nordisk vindkraft

Study of wind turbine foundations in cold climates

Background

This report provides an overview of the processes at work in soil in cold climates and their effect on wind turbine foundations.

Havsnäs wind farm consists of 48 turbines located in Jämtland county in central Sweden. Havsnäs has provided an appropriate research environment to investigate the engineering challenges related to the design and construction of wind turbine foundations in sub-arctic conditions and the experienced gained from this project informs this report.

There has been much input from Nordisk Vindkraft into the completion of this report. There are also a number of individuals the authors would like to acknowledge, starting with Project Engineer and BAS-P, Anders Bernholdsson, Civil Design Manager Vincent Morgan, MSc. Julia Öman and Dr. Tommy Edeskär (Luleå University of Technology), MSc. David Klemetz and Anders Helander (Tyréns).

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1. Introduction

Wind turbines in cold climates are exposed to extreme temperature conditions. Cold climate phenomenon normally associated with wind turbines are:

Icing on components of the turbine e.g. rotor blades, wind sensors, nacelle etc. Damage of the concrete in the foundation exposed to freeze and thaw cycles.

Freezing of the ground adjacent to the foundation, subjecting the foundation of frost heave, thaw settlement and thaw weakening of the soil.

The purpose of this study is to briefly explain the challenges associated with foundation design in cold climates and document suitable strategies to meet them.

Figure 1. Wind power turbine in cold climate.

Cold regions may be defined in terms of air temperature, snow depth and ice cover on lakes or depth of ground freezing. Issues regarding the design of wind turbine foundations in cold climates do not occur in all regions with cold climate, due to the depths of the foundations. If only accounting for Sweden when defining cold climates regarding foundation design, it starts approximately north of 60 ° latitude.

2. Wind power foundation

The two most common types of wind power foundations on shore are gravity foundations and rock anchored foundations.

Gravity foundations are normally founded 2-3 meters below ground surface, and are usually rectangular, circular or octagonal in shape, (figure 2). In general, the principle of gravity foundation design is to transfer loads from the structure to the subgrade and act as a counterweight to the resulting forces and momentum from the wind power turbine and the supporting structures and systems.

Figure 2. Example of gravity foundation under construction.

If wind turbines are founded on rock, an alternative for gravity foundations is rock anchored foundations, (figure 3). Rock anchored foundations will only bear directly on good quality bedrock.

The challenge in foundation design in cold regions is to control the frost and thawing processes adjacent to the foundations.

Figure 3. Example of rock anchored foundation under construction.

3. Frost action

Three important phenomena are associated with frost action:

- **Frost heave**
- **Thaw weakening**
- **Thaw settlement.**

Heaving may displace foundations and cause frost-jacking. During thawing the soil strength is reduced as an effect of excessive water in the soil profile and thaw settlement is a result of the subsequent consolidation of a thawing event, (Eranti & Lee. 1986).

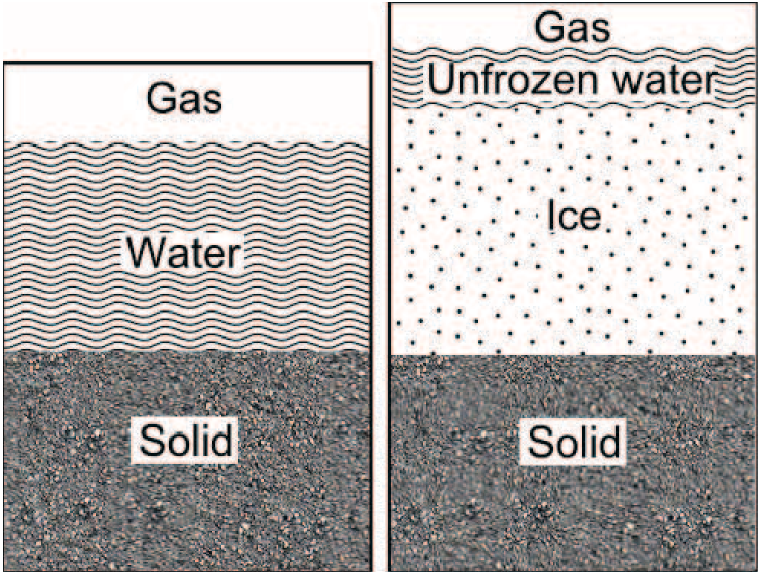


Figure 4. Illustration of components in unfrozen (three phase system) and frozen soil (four phase system).

