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Report

Case study of pile foundations for a building on a sloping terrain in Longyearbyen

Project Report 2018

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ABSTRACT

The effects of increased lateral loads, as a result of thawing and warming permafrost, on the pile foundations of a selected building in Longyearbyen located on a slope are investigated through numerical analyses. A range of active layer thicknesses are considered in the analyses taking current and projected climate scenarios into account. The axial loads on the piles are estimated based on standard methods for residential buildings, and variations are considered to account for uncertainties. The lateral loads on the piles are assumed to mainly originate from slope movements and loads transferred from crest of the slope through earth pressure. It is shown that the pile head deflections are expected to increase as the active layer thicknesses increase. A similar trend of increase is observed in the internal forces generated in the piles.

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1 Introduction

1.1 Background and objectives

This report presents a continuation of the study on the effect of climate change on infrastructure in Longyearbyen, in particular on pile foundations on sloping terrains. A general evaluation was performed and reported in the previous phase of the project, [1]. Based on historical temperature trends and future climate projections for Longyearbyen, the changes in ground temperature were analysed. It was shown that, based on RCP8.5 projections, the active layer thicknesses are expected to increase, and the underlying permafrost is expected to get warmer. The effect of these anticipated changes in the ground thermal regime on infrastructure stability were investigated through slope stability analyses and pile capacity modelling. Analytical and numerical calculations were performed in a generic and representative way for the climate and ground conditions in Longyearbyen. The results have shown that the stability of slopes is expected to be affected by the changes in the ground thermal regime and pile foundations are expected to be subjected to increased lateral loads.

The objective of the current study is to perform a specific case study for a representative building on a sloping ground and assess the load carrying capacity of the pile foundations under changing ground conditions. The results from the previous study provide inputs required for the specific evaluations. In addition, field and laboratory investigations have been performed in the area; see [2] and [3]. The necessary soil parameters are interpreted based on these investigations and experience for similar ground conditions.

1.2 Building selected for the case study

The building selected for a specific case study is Building 33 on veg 236; see Figure 1. A satellite image of the building and the surrounding area is shown in Figure 2. The selected building is one of a series of attached houses along veg 236. The area features a parking space and a road to the South-West of the building and a sloping ground to the North-East.

