harbour House. Picture: © Anatoly Sinitsyn/SINTEF AS.

Luftskipsmasta

Luftskipsmasta is supported by shallow foundations. The structure has a total weight of approximately 14 tonnes. The primary focus of the evaluation is to assess the terrain settlement, active layer thickness development, and changes in permafrost temperatures associated with the shallow foundation type, providing critical insights into the long-term performance of foundations under the impacts of climate change. A picture of Luftskipsmasta is shown in Figure 14.

Figure 14: Luftskipsmasta, Ny-Ålesund. Picture: © Anatoly Sinitsyn/SINTEF AS.

Table 2 summarizes the foundation characteristics of the selected PCCH-Arctic structures in Ny-Ålesund.

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

Object	Foundation type	Dimension	Load on foundation	Soil properties
Green harbour house	Surface foundation	11 m x 4 , 5 logs x 6 logs, each log ca. 15 cm; Total area ca. 12.2 m^2 (Effective B x L = 5.80 m × 2.11 m)	250 kN*	Ice-rich silt
Luftskipsmasta	Shallow foundation		Total weigh is ca. 14 tonn.	Ice-rich silt

*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, m

$\frac{\Delta V}{V}$ = 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 behaviors 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 behaviors 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 (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.

$$u = u_t + u_c$$

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.

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. These values for different soils are referred from (Andersland & Ladanyi, 2003).

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

Thaw settlements

We start the settlement evaluation for structures in Longyearbyen by evaluating the thaw settlements. Figure 15 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.

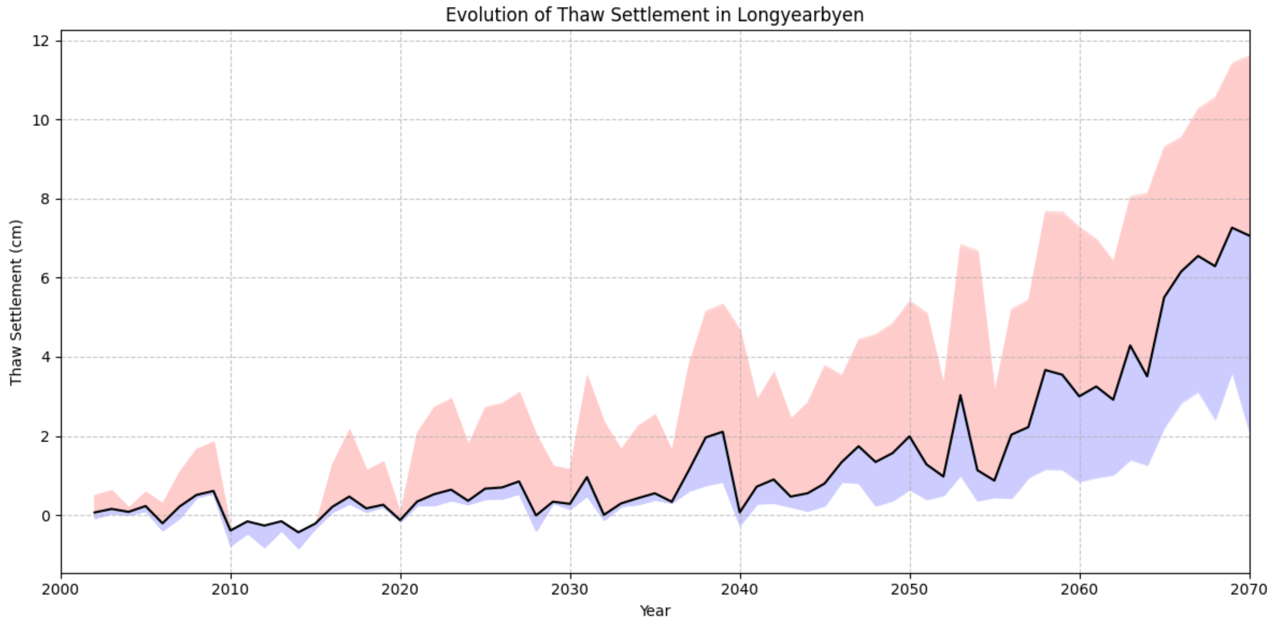

Figure 15: Predicted thaw settlements in Longyearbyen.

<u>**Cableway Post Nr. 6, Line 5-6**</u>

To capture the long-term performance of Cableway Post Nr. 6 (Line 5–6), creep settlements were computed in addition to thaw settlements. Figure 16 shows that creep deformation remains relatively modest during the initial years, but it gradually becomes more significant as permafrost temperatures rise. When these creep settlements are superimposed on thaw settlements (Figure 17), the total settlement by 2070 becomes significant and could pose a risk to foundation stability.