Frost action phenomenon is a result of soil being a multiphase system that undergoes changes during the freezing and thawing processes. Soil is in general a three phase system consisting of a solid phase, a liquid phase and a gaseous phase. If completely dry or at saturated conditions the soil is reduced to a two phase system. Frozen soil is a four phase system consisting of solid soil particles, pore water, pore air and ice.

The components of an unfrozen soil and a frozen soil can be represented by a phase diagram shown in figure 4.

3.1 Frost heave

Heaving is a result of ice segregation during the freezing process and formation of alternating bands of soil and ice, creating ice lenses, (figure 5).

In order for ice lens formation to occur, three conditions must be fulfilled; low temperature, a water source and a water transportation medium (frost susceptible soil) as illustrated in figure 6.

Figure 5. Ice lens in a silty soil.

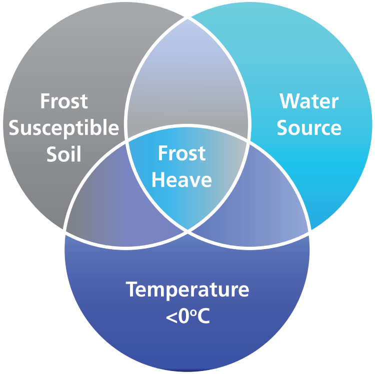


Figure 6. The three conditions which need to interact to create frost heaving.

According to Knutsson (1981) frost heave is caused by the following two processes:

1. **Freezing of existing pore water at the freezing front**
2. **Accumulation of ice lenses caused by a thermal gradient which draws capillarity water to the freezing front. Leading to an overflow of water during winter time.**

Freezing is associated with volume expansion of water by about 9%, meaning that usually the first process is almost negligible to the total frost heave. Ice lenses are oriented parallel to the surface exposed to the freezing temperature, usually parallel to the ground surface, (figure 7). The thickness of the lenses depends on several factors such as water supply, permeability, type of soil, thermal gradient etc.

Foundations in frost susceptible soils can be subjected to large uplift forces resulting from frost heaving of the soil. Frost heave forces can be divided into normal or lateral forces. Normal forces are those perpendicular to the freezing front, acting vertically on a gravity foundation, shown in figure 8. When the foundation depth is below the maximum frost depth, the footing base will not experience any normal forces, if not the foundation member will locally accelerate the frost penetration, (Phukan, 1993).

The heave force increases as the frost line penetrates the unfrozen soil during freezing of a frost susceptible soil. To predict the magnitude of these forces is difficult because of the many variables involved, (Andersland & Ladanyi, 1994).

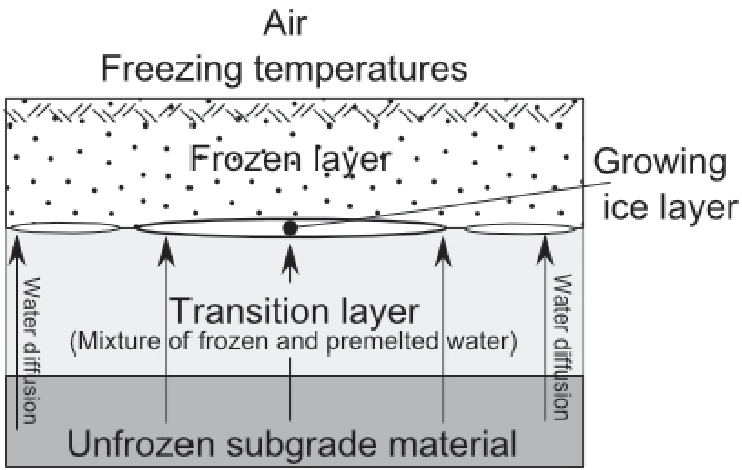


Figure 7. Formation of ice lenses.

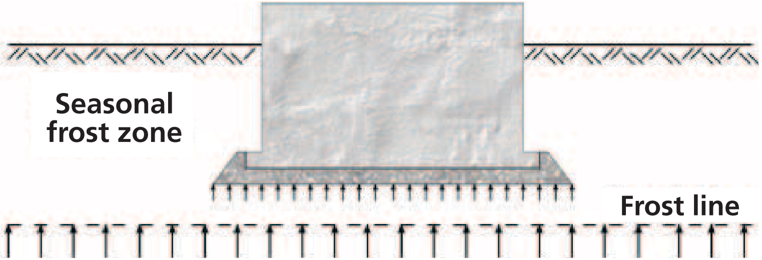


Figure 8. Normal forces acting on a shallow foundation (Andersland & Ladanyi, 1994).

