



CHALMERS
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Sustainable Frost-Protected Foundation Solution in Subarctic Climate: A Case Study of Skellefteå

Master's thesis in Master Program Infrastructure and Environmental Engineering

Xinzhi Wu

MASTER'S THESIS ACEX30

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Göteborg, Sweden 2025

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Institutionen för arkitektur och samhällsbyggnadsteknik
Chalmers tekniska högskola, 2025

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ABSTRACT

This report focuses on sustainable foundation solutions for buildings in very cold places like subarctic climate, special in Skellefteå, Sweden. The research want find good ways to build foundations that not harm environment and stop temperature variation problems. It studies two main things: first, using special shallow foundation with insulation mat (XPS foam) to keep heat and block frost entering under building. Second, checking better time for construction to avoid worst freezing periods. The method uses computer model (PLAXIS 2D) to test how temperature change affect ground and foundation in one full year. Result show that foundation with insulation mat and construction period in March to August time is a better choice. However the study has limitations, which is that only use 2D model and not able to simulate real word condition, and test period is short term that unexpected weather change is not considered.

Key words: shallow foundation, construction window, temperature variation, heat analysis.

Hållbar frostskyddad grundlösning i subarktiskt klimat: En fallstudie av Skellefteå

Examensarbete inom masterprogrammet *Infrastruktur och miljöteknik*

Xinzhi Wu

Institutionen för arkitektur och samhällsbyggnadsteknik

Avdelningen för Geoteknik och Geologi

Chalmers tekniska högskola

SAMMANFATTNING

Denna masteruppsats fokuserar på hållbara grundlösningar för byggnader i extremt kalla regioner, såsom subarktiska klimat, och i synnerhet Skellefteåregionen. Forskningen syftar till att utforska sätt att konstruera grunder som både är miljövänliga och förhindrar frostproblem. Avhandlingen fokuserar på två aspekter: för det första, att jämföra effektiviteten hos grunder med och utan isoleringsmattor (XPS-skum) när det gäller värmeållning och att förhindra frostinträning i byggnadsjorden. För det andra, att bestämma den bästa tiden att bygga för att undvika de värsta frysperioderna. Metoden använder en datormodell (PLAXIS 2D) för att testa effekterna av temperaturförändringar på jord och grund under hela året. Resultaten visar att grunder med isoleringsmattor och en byggperiod från mars till augusti är bättre alternativ. Forskningen har dock också begränsningar, såsom det faktum att den endast använder en tvådimensionell modell, som inte kan simulera verkliga förhållanden, jordmodellens höjd är inte tillräcklig för att analysera värmeövergången och den korta testperioden tar inte hänsyn till oväntade väderförändringar.

Nyckelord: grundläggning, konstruktionsfönster, temperaturvariation, värmeanalys.

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Preface

Göteborg June 2025

Xinzhi Wu

1 Introduction

1.1 Background

Subarctic regions experience very long winters, fast seasonal thawing, and repeated freeze-thaw cycles. These conditions create complex soil behaviours that threaten building foundations. Key issues include frost heave, ice lens formation, and changes in soil strength and water movement. Such processes damage both natural ground and human-built foundations causing uneven settlement and structural failure. In Skellefteå, Sweden, freezing temperatures combined with soil moisture cause ground expansion during winter and strength loss during thawing, reducing foundation performance over time (Andersland & Ladanyi, 2004).

Climate change worsens these challenges by increasing the frequency and intensity of freeze-thaw cycles in northern areas of Sweden. Traditional deep foundations – once reliable solutions – now struggle because they cannot handle dynamic interactions between soil temperature, water movement, and mechanical stress under changing climate conditions. This limitation is especially critical in Skellefteå, where seasonal temperature changes strongly affect soil-foundation interactions.



Figure 1.1 Location of Skellefteå (SGU)

The complex physics of freezing soils further complicates foundation design. Cryogenic suction governed by thermodynamic laws moves unfrozen water toward

freezing zones, increasing frost heave pressure (Williams & Smith, 1989). Combined with Skellefteå's highly variable groundwater levels, this process accelerates infrastructure damage. These factors highlight the need for climate-adaptive construction solutions in subarctic regions.

1.2 Aim

The report is to develop and evaluate sustainable foundation solutions and construction windows adapted to the subarctic climate. The research focuses on minimizing environmental impact, optimizing material use, and improving performance to withstand local climate conditions.

1.3 Research Questions

The following questions need to be answered :

1. What are the cementitious materials with lower environmental impact that are also suitable for the unique challenges of the subarctic climate?
2. What are foundation design solutions that avoid traditional deep foundations and explore other ground improvement methods?
3. How to develop and test a promising foundation solution in the subarctic climate of Skellefteå to minimize the temperature variation in the foundation?
4. What is the preferred “construction window” to build the foundation to minimize the effect of temperature variation in skellefteå.

1.4 Methodology

The first two questions will be answered by literatures study and thereby set the basis for the modelling. To answer the last two questions, Modelling will be set on a test sample and a stable ground sample in Skellefteå in PLAXIS 2D Ultimate.

1.5 Limitations

This research focuses only on Skellefteå area. The special ground profile will be studied: glacial moraine soil where groundwater level stays at the same level. Results may not fit other cold places. This is because other places could have always frozen ground or different soil layers. This makes our heat modeling easier.

The findings only focus on the challenges caused by freezing and thawing. That means temperature change and time passing are the main dangers to foundations we consider. Other possible threats are not included in this study.

Also, the soil model is 2D but real world has three dimensions. So, the model is a simpler version of real life. It is important to remember that the model is not the same as true reality.

2 Theory

2.1 Frost heave

Frost heave is a critical geotechnical phenomenon in cold regions where soil expands upward due to subsurface ice formation. It occurs when unfrozen pore water migrates toward freezing zones and crystallizes into layered ice structures called ice lenses. This process displaces soil particles, causing significant ground deformation that directly threatens infrastructure stability (Konrad & Morgenstern, 1980). Its destructive potential makes it a primary concern for engineering in subarctic climates like Skellefteå.

When weather gets cold, water inside rock cracks freezes into ice. Ice takes more space than water so pushes hard against rock walls. This strong push breaks rocks into many small pieces - sometimes even single mineral grains. Later when temperature warms up, ice melts and releases all broken bits into nearby soil. This cycle repeats each winter, slowly turning rocks into soil over time. see Figure 2.1

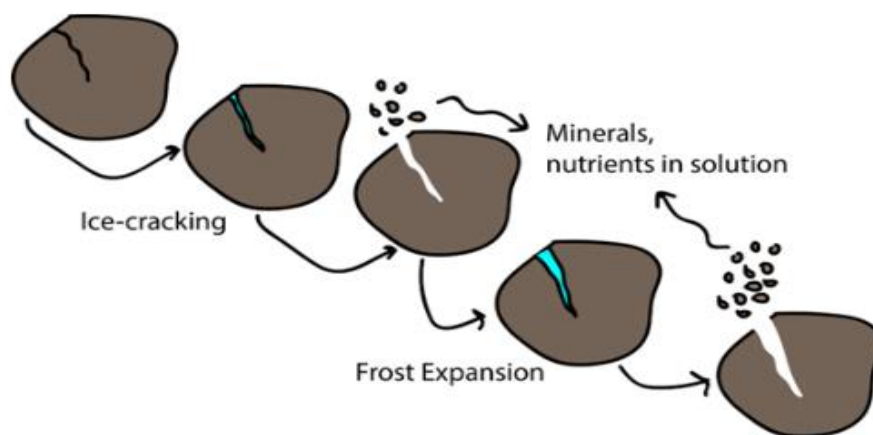


Figure 2.1 freeze-thaw processes and frost heave (Erin Rooney,2022)

Frost heave initiates when subfreezing temperatures create thermal gradients in soil. Unfrozen pore water migrates toward colder zones through cryogenic suction – a thermodynamic process where ice exerts lower pressure than liquid water, governed by the Clausius-Clapeyron equation, see equation (2.1):

$$\frac{dP}{dT} = \frac{L}{T\Delta V} \quad (2.1)$$

Where:

$\frac{dP}{dT}$ = change in pressure with temperature at the freezing point

L = latent heat of phase transition

ΔV = volume change per unit mass from water to ice

T = absolute temperature

This suction draws water toward freezing area, where it crystallizes into ice lenses. Lens formation requires cryogenic suction to exceed overburden pressure, displacing soil particles vertically, see Figure 2.2. The process is amplified in fine-grained soils where capillary forces enhance water retention and migration (Williams & Smith, 1989).

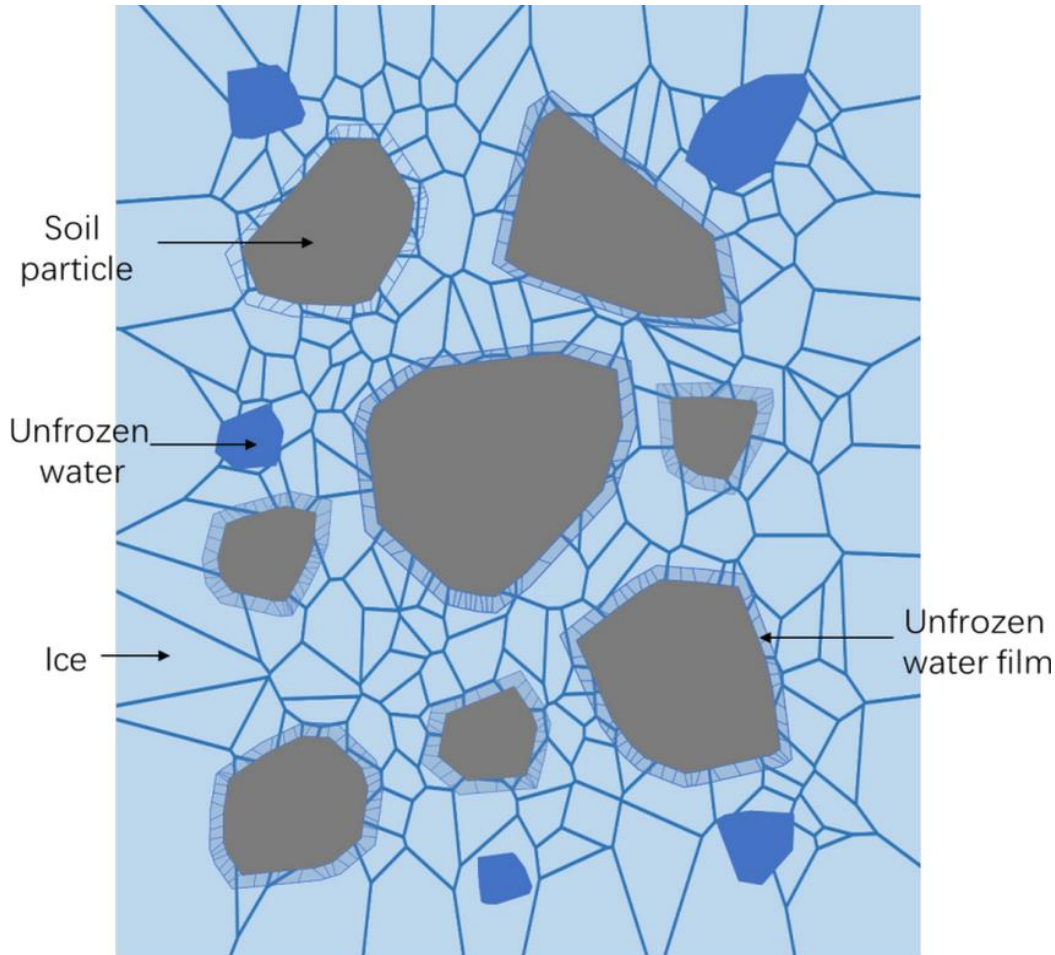


Figure 2.2 Diagram illustrating cryogenic suction in air-free frozen soil (Sun, K., & Zhou, A. 2021)

Soil properties critically influence heave severity. Fine soils exhibit strong heave due to high surface area and slow drainage, while coarse soils resist heave through rapid water escape.

Frost heave compromises structures via differential settlement, foundation uplift, and reduced bearing capacity. Mitigation strategies include thermal insulation to minimize temperature gradients, drainage systems to limit water supply, or replacing frost-susceptible soils with granular fills.

2.2 Impact of temperature variation on Frost heave

Higher temperature changes make frost heave worse. When temperatures drop fast and far below freezing point, it creates stronger cryogenic suction in the soil. This suction

pulls unfrozen water toward the freezing area. This accelerates the influx of unfrozen water to ice lenses, enhancing their growth rate and thickness (Williams & Smith, 1989).

Steeper temperature differences also make freezing go deeper into ground. When soil experiences big temperature jumps, the frozen zone becomes thicker. This gives more space for ice lenses to form. Also, repeated freeze-thaw cycles break soil structure over time. This damage lets water move easier in soil. (Konrad, 1994).

