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Review

Foundations in Permafrost of Northern Canada: Review of Geotechnical Considerations in Current Practice and Design Examples

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Abstract: In northern Canada where permafrost is prevalent, a persistent shortage of accessible, affordable, and high-quality housing has been ongoing for decades. The design of foundations in permafrost presents unique engineering challenges due to permafrost soil mechanics and the effects of climate change. There is no specific design code for pile or shallow foundations in northern Canada. Consequently, the design process heavily relies on the experience of Arctic engineers. To clearly document the current practice and provide guidance to engineers or professionals, a comprehensive review of the practice in foundation design in the Arctic would be necessary. The main objective of this paper is to provide an overview of the common foundations in permafrost and the geotechnical considerations adopted for building on frozen soils. This study conducted a review of current practices in deep and shallow foundations used in northern Canada. The review summarized the current methods for estimating key factors, including the adfreeze strength, creep settlement, and frost heave, used in foundation design in permafrost. To understand the geotechnical considerations in foundation design, this study carried out interviews with several engineers or professionals experienced in designing foundations in permafrost; the findings and the interviewees' opinions were summarized. Lastly, in order to demonstrate the design methods obtained from the interviews and review, the paper presents two design examples where screw piles and steel pipe piles were designed to support a residential building in northern Canada, according to the current principles for adfreeze strength, long term creep settlement, and frost heave. The permafrost was assumed to be at −1.5 °C, and the design life span was assumed to be 50 years. The design examples suggested that for an axial load of 75 kN, a 12-m-long steel pipe pile or a 7-m-long screw pile would be needed.

Keywords: frozen soil; foundations in permafrost; pile design; screw piles; climate change

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1. Introduction

About half of Canada's land is located in permafrost regions, extending across the Northwest Territories, Yukon, Nunavut, and the northern regions of most provinces. The growth and expansion of communities in the Arctic are increasing due to factors such as population growth and the need to utilize natural and mineral resources. This rise in activity requires new infrastructure and facilities, presenting new engineering challenges as unique problems arise when working with frozen soils [1].

Constructing on permafrost presents challenges, especially in foundation work, due to the unique properties of frozen soil. One of the challenges in dealing with permafrost is addressing old buildings that were constructed using inadequate methods and designing new constructions to mitigate the effects of climate change while also aiming to reduce building costs [2]. There is no design code for foundations in permafrost in Canada, so the design of deep or shallow foundations largely relies on the experiences of professional engineers or contractors.

A literature search suggests that there is no review on the practice of deep or shallow foundations in permafrost regions, particularly in northern Canada. The objectives of this review paper are to provide a comprehensive summary of the current criteria for foundation engineering in the permafrost regions of northern Canada. The present paper reviews the currently common foundation types and their pros and cons. Interviews were carried out with engineers and professionals residing in northern Canada or possessing expertise in designing foundations in permafrost. This paper compiles insights from these interviews to guide the practice of foundation design in northern Canada. Finally, a screw pile and steel pipe pile were designed and compared in accordance with the criteria for adfreeze strength, long-term settlement, and frost heave.

This review paper targets arctic geotechnical engineers, civil engineers, construction professionals, or property owners. It is anticipated to assist potential readers with a facilitated guide to foundation design principles.

2. Foundation Engineering in the Permafrost Regions of Northern Canada

Permafrost covers about 20% of the world's land area. When the soil temperature increases to 0 °C, the resistance of the soil decreases significantly due to the increase in unfrozen water and decrease in the adfreeze bond strength. Therefore, maintaining the lowest soil temperature possible is vital for foundations in frozen soils. Unfortunately, global warming is increasing the soil temperature in permafrost, which is causing a significant loss of soil-bearing capacity and shear strength, and increasing frost heave forces on foundations, posing a problem for both old and new buildings.

Zhang et al. [3] conducted a simulation to assess the dynamic changes in ground thermal regimes and permafrost conditions in Canada from 1850 to 2100. The simulation involved the use of software tools and included a comparison of six different global general circulation models of the atmosphere, considering depths up to 120 m at a specific site located at 60° N, 105° W. Table 1 summarizes the thermal variation predictions at a depth up to 40 m by three proposed models. The first model, from the National Center for Atmospheric Research (NCAR), shows the least thermal variation among those analyzed. The second model, the Coupled General Circulation Model (CGCM), presents intermediate variations. Finally, the CSIRO Atmospheric Research (CSIROM) model predicts the highest thermal variation. The results demonstrate that ground temperature variations can reach up to 7 °C at the surface and over 2 °C at a depth of 40 m. The author also explained that this tends to increase the thickness of the active layer and induce permafrost thaw.

Table 1. Changes in Air and Ground Temperatures from the 1850s to the 2090s (adapted from Zhang et al. [3]).

Soils Depth	Temperature Increases (°C)			
	From 1850s to the 1990s	From 1990s to the 2090s		
		NCAR	CGCM	CSIROM
0 m	1.6	2.8	3.8	7.0
0.2 m	1.3	2.2	2.7	5.1
2 m	1.0	2.2	2.5	4.6
10 m	0.8	2.0	2.3	3.9
40 m	0.3	1.4	1.6	2.3

A study conducted in Russian territory by Streletskiy et al. [4] showed that climate change has led to an increase in the active layer and a decrease in the bearing capacity of foundations, potentially damaging over 50% of residential buildings and approximately 20% of commercial and industrial structures due to significant permafrost degradation by the middle of the 21st century. The total estimated cost of buildings and infrastructure due to permafrost degradation is almost USD 250 billion, imposing a significant economic burden on the nation.

The first constructions in northern Canada were limited to small buildings supported on pads or footing only in areas with shallow deep permafrost due to the frost action. Therefore, as the community and industrial development expanded, there was a need for new construction methods to support higher loads and withstand frost action forces [5]. Since the 1950s, the use of piles has been growing because they can be long enough to have adequate embedment, providing a stable foundation capable of resisting forces and displacements related to frost heaving [6]. The constant pursuit of cost-effective solutions in permafrost regions has led to an expansion in the variety of foundation options, not only in deep foundations but also in shallow foundations. Furthermore, techniques to lower the soil temperature are being implemented, such as the application of thermosyphons in the foundations.

The purpose of this section is to provide a comprehensive overview of the practice of foundation engineering in northern Canada. The objective is to examine the prevalent and promising methods, emphasizing their distinctive characteristics, advantages, and disadvantages.

2.1. Existing Guides to Foundation Practice in Canadian Permafrost

Despite the absence of a specific design code for foundations in Canadian permafrost, manuals are available to assist engineers and builders. In Canada, geotechnical engineers frequently refer to the Canadian Foundation Engineering Manual (CFEM) regarding the design of foundations underpinning commercial or residential structures. CFEM 2023 [7], the latest version of the manual, outlines the permafrost investigation techniques and general design considerations of foundations for building structures.

The Canadian Standards Association (CSA Group) has published some manuals related to permafrost and foundations. One of them addresses moderating the effects of permafrost degradation on existing building foundations [8]. This manual discusses the factors that cause permafrost degradation, outlines techniques to mitigate these effects, and provides insights into frozen soil properties and various foundation types.

CSA PLUS 4011.1 [9], a design and construction report, offers detailed technical information considering various foundation systems, ground conditions, and different scenarios in permafrost. The guide includes a review of the distribution and climate conditions of permafrost in Canada. Additionally, the report correlates how climate and soil conditions impact foundations in permafrost, providing insights into the relationship between environmental factors and foundation performance in these regions.

In 2017, the National Standard of Canada published guidance on specified minimum requirements for geotechnical investigations for buildings in permafrost [10]. Furthermore, the Government of the Northwest Territories published a manual of building practice for northern facilities [11]; this publication serves as a technical reference and design guide to assist building developers in frozen soils, addressing not only foundations but also encompassing all stages of building construction.

The literature provided valuable guidance on foundations in permafrost and detailed considerations for various situations. However, none of them provide a practical method to follow and design in permafrost. Consequently, engineers may interpret and design foundations in different ways based on their knowledge and expertise.

2.2. Thermosyphon Method

The thermosyphon method is commonly used to maintain a low-temperature permafrost temperature, particularly against the hot seasons of the year and climate change. Lower temperatures prevent the frost action effect and maintain the soil's adfreeze bond capacity by preventing its temperature from rising. This method utilizes the natural circulation of a fluid, such as water or a refrigerant, to transfer heat from the warm soil to the air. The heat transfer occurs as the fluid rises to the surface and releases heat, and then sinks back to the deeper, colder layer, where it picks up more heat. This cycle continues until the soil temperature reaches a state of thermal equilibrium with the air. The thermosyphon method can be applied to all types of foundations in the Canadian Arctic.