Differential frost heave is a particularly serious problem and can result in severe distortion of structures, (figure 9).

In addition, heaved foundations may not return to their original position at the end of the thaw season because the underlying voids have been filled with soil or stones. After several seasons of frost heaving, the cumulative effect may be a permanent upward and uneven displacement of the foundation and the structure, (Johnston, 1981).

Figure 9. Example of stone lift under pavement caused by frost heave.

3.2 Thaw weakening

Ice in the frozen ground can be found in the coatings on individual soil particles, in the small ice lenses and in large ice inclusions. At thawing the amount of water resulting from ice melting may exceed the absorption of the soil skeleton. Until complete drainage, excess pore pressure may develop temporarily in fine-graded soils with low permeability, which will result in weaker soil after thawing than before freezing. The frozen ground is transformed into a slurry of soil particles and water being unstable to support any significant load.

Figure 10. Thaw weakening of a gravel road.

For many constructions in northern regions, the periods of subsoil thawing represent the most critical conditions affecting the preservation of integrity of supported structures, (figure 10).

3.3 Thaw settlement

Settlements of the soil will occur as a result of the heaving that has developed during freezing. The total thaw settlement will originate from three sources; phase change, settlement of the soil under its own weight, settlement of the soil under applied loads. The magnitude of the settlement and the consolidation depends on several factors. According to Phukan (1985) the most significant are:

- **Nature of the soil**
- **Ice content**
- **Density**
- **Excess pore pressure**
- **Soil compressibility**
- **Velocity of thawing i.e. thermal gradient.**

4. Frost susceptibility

Frost-susceptible soils are classified by frost heaving and thaw weakening behaviour. Considerable damage to engineering structures can be caused by both. Some soils are more liable than others to exhibit this extreme behaviour. Importantly frost heave is not consequently followed by the thaw weakening; some clay soils develop segregated ice while exhibiting little or no heave, (Andersland & Ladanyi, 1994).

Soil	Grain size (mm)	Capillary rise (m)	Permeability (m/s)	Frost Heave Susceptibility
Gravel	2 – 60	<0,03	$10\text{-}10^{-3}$	4
Sand	0,06 – 2	0,03-0,5	$10^{-4}\text{-}10^{-6}$	3
Silt	0,002 – 0,06	0,3-12	$10^{-5}\text{-}10^{-9}$	1
Clay	<0,002	>8	$>10^{-9}$	2

Table 1. Properties and frost heave susceptibility of four common soils. The frost susceptible column is ranking the relative frost susceptibility among the listed soil types where silt is the most susceptible soil (graded 1).

A frost-susceptible soil is characterised by an ability of high capillary rise and a reasonably high hydraulic conductivity to create conditions for ice lens growth. In Table 1 four common soils are listed together with properties influencing their frost susceptibility. The frost heave susceptibility of the soils are also ranked from 1-4, where 1 is the soil that is most frost heave susceptible.

The most frost-susceptible soils are those comprised of particles of silt size, when seasonal freeze-thaw cycles are involved. Silt has particles small enough to be easily rejected by slowly growing water crystals and at the same time the hydraulic permeability of silt is sufficiently high, which maintains a steady supply of water from a source nearby. Gravels are not frost susceptible because of the large particle-sizes that make up the material, such as pebbles, cobbles and rock, leading to a low ability of capillary rise. Even though clay particles are very small, meaning that they easily get rejected during the growing of water crystals, they are not highly frost susceptible since the very low hydraulic permeability, (Phukan, 1993).

At present there is no generally accepted criterion that characterises a non-frost-susceptible soil material, but the most commonly used criteria is based on grain size. The amount of fines is usually specified although the smallest size and the amount of fines vary considerably. There is also a limitation on gradation, (Johnston 1981). Often the soil frost susceptibility is decided upon by the grain size distribution and, if a more detailed investigation is needed, complementary capillarity-tests and freezing-tests are carried out.