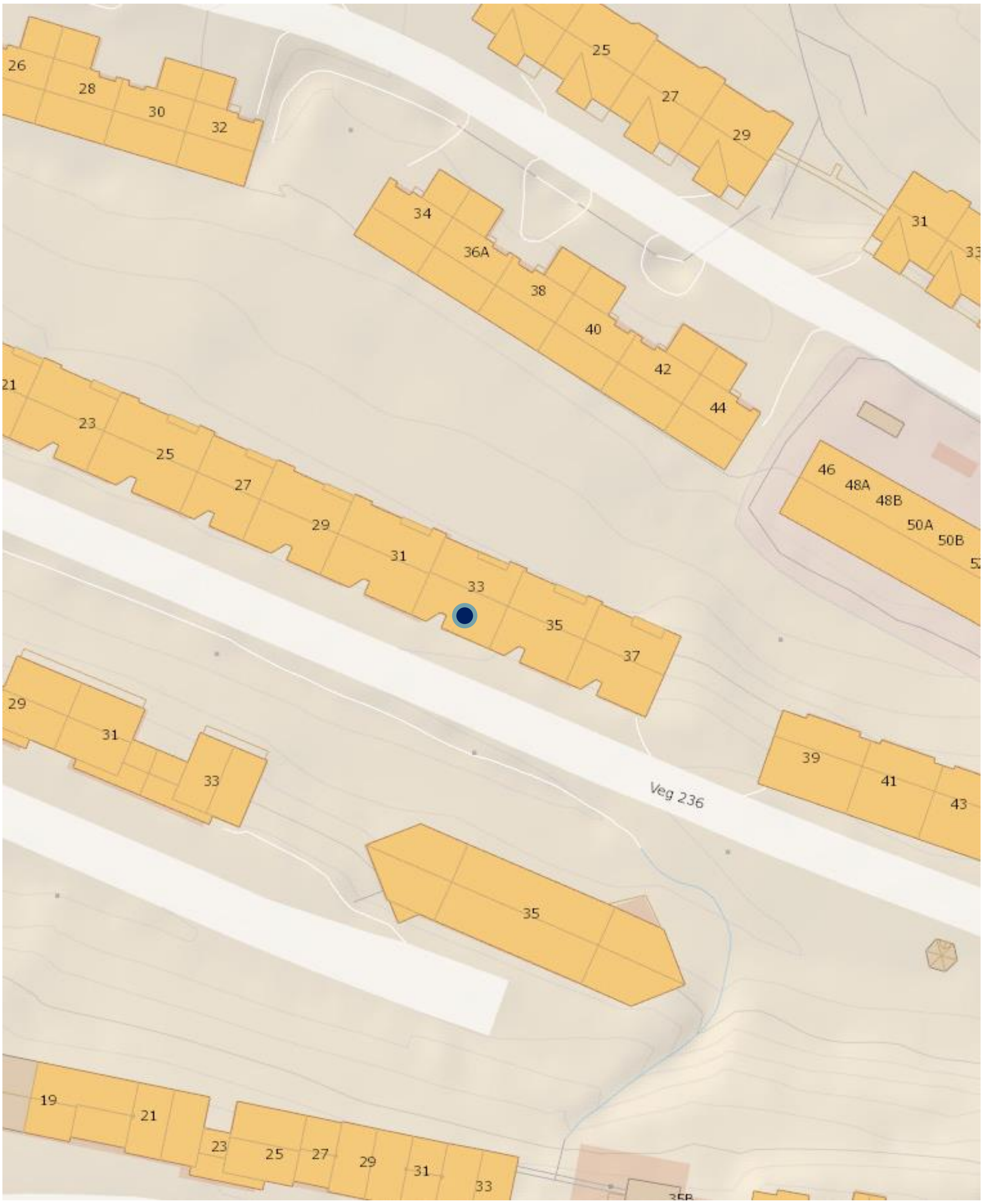

Figure 1: Location of the building selected for the case study; Map: [4].


Figure 2: Satellite view of the building for the case study and the surrounding area; Picture: [4].

2 Site Data

The details of the selected building and the arrangement of the pile foundations is presented in the following section. The ground soil properties required for analyses are presented based on interpretation of the field and laboratory investigations ([5]). The thermal regime of the ground based on ground temperature measurements in the area and thermal analyses from the previous study in the project ([1]) are also summarized here.

2.1 Arrangement of Piles

A plan view illustrating the number of piles supporting house 33 and their spacing is shown in Figure 3. The house is supported on 12 timber piles with a spacing of 3.8 m in the direction parallel to the road. The corresponding spacing in the perpendicular direction are 4.4 m and 3.8 m.