Thermopile is a method in permafrost regions that combines the features of both a thermosyphon and an adfreeze pile. Thermopiles can be implemented using either steel pipe piles or screw piles. These structures serve to transfer heat from the ground to the atmosphere, helping to maintain low soil temperatures and preserve the adfreeze bond capacity of the soil. The thermopile comprises two primary components: an evaporator section in the ground and a radiator section above the ground. The evaporator section absorbs heat from the surrounding soil, while the radiator section dissipates this heat into the air (Figure 1). This passive heat transfer increases soil strength and reduces the rate of pile creep, making the thermopile an effective solution for foundation design in permafrost regions [12].

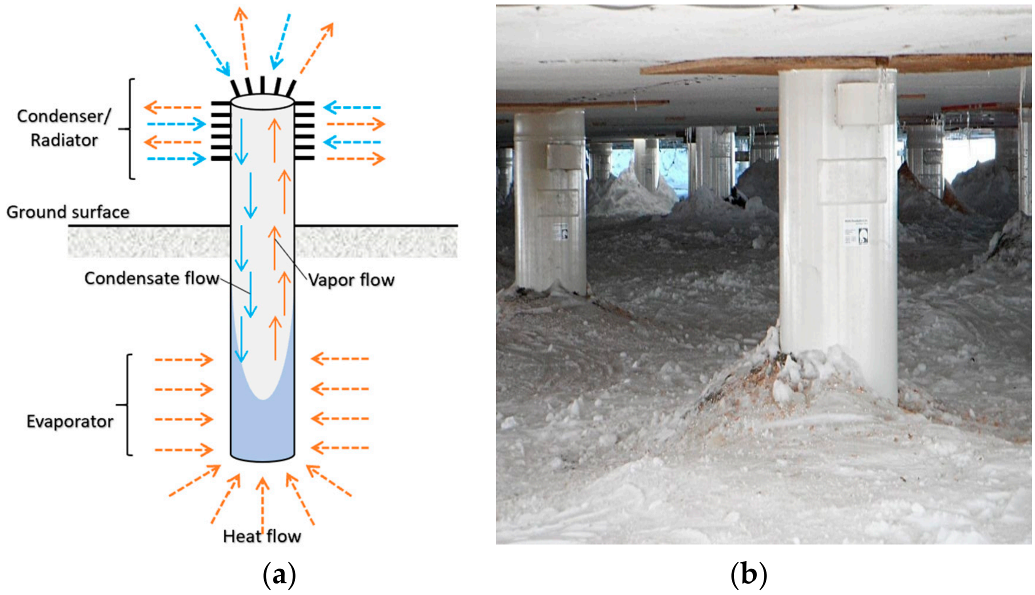
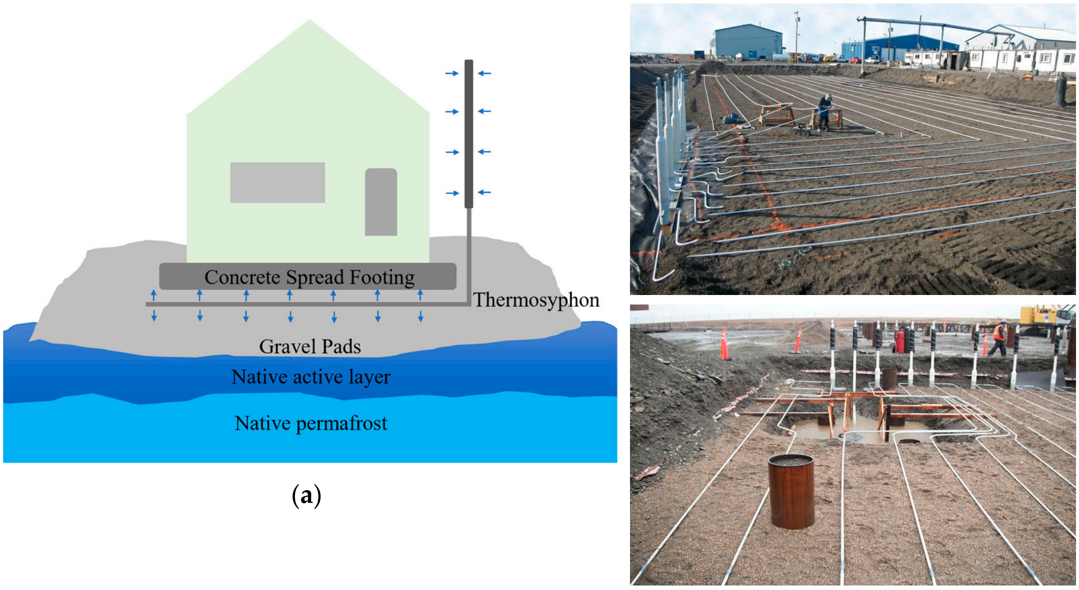


Figure 1. (**a**) Schematic of passive thermopile operation (adapted from Wagner [13]); (**b**) Thermo Helix-Piles used in a school in Kipnuk, AK. Courtesy of https://arcticfoundations.com/ accessed on 16 December 2023.

Another method of utilizing thermosyphons to cool the soil involves using them in the form of a flat loop. Unlike traditional thermopiles, which only cool the circumferential area around the pile foundation, flat loop thermosyphons aim to cool down the entire footprint of the building. This design involves creating a large, flat loop of pipes buried within the permafrost layer. These pipes continuously circulate a refrigerant to transfer heat away from the soil underneath the building, keeping the permafrost layer cool (Figure 2). This method may be particularly effective for large structures, such as factory buildings, where maintaining a consistent temperature throughout the entire perimeter is important for preserving the stability of the structure.



(**a**) (**b**) (**c**)

Figure 2. (**a**) Illustration of a concrete spread footing foundation with a thermosyphon (Drawings are not to scale); (**b**,**c**) Use of Flat Loop Thermosyphons in Nome and Point Lay, Alaska. Courtesy of https://arcticfoundations.com/ accessed on 16 December 2023.

2.3. Spread Footings

Shallow foundations, such as spread footings, are also used in permafrost regions due to their relatively simple design and cost-effectiveness. However, designing and constructing footings in permafrost presents several challenges. The freezing and thawing of soil can cause significant movement and instability, making it difficult to predict the behavior of the foundation. As a result, a spread footing is generally designed to support smaller loads and is usually not suitable for larger structures or heavy loads. Additionally, the depth of the active layer, which is the layer of soil that thaws and refreezes each year, can vary greatly, and if it is too deep, it can become impractical to use footings as they must reach the permafrost layer to provide adequate support [14].

To address these challenges, various techniques have been developed to improve the performance of footings in permafrost. For example, it is essential to minimize soil disturbance during excavation and construction and allow the soil to freeze back quickly after construction. One approach is to excavate and build the foundation in the fall when the soil is already starting to freeze or to use insulation and thermal barriers to reduce heat loss from the structure [15].

Another important consideration is the material used to backfill the foundation. Gravel or sandy soil is typically used, as it is less prone to freezing and thawing than other types of soil. Additionally, a crawl space is often incorporated below the floor to allow for ventilation and dissipation of heat. Furthermore, protecting the columns and footings with a low-adhesion coating helps prevent adfreeze uplift forces.

Figure 3 illustrates an example of a possible footing foundation with techniques to mitigate frost heave effects. The footing is placed as deep as possible into the permafrost. The natural soil beneath and around the foundation should be replaced with non-frost-susceptible fill to reduce frost heave. A polyethylene sleeve is added to minimize the uplift force caused by frost heave. Insulation is applied on top of the soil, and a crawl space is included to reduce the soil temperature and prevent thawing.