Countries like the U.S., Sweden, Norway and Finland all use different methods when classifying soil frost susceptibility, though review of grain size distribution is common to all. The differences between the methods are limits regarding the grain size distribution, factors/tests used when classifying and the number of classes. For instance Finland uses only two classes when classifying in contrast to Norway and Sweden, who use four, and the U.S., which has six classes. The different factors regarding classification of frost susceptible soils used in the different countries are presented in table 2.

All of the countries mentioned above use grain size distribution, but differences can be seen in both the percentage and sieve limits. The different limits of grain size distribution used for classifying soil frost susceptibility, in different countries, could cause issues.

Country	Grain size distribution	Capillarity	CBR	Freezing test
U.S.	x			x
Sweden	x			
Norway	x		x	
Finland	x	x		

Table 2. Factors regarding classification of frost susceptibility soils.

5. Frost depth mapping

The frost depth penetration differs depending on site conditions. Examples of factors influencing the depth of frost penetration are:

- **Soil profile (homogenous, inhomogeneous)**
- **Properties of the soil**
- **Thermal properties of the soil**
- **Groundwater table**
- **Insulation cover consisting of vegetation or snow.**

A superficial inventory of maximum frost depth for two typical frost-susceptible soils in Norway, Sweden and Finland is presented in figures 11 and 12. The basic assumptions that the maps are based upon are:

- **A homogenous soil profile**
- **The groundwater table is below the maximum frost depth**
- **No insulation of snow cover is included in the analysis**
- **Seasonal freezing index is used as temperature input**
- **Only latent heat is included in the analysis.**

The frost depth calculations are performed on two different soil types; clay and a frost susceptible till. The frost depth model commonly used is Stefan's formula, which is generally recommended for estimating ultimate frost depth since the model over-estimates the frost depth.

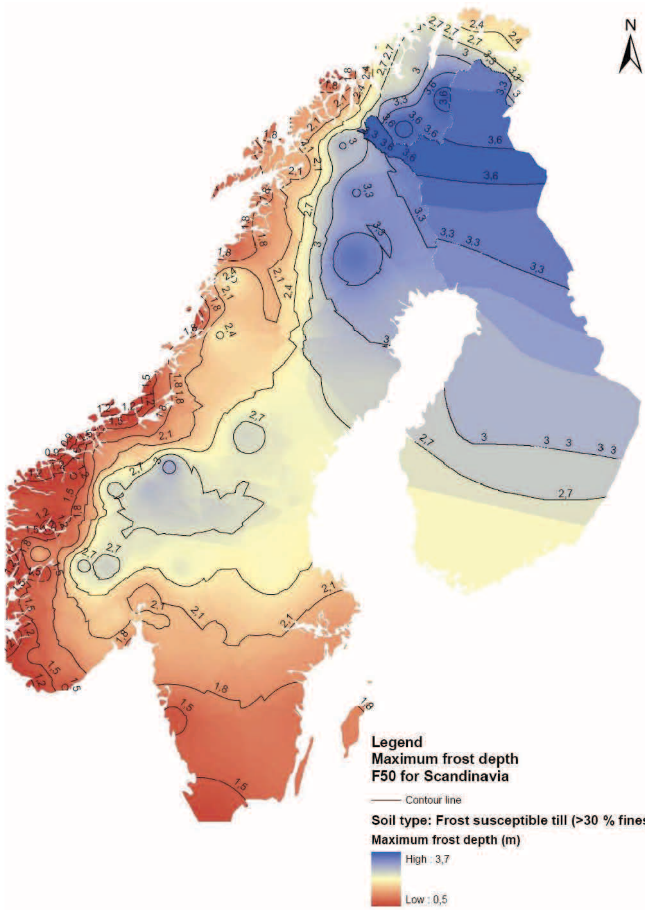


Figure 11. Frost depth in frost susceptible till, with content of fines > 30% at design winter seasons of 50 years statistical occurrence.