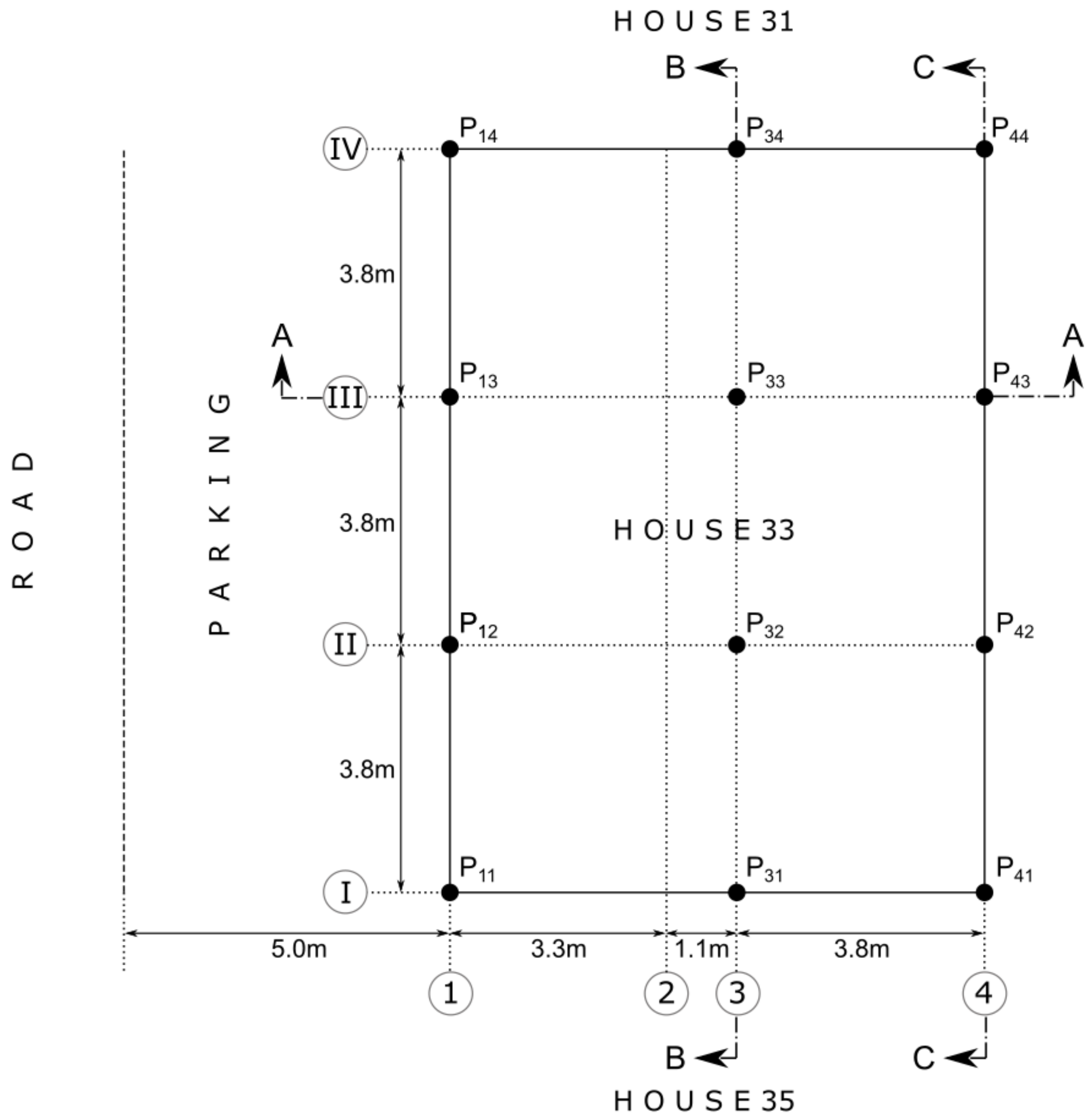

Figure 3: Plan view of house 33 showing the arrangement of the pile foundations.

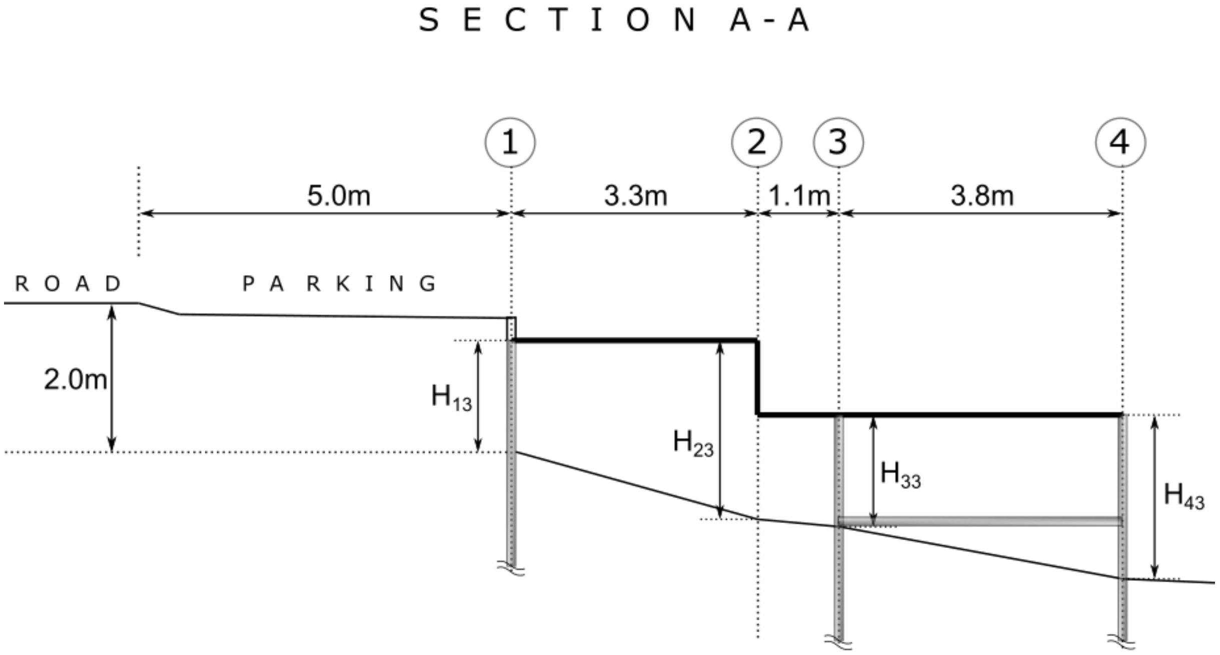

Figure 4: Section A-A.