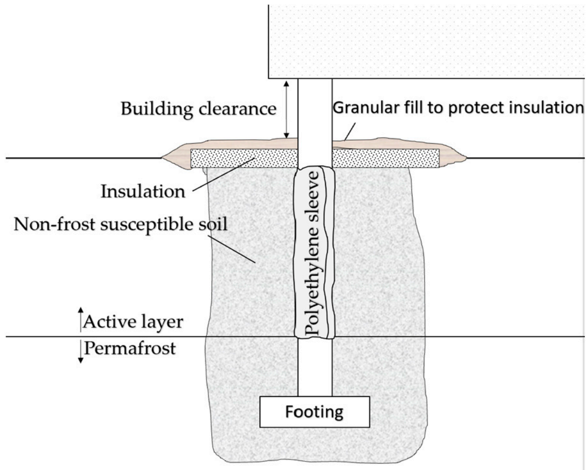
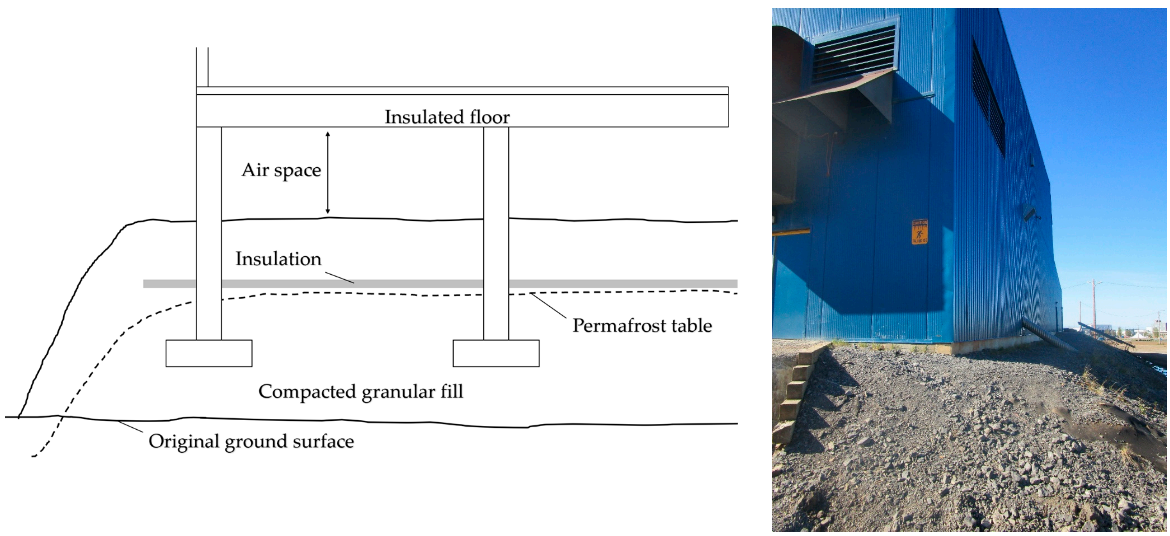


Figure 3. Example of a possible footing foundation (adapted from McFadden [16]).

Backfilling the footing with non-frost susceptible soils (NFS) may not be sufficient to combat the freeze–thaw effect, as the surrounding soils will still be affected by this process. One option is to replace all the active layer soil with NFS soil and embed the footing in the permafrost or ground. However, more often, a layer of NFS soil is added on top of the original soil, causing the permafrost layer to rise. The use of insulation, ventilation ducts, crawl spaces, and thermosyphons should be considered to decrease the temperature of the soil and increase its stability.

Figure 4a depicts a schematic example of a footing embedded in permafrost and insulated by a gravel pad on the ground surface. In this example, the elevation of the permafrost layer to a new layer between the insulation and the footing is observed. This can be explained by the addition of a thick layer of NFS, crawl space, and insulation, which protect the lower layers to remain at temperatures below 0 °C throughout the year. Figure 4b shows an application example for this footing design. In this case, a building in Inuvik was constructed with spread footings covered by a layer of gravel and equipped with ventilation ducts. It is possible that insulation was also placed on top of the footing to ensure thermal stability.



(**a**) (**b**)

Figure 4. (**a**) Example of footing in permafrost embedded in an insulated gravel pad on the ground surface (adapted from Johnston [17]); (**b**) a building in Inuvik supported on spread footing covered by gravel with possible ventilated ducts.

For shallow foundations, whether involving insulation, ducts, or thermosyphons, periodic evaluation is necessary to ensure that all mechanisms are functioning as designed. Malfunctioning of any component or unforeseen temperature rise can be sufficient to damage the entire structure. For example, a hospital facility that was built in 2004 in northern Canada with concrete footings faced problems with several pipe loops of the thermosyphons, reducing the cooling capacity of the system and affecting the foundation's freeze-back. This issue affected the walls and floors above and even jammed an emergency exit [18]. Therefore, the application of thermosyphons alone does not solve all problems, and periodic monitoring of temperature and refrigeration equipment is still necessary.

2.4. Wood Blocking Method

The wood blocking method is a technique used to remediate building foundations that have been damaged by frost action. It involves replacing the original foundation, usually timber piles, with a wooden blocking system to prevent further frost damage. One of the main advantages of the wood-blocking method is its cost-effectiveness compared to other remediation techniques. The method utilizes locally sourced wood and does not require heavy equipment, making it a viable option for buildings in remote areas. Additionally, it is more sustainable than other techniques, such as concrete or steel piles for foundations. The blocking system can be customized to fit the specific needs of the building and the surrounding environment. This adaptability makes the wood-blocking method a versatile option for remediating buildings on different soil types, uneven ground, or high crawl spaces.

In a recent study by Liu et al. [19], the wood-blocking method was evaluated for its performance in remediating a building in the Canadian Arctic (Figure 5). The study monitored temperature, moisture content, and building movement over two years.

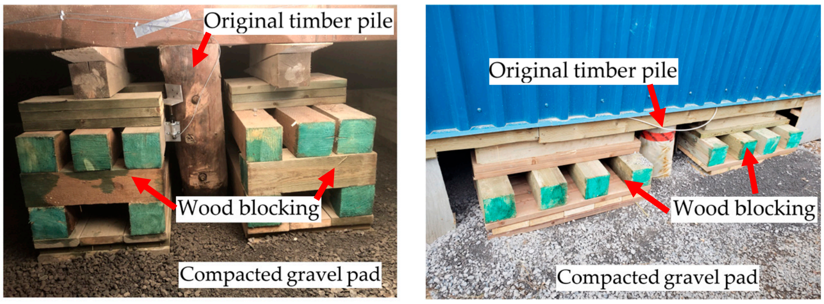


Figure 5. Wood blocking system supporting a building structure in Inuvik, NWT, Canada.

Liu et al. [19] demonstrated that the wood-blocking method effectively prevents lateral movements of a building. However, seasonal weather caused a small subsidence, leading to a gap of up to 7 mm in some blocks over 2 years (Figure 6). The positive aspect is that the wood blocking and the structure are connected by wood wedges that can be easily readjusted after seasonal movement. Therefore, the wood-blocking method can be a cost-effective and efficient solution for repairing damages caused by the freeze–thaw effect in the Canadian Arctic and other cold climates. The use of locally sourced materials and adaptability make it a sustainable and flexible option for remote areas with limited resources.

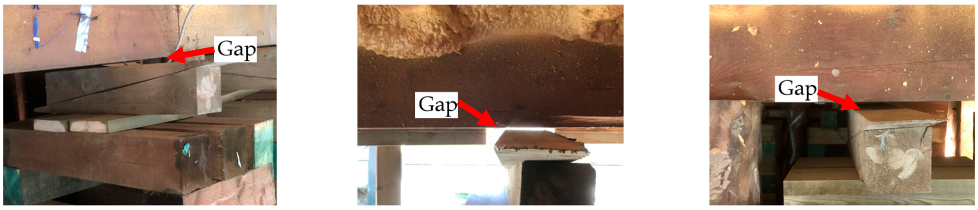


Figure 6. Vertical gaps caused by the seasonal weather between the wood block wedge and building base floor beam.

2.5. Jack Pads

Screw jacks are an economical foundation method in permafrost. To install them, one simply needs to select the number of supports required to sustain the foundation and install them directly into the soil without considering the active layer or soil temperature. It is recommended to level the ground and replace the surface layer with NFS soil. Additionally, a wooden or metal sheet must be placed beneath the screw jack to increase the contact surface area between the load transmitted by the jack and the soil (Figure 7). However, each support behaves differently due to the frost and thawing cycles, which can cause differential settlement in the building, resulting in cracking and structural damage.