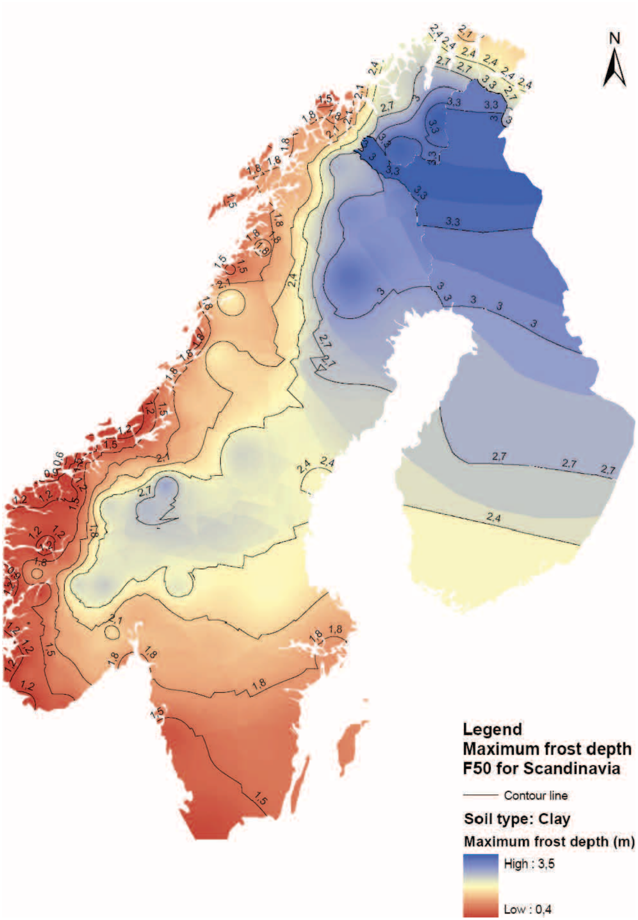


Figure 12. Frost depth in typical clay at design winter seasons of 50 years statistical occurrence.

6. Frozen ground modelling

There are several models for predicting frost depths. The choice of method depends on the purpose of the investigation, the need for accuracy, or the extent of available information. A list and comparison between different commonly used methods are presented in table 3.

Solutions	Dimensions	Heat flow	Primary use
Stefan's formula	1	No	Ultimate frost depth
Modified Berggren	1	Yes	Frost depth
Neumann solution	1	Yes	Frost depth
Numerical methods	2	Yes	Foundation design

Table 3. Comparsion between different methods for determining frost depth.

In Stefan's formula both the energy consumption during the freezing process and the heatflow from the freezing front to the ground surface are included in the analysis. These simplifications lead to an overestimation of the frost depth. Since the equation over-estimates the frost depth it is suitable for ultimate design purposes and is also preferable if the ground conditions are not sufficiently explored. The error (over-estimation of frost depth) is increased in dry soil.

The Modified Berggren solution and the Neumann solution are based on the same thermal model. The difference is that the solution is based upon different solution techniques. The Neumann solution requires an iteration procedure and is thus suitable for computer analysis. The Modified Berggren solution on the other hand was developed to solve "by hand calculation" and the iteration process is replaced by a diagram. The higher accuracy of the frost depth requires higher quality on the input data in the analysis in order to certify that the frost depth is not underestimated.

Numerical models, such as the finite-element-method (FEM) use boundary conditions to solve the thermal analysis in two or three dimensions, (figure 13). To be reliable, the numerical analyses require extensive input of data. The recommended use for numerical models is for design of frost mitigation actions and detailed analysis.