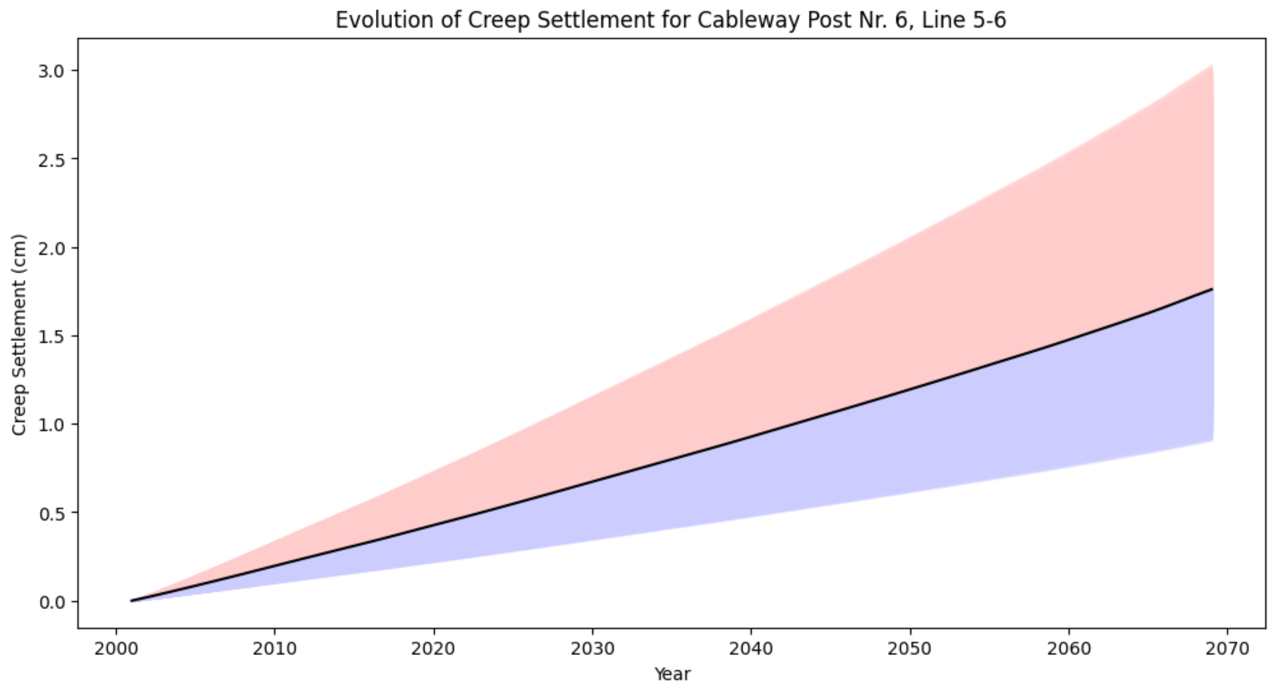

Figure 16: Evolution of creep settlement for Cableway Post Nr. 6, Line 5-6.

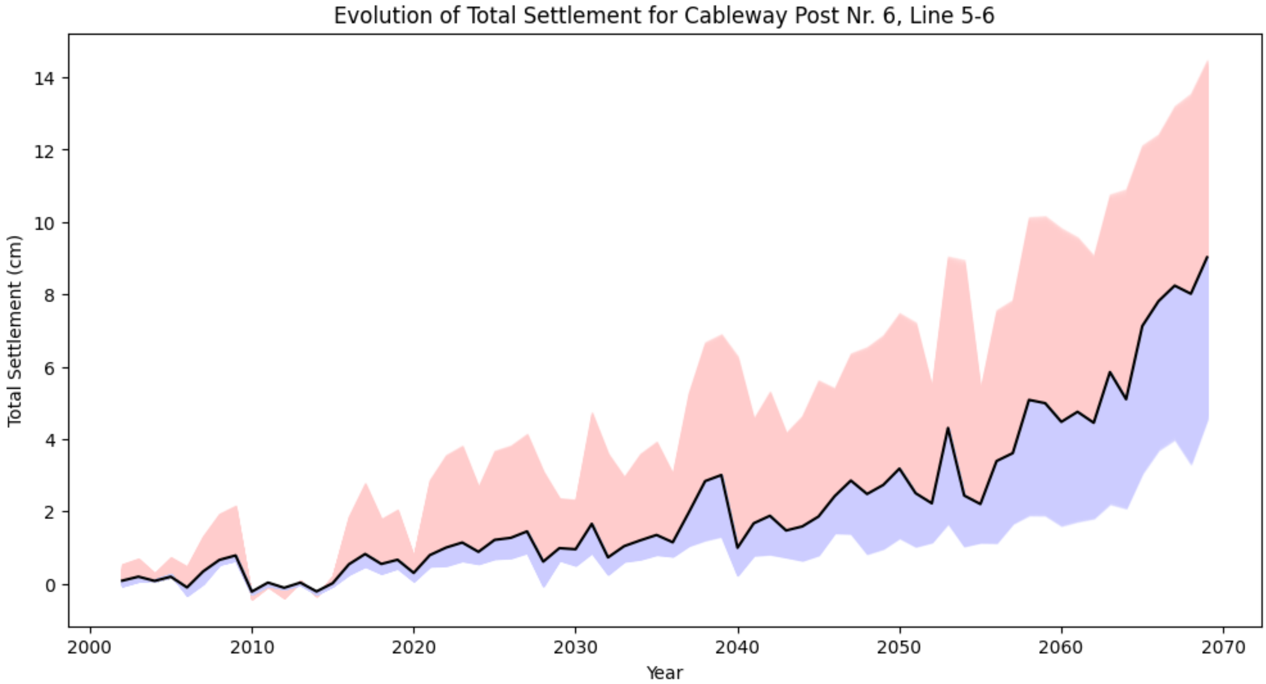

Figure 17: Evolution of total settlement for Cableway Post Nr. 6, Line 5-6.