Over time, temperature swings cause ice lenses to keep growing bigger or form new ones. Higher temperature changes damage soil structure more seriously. This broken structure can't resist water movement well, so heave gets worse cycle after cycle. The summary of the impact is show below Figure 2.3.

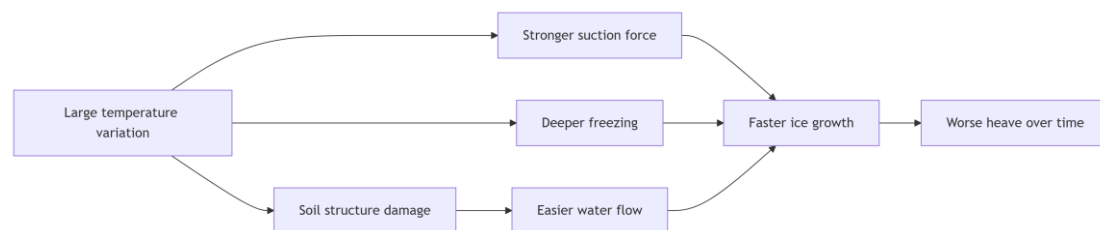


Figure 2.3 Impact of temperature variation on frost heave (Author own work)

2.3 Cementitious Materials for subarctic climate

2.3.1 Classic cementitious materials for subarctic climate

Ordinary Portland Cement has been the main available cement used in cold regions like Skellefteå. Builders choose OPC because it is easy to find and has known performance rules. OPC concrete gets hard when water reacts with its minerals, forming strong C-S-H gels. But in cold climates, OPC has problems that the high porosity lets water enter. When this water freezes below 0°C, it expands with huge pressure. This causes small cracks, surface peeling, and concrete breaking over time, making structures weak.

OPC also has other challenge which is making its main ingredient releases much CO₂. Also, extra materials like fly ash or slag don't work well in cold weather. So concrete gains strength slower, needing longer curing or heating. This is hard and expensive in cold areas. Plus, repeated freeze-thaw cycles damage concrete's inside structure bit by bit, making it weaker over years (Aïtcin, P. C., & Mindess, S, 2011). These OPC limits show that the cementitious with better performance for cold places need to be investigated.

2.3.2 Overview and need for innovative cementitious materials

The development of innovative cementitious materials for subarctic climates is urgently needed due to interconnected climate change and infrastructure resilience challenges. OPC production contributes approximately 8% of global CO₂ emissions, accelerating climatic changes that intensify freeze-thaw cycles in northern regions. Meanwhile, aging infrastructure suffers accelerated degradation from increasing thermal volatility. (IPCC, 2021).

Effective innovative materials must address three critical challenges: reduction of embodied carbon, improved freeze-thaw resistance without energy-intensive additives, and maintained performance in low-temperature conditions. Conventional supplementary cementitious materials (SCMs) like fly ash exhibit limited regional availability and inconsistent reactivity. While geopolymers offer low-carbon alternatives, their scalability is constrained by costly alkaline activators and corrosiveness. Calcium sulfoaluminate (CSA) cements achieve rapid strength gain but prove incompatible with sulfate-rich groundwater common in glacial till deposits (Habert et al., 2020).

An optimal subarctic binder would utilize locally available raw materials, minimize clinker content, and demonstrate intrinsic resistance to cryogenic stresses. Achieving this requires fundamental redesign of cement chemistry to optimize microstructural pore architecture, phase composition, and low-temperature hydration kinetics. Such innovations could reconcile sustainability with the demanding thermal performance requirements of subarctic construction.

2.3.3 Introduction to LC³

Limestone Calcined Clay Cement is an innovative sustainable binder. It combines clinker, calcined kaolinite clay, limestone, and gypsum. This formulation halves clinker content versus OPC, significantly reducing CO₂ footprint. The calcined clay reacts with limestone to form dense carbo aluminate phases, enhancing microstructural density. (Zunino et al., 2021).

LC³'s freeze-thaw resistance originates from its refined pore structure. Through the Gibbs-Thomson effect, these nanoscale pores depress water's freezing point to a certain degree, preventing ice formation above this threshold. The carboaluminate phases also inhibit sulfate penetration, crucial for coastal applications (Sharma et al., 2021).

LC³ offers three main benefits: First, it reduces high CO₂ using waste limestone and abundant clay. Second, its dense structure prevents water penetration, protecting steel in concrete from rust. Third, it cuts material costs in regions like Scandinavia with plenty of clay, while speeding construction in short building seasons. Unlike other green cements, LC³ avoids swelling problems in sulfate-rich soils and outperforms regular cement during temperature changes, making it a strong solution for cold regions' building needs (Sharma et al., 2021).

2.4 Foundation design solutions for subarctic climates

2.4.1 Advantages of shallow foundation

Shallow foundations are preferred over deep foundations in subarctic zones due to lower costs and reduced thermal impact. Deep foundations extend below the frost line but face problems in seasonal freeze-thaw areas. Permafrost thaw weakens soils and causes uneven settlement. Shallow types minimize digging in frost-sensitive soils and avoid unstable frozen layers. They also simplify construction and cut costs in remote locations with limited heavy equipment (Andersland & Ladanyi, 2004). Different foundation types are shown below Figure 2.4.

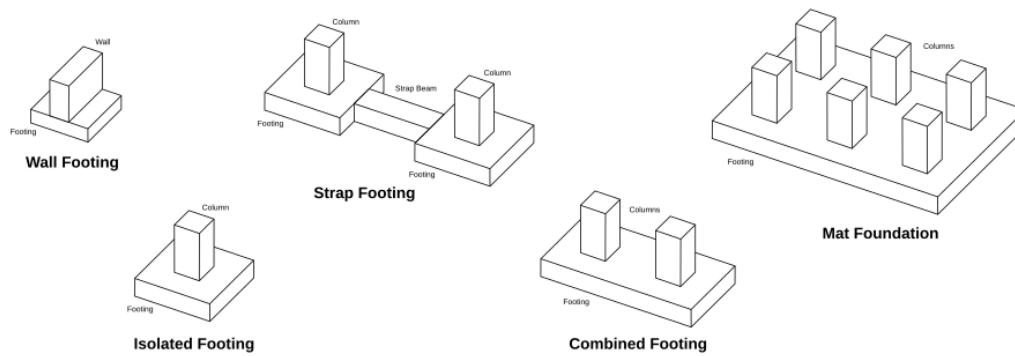


Figure 2.4 Shallow foundation types (Ripon, 2023)

Shallow foundations align with sustainable design by reducing energy use. Deep foundations require significant materials and installation energy, while shallow systems use natural soil strength near the surface. However, controlling temperature is essential for success. Adding insulation or soil improvement maintains stability sustainably.

Theoretical models from (Andersland & Ladanyi, 2004) show foundations should separate from frost-active soils. Shallow designs must consider combined thermal-hydraulic-mechanical interactions to prevent heavy damage. This requires materials and techniques handling both structural loads and freezing stresses.

2.4.2 Shallow foundation design

Shallow foundations like spread footings and slab-on-grade systems transfer structural loads to underlying soils through base contact pressure. These systems utilize C30/37 reinforced concrete per EN 206 standards, providing adequate compressive strength and freeze-thaw resistance through air-entrained microstructures. Foundations are typically embedded below seasonal frost depth in non-frost-susceptible soils such as dense glacial till. The bearing capacity follows Terzaghi's ultimate limit state equation (2.2):

$$Q_u = C \cdot N_c + q \cdot N_q + \frac{1}{2} \gamma \cdot B \cdot N_\gamma \quad (2.2)$$

Where:

C = Soil cohesion

γ = Soil unit weight

D = Footing depth

B = Footing width

N_c, N_q, N_γ = Terzaghi's bearing capacity factors depend on soil friction angle, ϕ .

C30/37 concrete's durability stems from its optimized pore structure accommodating ice expansion pressures. However, in frost-susceptible soils like silts and clays, cyclic heave generates differential uplift forces exceeding the foundation's resistance capacity. This mechanistic failure occurs when cryogenic suction draws water toward freezing fronts, forming ice lenses that displace both soil and foundation elements. These inherent vulnerabilities necessitate mitigation strategies in subarctic conditions.

Conventional practice involves excavating frost-susceptible soils to below frost depth and replacing with compacted granular fills. This method creates capillary breaks that limit water migration while providing stable bearing strata. The granular replacement layer acts as both structural support and hydraulic barrier, disrupting the thermal-hydraulic-mechanical couplings that drive heave. While effective, this technique requires significant earthworks and material transport, increasing environmental impact and construction costs. This limitation has driven innovation toward insulated foundation systems that achieve similar performance with reduced resource consumption (ASCE 32-01).

2.4.3 Shallow foundation with insulation mats

Shallow foundations with XPS insulation integrate extruded polystyrene foam boards beneath concrete structures to prevent damage by temperature variation. This system places rigid insulation between the foundation and underlying soil, maintaining stable thermal conditions that inhibit ice lens formation. The insulation acts as both thermal barrier and capillary break, decoupling the structure from frost-active soils while providing sufficient load distribution for C30/37 concrete elements. Design follows established engineering standards that specify insulation thickness based on climate severity, ensuring reliable frost protection without deep excavation (ASCE, 2001).

XPS insulation effectively disrupts the thermal-hydraulic-mechanical interactions driving frost heave. By reducing heat transfer between the structure and ground, it maintains consistent subsurface temperatures that prevent cryogenic suction forces from developing. Field studies in subarctic regions demonstrate near-complete elimination of differential heave, with long-term monitoring showing minimal displacement compared to uninsulated foundations. The closed-cell structure additionally blocks water migration toward freezing fronts, addressing the primary moisture pathway for ice lens growth (Salomovich, T. E et al., 2021).

Insulated foundations offer significant sustainability and practical benefits over traditional approaches. They eliminate resource-intensive soil replacement by working effectively in frost-susceptible soils, reducing construction time and disturbance. Lifecycle analysis confirm lower environmental impacts through decreased material consumption and transport emissions. Economically, reduced maintenance needs and energy savings from thermal efficiency provide long-term cost advantages, particularly in remote regions.

3 Verification and Case Study

3.1 Soil at Skellefteå

3.1.1 Soil properties and characteristics

3.1.1.1 Moraine ground profile

The ground in Skellefteå consists of glacial moraine - mixed-up layers of clay, silt, sand, and gravel left behind when ice sheets melted long ago. This soil contains high silt and clay, making it very sensitive to freezing because its small holes help water move upward slowly. Water flows through this soil at medium speed, while its strength varies with cohesion and friction angle. These features make ground stable normally but react strongly to temperature changes, causing frost heave in winter (SGU, 2018).

The soil composition reflects how ice sheets moved during different ice ages. The materials show different sizes and mixtures over small distances because ice deposited them unevenly over time. Some places have more stones and sand, others more fine clay - these changes the water movement and ground stability (Benn & Evans, 2014). Areas with tightly packed soil hold water differently than loose zones. These differences help understand both current ground stability and historical ice movements in Skellefteå region.

3.1.1.2 Water table with seasonal fluctuation

In Skellefteå, groundwater levels change significantly throughout the year. During spring melting snow and rain make water table rise quickly. This happens because ice age soils act like uneven sponge - water fills holes fast in sandy areas but moves slowly through clay patches. Come summer and winter dry periods, water table drops as less water enters ground and plants drink more moisture. These seasonal swings are bigger than in southern Sweden and directly impact building foundations (SMHI 2018).

The mixed glacial deposits create complex groundwater behavior. Areas with sandy soils allow rapid water movement, causing quick water table rises during snowmelt. In contrast, clay-rich layers slow water movement significantly, reducing the speed of water level changes. This directional variation in water flow occurs because ice age processes created layered soil patterns. (Broms, 1981).

Spring groundwater saturation increases frost heave risk because freezing creates pressure differences that draw moisture upward toward cold zones. The soil's thermal characteristics control freezing depth: heat transfer capacity and heat storage capacity limit winter frost penetration to certain shallow depth. Below this, soils remain near Skellefteå's average annual temperature of slightly higher than zero. This thermal behavior interacts with water movement, particularly where sand layers disrupt uniform water flow.

3.1.1.3 Thermal content

Thermal conductivity shows how fast heat travels through soil. In Skellefteå's moraine, this depends on soil composition and especially water content. When soil is wet, heat moves better because water transfers heat better than air. Saturated soils have higher values.

Moraine soils in Skellefteå store has high specific heat which is the volume of heat energy soil can store per degree capacity, but it is also depending on rock types and particle sizes. This high storage capacity means soil temperatures change slowly with weather changes.

In Skellefteå's moraine, wetter soils have higher diffusivity which indicates how quickly temperature changes spread through ground because water boosts both heat movement and storage. This controls how fast winter cold penetrates ground - important for predicting frost depth.

3.1.1.4 Air temperature and ground temperature in Skellefteå

Skellefteå experiences a subarctic climate with marked seasonal variation in air temperature. Winter months are characteristically cold, with average temperatures often well below 0 °C, while summer months are relatively mild. The annual mean air temperature in the region is generally slightly higher than zero degree. These seasonal extremes are a key driver not only for local weather but also for the thermal condition of the ground, affecting the depth of frost and the level of seasonal thaw. (SMHI, 2023).