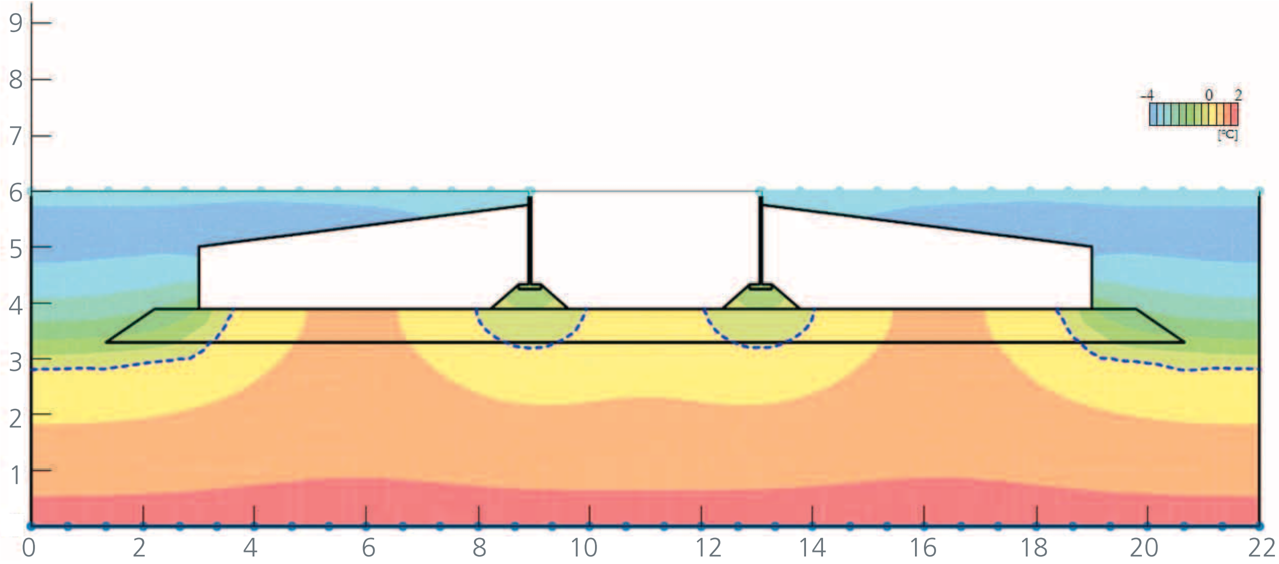


Figure 13. Ground temperature distribution simulated with the FEM software TEMP/W.

7. Cold climate engineering

To control the frost and thawing processes adjacent to foundations, field investigations and data acquisition at the specific site has to be made. Frost mitigation in the foundation design could be used to prevent damage of the foundation due to phenomenon associated with frost action.

7.1 Investigation

Temperature

Design temperatures, i.e. freezing index, in construction practice are either based on statistical returning periods or maximum events during a certain time period, usually the 30 year periods used by meteorologists to monitor short time climate events. This temperature data is sufficient for estimation of maximum frost depths.

To perform a detailed analysis local temperature data is needed since temperature has a high spatial variability. Temperature is easy and cheap to measure. It is recommended that the temperature one metre above the ground surface at least is measured as soon as the site specific wind measurements begin in the project.

This data needs to be correlated over a long time period measurement series to be useful in an ultimate design perspective.

Figure 14. Field investigation in cold climate.

Snow depth

The snow depth could be included in the frost depth analysis as an insulation layer. Snow maps available from meteorological institutes are based on a too sparse measuring net to be reliable, and often only include the average or maximum snow cover of the season. The spatial variation of the snowpack depth is very high and consideration of the seasonal variation of the snowpack needs to be considered. The construction of the wind power plant itself also affects the thickness of the snowpack. If constructed in a forest and the trees around the site are preserved, a local increase in snowpack could be expected. If the trees are removed the snowpack will, as a consequence of wind, usually decrease. In cold climate design snow cover is not included because of its uncertainties.

Geotechnical investigations

The extent of the geotechnical investigation is based on the analysis needed. To perform rough ocular inspection of soil type, you will need dry sieving, sounding for retrieving stiffness and strength properties and groundwater monitoring.

7.2 Frost mitigation in foundation design

Different kinds of mitigation action exist to prevent frost action in cold climates. Insulation of the foundation, drainage of the soil and disposal of thermopiles are examples mentioned in this study.

Insulation

Protection of cold structures relies on available soil heat that has been stored in the ground during summer. Insulation is used to reduce the upward loss of this soil heat, thereby preventing frost from penetrating down to the frost susceptible soils. If insulation of a wind turbine foundation is undertaken, the insulation is placed above the foundation, covered and protected with soil, (figure 15).

Drainage

The effect of drainage on frost action is a reduction in frost heave but also an increased frost depth if the groundwater table is lowered. The drainage system is in general combined with a foundation ballast layer.

Thermopiles

Thermopiles are thermosyphons that carry a structural load and maintain permafrost soils. Thermopiles lower the frozen soil temperature thus increasing the ad-freeze and compressive strengths of the soil.

Figure 15. Insulated wind power foundation.

7.3 Foundation design

In general there are four approaches in frost design of shallow foundation in frozen ground engineering.