Settlements after restoration using pile foundations

An assumed restoration in 2026 introduces four new piles embedded 10 m into permafrost. The effective pile length gradually diminishes over time as the active layer thickness increases (Figure 18). Figure 19 highlights that creep settlement remains relatively small for these new piles, reflecting the improved load transfer to deeper, colder layers. Consequently, total predicted settlement through 2070 remains noticeably lower than that of the shallow foundation, making pile retrofitting an attractive mitigation strategy if field investigations confirm suitable conditions for pile foundations.

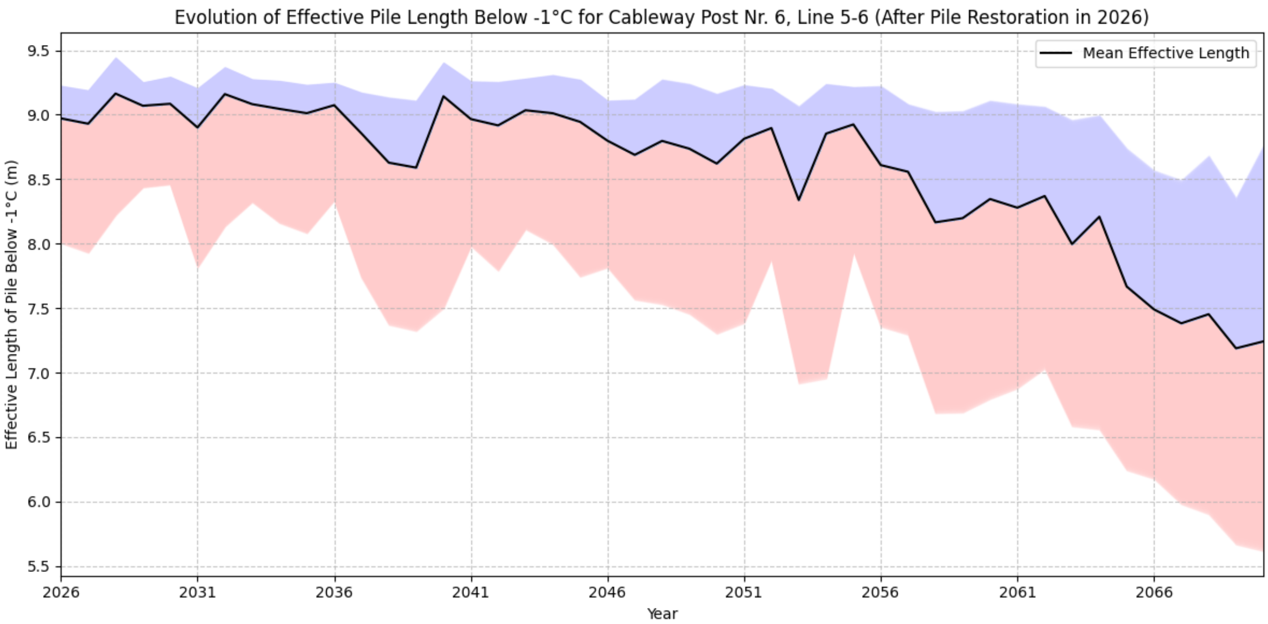

Figure 18: Evolution of effective pile length for Cableway Post Nr. 6, Line 5-6 after assumed pile restoration in 2026.