The near-surface ground temperature in Skellefteå is closely related to the ambient air temperature, but with a moderating effect due to soil's thermal inertia. On the ground surface—and within the shallow active layer affected by seasonal freezing and thawing—the temperature fluctuates almost in phase with the air temperature, though with reduced amplitude. During the winter, the ground may freeze to depths of one to two meters, while in summer, the top layer warms substantially, but below to certain meters, the temperature tends to stabilize at a value near the mean annual air temperature. (Smith & Riseborough, 2002).

3.1.2 Study area description

The Northvolt battery factory (64.79°N, 20.59°E) is the focus area for this foundation study, located 8 km northwest of Skellefteå city center. This industrial site sits on glacial till plains near the Skellefte river, making ground very sensitive to freezing. Being close to river means big groundwater changes. These conditions create strong frost heave risks for heavy factory foundations. The site's mix of natural challenges and heavy industrial loads makes it perfect case for testing frost-proof foundation solutions, see Figure 3.1.

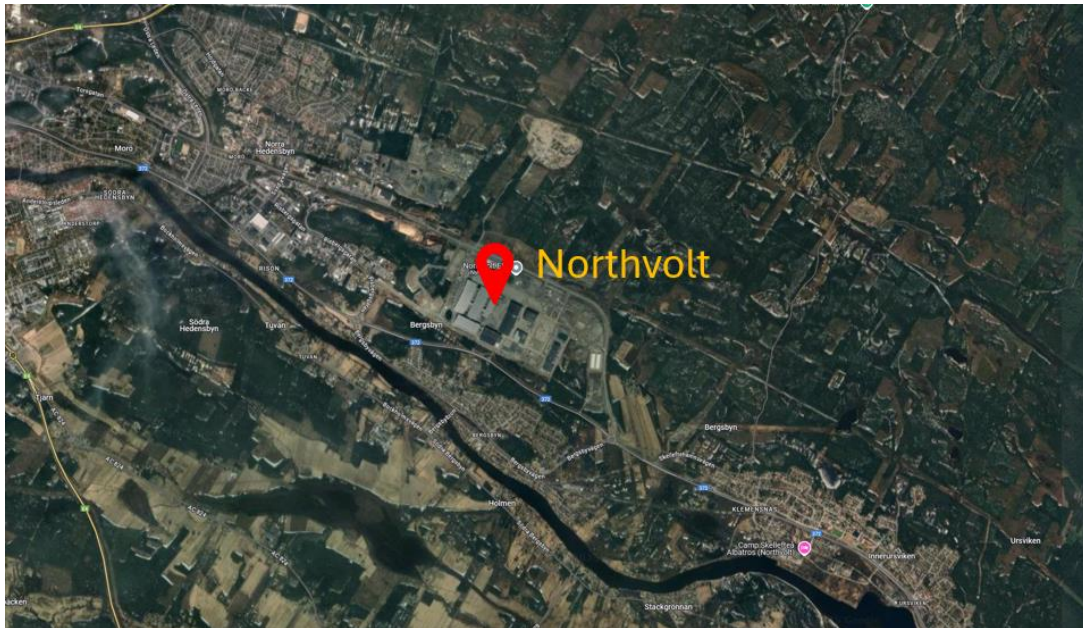


Figure 3.1 View of study area (Google map)

3.2 Verification of the frozen soil model

3.2.1 Climate temperature in Skellefteå in 2024

The air temperature in Skellefteå 2024 come from SMHI stations. Big difference between summer and winter: highest $+35.4^{\circ}\text{C}$ on 26 June, lowest -20.7°C on 4 January. This 56°C change cause many freeze-thaw cycles during year. The temperature curve shows cold period November-March and warm June-August. This real data is used as top boundary for soil model to make simulation close to real condition, see Figure 3.2

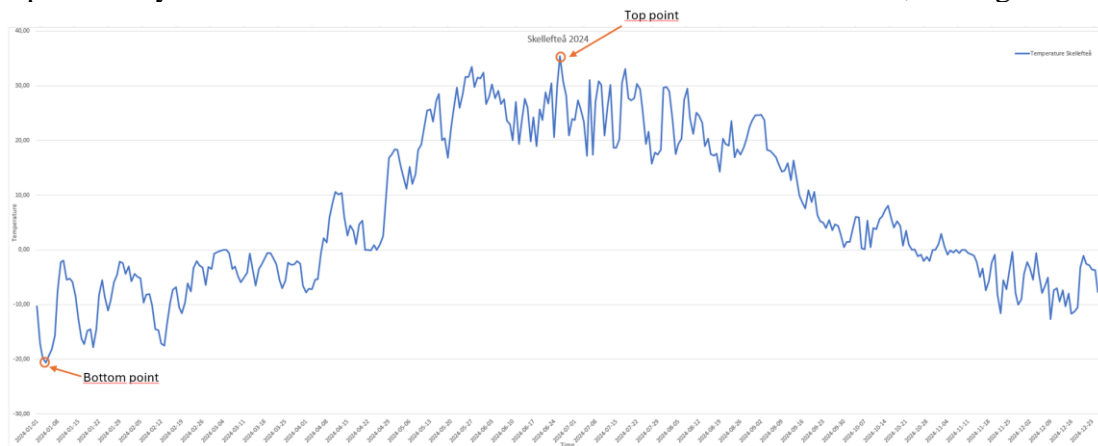


Figure 3.2 Climate temperature variation in skellefteå in 2024

Temperature underground at different depths (-1m, -2m, etc.) is based on measurements from Trafikverket year 2024. To check the soil model's feasibility, its temperature results are compared with Trafikverket data at same depths.

3.2.2 Ground geometry and boundary conditions for PLAXIS 2D Modelling

The computer model uses soil block 24 meters wide and 5 meters deep. This size chosen to see heat movements clearly without slow calculations. Width can fit the foundation to avoid edge effects messing temperature results. Depth includes important freeze-thaw zone and goes below to stable ground to study how heat moves between layers, see Figure 3.3.

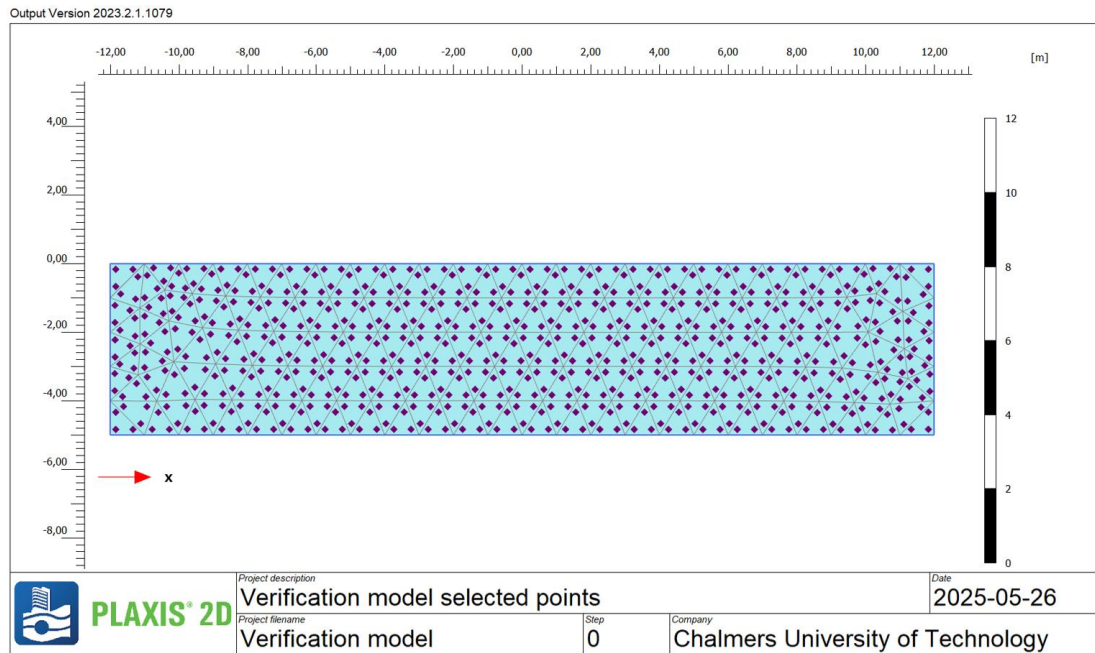


Figure 3.3 Soil verification model with stress points

Soil Model made with Skellefteå moraine soil properties from Swedish Geological Survey (SGU) and Geotechnical Institute reports (SHMI), specially the thermal expansion coefficient is used for moraine, the soil parameter is shown in Table 7.1.

Table 7.1 Soil parameter in PLAXIS 2D

General	
$\gamma_{unsat} (kN/m^3)$	18
$\gamma_{sat} (kN/m^3)$	18
e_{init}	0,5
Mechanical	
$E_{ref} (kN/m^2)$	40×10^3
ν_{nu}	0,25
Groundwater	
$k_x (m/s)$	1×10^{-6}
$k_y (m/s)$	1×10^{-6}
Thermal	
$c_s (kJ/t/^\circ C)$	1050
$\lambda_s (kW/m/^\circ C)$	4×10^{-3}

$\rho_s(t/m^3)$	2,2
$\alpha_{sv}(1/^\circ C)$	$2,5 \times 10^{-5}$

Groundwater table is fixed at 1 meter depth. Hydraulic boundary conditions (BCs) are set to closed for the sides and bottom, but top allows seepage. The thermal BCs is setup to be closed for side boundaries and the top and bottom boundary are set as convection.

3.3 Case study of foundation solutions comparison

This study tests two foundation types - shallow foundation without and with XPS insulation mat—in the same PLAXIS 2D soil model of Skellefteå moraine under 2024 climate conditions. Both designs use C30/37 concrete, but the insulated version adds 300mm XPS foam. Temperature and deformation data will be measured at key points near each foundation during a full-year freeze-thaw simulation. Comparing these results will show which solution better minimizes damage by temperature variation in subarctic climates by controlling soil movements and temperature changes.

3.3.1 Shallow foundation without insulation mat

3.3.1.1 Material property

The foundations use standard C30/37 reinforced concrete (EN 206 standard) common for cold climate construction. The material property is based on EN 206 Standard, shown in *Table 7.2*.

Table 7.2 Concrete parameter in PLAXIS 2D

General	
$\gamma_{unsat}(kN/m^3)$	24
$\gamma_{sat}(kN/m^3)$	24
e_{init}	0,5
Mechanical	
$E_{ref}(kN/m^2)$	$3,3 \times 10^7$
ν_{nu}	0,3
Groundwater	
$k_x(m/day)$	0
$k_y(m/day)$	0
Thermal	
$c_s(kJ/t/^\circ C)$	900
$\lambda_s(kW/m/^\circ C)$	$1,5 \times 10^{-3}$
$\rho_s(t/m^3)$	2,5
$\alpha_{sv}(1/^\circ C)$	$0,3 \times 10^{-4}$

3.3.1.2 Geometry and BCs

The designed foundation—with an embedment depth of 3 m and width of 10 m classified as shallow foundation according to equation (3.1):

$$D_f/B \leq 1 \quad (3.1)$$

Where:

D_f = Depth of foundation

B = Width of foundation

This depth deliberately exceeds Skelleftea’s maximum frost penetration while avoiding deep foundation criteria, aligning with subarctic frost-protected shallow foundation principles, see Figure 3.4

For the concrete, all the thermal boundaries are setup to convection to be more accurately simulate heat transfer driven by fluid and air motion.

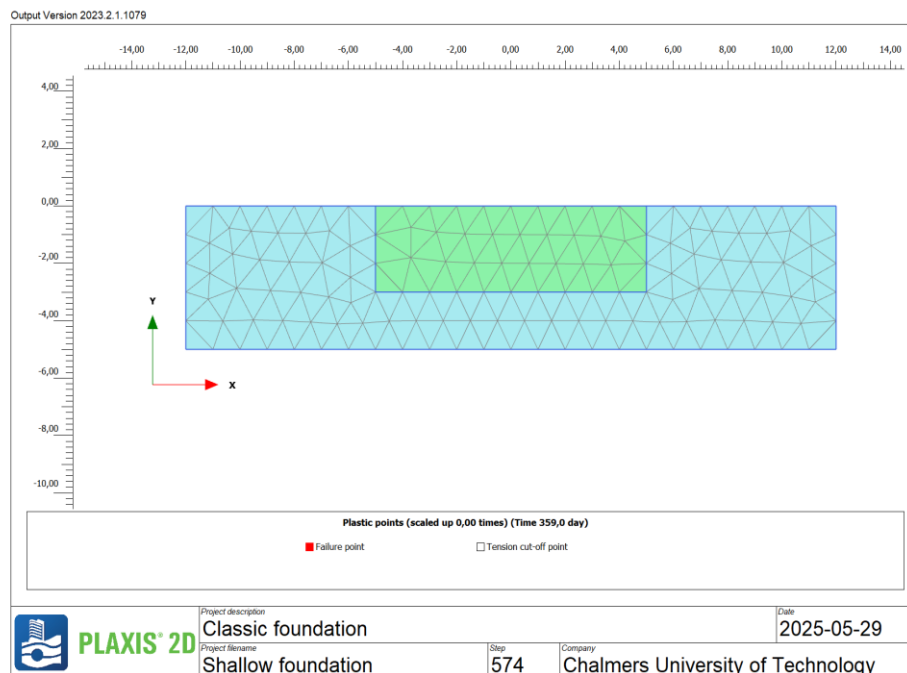


Figure 3.4 Shallow foundation without insulation mat in soil model

3.3.2 Shallow foundation with insulation mat

3.3.2.1 Material property

The concrete is using C30/37 Reinforced Concrete (EN 206 Standard), which is the same used by the first case. The insulation uses XPS 300 foam boards (EN 13164 standard) common in cold area foundations. The material property is based on EN 13164 Standard, shown in Table 7.3.