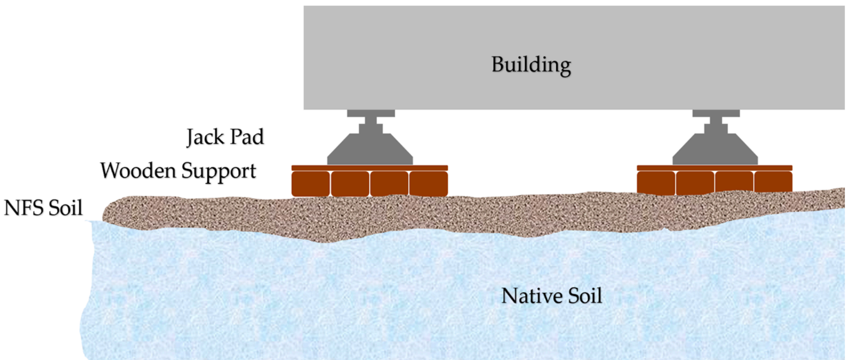
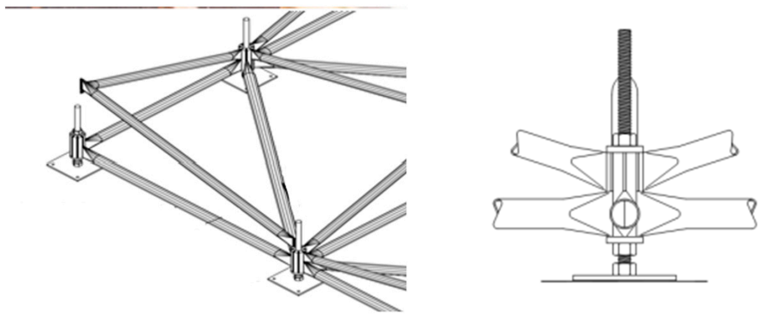


Figure 7. Example of jack pads in permafrost.

Periodic adjustment of the jacks may be necessary to prevent damage to the structure. Generally, screw jacks are used for light loads, making them a popular choice for residential buildings. However, they may not be suitable for larger or heavier structures, as the load capacity of each jack is limited. Additionally, the installation process can be time-consuming and require a significant amount of labor. As with any foundation type, proper design and installation are crucial to ensure the safety and stability of the structure. This technique is also important for foundation repairs or if an extra crawl space is needed. [20].

2.6. Space Frame System

A new technique for shallow foundations known as the space frame system has been developed to overcome the challenges posed by frost heave. This system is composed of interconnected steel or aluminum members that form a framework or grid structure that supports the building or structure (Figure 8). The space frame system is designed to distribute the load of the structure across a larger area, reducing the pressure on individual points and providing a more stable foundation. The space frame system ignores the soil conditions and is placed directly on top of the ground [21].

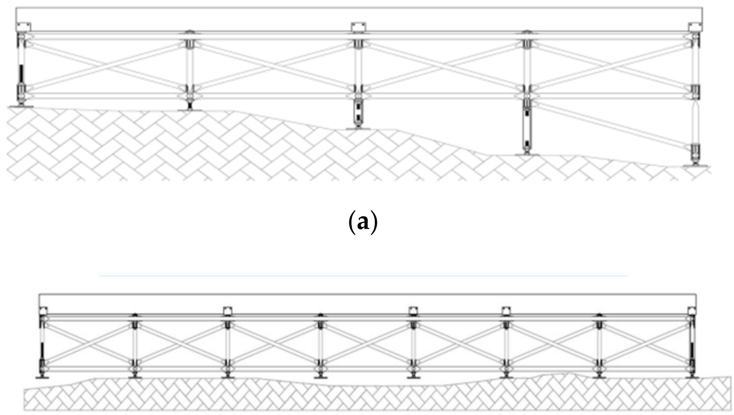


(**a**) (**b**)

Figure 8. Schematic detail showing: (**a**) bottom hub and joints and (**b**) assembled connections enabling structural movement and flexibility. Courtesy of http://multipoint-foundations.com accessed on 16 December 2023.

One of the advantages of the space frame system is its efficient use of space, as it eliminates the need for excavation of large amounts of soil or the use of heavy equipment. Additionally, a sand or gravel pad is not necessary. Simply clear and level the area to facilitate the construction of the foundation frame, avoiding the high costs associated with soil excavation or the application of piles and the equipment required to access permafrost areas. Additionally, this system is versatile and can be used for a wide range of building types, such as commercial buildings, industrial buildings, and residential buildings [22].

The space frame system can adjust the frame according to the displacement of the structure, which is important when working in frozen soils. The system is designed to accommodate movement by using flexible connections and joints between the members of the frame (Figure 9). These flexible connections and joints allow the structure to move and shift without causing damage to the system, making it a suitable solution for foundations in permafrost areas [21].



(**a**)

(**b**)

Figure 9. (**a**) Foundation detail in slope terrain; (**b**) foundation detail functioning as a rigid slab under frost heave. Courtesy of http://multipoint-foundations.com accessed on 16 December 2023.

The space frame system can adapt its frame to align with the structure's displacement, which is an important consideration when dealing with frozen soils. The system's design incorporates features that allow for movement by utilizing flexible connections and joints among the frame members (Figure 8). These flexible connections and joints not only enable the installation of the foundation on uneven ground but also facilitate adjustments after any displacement caused by frost heave [21]. Even if the pads lose contact with the soil and their connections are not adjusted, the load distribution among the multiple pads in direct contact with the ground remains effective. This is because the foundation frame's ability to bridge soft spots and function as a rigid slab under frost heave and thaw conditions helps preserve the structural integrity of the building (Figure 9b).

2.7. Timber Piles

The first use of piles in the Canadian Arctic was timber piles because of their availability. They typically range from 6 to 15 m in length and have diameters between 150 and 250 mm. One advantage of timber piles is their rough surface, which increases their shear strength capacity. Additionally, they have better insulation properties than steel piles, which is important for hindering the flow of warmer temperatures from the surface to the soil. Moreover, in some remote locations, heavy shipments may be inaccessible for part or all of the year, making the application of other foundation types or technologies challenging. This difficulty in transportation and accessibility makes timber a practical choice as it is readily available in the natural environment and helps save on transportation costs.

However, a concern arises regarding the contact of the timber with the active layer, where ice melts and refreezes. When the ice melts, water penetrates the wood, causing it to swell. During the winter, the wood dries and shrinks. This cycle of swelling and shrinking can cause cracks, which, after repeated episodes, will grow, damaging and compromising the performance of the pile.

Protecting the timber from water is a common attempt to maintain the integrity of the pile, for example, using tuck tape around the pile from the ground to the depth of the permafrost table (Figure 10). However, the soil temperature may change due to reasons such as global warming or soil disturbance, leading to an increase in the depth of the active layer, and creating a gap for water infiltration. Predicting the changing temperature accurately is difficult, and it is not possible to cover the entire pile with tuck tape, as it would lose its adfreeze bond capacity, thereby undermining the reliability of this method.

(**a**) (**b**)

Figure 10. (**a**) residential construction using a timber pile foundation in Inuvik, NWT, Canada; (**b**) tuck tape protecting timber from the water.

2.8. Steel Pipe Piles

Steel piles have been a viable solution to replace timber piles in the Canadian Arctic for several decades. Usually, steel piles have less roughness than timber piles; however, the capacity to build larger steel piles helps reach deeper bedrock which can provide higher adfreeze strength. Steel piles can be driven or backfilled. The first ones are usually H-piles; they can be installed two or three times faster than the backfill type and cause less physical and thermal disturbance in the soil. Thus, driven piles can be loaded sooner than other ones. However, the strength of permafrost will rarely allow the use of driving equipment, such as a vibratory hammer, and will likely cause the pile to be crushed [23,24].

A backfill pile is constructed by inserting a freeze pipe into a drilled hole that is larger than the pile diameter. Normally, this results in an annular void between the pipe and the soil (Figure 11). This void can be filled with sand and water or grouted with cement. However, this process can cause significant physical and thermal disturbance in the soil.

The drilling process and the vibration of the backfill to remove void spaces can disturb the soil, causing settlement and warming the soil. Additionally, the backfill temperature should be above freezing, and in the case of grouting, the temperature remains higher due to the cement curing. All these processes contribute to warming the soil surrounding the pile, reducing the shear strength capacity of the pile and potentially causing settlement. To effectively apply a load, the soil temperature needs to return to its original state, freezing back and, thereby, restoring the strength and stability of the foundation. During the winter, heat dissipates faster, resulting in a shorter freezeback time, while during the summer, the freezeback time will depend on the cold reserve of the permafrost below the thawed active layer.

Figure 11. Typical steel pipe pile foundation in permafrost with backfill.