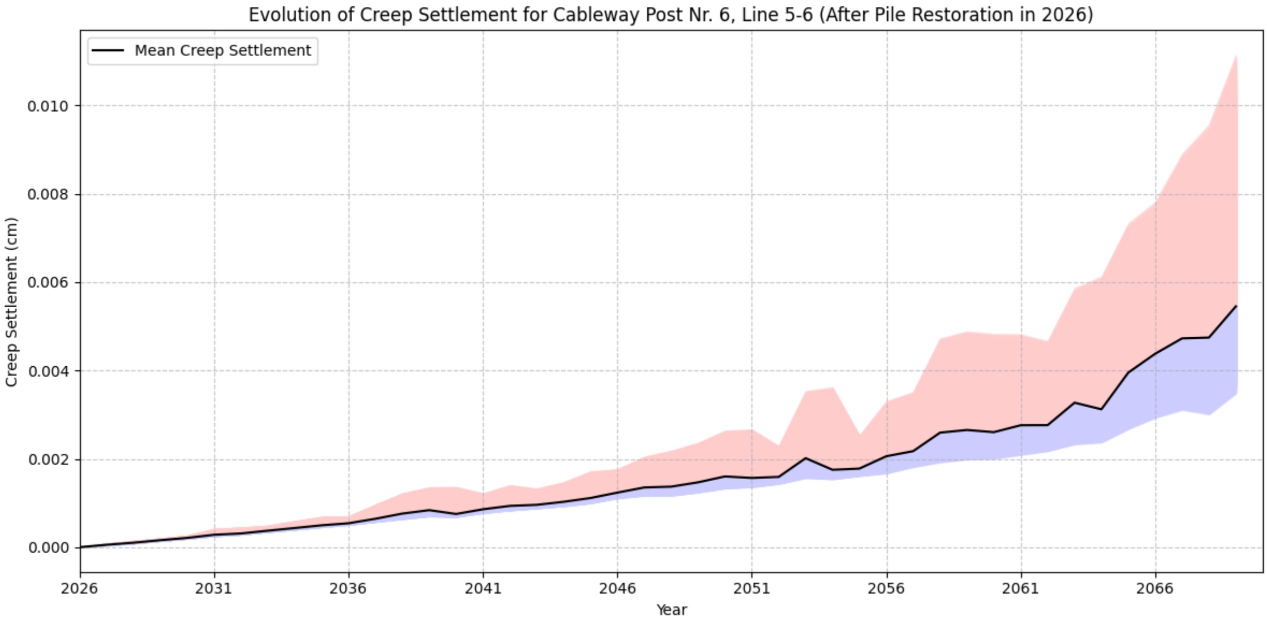

Figure 19: Evolution of creep settlements for Cableway Post Nr. 6, Line 5-6 after assumed pile restoration in 2026.

Cableway Post Nr. 32, Line 3 and Cableway Post Nr. 34, Line 5-6

Similar analyses were conducted for Cableway Posts Nr. 32 (Line 3) and Nr. 34 (Line 5–6). Figure 20 illustrates how creep settlement accumulates over the time horizon for both posts; although initial deformation is modest, the rate gradually increases as ground temperatures rise. The summation of creep and thaw deformation is shown in Figure 21, suggesting that total settlement by 2070 could surpass practical serviceability limits for sensitive heritage structures.

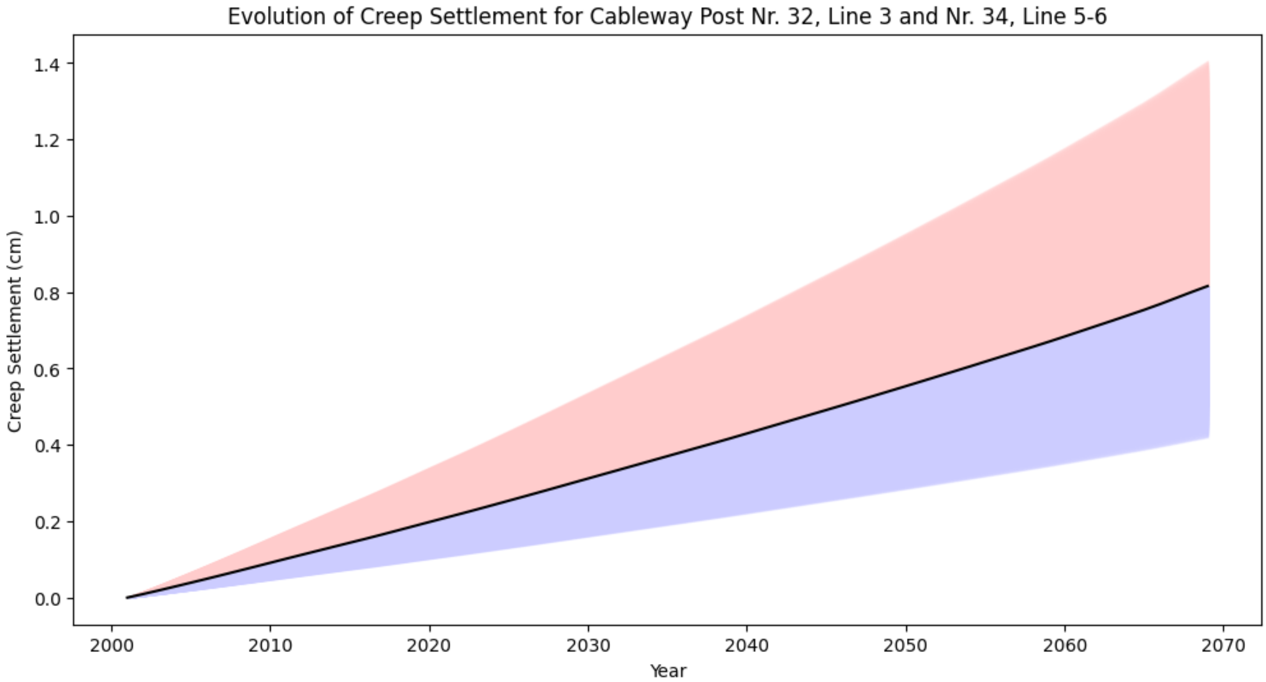

Figure 20: Evolution of creep settlement for Cableway Post Nr. 32, Line 3 and Nr. 34, Line 5-6.