Table 7.3 XPS300 parameter in PLAXIS 2D

General	
$\gamma_{unsat}(kN/m^3)$	0,3
$\gamma_{sat}(kN/m^3)$	0,3
e_{init}	0,5
Mechanical	
$E_{ref}(kN/m^2)$	2×10^3
ν_{nu}	0,3
Groundwater	
$k_x(m/day)$	0
$k_y(m/day)$	0
Thermal	
$c_s(kJ/t/^\circ C)$	1500
$\lambda_s(kW/m/^\circ C)$	$0,3 \times 10^{-4}$
$\rho_s(t/m^3)$	0,03
$\alpha_{sv}(1/^\circ C)$	$0,7 \times 10^{-4}$

3.3.2.2 Geometry and BCs

The 0.3 m thickness of the XPS insulation mat was determined through climate-adaptive design principles specific to Skellefteå's subarctic conditions, see Figure 3.5. This dimension exceeds the minimum requirements established by ASCE 32-01 standards for the cold region, providing a conservative thermal buffer against extreme winter temperatures.

The boundaries condition for soil and concrete is the same with the first case. For the insulation mat, all the thermal boundaries are setup to convection to be more accurately simulate heat transfer driven by fluid and air motion.

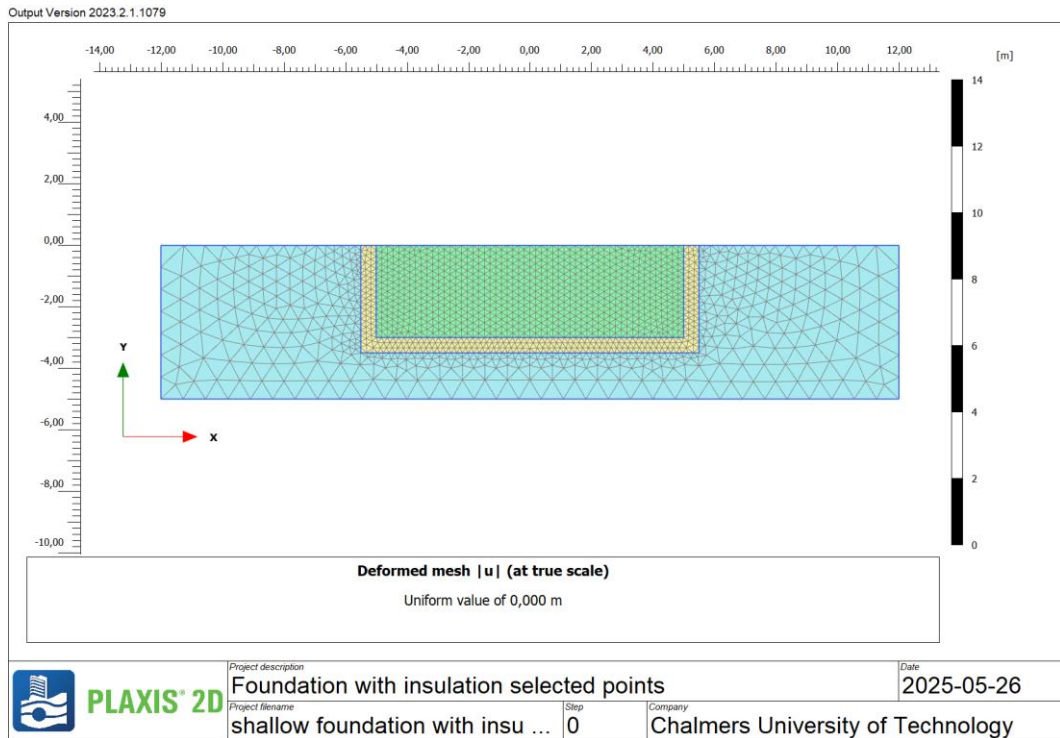


Figure 3.5 Shallow foundation with insulation mat in soil model

3.4 Case study of construction window comparison

It is very important to choose the correct construction window in the subarctic climate to lower the difficulty of construction due to the high variation of temperature during the year. There are three steps for the construction. First step is for the excavation for the foundation installation and assuming take 2 months. The second step is for the shallow foundation with mat installation and assuming take another 2 months. Last step is for the superstructure installation and the constant load on the foundation is used to represent the superstructure.

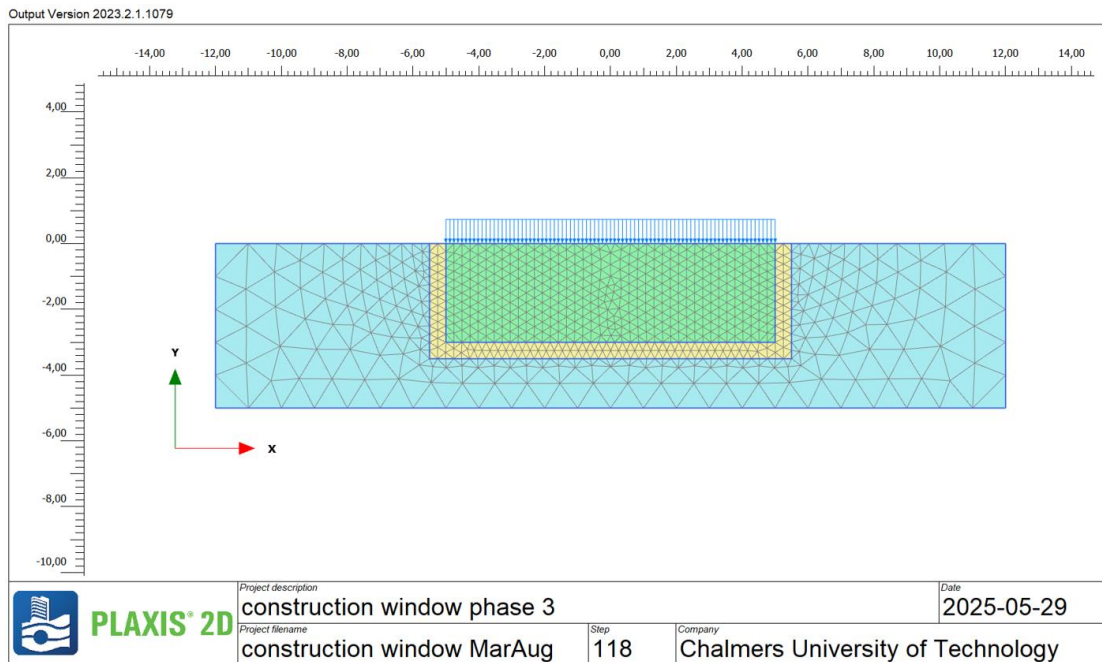


Figure 3.6 Shallow foundation with superstructure affect in soil model

Based on this, two scenario of construction period is considered. First construction window is from March to Aug, which all the construction period with warm temperature. Second construction window is from July to December, which the warm and cold temperature all have been through all the construction work. Construction period through all the winter is not considered because working in extreme cold climate is not recommended for human and machine availability and capacity.

4 Results and Discussion

In this chapter, the results of the verification of soil model and case study will be presented and discussed. Figures and data presented in this chapter are generated by author from PLAXIS 2D model.

4.1 Verification of Soil model

Three points for analysis are chosen as reference points during the testing, which are top point, point at -1m (ground water level) and point at -2m. These points will be used to compare with the climate temperature in reality to verify the model's feasibility, see Figure 4.1.

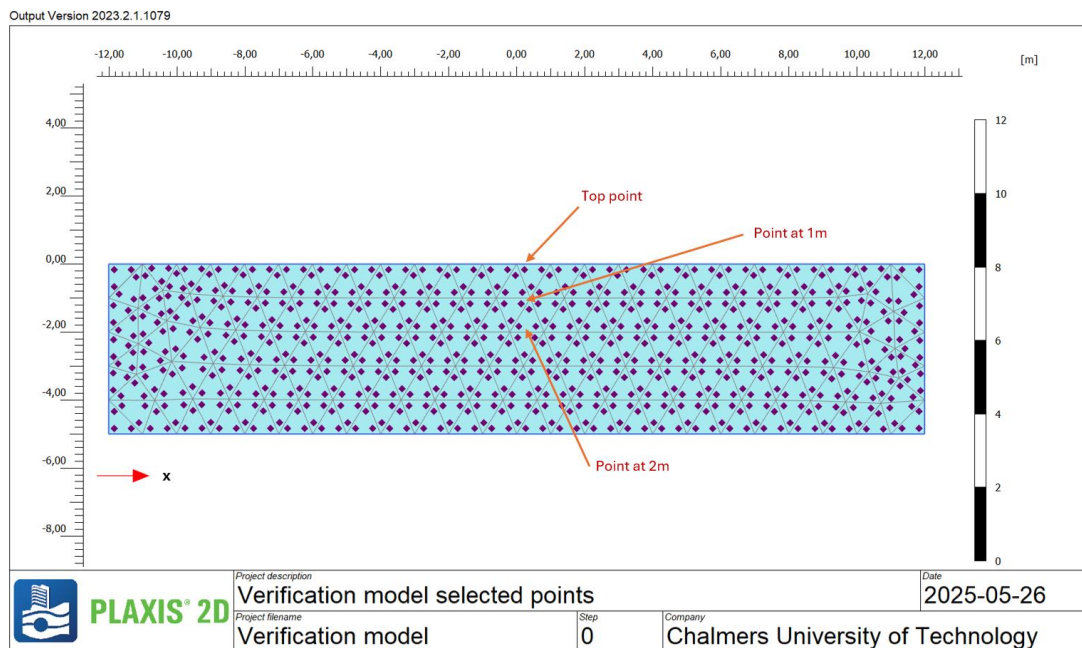


Figure 4.1 Selected point for analysis

4.1.1 Heat analysis of the test model

The PLAXIS 2D soil temperature model shows high consistence with real annual data across all three validation cases—ground level, ground water level, and below ground water level—with peak deviations of 5.11°C, 3.57°C, and 2.73°C respectively, see Figure 4.2, 4.3 and 4.4. These realistic seasonal trends confirm the model's usefulness for predicting thermal behaviour. The small but consistent offsets probably come from real-world messiness the model can't perfectly capture things like unexpected soil layers, unexpected weather changes, or local site activities that are not fully measured or included.