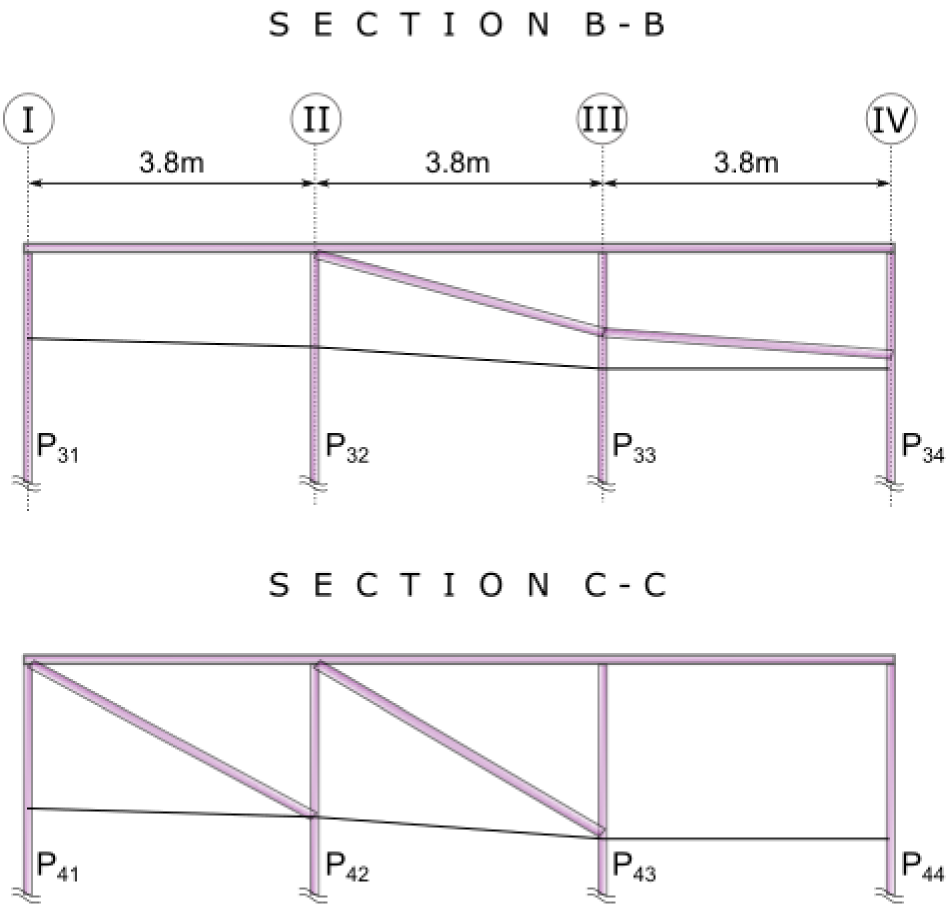

Figure 5: Section B-B and Section C-C.

Cross-section A-A, which shows the pile foundations along the sloping direction of the ground, is shown in Figure 4. Sections B-B and C-C are shown in Figure 5. The pile foundations are elevated from the ground level and there is a number of bracings between some of the piles. The diameter of all piles is ca. 250 mm. The average embedment length of the piles is ca. 6 m, where there may be slight variations from pile to pile because of ground layer conditions. The piles are assumed to be embedded 1.5 m into the underlying rock bed.

2.2 Soil Properties

Two boreholes were drilled close to house 33, where the locations are given in [5]. The depths of the boreholes were 4.6 m and 3.0 m deep. Laboratory testing was performed on soil samples from the boreholes. The average index properties from the laboratory tests are summarized in Table 1.

Table 1: Soil properties from laboratory tests.

Borehole A			
Depth (m)	Water Content (%)	Salinity (%)	Description
0.0 – 0.5	101.5	0.08	Silt or silty clay of low plasticity (OL)
0.5 – 1.0	78.5	-	-
1.0 – 1.5	54.9	-	-
1.5 – 2.0	25.7	0.6	Inorganic silt or clay (ML-CL)
2.0 – 2.5	26.8	-	-
2.5 – 3.0	25.4	-	-
3.0 – 3.5	21.0	0.3	Sand with fines (SM or SC)
3.5 – 4.05	23.0	-	-
4.05 – 4.8	14.0	-	-
Borehole B			
0.0 – 1.0	5.0	-	-
1.0 – 2.0	11.0	-	-
2.0 – 2.65	8.2	0.012	Fine-grained soil

Further index tests on a sample from Borehole A (depth 0.5–1.0 m) resulted in liquid limit, w_L = 38% and plastic limit w_P = 11%, implying a plasticity index of PI = 27%. Based on these index properties, the following soil parameters are assumed for the active layer; Table 2. The properties for permafrost are estimated based on these assumed parameters and the temperature of the permafrost.

Table 2: Soil parameters assumed for analysis.

Parameter	**Lower Bound (LB)**	**Upper Bound (UB)**
Unit weight, γ (kN/m^3)	15.0	19.0
Friction angle, ϕ (deg)	25.0	30.0
Cohesion, c (kPa)	10.0	30.0

Ways of estimating drained strength parameters based on index properties such as plasticity index may be referred from [6].

2.3 Ground Temperature Data

Ground temperature at the site was monitored using a thermistor string. The first plot in Figure 6 shows the temperature reading on November 1st 2017. Ground thermal analyses were performed based on projected air temperature data and the expected temperature profiles for selected years are shown in the second plot in Figure 6. The profiles are shown for the last dates of the thawing season for each year, before the active layer starts freezing again. The active layer thicknesses are expected to increase as a result of climate change. Some of the ground temperature measurements, for example the one shown here, indicate an active layer thickness of about 2 m. The thermal analyses show active layer thicknesses from about 1 m to ca. 2 m based on projections. Such differences are expected to result from uncertainty in soil parameters and variation of soil properties in Longyearbyen. For pile capacity analyses, a range of active layer thicknesses will be considered to account for current conditions and future projections.