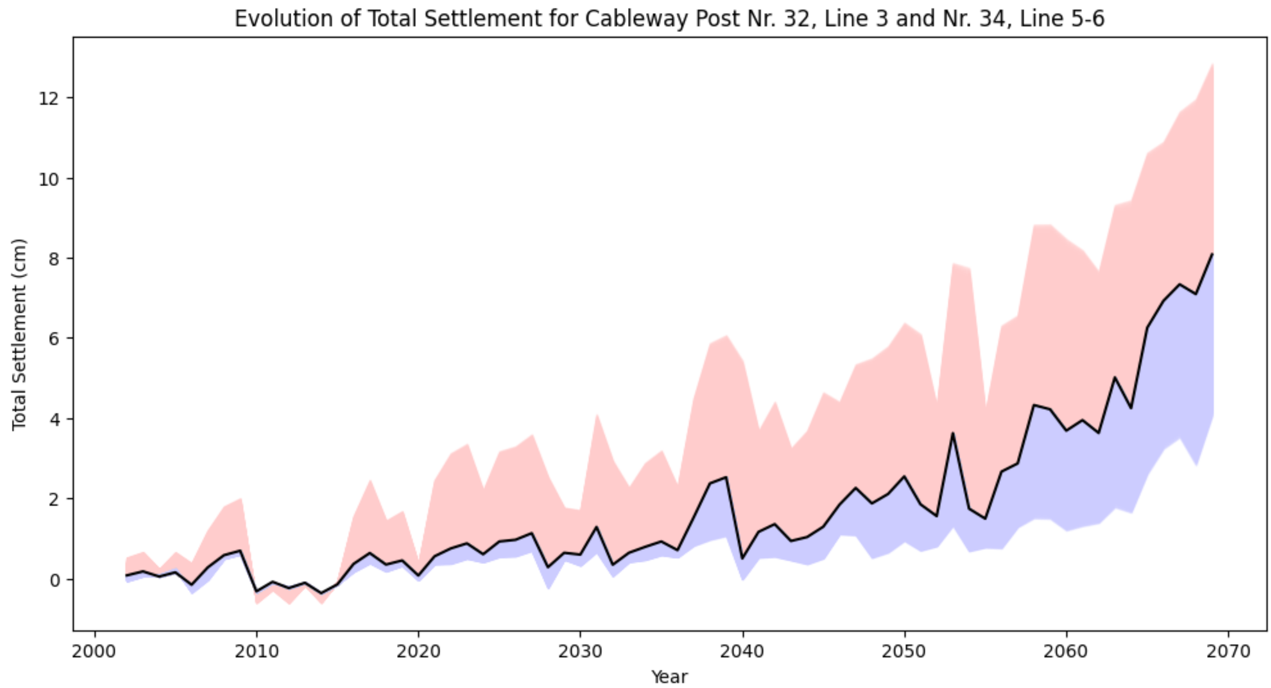

Figure 21: Evolution of total settlement for Cableway Post Nr. 32, Line 3 and Nr. 34, Line 5-6.

Settlements after restoration using pile foundations

If these cableway posts are restored using pile foundations in 2026—mirroring the approach for Cableway Post Nr. 6 (Line 5-6)—predicted settlements remain considerably lower (Figure 22). In these scenarios, deeper permafrost layers sustain the foundation loads more reliably, resulting in moderate creep rates and improved long-term stability.