Biggar and Sego [25–27] highlighted the impact of using a cementitious grout backfill in enhancing the load-carrying capacity of steel pipe piles in low-salinity frozen soils, particularly where conventional sand backfilled piles were limited by adfreeze bond strength. They demonstrated that grout backfill, especially when combined with sandblasting the pile surface, could considerably increase the pile capacity. This approach underlined the importance of backfill material selection and surface preparation in the pile performance. Biggar and Sego [27] carried out a comprehensive laboratory testing program on the long-term settlement rate of steel pipe piles in saline soils. They then summarized the effects of soil temperature, salinity, and water content on the rate of settlement. The results provided practical guidance for the design of steel pipe piles that may be governed by settlement.

Artificial freezeback has been used for a long time to restore the ground temperature and, thereby, restore the frozen soil properties. Thermopile is one of the oldest examples of the application of artificial freezeback in the soil. It can be used with glycol lines that freeze the backfill during, but not after, construction or using thermosyphons that keep working continually after construction, removing heat from the ground [28,29].

The first time that thermopiles were used to stabilize pile foundations was in 1960 at the Aurora and Glennallen communications sites in Alaska [30]. This technique has since become a widely accepted method for foundation stabilization in permafrost regions. Initially, propane was the refrigerant of choice, but it was later replaced by carbon dioxide due to safety concerns. This approach reduced the frozen temperature in lower layers and even increased the permafrost layer, potentially enhancing the adfreeze strength between the soil and foundation and improving the load capacity of the foundation.

2.9. Screw Piles

Helical piles, or screw piles, consist of a helically shaped bearing plate or multiple plates attached to a central shaft [7]. In frozen soils, they are typically made of steel and can be installed by applying torque. However, when the frozen soil is extremely cold, installation through torque may not be possible as the soil could be too strong, potentially damaging the pile during penetration. In such cases, predrilling a hole and using a non-frost susceptible backfill may be necessary for installation. Screw piles have been widely used in permafrost areas because they can have various helix and shaft diameters and embedment depths, can be quickly installed, are removable, and can be reused [31].

The presence of helices or threads in the piles increases the strength of the pile–soil system and has a great advantage in mitigating frost-jacking forces caused by the freezing soil in the active layer. Figure 12 shows an uplift bearing resistance being formed by the cylindrical shear resistance along the bottom and top of the pile. This increase in strength helps counteract the frost-heaving forces. The helices must be placed below the active layer and their use does not eliminate the need for other methods of combating frost heave forces. Instead, the use of screw thermopiles is also recommended to counter soil heating and reduce the effects of frost heave.

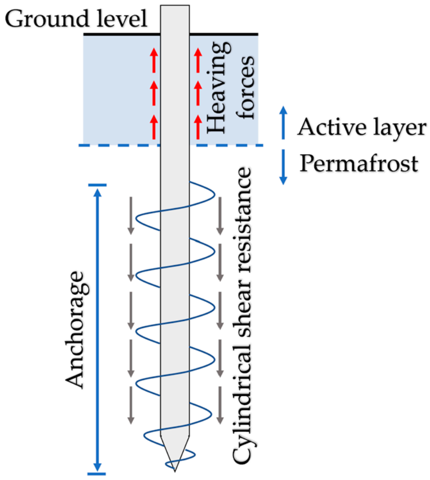


Figure 12. Example of forces acting on a screw pile acting as an anti-jacking force (adapted from Wang et al. [32]).

The foundation used for a commercial building in Inuvik consisted of screw piles with thermosyphons, with a design life of the building of 50 years (Figure 13). The project involved a 3-m active layer, and the bedrock was too deep. Several procedures were implemented to ensure soil stability. Initially, the native soil was excavated and dewatered, then replaced with NFS soil, and slab insulation was added below the building. The use of thermo screw piles was important for the design to enhance the interaction between the foundation and soil and to maintain the soil temperature as low as possible. This is evident from the author's justification for reducing the factor of safety to 1.0 in the design for frost heave [12].

Figure 13. A commercial building in Inuvik, NWT, Canada, and foundation.

Gao et al. [33] conducted laboratory tests on screw pile segments in frozen soils to assess their short-term mechanical performance and examine the effects of soil temperature, salinity, and water content. They found that the presence of flights (i.e., plate-bearing resistance) indicated a potential advantage of continuous-flight piles over conventional smooth piles due to the mobilization of adfreeze stress and plate-bearing stress. Gao et al. [34] measured the creep settlement rate of screw pile segments from lab experiments and adopted an "end bearing" model to estimate the settlement rate.

2.10. Consideration of Greenhouse Gas Emission in Foundation Engineering

The construction sector emitted 6.9 billion tons of CO_2 in 2019, accounting for 19% of global carbon emissions [35,36]. In the past decade, there has been a trend towards integrating sustainability metrics into geotechnical design considerations. Life cycle assessment (LCA) is a tool used to evaluate the environmental impacts of a system, process, or product over its entire life cycle. LCA provides a precise carbon emission footprint for piling construction, enabling geotechnical engineers to consider them when sustainable construction is mandated.

However, LCA is still relatively new to pile designers across Canada. To the best of the author's knowledge, there is no relevant publication regarding the LCA of alternative foundation options used in the permafrost regions of northern Canada. De Melo et al. [37] conducted a comprehensive review of LCA studies on piles, retaining walls, and ground improvement technologies. They [37] reported that there were only eight studies on the LCA of deep foundations, with references generally comparing the environmental impacts of drilled shafts, driven piles, or caissons [38,39]. Hamza et al. [40] evaluated the embodied carbon of four foundation design options for a residential modular building, incorporating factors such as material production, transportation, and construction processes. It was noted that helical piles and reinforced concrete slabs with Geofoam support emerged as the most sustainable options in terms of minimizing embodied carbon emissions.

3. Findings from Interviewing Arctic Foundation Professionals

This section aims to provide a practical insight into foundation engineering and business in the Canadian Arctic. The discussion is based on interviews with engineers and companies experienced in the region. Six participants were interviewed by the authors and are referred to as interview guests IG1 to IG6. The guests included three Arctic geotechnical/civil engineers, one architect/developer, and one Arctic community leader. The guests reside in Edmonton (AB, Canada), Yellowknife (NWT, Canada), Inuvik (NWT), and Cambridge Bay (Nunavut, Canada).

3.1. Interview Questions and Responses

Major questions and their responses are provided herein.

1. What is the major concern regarding foundations in permafrost?

IG1, IG3, and IG4 commented that a major concern in permafrost is the effects caused by frost heave, which can cause differential movements in the structure, so all possible methods should be used to reduce this effect. IG1 and IG2 emphasized the importance of keeping the permafrost temperature as cold as possible because the adfreeze strength of the foundation with the frozen soil is crucial for the integrity of the pile and supported structure.

2. What are the challenges regarding logistics in the construction of a foundation in permafrost?

All IG's agreed that bringing technology to certain areas that are difficult to access is a significant challenge. Some areas can only be reached by plane, while others have roads available only in certain seasons of the year. IG4 mentioned that, for modular houses, using piles or concrete foundations can disrupt planning because a perfect schedule must be made between the foundation installation, freeze-back time, and shipping of the house, which can only travel during a specific time of the year, when river access is frozen, for example. Therefore, if anything is delayed, it would have to wait for another season. In this case, screw jacks are often preferred because their installation is more practical and faster.

IG3 commented that the ideal approach is to look for local suppliers and adapt the design to what is available. When choosing steel pipe piles, one should select the model provided locally to avoid logistics and shipping issues.

3. What are common techniques used to reduce the frost heave effect?

IG3 commented that most studies are theoretical and laboratory-based and do not consider the practical application of foundations and certain properties that may not occur as planned. IG3 commented that using a protective jacket to reduce the surface area of contact between a pile foundation and the active layer (thus reducing frost heave) and waterproofing timber piles is not as effective as it may seem, as it does not consider its durability. In practice, it has been observed that this solution deteriorates over time due to soil and foundation movement. Therefore, it is a significant risk to rely on this effect when designing a foundation, as it may eventually lose its effectiveness over time.

Replacing the soil with non-susceptible soil and adding insulation are also common practices to reduce the frost heave effect. Sands and gravels are cohesionless and tend not to be affected by freeze–thaw cycles, offering protection to the foundation. However, frost heave jacking still occurs even with NFS soils. Moreover, according to IG2, this method is usually only applied directly around the foundation, such as a pile or footing. The rest of the soil in the vicinity of the foundation remains exposed and continues to be impacted by frost action, affecting the foundation system. The option of replacing the entire soil of the active layer around the foundation is very expensive and usually not feasible.