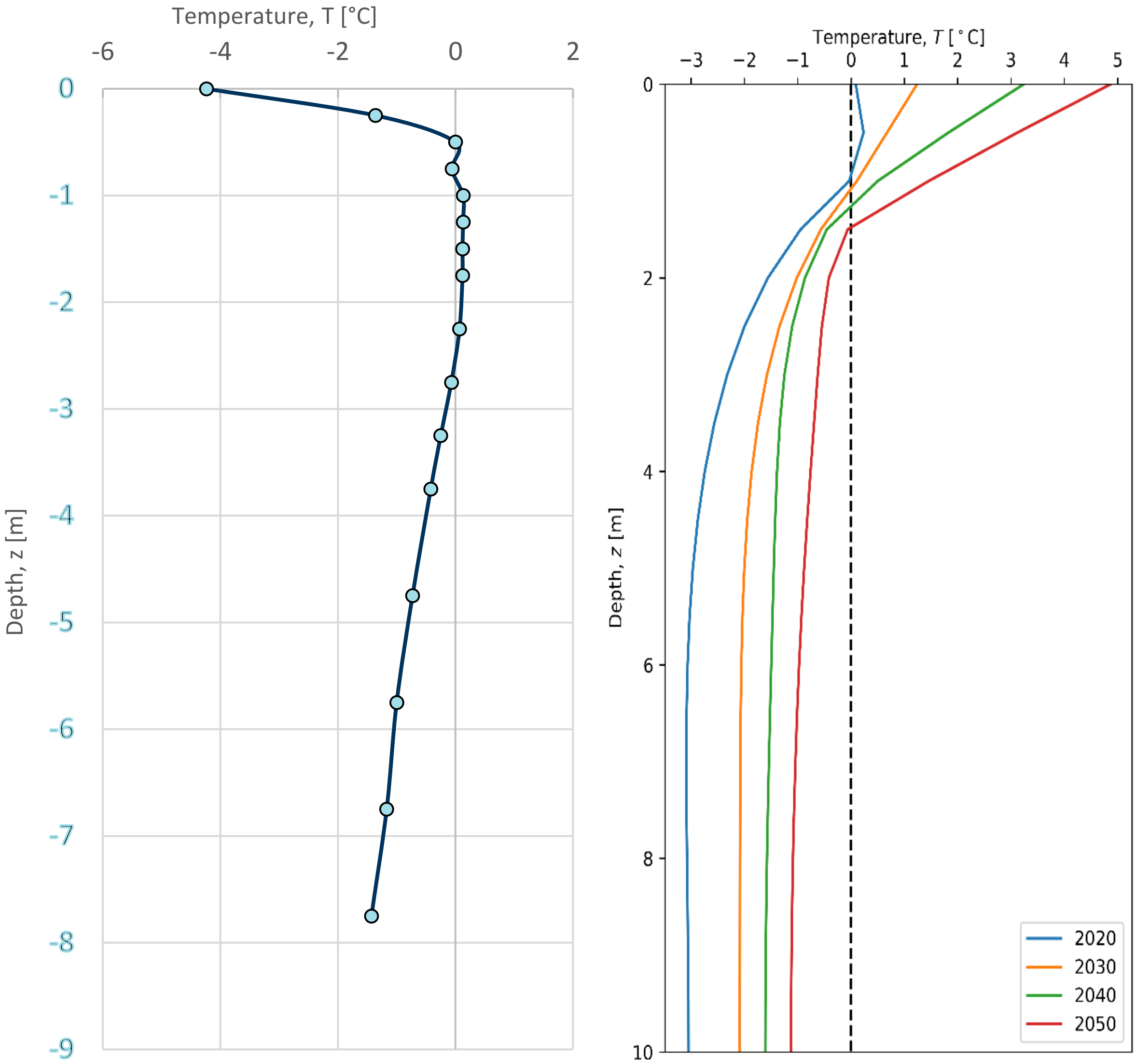

Figure 6: Left - Ground temperature measurements on November 1, 2017 and Right – Ground temperatures estimated based on projected air temperature data; the temperature profiles are shown for dates corresponding to the end of the thawing season for each year.

3 Approach and Hypotheses

The analysis approach and the assumptions necessary for the analysis are presented in the following sections. The assumptions for estimating the loads acting on the piles are discussed.

3.1 Loads on Piles

The axial loads acting on the pile are estimated based on standard calculation procedure considering dead and live loads. The calculations are performed according to the SINTEF Byggforsk Anvisninger (Codes of Practise) [7] and [8], which present estimation of line loads on foundation beams for a two-storey building considering the self-weight of the building and other loads. The axial loads on each pile are estimated by assuming an equal distribution of the load among the piles.