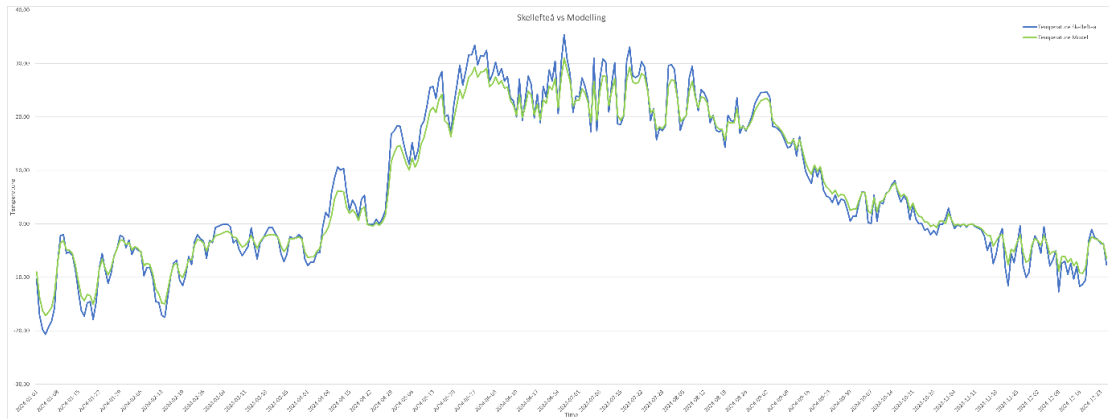


Figure 4.2 Temperature comparison at the ground level $z = 0 \text{ m}$

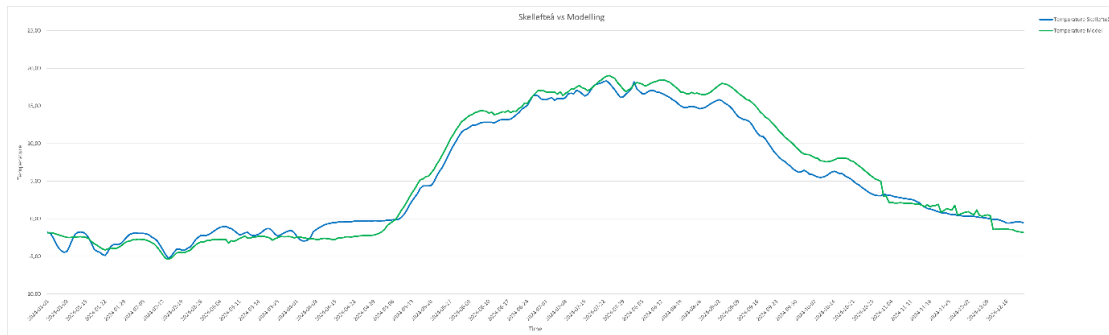


Figure 4.3 Temperature comparison at $z = -1 \text{ m}$

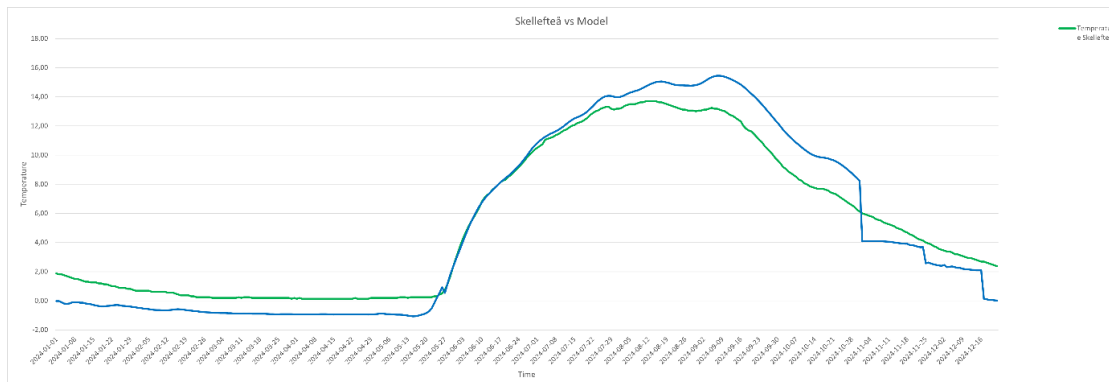


Figure 4.4 Temperature comparison at $z = -2 \text{ m}$

4.2 Case study of foundation solutions comparison analysis

Four edge points on each foundation were selected for simulation because they show strongest reactions to freezing and thawing, see Figure 4.5 and 4.6. These spots experience biggest temperature changes and soil movements next to the foundation during winter, making them good indicators for frost heave damage. By checking both temperature changes and total displacement at same positions on insulated and bare foundations, the efficiency for each design handles temperature variation will be seen. Temperature data shows if insulation keeps stable heat, while movement numbers tell us how much heave happens.

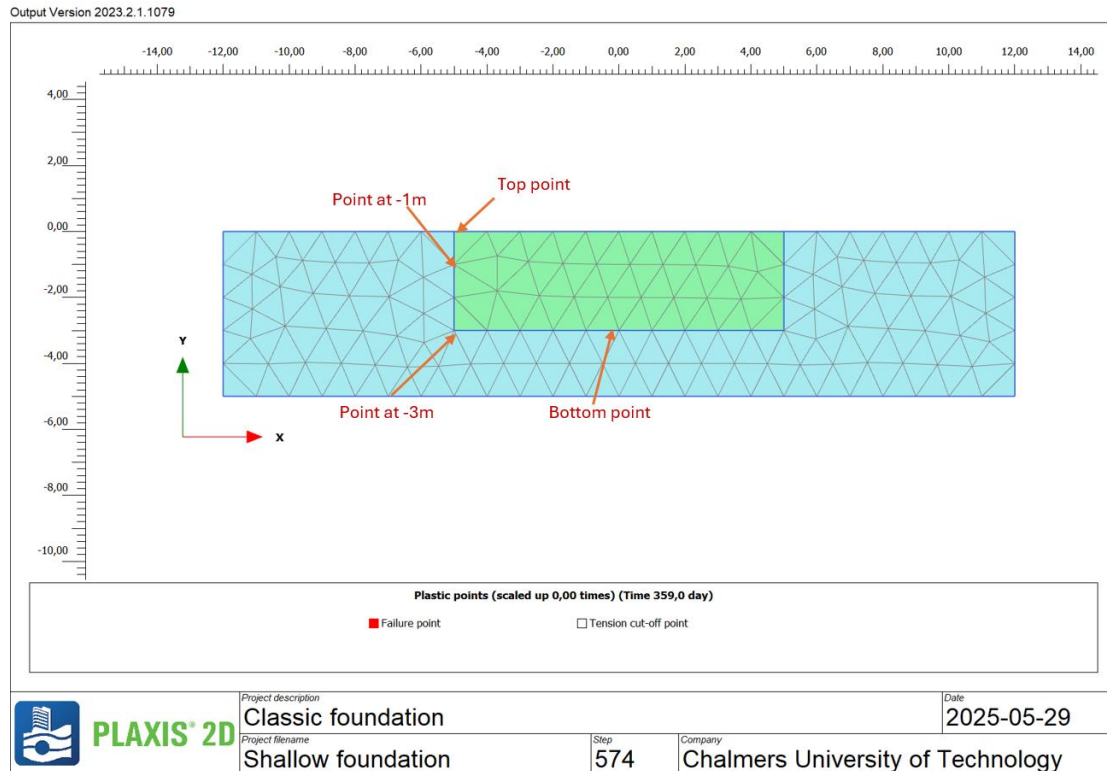


Figure 4.5 Selected points for analysis of foundation without insulation mat

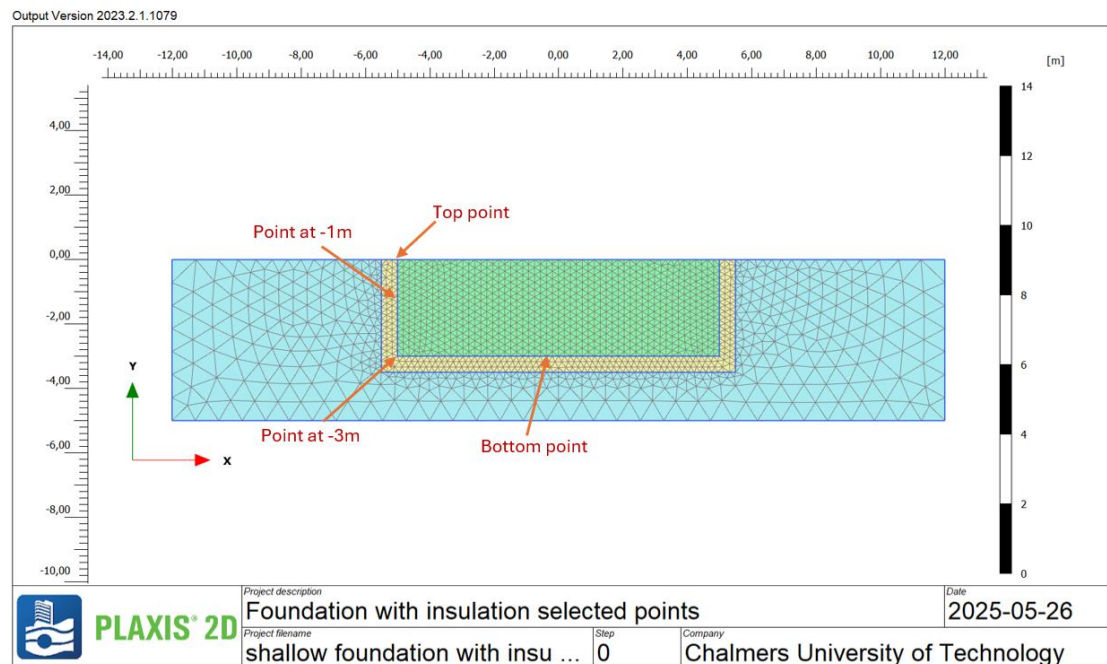


Figure 4.5 Selected points for analysis of foundation with insulation mat

4.2.1 Heat analysis of the test model

The temperature differences on day 359 shows the insulation mat stabilize the heat around the foundation more, see Figure 4.6 and 4.7. It reduces a lot of the heat moving between the foundation and the soil nearby, so temperatures at the foundation edges stay more the same – these are important places where damages can happen. This stable

temperature helps stop the freeze-thaw cycles that cause the ground under the building to move unevenly in cold places. However, our model maybe wasn't deep enough, and the elements used had restrictions, so the temperature at the soil's bottom is higher than expected.

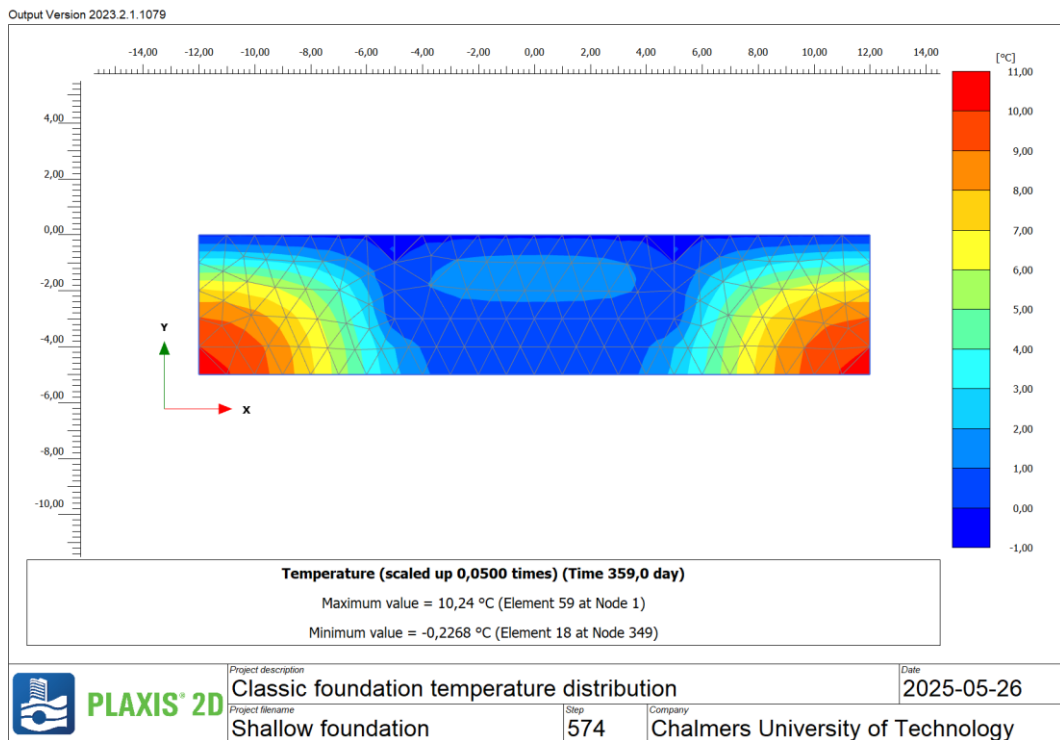


Figure 4.6 Temperature profile for the concrete foundation at the end of the 359 days

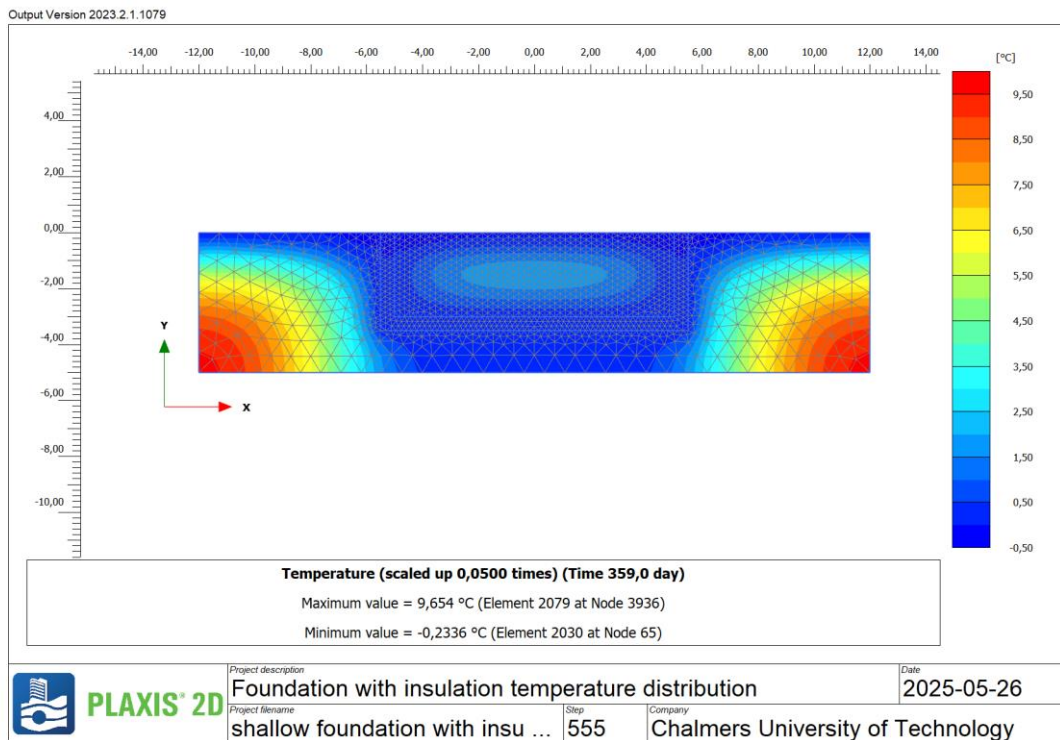


Figure 4.7 Temperature profile for the foundation with insulation mat at the end of the 359 days

Comparative analysis of temperature variations at four critical depths (ground level, -1 m, -3m, and bottom of foundation) shows that temperature variation around the insulated foundation is much stable and low compared to the one without insulation, especially below the depth of -1m, see Figure 4.8, 4.9, 4.10 and 4.11.