IG1 and IG4 commented that for small loads where screw or timber pads are used, frost jacking is often not effectively addressed, and builders simply accept this effect and propose periodic inspections to analyze differential settlements. Typically, they only apply the presence of a crawl space and sometimes insulation on the ground. When a pile foundation is necessary, it becomes important to combat frost jacking, and in this case, the use of thermopiles is highly recommended by IG1. To combat frost jacking, a greater embedded length should be designed, and the convection system will work to decrease the temperature of the soil while also addressing climate change.

IG6 mentioned that with the space frame system (multipoint foundations), there is no need to worry about the effects of frost heave. The multiple pads touching the ground distribute the load among themselves. Therefore, if there is any movement of the soil that causes one or more pads to lose contact, the remaining pads will be sufficient to support the load. He also stated that even foundations that have been in place for 40 years have not shown any issues with frost heaving.

4. What is the efficacy of convection systems such as thermopiles?

The convection systems aim to keep the soil frozen throughout the year, but in practice, this is not achieved because the air temperature is too warm in spring and summer. Even with insulation and a crawlspace, part of the soil will thaw. On the other hand, IG1 and IG2 emphasized that a critical factor is not the freeze–thaw effects but rather the settlement caused by the interaction between the applied load on the foundation and its adfreeze bond capacity. Therefore, although thermosyphons and insulation do not completely alleviate the frost heave effects, they might be important in keeping the permafrost temperature as cold as possible to ensure increased shear strength, higher load-bearing capacity, and protection against frost action.

However, a point raised by IG3 should be noted. Often, pipes, connections, and devices of the thermosyphon are damaged by soil movements caused by freeze–thaw cycles, compromising their efficiency. Therefore, the system needs to be installed properly and monitored adequately to ensure its functionality.

5. What are the common foundations for residential construction?

When it comes to residential construction with light loads, footings or screw jackings were the unanimous choice among the interviewees due to their affordability, ease of installation, and lack of requirement for specialized labor or machinery. Unlike pile foundations, footings and screw jackings do not necessitate geotechnical design for construction. Therefore, they are considered cost-effective options.

However, IG5 shared their experience of a building in Inuvik, where even for residential buildings with two to three stories, they typically opt for thermopiles and the space frame system. Despite being more expensive, these pile foundations are favored in certain cases. Steel pipes are more effective in combating frost heave, a common issue in cold regions, while space frames can provide structural stability and can easily accommodate ground movements. These advantages make them a preferred choice for ensuring the levelness and durability of the construction in Inuvik's specific environmental conditions.

IG6 confirmed that the space frame system is commonly used for residential construction as well, including both new houses and retrofit projects. He mentioned that when there is a need to relocate villages from the coast, dragging houses using skis and the space frame system is a practical application.

6. What is the difference in cost between shallow foundations and pile foundations for residential construction?

There were not many direct answers regarding this question because most of the interviewees responded that each case is completely different, so several aspects must be analyzed for the formulation of the cost, such as the type of soil, temperature, region, load, and foundation choice. Nonetheless, IG4 gave a brief idea of how much the foundation for a residential construction could cost. He mentioned that screw jacks cost around CAD 500 per unit while steel pipe pile values can exceed CAN 3000 dollars per unit.

7. Do all foundations in permafrost need to be designed by geotechnical engineers?

IG1 explained that for shallow foundations, it is not necessary to have a geotechnical engineer design, which makes the project even cheaper. However, for pile foundations and space frames in general, a specialist engineer is required. IG4 commented that although it is not required, he always consults a specialist engineer for designing jack pads foundations.

8. Can screw piles be a good choice for residential construction?

Most of the interviewees responded that generally, residential buildings with up to 2 or 3 stories have a low enough load not to require any type of pile foundation, making their use too expensive. Therefore, simpler constructions, such as screws and timber pads, are preferred. However, for higher loads and when the soil is more unstable, with warm permafrost and a thick active layer, thermopiles may be the option, as proposed by Zhang and Hoeve [12]. Thus, each case must be analyzed individually.

9. Other comments made by the interviewees.

IG3 and IG6 mentioned the space frame system as a promising system in permafrost because it is an easy-to-install system that does not require specialized labor or heavy machinery, supports high loads, and allows for ground movement caused by settlement or frost heave. Therefore, it is being increasingly used by builders. However, when choosing the space frame system, in addition to its high cost, there is the issue of architectural limitations. IG1 commented on the problems involving architectural limitations as they require at least 1.50 m for the space frame along with additional space for the crawl space and pipes located beneath the floor. This creates a high degree of unevenness that is often not architecturally feasible.

3.2. Summary of Interview

Based on a review and findings from interviews, Table 2 is prepared with the purpose of comparing the pros and cons of the common foundations in permafrost that have already been discussed.

Table 2. Comparison between different types of foundations in permafrost.

Parameters	Footings	Jack Pads	Space Frame System	Timber Piles	Steel Pipe Piles	Screw Piles
Installation Methods	Trench excavation, concrete pouring, backfilling, reinforced steel	Assembly of prefabricated components	Assembly of prefabricated components	Hammering or driving piles into the ground	Excavation, driving or vibrating piles into the ground, grouting	Screwing piles into the ground
Use of Heavy Equipment	Low	None	Low	High	High	Moderate
Load Capacity	Low	Low	High	Moderate	High	High
Soil Disturbance	High	Low	Low	Moderate	Moderate	Low
Vulnerability to Freeze–Thaw Instability	High	Low	Low	High	Moderate	Low
Reliability and Longevity	Moderate	Moderate	High Potential	Low	High Potential	High Potential
Differential Movement Between Supports	High Potential	Moderate	Low	High Potential	Moderate	Moderate
Material Availability and Shipping	High	High	High	Low	Low	Low
Availability of Qualified Contractors	High	High	Low	High	High	High
Building Type	Residential	Residential	Residential and Commercial	Residential and Commercial	Residential and Commercial	Residential and Commercial

In conclusion, all types of foundations should be carefully selected and designed, considering various factors such as material availability, equipment, skilled labor, soil characteristics, annual temperatures, and design period, among others. The key is to evaluate the cost–benefit ratio for each foundation option, not only in terms of initial construction but also future maintenance. Each foundation should be treated as a unique solution, tailored to the specific needs and challenges of the project to ensure long-term stability and performance.

4. Design Manual and Case Study of Screw Piles and Steel Pipe Piles in Residential Foundations

Given the absence of a specific design code for pile foundations in northern Canada, this section aims to demonstrate the methods for designing steel pipe piles and screw piles specifically tailored for a single-family home in the Canadian Arctic. The methods considered the criteria for long-term adfreeze strength, frost heave, and long-term creep settlement, in accordance with findings from interviews in the previous section, CFEM 2023 [7], and appropriate references as will be cited later. Two pile foundation types were designed for an actual two-story single-family house located at a site near Inuvik, Northwest Territories, Canada. Inuvik was selected because it is one of the largest towns within the Arctic Circle of Canada. In Inuvik, both pile foundations and shallow foundations have traditionally been adopted for residential buildings. Geotechnical considerations (i.e., adfreeze strength, frost heave, and long-term creep settlement) were incorporated following recent studies, considering soil properties, temperature, and salinity [24–27,33,34].

4.1. Loads, Permafrost Conditions, and Piles

A single-family detached house is selected for the present study. The 2-story single-family house project has an area of 75 m^2 on each floor. The construction of this house was completed in NWT, Canada. The chosen dead load is 5 kPa, and the live load is 6 kPa. For design according to ultimate capacity, the load factor considered is 1.2 for dead load and 1.5 for live load. Therefore, the total factored load on the house was calculated as 2250 kN.

For the serviceability limit state, the load factor considered is 1.0, and the total load was calculated as 1650 kN. For a possible installation of 30 piles, the determined unit load is 75 kN for ultimate capacity and 55 kN for the serviceability limit state.

To determine the soil characteristics required for designing in permafrost, it is necessary to assess the active layer thickness, soil temperature profile, salinity, and soil type. The selected reference soil was investigated by Kanigan et al. [41], who conducted monitoring of surface conditions and ground temperature ranging from 50 cm to 20 m depth in communities located in the Mackenzie Delta area near Inuvik, NWT, Canada. Figure 14 displays two of these monitoring sites. In these locations, the active layer in the region extends to approximately 1 to 2 m deep. Beyond this depth, maximum temperatures tend to decrease until reaching a peak, remaining constant or slightly increasing afterward. The maximum permafrost temperatures in these regions range between −1.5 °C and 2.5 °C. Kanigan et al. [41] revealed that soil is clayey silt from near-surface permafrost and becomes ice-rich after the active layer.