As the building is located on a sloping terrain, the piles will be subjected to lateral loads as a result of earth pressure. These earth pressure may be a result of slope processes in the active layer (for example due to solifluction, which includes creep of permafrost beneath the active layer) and from direct loads at the crest (from parking and road). The lateral loads from these sources are difficult to estimate accurately. The approach followed here is to rely on the numerical simulation performed previously by initiating slope processes with various active layer thicknesses, [1]. The pressure on the pile for these different active layer thicknesses are used as a basis and converted to resultant systems at the pile top. These are presented in the next chapter together with the analyses cases, results and discussions.

3.2 Pile-Soil Response Based on p-y Curves

The capacity of the piles for the selected building is calculated analytically based on p-y curves. For frozen soil, according to [9], the ultimate soil response per unit depth of pile length may be calculated from

$$p_{ult} = N_p c D \tag{3.1}$$

where N_p is the ultimate bearing capacity coefficient, c is the soil shear strength (which is temperature dependent for frozen soil) and D is the pile diameter or width. For a sloping terrain with a slope angle θ, the ultimate capacity is obtained from

$$p_{ult} = N_p c D \left(\frac{1}{1 + \tan\theta}\right) \tag{3.2}$$

The bearing capacity coefficient increases with depth and may be calculated from

$$N_p = 3 + \frac{\sigma_v}{c} + \frac{Jz}{D} \tag{3.3}$$

where σ_v is the vertical overburden pressure at depth z, J is an empirical coefficient with a typical value of 0.5 and z is the depth below ground level. The p-y curve is then approximated by the parabola

$$p = \frac{1}{2} p_{ult} \left(\frac{y}{y_{50}}\right)^{\frac{1}{n}} \tag{3.4}$$

where p is the soil reaction to a lateral pile deflection, y is the lateral pile deflection and y_{50} is the lateral deflection at which $p = p_{ult}/2$ and n is a stress-strain exponent. The value of y_{50} can be approximately calculated from

$$y_{50} = 2.5\varepsilon_{50}D \tag{3.5}$$

where ε_{50} is the strain at one-half of the ultimate soil strength. A typical value of $\varepsilon_{50} = 0.25\%$ is used for the short-term strength and increased for the long-term depending on various factors.

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4 Results and Discussion

In the following sections, the representative analysis model is presented and the variations in active layer thickness and applied loads are discussed. The corresponding results in terms of pile deflection and internal forces are presented.

4.1 Model Conditions

Borehole data at the site shows that the bedrock is located at ca. 4.5 m below ground surface. The piles are estimated to be embedded at least 1.5 m into the bedrock, which may be characterized as a soft/brittle rock.

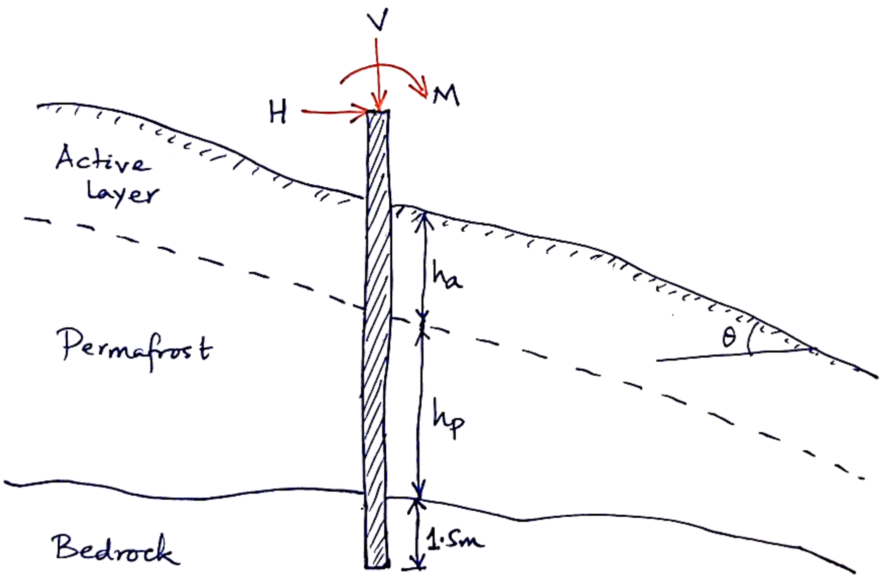

Figure 7: Representative model for pile response analysis.

The model shown in Figure 7 is used as a basic template for various analyses. Different variation in the active layer thickness h_a and the permafrost thickness h_p are considered. Different combinations of axial, lateral and bending moment loads (V, H and M) are also considered. In particular, the lateral load is expected to be dependent on the value of the active layer thickness for lateral loading which is initiated by slope processes such as solifluction. The analyses combinations considered are summarized in Table 3.