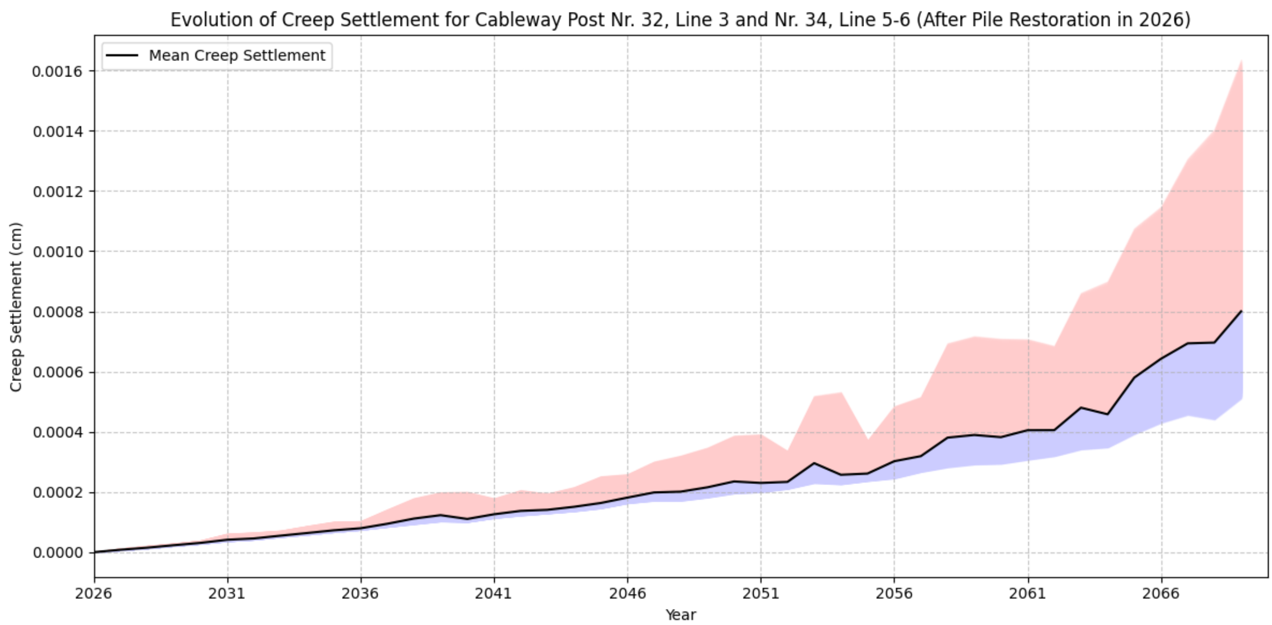

Figure 22: Evolution of creep settlements for Cableway Post Nr. 32, Line 3 and Nr. 34, Line 5-6 after assumed pile restoration in 2026.

Taubanesentralen and Titankrana

Taubanesentralen and Titankrana are both presumed to involve a combination of shallow and deeper support elements. While detailed numerical settlement results are not presented here, the same warming trends as indicated by the thaw settlements presented in Figure 15 will influence both structures. Progressive thaw of ice-rich soils will augment potential differential settlement, and any deeper foundation elements may experience higher creep rates if subjected to sustained loads considering the gradual warming of permafrost as predicted in Figure 3 in Chapter 2. For both Taubanesentralen and Titankrana, routine ground-temperature measurements and active-layer monitoring are recommended to detect evolving permafrost conditions.

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 23. 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 foundations in Ny-Ålesund.

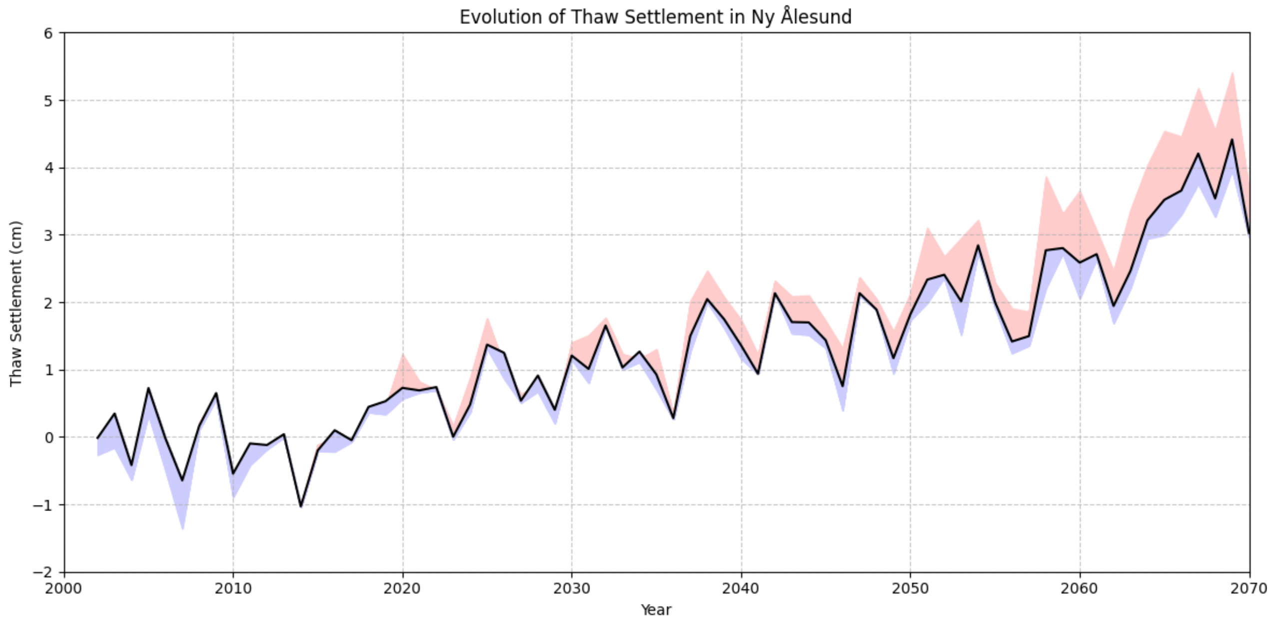

Figure 23: Predicted thaw settlements in Ny-Ålesund.

Green Harbour House

Green Harbour House rests on a series of surface foundations (logs supporting a simple frame). As shown in Figure 24, creep-related deformation remains relatively limited up to around 2040, after which incremental increases become more apparent in tandem with warming temperatures. By 2070, total settlement (Figure 25) begins to approach levels that, especially if uneven, might compromise the structure's alignment or functionality. Although these absolute values remain moderate, heritage structures in permafrost often have little tolerance for differential movement. Therefore, even a few centimeters of settlement can become problematic over time.