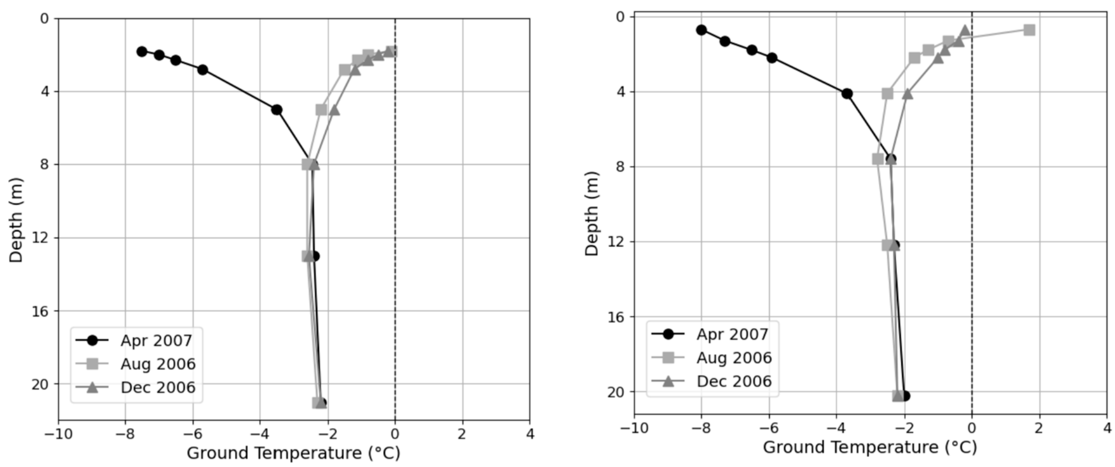


Figure 14. Ground temperature envelopes at two sites near Inuvik, Northwest Territories, in late August 2006, mid-December 2006, and early April 2007 (adapted from Kanigan et al. [41]).

The design of steel pipe piles and screw piles will be described herein. These pile types were selected because (1) steel pipe piles are one of the most common piles used for commercial and residential development, and (2) screw piles, which are an emerging pile type, may be a viable solution for foundations in the Arctic.

The engineering performance of screw piles in both frozen and non-frozen soils has been reported in the literature. Khidri and Deng [42] conducted a field test program of screw piles in sand and developed a theoretical torque model using cone penetration test sleeve friction. Guo et al. [43] and Khidri and Deng [44] performed field axial cyclic loading tests in cohesive and cohesionless soils, respectively. For screw piles in permafrost, Gao et al. [33,34] investigated the long-term creep settlement rates, short-term adfreeze strength, and failure pattern of screw pile segments in frozen soils via laboratory axial loading tests.

As shown in Figure 15, a screw pile consists of two segments: a smooth cylindrical segment (L_s), which is the layer without threads located in the active layer to reduce frost jacking. The value of L_s was taken as the active layer thickness (L_{act}) plus 1 m, which is the space reserved between the ground and the building. The second part is the threaded segment (L_{th}), a layer located in the permafrost region below the active layer. The diameter (D) of the smooth segment is 140 mm. The thread (W_{th}) width and thickness of all piles are 20 mm and 2 mm, respectively, and the spacing between threads (S_{th}) is 50 mm. The pile shaft and threads are made of structural steel having a Young's modulus of 210 Gpa and a yield strength of 248 Mpa. The dimensions of screw piles (i.e., D, W_{th}, S_{th}) were taken based on existing literature [33,34,43] and are commonly available in the market.

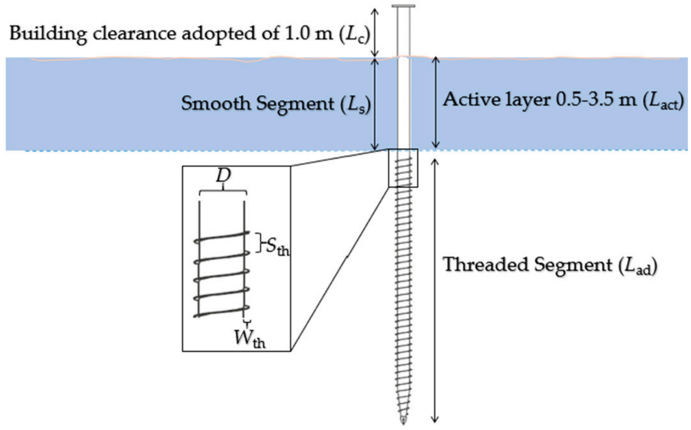


Figure 15. Schematic of a screw pile embedded in permafrost.

For comparison, the steel pipe pile considered in the present work has the same shaft diameter as the screw pile but has no threads. Therefore, its diameter will also be 140 mm.

The design aims to estimate the minimum pile embedment depths based on pile long-term adfreeze strength, design criteria against potential frost jacking, and pile long-term creep settlement criteria.

4.2. Design Criterion for Long-Term Adfreeze Strength

According to Weave and Morgenstern [45], the long-term adfreeze strength (τ_a, kPa) is primarily dependent on the ground temperature, the roughness of the pile (m), and the cohesion (C_{lt}) of the soil according to its soil type. Pile axial resistance should only be determined for the length of the pile embedded in permafrost colder than −1 °C, so it cannot be considered immediately after the active layer. A transition pile length (L_t) of 0.5 m below the active layer was thus considered. The maximum temperature below the active layer starts from 0 °C, reaches its peak around −2 and −3 °C, and then stabilizes between −2.5 and −1.5 °C, depending on the location. For a more conservative design and considering the impact of climate change on permafrost, a temperature of −1.5 °C was applied for the entire permafrost depth.

The soil is composed of a top layer of coarse-grained soil, while the permafrost layer is composed of ice-rich clayey silt. Based on long-term cohesion parameters for frozen soils, at a temperature of −1.5 °C, the ice-rich silt has a cohesion of approximately 120 kPa, ice has 180 kPa, and ice-rich varved clay has 270 kPa. These values were derived from analyses performed by Weave and Morgenstern based on various sources [46–48]. Considering that the soil is not 100% ice-rich silt, the adopted soil cohesion was 140 kPa.

The roughness factor m for steel pipe piles was taken as 0.6 [45]. For screw piles, the roughness factor considered was 1.0, the same factor as the "corrugated steel pile". This results in an adfreeze strength (τ_a) equivalent to 140 kPa for screw piles and 84 kPa for steel pipe piles, as in Equation (1):

$$\tau_a = m \cdot C_{lt} \quad (1)$$

The next step is to determine the minimum length of the pile (L_{ad}) using Equation (2):

$$L_{ad} = \frac{Q_{adopt}}{(\tau_a/FS)\,\pi(D + 2W_{th})} \tag{2}$$

where Q_{adopt} is the axial load to be supported from the building, FS is the factor safety (=2.0), and D_{th} + $2W_{th}$ is the outer pile diameter, which in the case of the screw pile, corresponds to the external diameter between the threads.

The total length of the pile will be given by Equation (3):

$$L = L_{ad} + L_{act} + L_c + L_t \tag{3}$$

where the building clearance (L_c) is 1 m and transition pile length (L_t) is 0.5 m.

4.3. Design Criterion for Frost Heave

Some studies have proposed theoretical and numerical analyses of frost heave and thaw settlement in pile foundations in frozen soils [32,45,49,50]. CFEM 2023 [7] simplifies these calculations by recommending uplift forces due to frost heave from 65 to 150 kPa, depending on soil and foundation characteristics. Engineers have confirmed the use of the conservative value of 150 kPa, which is also corroborated by Hoeve [12], applying this value across the entire active layer in their designs.

The depth of the active layer has a direct impact on the uplift force caused by frost heave, as shown in Figure 16. The sum of the structural loading (Q_{adopt}) and the loading allowed by the adfreeze bond capacity of the pile (Q_{ad}) must be greater than the force caused by frost heave of the forces acting during frost heave (Q_h) multiplied by a factor of safety (FS_{heave}), as represented by Equation (4):

$$Q_{ad} + Q_{adopt} > Q_h\, FS_{heave} \tag{4}$$

where Q_h is the resulting force from frost heave, estimated from Equation (5):

$$Q_h = \sigma_h(\pi D L_{act}) \tag{5}$$

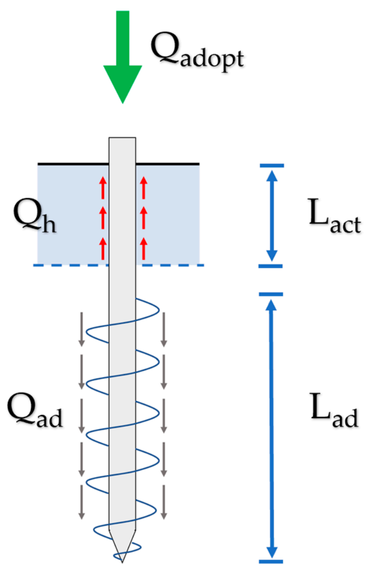


Figure 16. Forces acting on a screw pile during the frost heave.