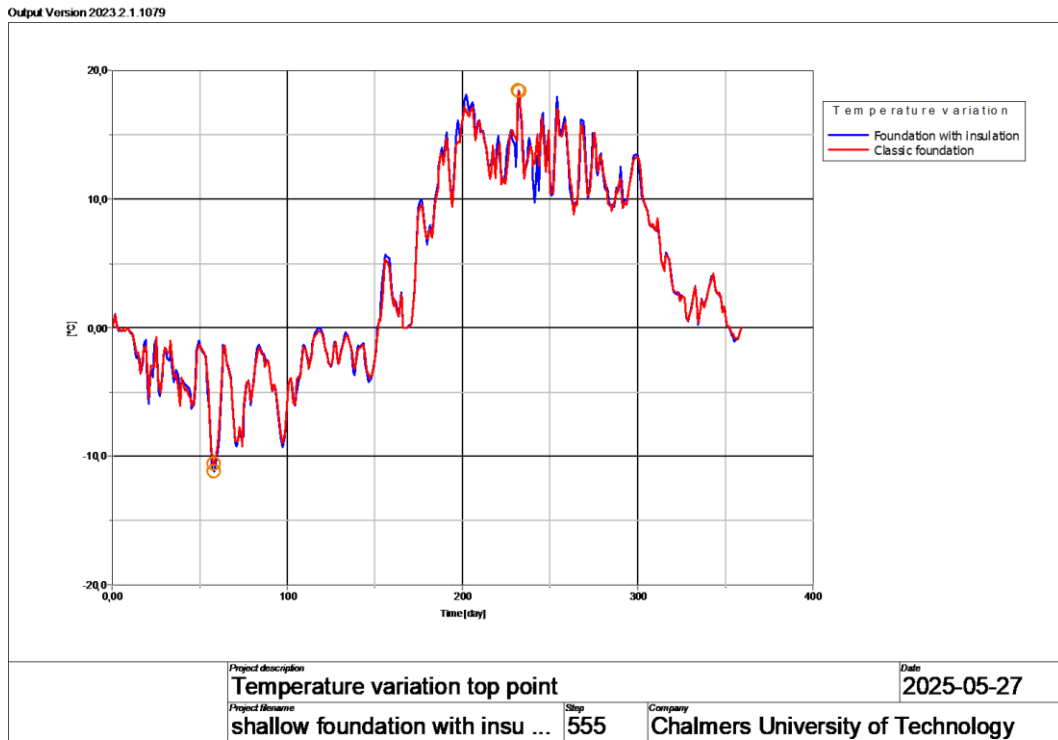


Figure 4.8 Temperature comparison at top point

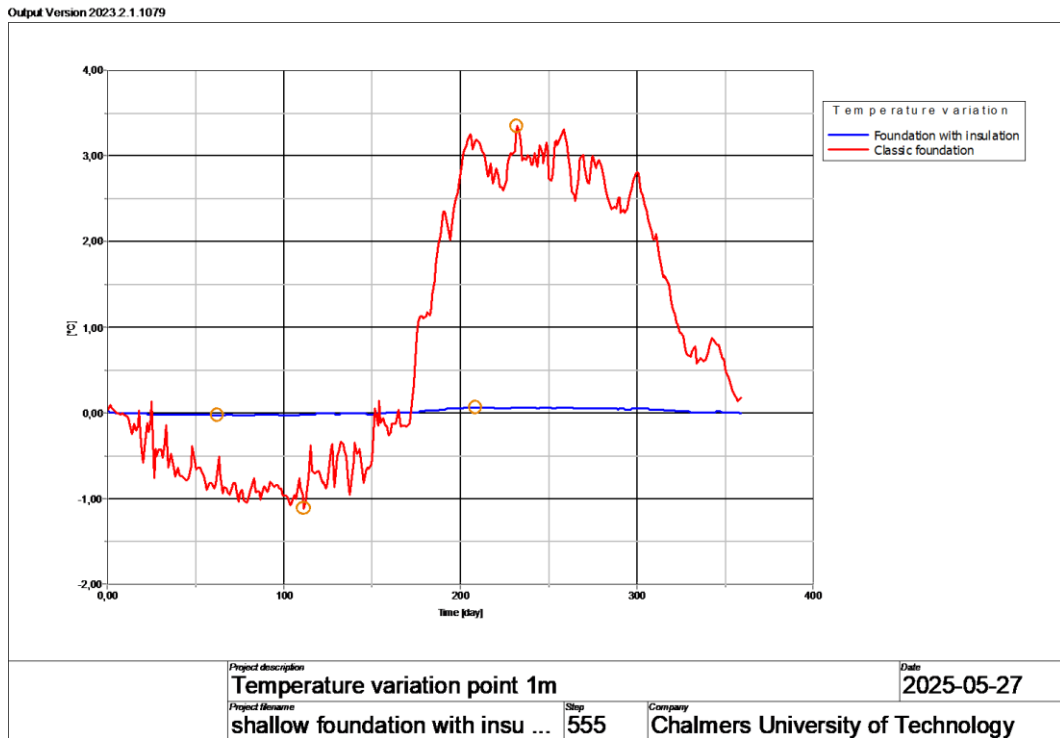


Figure 4.9 Temperature comparison at $z = -1m$ point

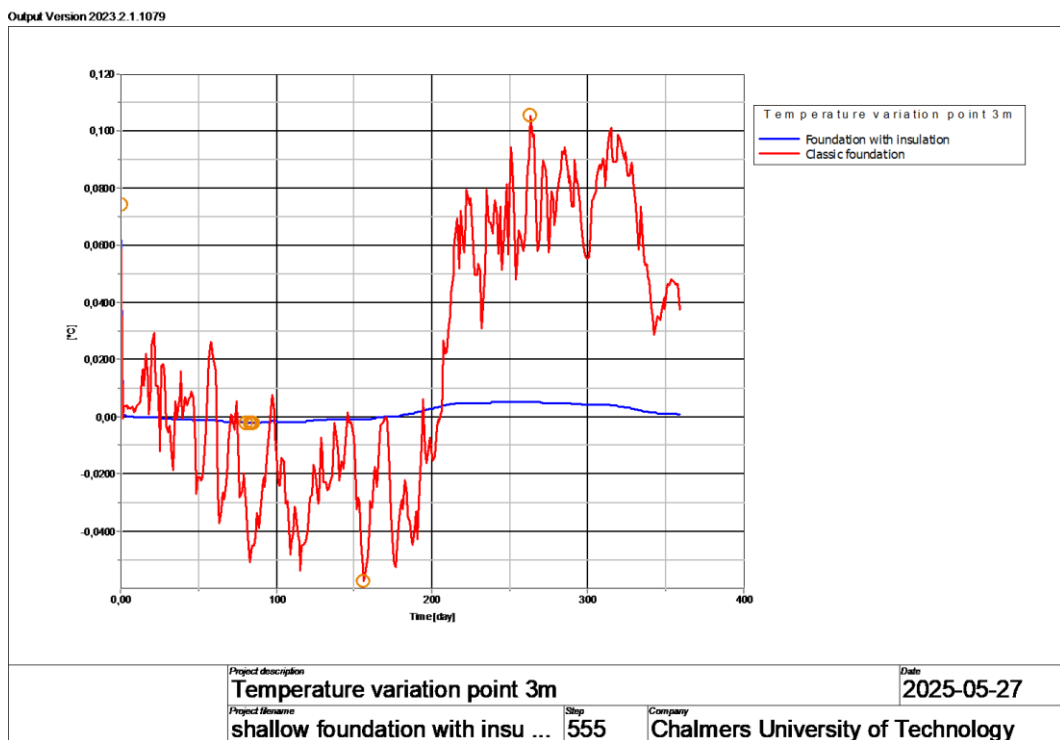


Figure 4.10 Temperature comparison at $z = -3m$ point

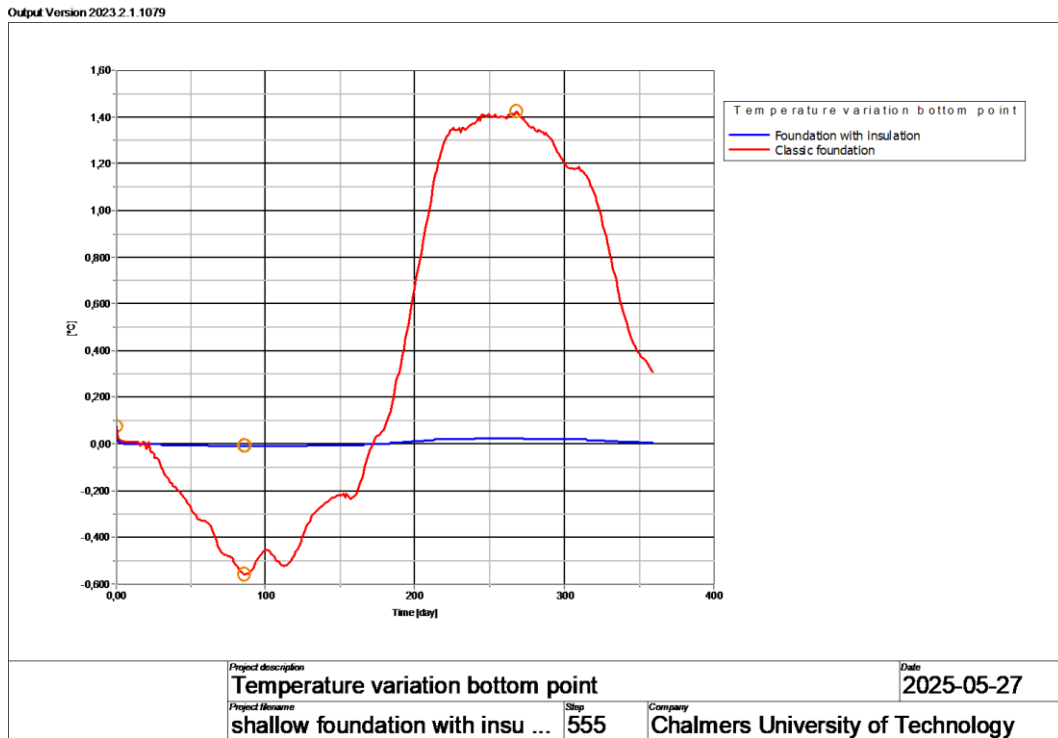


Figure 4.11 Temperature comparison at bottom point

4.2.2 Deformation analysis of foundation solutions

Total displacement over time at four same points shows both foundation types hardly move. The insulated one and the normal one have very small difference between them, however, the insulated foundation moves a smaller amount than bare foundation (0.0018 m vs. 0.0020 m), see Figure 4.12, 4.13, 4.14 and 4.15. Important is that because ground doesn't move very differently, it cannot alone prove the insulation stops damage. This is because ground moves in freeze-thaw places because many reasons.