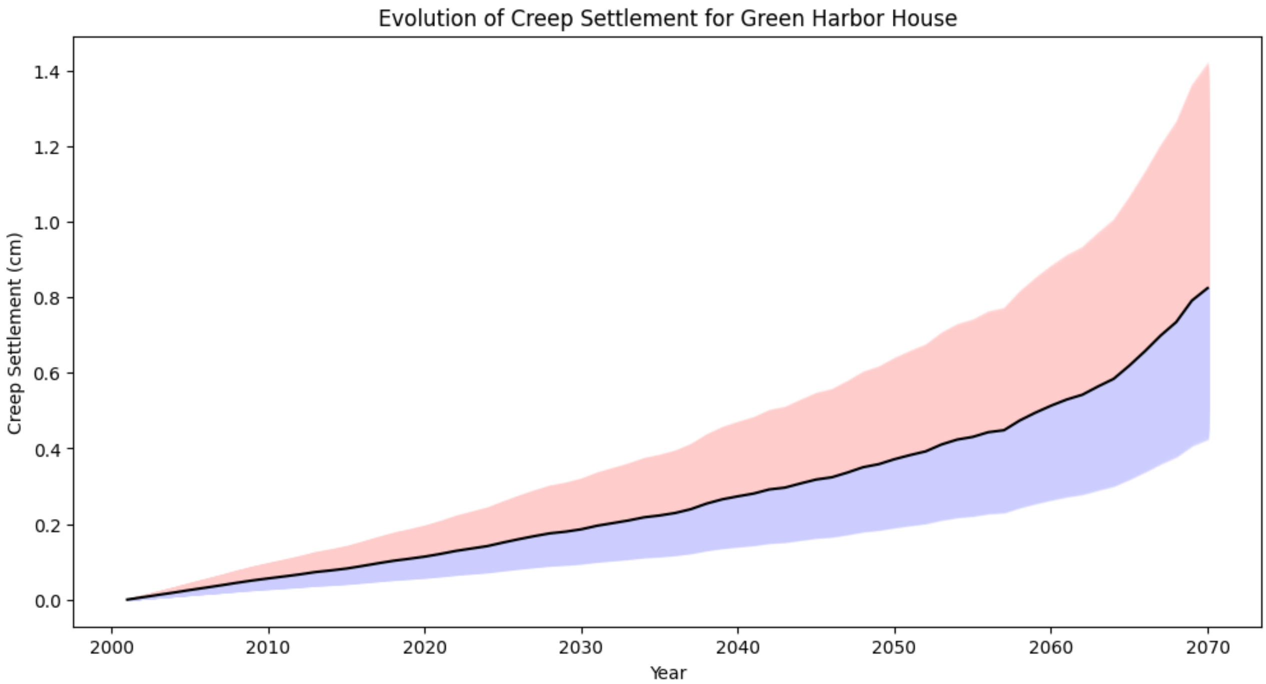

Figure 24: Evolution of creep settlement for Green Harbour House.