Table 3: Active layer thickness and load combinations.

Active Layer, h_a (m)	Axial Load, V (kN)	Lateral Load, H (kN)
1.5	50	20
	100	25
	150	30
2.5	50	40
	100	45
	150	50
3.5	50	60
	100	65
	150	70

In the analyses performed here, a resultant loading system at the top of the pile is assumed. The actual lateral loads due to slope processes are applied as a distributed load along the length of the pile embedded in the active layer. These lateral loads are converted to resultant forces and moments at the top of the pile through simple equilibrium considerations. Some of the piles have bracing supports and the expected support contributions are indirectly considered in the resultant system reducing the lateral loads and bending moments. The pile stick-up length above the ground varies throughout the building, and an average of ca. 1.0 m is assumed. Other variations are compensated by considering various load combinations.

4.2 Results

Figure 8 presents the pile head deflection, bending moment and shear force for a pile subjected to an axial load of 50 kN and lateral loads ranging from 20 to 60 kN. The range of lateral loads correspond to active layer thicknesses of 1.5, 2.5 and 3.5 m which consider current and anticipated changes in the ground thermal regime. These combinations result in pile head deflections from around 20 mm for the lowest lateral load to more than 60 mm for the highest.

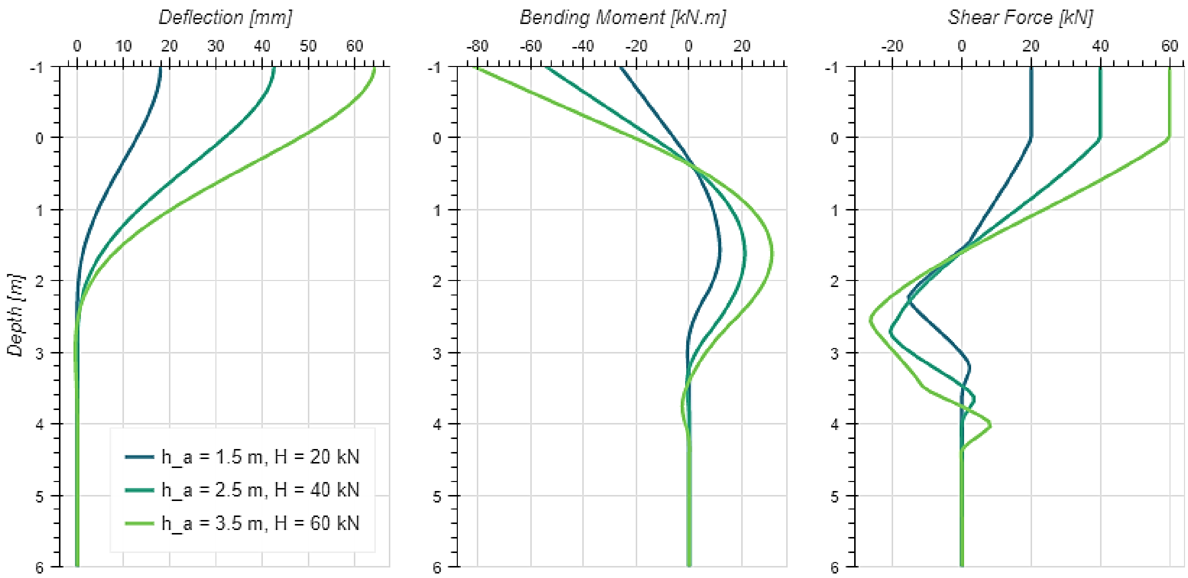

Figure 8: Pile deflections and internal forces; axial load V = 50 kN.