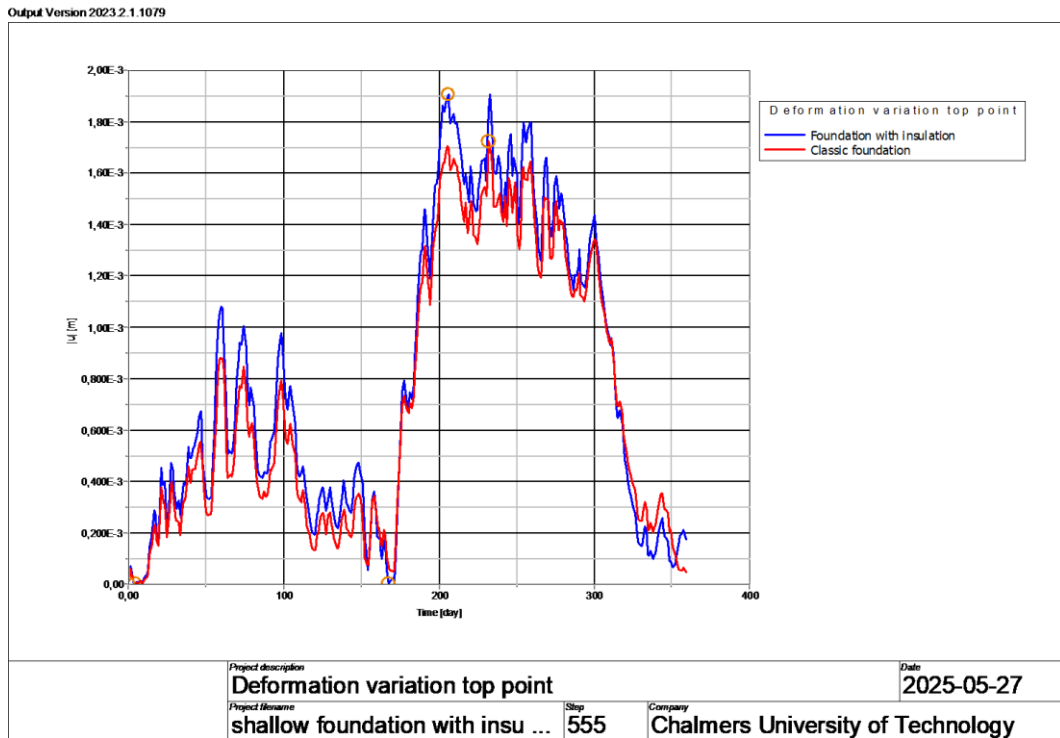


Figure 4.12 Total displacement comparison at top point

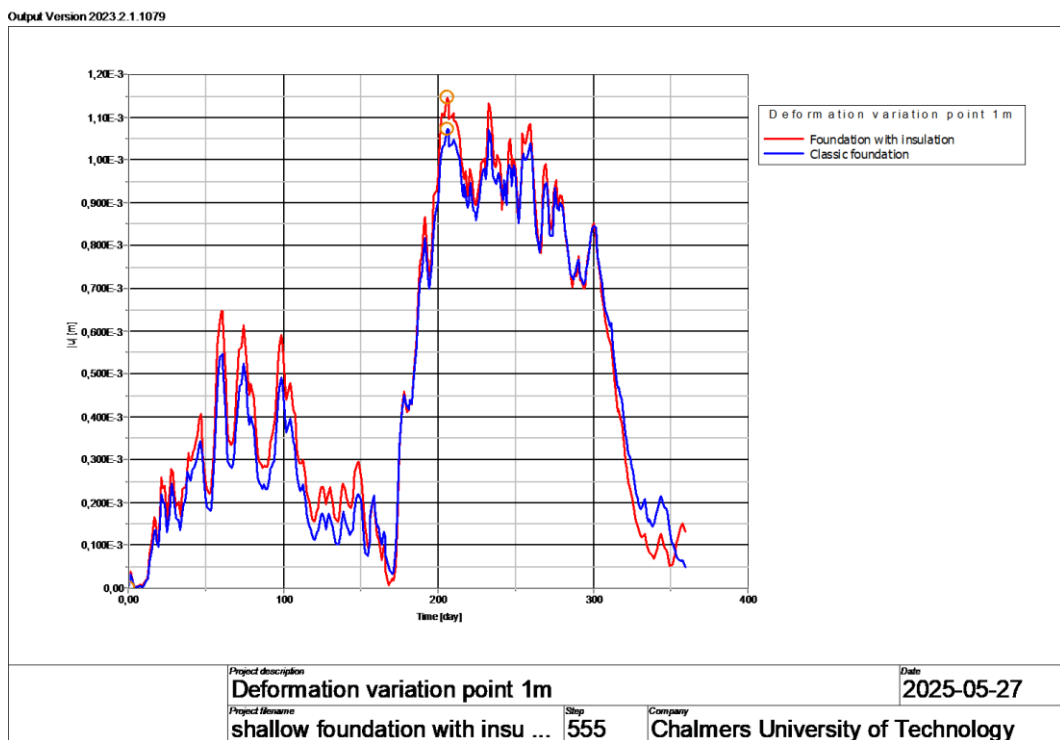


Figure 4.13 Total displacement comparison at $z = -1m$ point

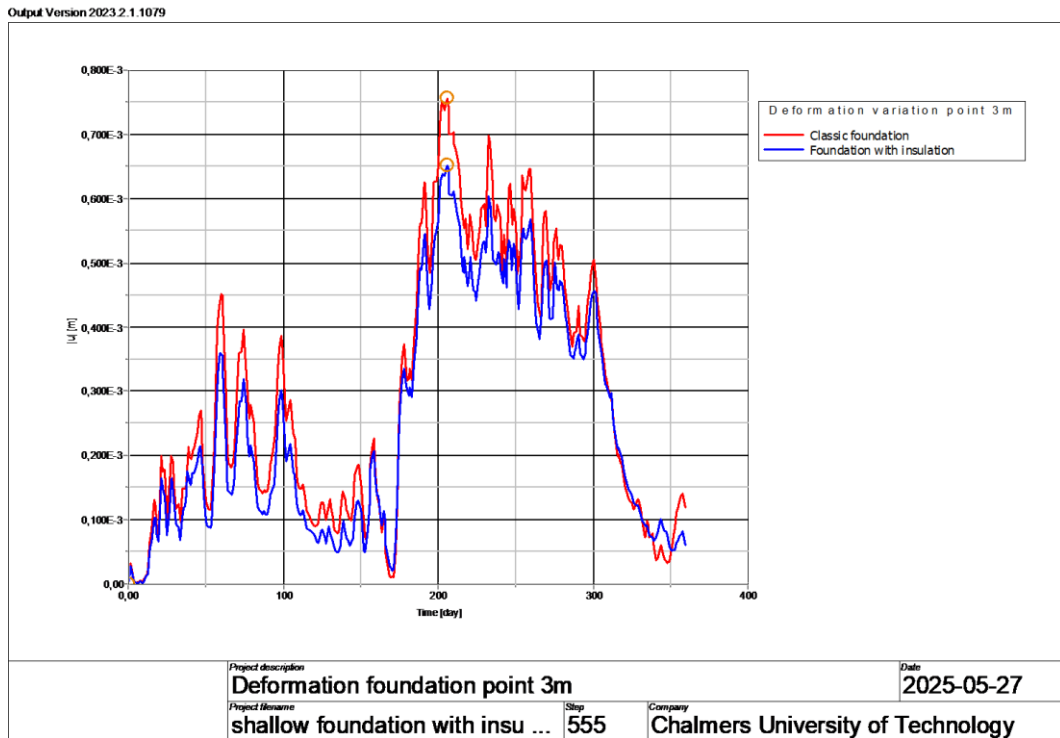


Figure 4.14 Total displacement comparison at $z = -3m$ point

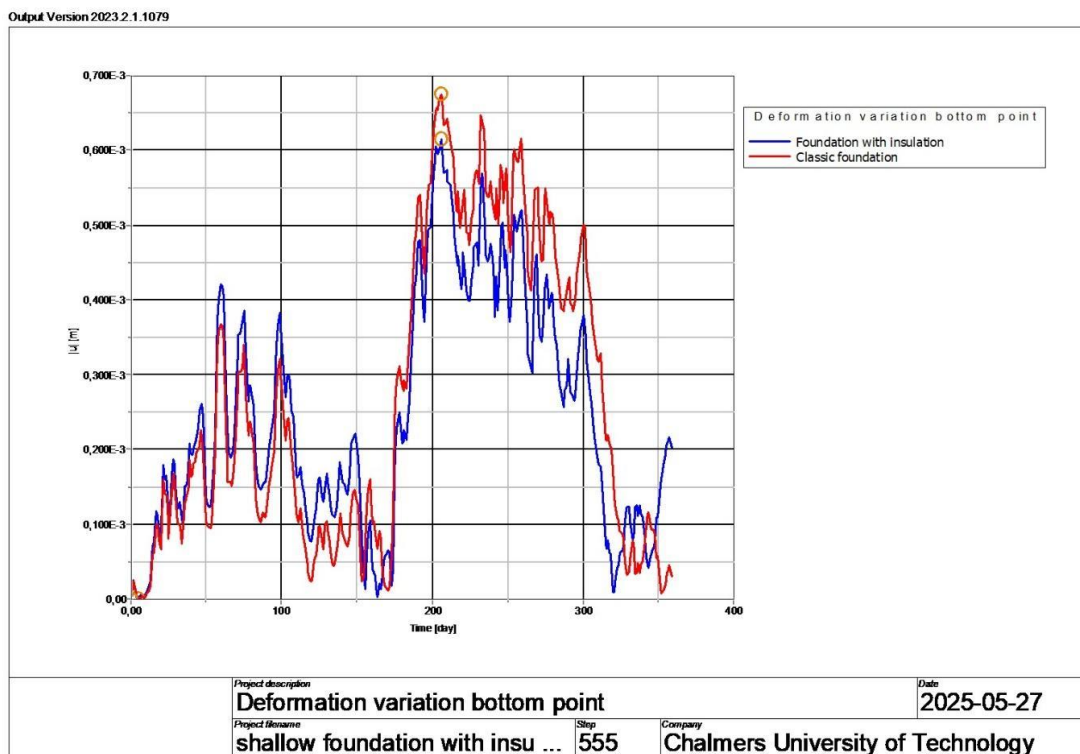


Figure 4.15 Total displacement comparison at bottom point

4.3 Construction window comparison analysis

Four critical points at the insulation edge were chosen: top, depth of -1m, -4m, and bottom. These points show how heat changes affect the foundation strength during building steps (excavation, foundation installation, superstructure installation). They

are key places where stress moves and where quick heat changes can cause issues because the foundation and soil react rapidly there, see Figure 4.16

By checking at temperature changes from March to August (foundation placed during spring thaw) and from July to December (structure built during autumn freeze), the study sees how the starting heat condition causes later effects. The spring cases have ground getting warmer. This reduces danger from temperature variation but makes settling worse because thaw happens faster. The autumn cases have much quick freezing. This causes immediate uneven ground rising

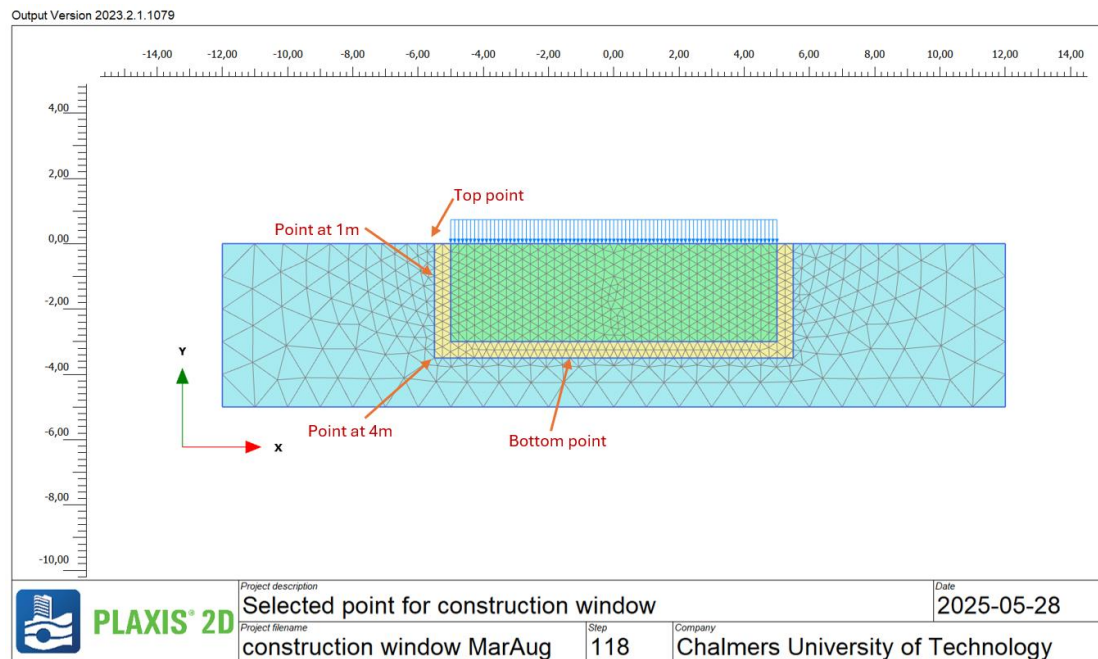


Figure 4.16 Selected points for analysis of foundation with superstructure affect

4.3.1 Heat analysis in different construction window

Measurements of subsurface temperatures at four deep levels shows that foundations built between March and August have much less thermal variation than those built between July and December. While the top layer of ground has large temperature variations in both time periods due to air contact, important subsurface points were very different: Below the depth of -1m, temperature variations getting more stable during March to August, see Figure 4.17, 4.18, 4.19 and 4.20. This is because the ground warms up during the thaw, which slows down the freezing process if the building is built before winter. Importantly, the insulation avoids the soil temperature around the foundation from varying too quickly, which getting stable after foundation installed. This indicates that the insulation mat has good performance on insulating the buildings from soil thermal variations. These findings support the idea that March to August is the best time to build, with the warm season and insulation working together to reduce thermal issues before a building is occupied.