For saturated frozen steel piles, the uplift stress caused by frost heave is assumed to be σ_h = 150 kPa [7]. The presence of continuous helices (threads) on screw piles causes the phenomenon of anti-uplift forces, reducing the effect caused by frost heave [51,52]. Although there are insufficient studies in the literature on the effect of this anchoring effect caused by screw piles, some studies confirmed the reduction of uplift effects [31,32]. Therefore, FS for the steel pipe pile, considering frost heave, was maintained at 2.0, whereas for the screw pile, FS was reduced to 1.5.

4.4. Design Criterion for Long-Term Creep Settlement

Based on prior interviews, it is appropriate to adopt an allowable long-term settlement of 50 mm over 50 years, equivalent to an annual settlement of 1.0 mm/year. This allowable settlement of 50 mm is greater than the commonly-acceptable 25 mm for piles in unfrozen soils. To avoid excessive settlement, the Igs also recommended that the pile and building should be inspected and retrofitted after 25 years of use when 25 mm settlement takes place.

As per Weaver and Morgenstern [45], the steady-state creep of friction piles in ice or ice-rich soils can be predicted using Equation (6), proposed by Nixon and McRoberts [53]:

$$\frac{\dot{u}_a}{a} = \frac{3^{(n+1)/2}\, B\tau^n}{n-1} \tag{6}$$

where $\dot{u}_a$ (m/year) is the pile's steady-state displacement rate, a (m) is the pile radius, τ (kPa) the average applied adfreeze load, B and n are creep constants. Values of the parameters in Equation (6) were taken as:

$\dot{u}_a$ = 0.001 m/year,

a = 90 mm for screw pile and 70 mm for steel pipe pile (half of outer diameter for each pile),

$B = 2.9 \times 10^{-8}$, for a permafrost temperature of -1.5 °C, obtained through interpolation of the values presented by Weaver and Morgenstern [45],

n = 3, for a permafrost temperature of -1.5 °C.

To find the value of τ, Equation (6) can be rewritten as Equation (7):

$$\tau = \left(\frac{\dot{u}_a}{a}\,\frac{(n-1)}{(3^{\frac{n+1}{2}})B}\right)^{\frac{1}{n}} \tag{7}$$

Finally, the value determined for shear stress (τ) is utilized in Equation (2) and then Equation (3) to determine the pile length, with an FS set at 1.0 and Q_{adopt} corresponds to the serviceability limit state (55 kN).

4.5. Results

Table 3 summarizes the shear stress and the factor of safety adopted for screw pile and pipe pile for each design criteria for the long-term adfreeze strength, frost heave, and long-term creep settlement.

Table 3. Shear stress and factor of safety adopted for screw piles and steel pipe piles for each design criterion.

Pile Type	Parameters	Criterion		
		Adfreeze	Frost Heave	Creep Settlement
Screw Pile	Average τ_{ad} or τ required (kPa)	140	140	43.5
	FS	2	1.5	Not applicable
Steel Pipe Pile	Average τ_{ad} or τ required (kPa)	84	84	47.2
	FS	2	2	Not applicable

Figure 17 illustrates the minimum total lengths for screw piles and steel pipe piles that meet each design criterion. It can be observed that the criteria for frost heave calculations govern the design for both foundations, with nearly 12 m for steel pipe piles, considerably larger than the design criteria for adfreeze (8.5 m) and creep settlement (7.2 m). For screw piles, the minimum length for frost heave criteria was 7 m, and for adfreeze and creep settlement, it was 6.4 m and 6.7 m, respectively.

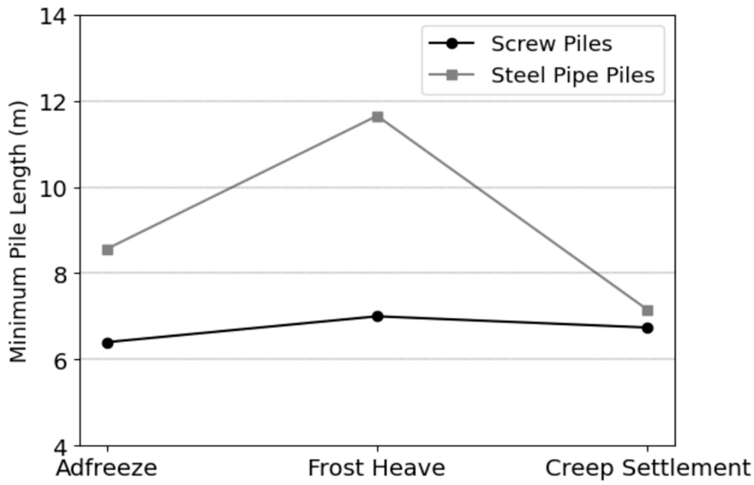


Figure 17. Minimum pile lengths for screw piles and steel pipe piles for each design criterion.

The stress induced by the adopted frost heave is 150 kPa, which already exceeds the calculated shear stress for both steel piles and screw piles (Table 3). With an active layer of 3 m, frost heave generates an uplift force of nearly 200 kN, requiring a significantly longer pile length to withstand this force. Consequently, in this scenario, the design for frost heave takes precedence.

Moreover, it is evident that, for all considered cases, steel pipe piles require a greater total pile length compared to screw piles. This outcome was anticipated, given that the presence of threads enhances the shear resistance of the structure across all calculated scenarios, particularly against frost heave. As previously discussed, helices or threads act as anti-uplift forces.

In conclusion, for the same chosen conditions, it was observed that steel pipe piles would require a total length of 12 m, whereas screw piles would need 7 m. It is believed that this difference could be even greater if it were possible to calculate the anchoring effect caused by the threads of the screw piles.

5. Conclusions

This review paper provides a summary of the challenges and practices associated with foundation design in northern Canada. The insights are derived from a comprehensive review of practices and interviews with professionals and geotechnical engineers specialized in this area. The paper also outlines the design methods for screw piles and steel pipe piles based on findings from the review and interviews. It aims to provide professional geotechnical/civil engineers with valuable insights into current engineering practices for foundations in permafrost.

The following conclusions may be drawn from the present work:

- Various methods are being researched for maintaining soil integrity in both shallow foundations and piles. For example, anti-adhesion coatings can be used to protect piles and columns and reduce frost heave. While these methods show promise in theory, there are still relatively few studies demonstrating their efficiency with actual foundations.
- It is unlikely that any technique can keep the soil completely frozen; however, it can at least maintain its temperature as low as possible, both in winter and summer, reducing the effect of frost action and increasing the adfreeze bond capacity between the soil and the foundation. Among all methods, thermosyphons appear to be indispensable.

- For smaller constructions with lower loads and shallow active layers, footings and jack pads may be the best option due to their cost-effectiveness, ease of installation, and low reliance on specialized labor or heavy machinery. However, for larger and more complex structures, screw piles, steel pipe piles, and space frame systems may be necessary.
- When designing piles in permafrost in northern Canada, it is essential to consider the adfreeze strength (axial stability), frost heave (axial serviceability), and long-term creep settlement (axial serviceability). Examples of designing screw piles and steel pipe piles showed that screw piles may require a length of 7 m, while the steel pipe pile requires a length of 12 m.

Climate change will continue to pose a substantial risk to the integrity of foundations and the underpinned infrastructure they support in the Arctic. Climate change potentially increases the depth of the active layer and warms the permafrost temperature, and both results will deteriorate the performance of foundations. It is recommended to predict foundation performance in the coming decades using hydro–thermal–mechanical simulations and field monitoring programs. Additionally, conducting a life-cycle assessment of foundations for residential and commercial buildings can be useful in assisting decision-makers in arctic communities. Finally, field investigations into the engineering performance of both screw piles and steel pipe piles in permafrost, particularly under warmer permafrost conditions, are necessary. This is especially important as current literature on design guides dates back to the 1980s, when climate change was not as prominent a concern as it is today.

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