1. **Improve or modify support material**
   This is recommended if the maximum frost penetration depth is close to the foundation level. It is easily performed by increasing the thickness of the supporting ballast layer beneath the foundation and could be combined by thermal insulation actions.
2. **Prevent freezing below foundation**
   This is recommended if it is unrealistic to prevent frost problems by replacing frost susceptible material, or the freezing front is considerably deeper than the foundation level. It is mostly done by increasing the foundation level or by insulating the foundation. It is recommended that this approach is combined with a part replacement of present subgrade material.
3. **Maintain frozen ground conditions**
   Maintaining frozen conditions is usually adopted in permafrost regions or could be considered if construction work needs to be performed during the winter season in the colder sub-arctic regions. Using a cooling system like thermopiles or insulating the ground are measures typically undertaken.
4. **Accept frost action**
   This implies a new foundation design, which allows for frost heave and thaw settlement within the foundation requirement.

8. Conclusion

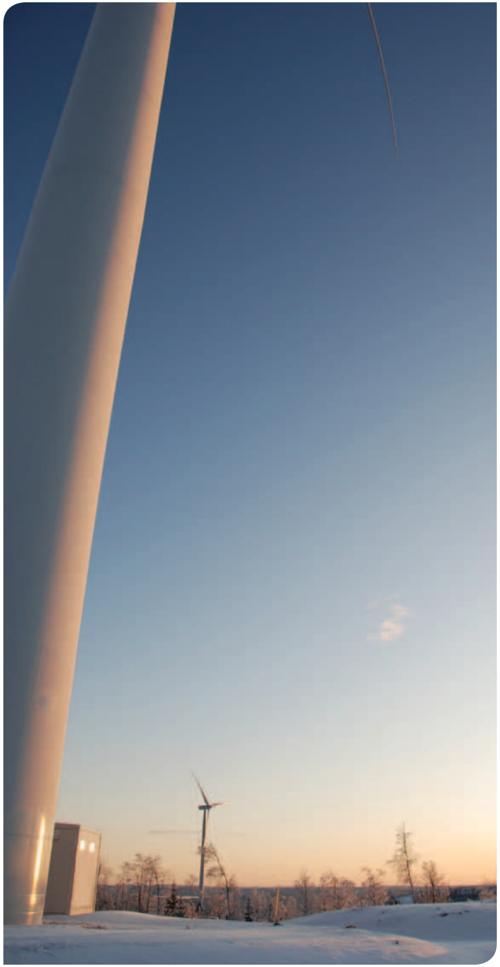
This report shows that it is possible to construct wind farms in colder climates if the right analysis is provided and the design criteria have been followed. The extent and quality of data and investigations supporting this conclusion are based on:

1. **The expected frost depth based on a rough estimation**
2. **The soil type at and below the foundation level**
3. **The need of optimisation of the foundation design.**

Rough estimation of the expected frost depth is generally made by guidance from the individual country's construction practice. In this report maps, based upon recommended design freezing indices, statistical forecasts of freezing events and soil types, have been produced as guidance.

If the soil type at or below foundation level is frost susceptible a more detailed investigation is needed if the expected freezing front is reaching these depths. This analysis should be based on site specific data. A high degree of accuracy or complex modeling requires a high quality of data.

Design temperatures, i.e. freezing index, in construction practice are either based on statistical returning periods or maximum events during a certain time period. Usually 30 year periods are used by meteorologists to monitor short time climate events.



This temperature data is sufficient enough for estimation of maximum frost depths.

To perform a detailed analysis, local temperature data is needed since temperature has a high spatial variability.

The snow depth could be included in the frost depth analysis as an insulation layer. This is only recommended in detailed site specific analysis since there is a risk of underestimating the frost depth. The spatial variation of the snowpack depth is very high and seasonal variation of snowpack needs to be considered. The construction of the wind farm itself will also affect the thickness of the snowpack. If constructed in a forest and the trees around the site are preserved, a local increase in snowpack could be expected. If the trees are removed the snowpack will, as a consequence of winds, usually decrease. A reasonable estimate in frost calculations is to assume a half average snow depth during the winter season and perform a sensitivity analysis.

There are four general approaches in frost design of shallow foundation design in frozen ground engineering.

Approach	Concept	Measures
1	Improve or modify support material	Replace frost susceptible material by proper fill material
2	Prevent freezing below foundation	Insulation -Deeper foundation level -Salting
3	Maintain frozen ground conditions	Cooling systems or insulation
4	Accept frost action	Include frost heave and thaw settlement within the foundation requirements

Table 4. Approaches to solve frost related foundation problems for shallow foundations (After Phukan 1985).

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