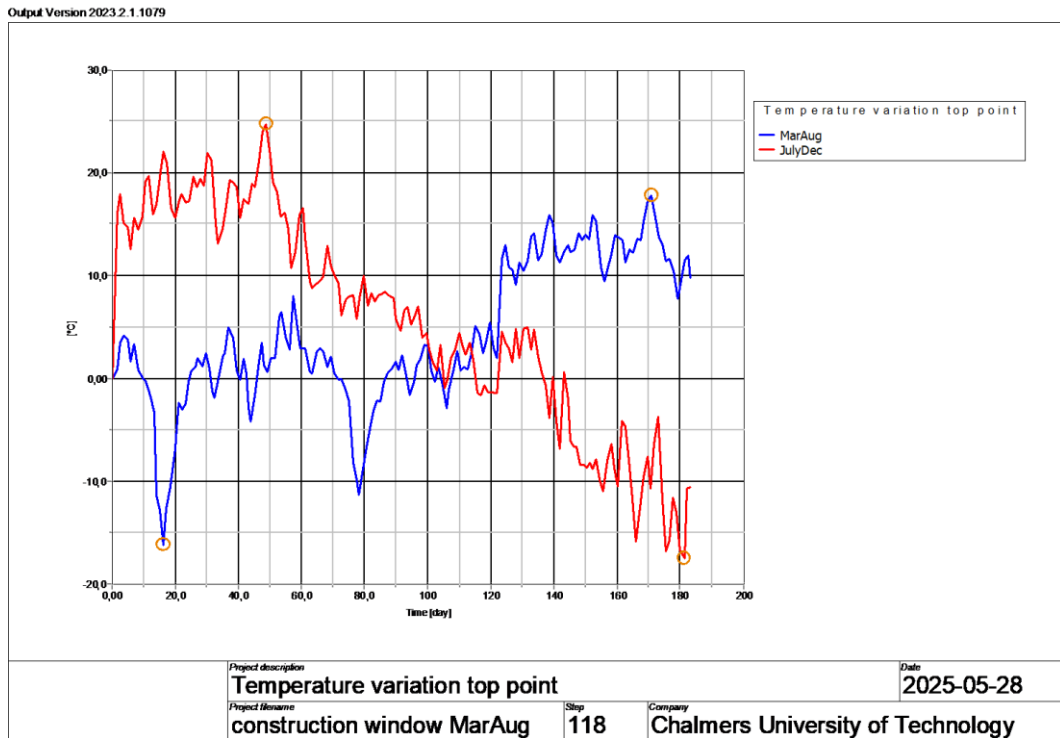


Figure 4.17 Temperature comparison at top point

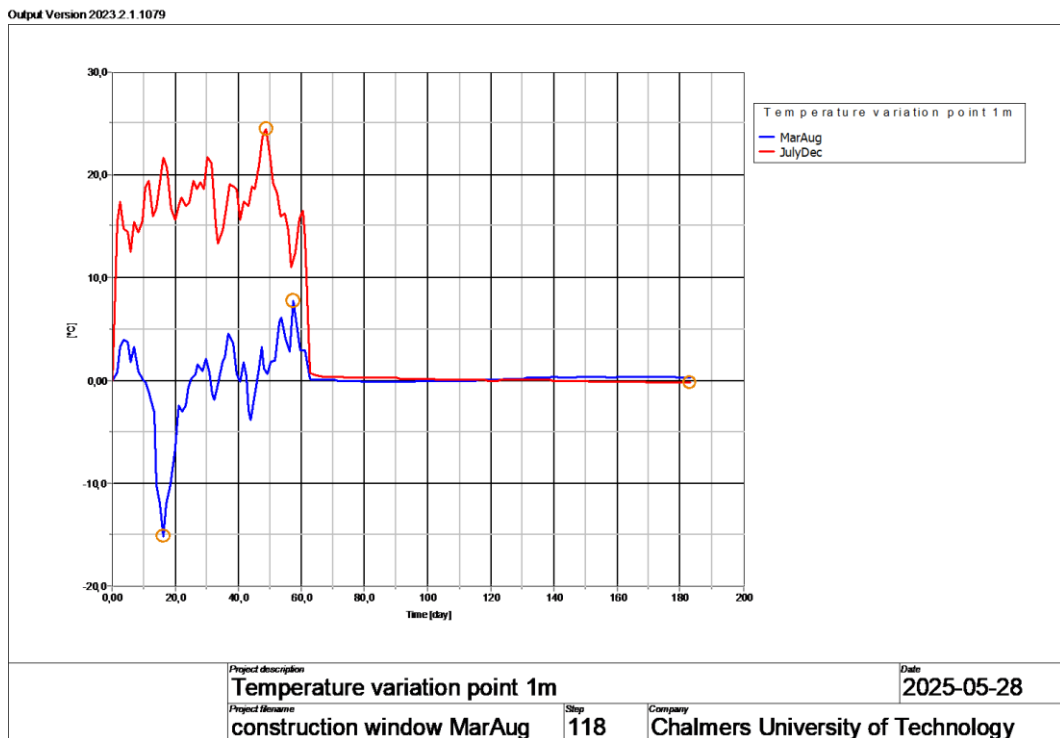


Figure 4.18 Temperature comparison at $z = -1m$ point

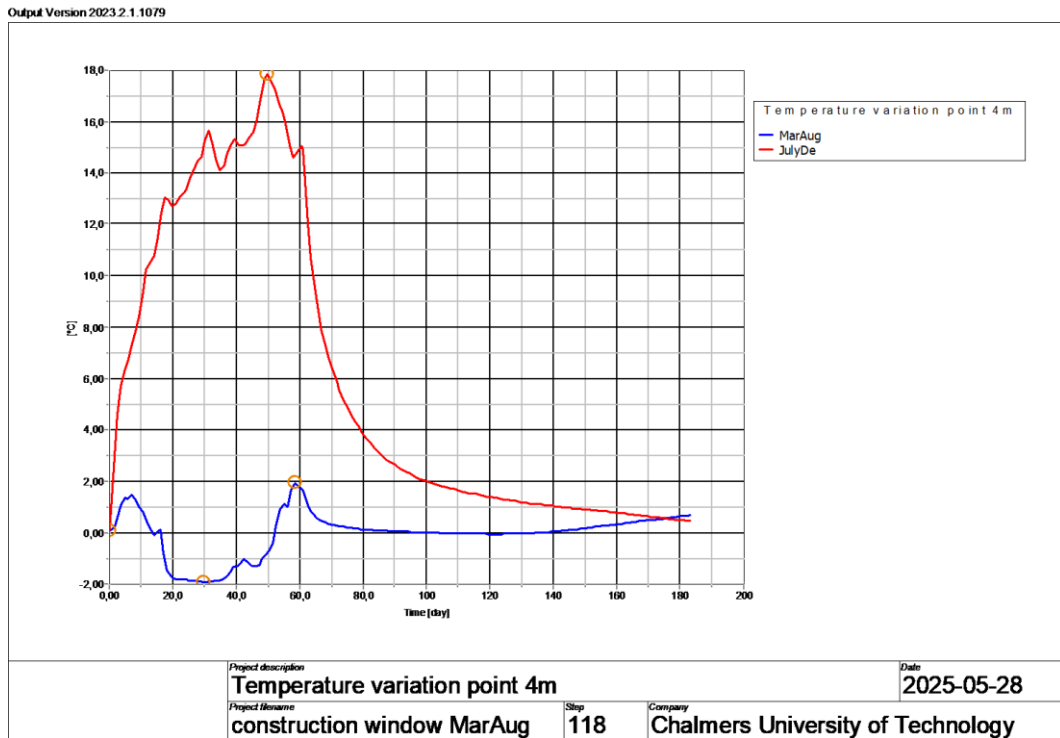


Figure 4.19 Temperature comparison at $z = -4m$ point

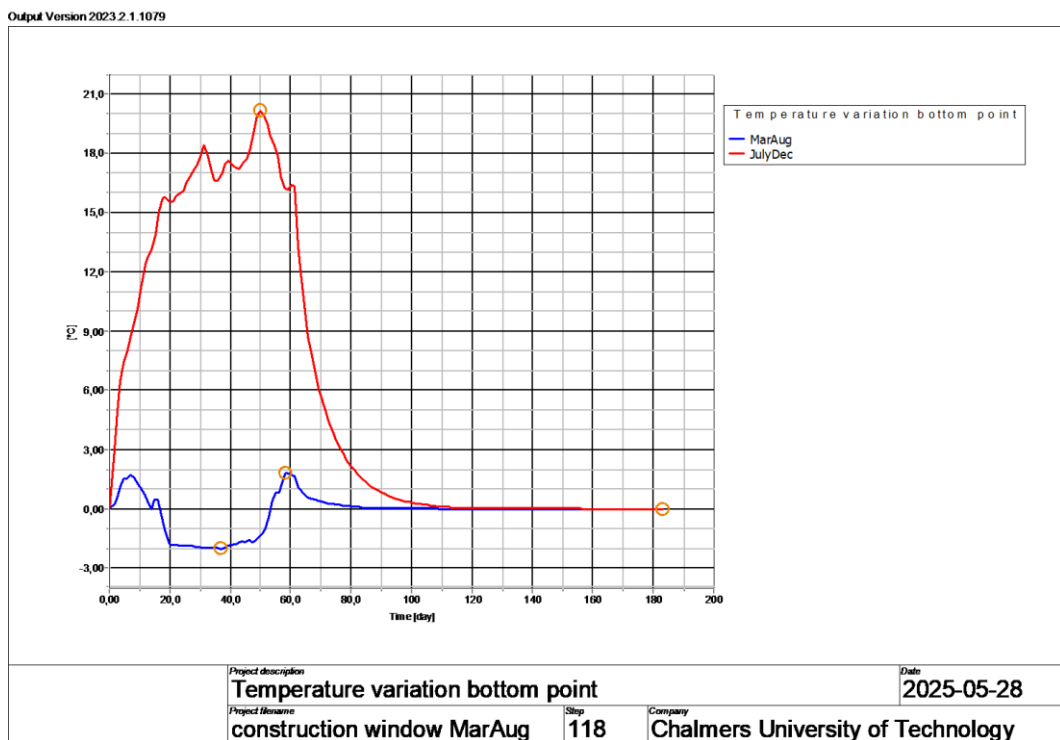


Figure 4.20 Temperature comparison at bottom point

5 Conclusion and further studies

5.1 Conclusion

Heat analysis shows insulated shallow foundations protect much better against temperature variation for buildings in cold Skellefteå than bare concrete foundation. This avoids the building reacting seasonal freeze-thaw cycles strong. This stable condition is key to prevent ice layers forming—which is main reason for frost heave. The C30/37 concrete stays strong even with big temperature changes, showing it has good performance for cold places, which has very less displacement during the simulated year.

March-August is best time to build, and foundations made this time have more stable heat transfer and less damage by temperature variation than other construction window. This uses ground warming during thaw to make stable condition quicker. This reduces ground moving before winter comes. Mixing right building time and insulation together lowers the temperature variation in the foundation material. It also means less need for expensive deep foundations or soil changing.

5.2 Limitations

Three main problems should be mentioned. First, the 2D PLAXIS model makes simple the real 3D heat actions, special at foundation corners where frost can go deeper. The main issue with the numerical work is that the domain size is too small, which can not show more reaction after long-term period. This simple model maybe not show real stress at edges, needing real field check.

Second, the model showed Skellefteå ground like same material everywhere. But real ground has different layers—like sand and clay. These can change how water moves, or frost pull happens locally. This model is not able to captured the real ground profile correctly.

LC³ cement was not used in this master study because it makes things too complicated. It is not common material yet, so hard to get and costly. Also, no experience working with it for cold places like Skellefteå. Without knowing how it behaves in real, it was safer to just used normal C30/37 concrete what we know works good here.

Last, the model run only for one year (2024). It cannot show long time climate changes. If ground ice melts more or freeze-thaw gets stronger later years, this maybe change water underground different way. It is more critical because of the long lifecycle of the superstructure.

5.3 Further studies

Further study needs to be done, LC3 cementitious material can be used for analysis if it can be the best choice for subarctic climate. Enlarging the domain size for long-term reaction and creating 3D models with more details to fix the simple 2D model problems include building shape and heat moving sideways to see mistakes at corners. Also, better show different ground layers using cracked rock networks. And run models for many years using future weather predictions—see how foundations hold up if freeze-thaw changes later.

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