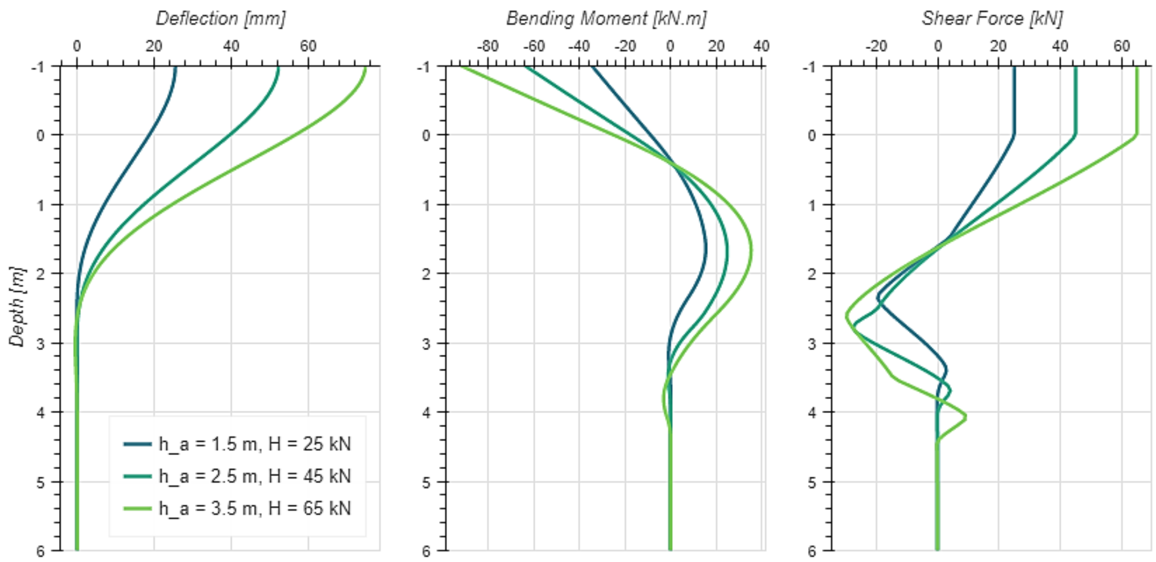

Figure 9: Pile deflections and internal forces; axial load V = 100 kN.

Similar results for an axial load of 100 kN and the same range of active layer thicknesses are shown in Figure 9. Slightly increased lateral loads from 25 to 65 kN are applied at the pile heads, which are estimated based on equilibrium resultant systems. Increased deflections and internal forces are observed, as expected.

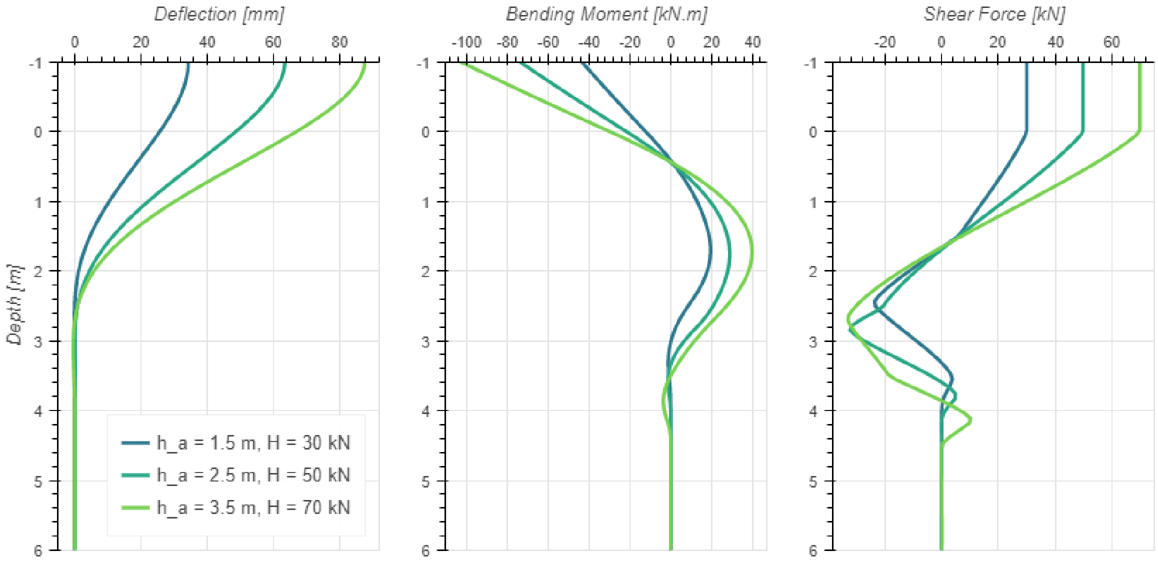

Figure 10: Pile deflections and internal forces; axial load V = 150 kN.

The results for an axial load of 150 kN are shown in Figure 10. Significantly higher pile deflections and internal forces are observed.

5 Summary

The effects of increased lateral loads, as a result of thawing and warming permafrost, on the pile foundations of a selected building in Longyearbyen located on a slope are investigated through numerical analyses. A range of active layer thicknesses are considered in the analyses taking current and projected scenarios into account. The axial loads on the piles are estimated based on standard methods for residential buildings, and variations are considered to account for uncertainties. The lateral loads on the piles are assumed to mainly originate from slope movements (such as solifluction) and loads transferred from crest of the slope through earth pressure. The finite element simulations performed in [1] are used a basis to estimate the earth pressures on the piles and the loads are converted to an equivalent resultant system at the pile head for simplicity of the analyses. Variations in the lateral loads are considered corresponding to the range of active layer thicknesses. Analyses based on p-y curves are performed for the different active layer thicknesses and loads considered. The results are presented in terms of pile head deflections, bending moments and shear forces. It is shown that the pile head deflections are expected to increase as the active layer thicknesses increase. A similar trend of increase is observed in the internal forces generated in the piles.

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