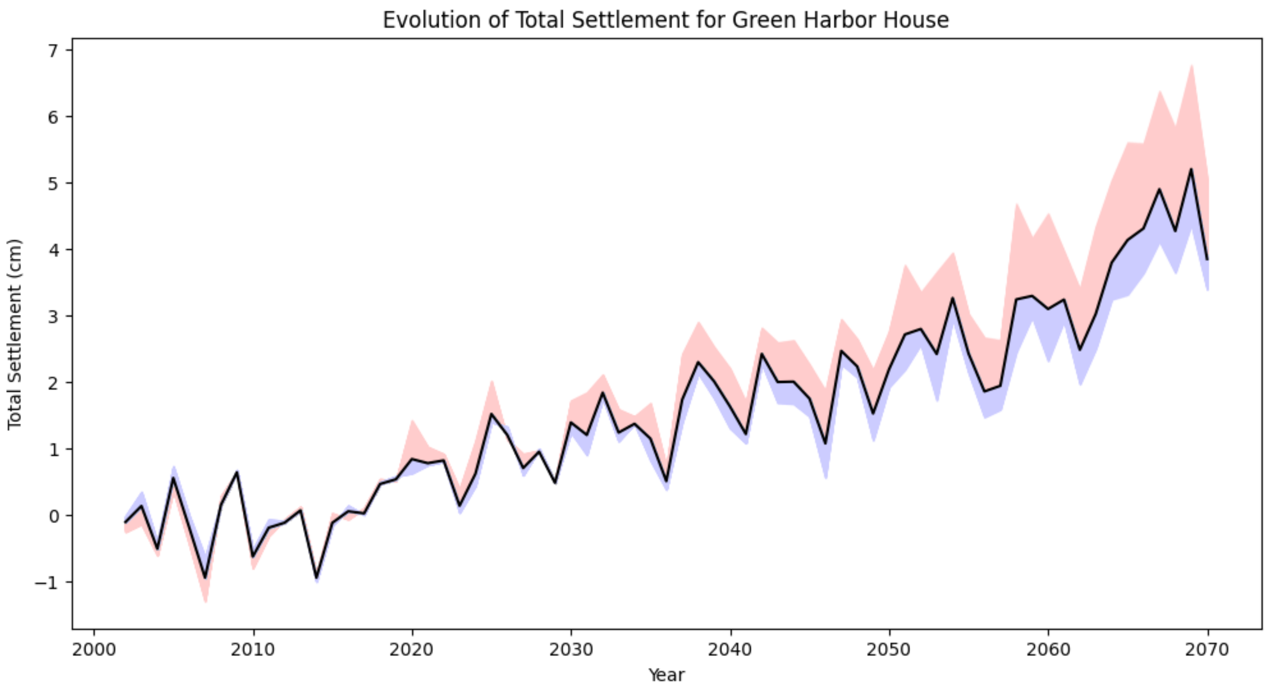

Figure 25: Evolution of total settlement for Green Harbour House.

Luftskipsmasta

Luftskipsmasta is supported by shallow foundations and bears an estimated total weight of approximately 14 tonnes. Although specific creep settlement calculations are not shown here, the thaw settlement projections in Figure 23 apply similarly to this structure, and the added creep component could further elevate total long-term deformation. Given the historical and symbolic significance of Luftskipsmasta, installing temperature/settlement monitoring instrumentation—such as ground-embedded thermistors and surveying markers—could provide early warnings of foundation distress.

6 Summary and conclusions

This report investigated the potential impacts of climate change on foundation stability for selected cultural heritage structures situated in the permafrost regions of Longyearbyen and Ny-Ålesund, Svalbard. The study focused on evaluating foundation settlements resulting from projected climate warming trends through 2070. Permafrost degradation, driven by rising temperatures, poses significant risks to structural integrity due to thaw and creep settlements.

The evaluation methodology utilized climate projections to estimate the future evolution of active layer thickness and permafrost temperatures in Longyearbyen and Ny-Ålesund. Two primary settlement mechanisms influencing foundation stability in these warming permafrost conditions were analyzed: thaw settlement and creep settlement. Thaw settlement, resulting from the volume reduction as ice-rich soil melts due to increasing active layer depth, was calculated based on soil porosity and the depth of newly thawed soil. Creep settlement, representing the gradual, time- and temperature-dependent deformation of frozen ground under sustained foundation loads, was assessed using established methods for different foundation types, including shallow foundations and pile foundations (friction and end-bearing) in various soil conditions. For shallow foundations, the total settlement was considered the sum of thaw and creep settlements. For pile foundations, however, increasing active layer thickness primarily affects the calculation of creep settlement by reducing the effective load-bearing length of the pile within the permafrost; thaw settlement itself does not add directly to the total pile settlement, which is dominated by creep.

Climate projections for both Longyearbyen and Ny-Ålesund indicate consistent warming trends through 2070, leading to a progressive increase in the thickness of the active layer (the ground layer that thaws seasonally) and a gradual warming of deeper permafrost temperatures. These environmental changes drive increased foundation settlement risks. Predicted thaw settlements show a significant increase, particularly after mid-century, reflecting the deepening active layer. Structures on shallow foundations (like the Cableway Posts and Luftskipsmasta) and surface foundations (like Green Harbour House) are vulnerable; the combination of thaw and accelerating creep settlement as the ground warms could lead to total settlements posing risks to stability and serviceability, especially given the low tolerance of heritage structures for differential movement. Hypothetical restoration of Cableway Posts using deep pile foundations showed significantly reduced long-term settlement, indicating that transferring loads to colder, deeper permafrost via piles is a potentially effective mitigation strategy, though the effective load-bearing length diminishes over time. For complex structures like Taubanesentralen and Titankrana, presumed to have mixed foundations, the general warming trends and increasing active layer thickness will augment settlement potential and necessitate monitoring.

Climate change, through permafrost warming and degradation, presents a clear and increasing threat to the foundation stability of cultural heritage structures in Svalbard. Both thaw settlement and creep settlement contribute significantly to the overall deformation, particularly accelerating in the latter half of the projection period to 2070.

- Shallow and surface foundations are particularly vulnerable to increasing active layer depths and rising ground temperatures, leading to potentially problematic levels of total settlement.
- Restoration or retrofitting with deeper pile foundations appears to be a viable mitigation strategy, effectively transferring loads to colder, more stable permafrost layers and significantly reducing long-term settlement, although effectiveness depends on site conditions.
- For structures with complex or unknown foundations (like Taubanesentralen and Titankrana) and significant structures like Luftskipsmasta, ongoing monitoring of ground temperature, active layer thickness, and settlement is crucial for early detection of potential distress.

- The analyses highlight the importance of considering both thaw and creep phenomena in settlement predictions for infrastructure on permafrost under climate change scenarios.

Further site-specific geotechnical investigations are recommended to refine material parameters and validate foundation assumptions before implementing mitigation measures. Continued monitoring and adaptation strategies will be essential for preserving these cultural heritage assets in a warming Arctic.

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