Frost Heave in Swedish Slab-on-Grade

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ABSTRACT

This paper discusses the risk for frost heave in modern Swedish slab-on-grade. Theoretical simulations are undertaken in order to model the frost front below the slab. Different designs of the slab-on-grade for a north (Luleå) and a south (Lund) location in Sweden are studied. For example, the insulation thickness below the slab is varied and frost protection insulation is applied with different thicknesses and widths.

The results show that there is a risk of frost heave. In a well-insulated slab-on-grade, the frost front will extend below the edge beam of the slab. However, with frost protection insulation, the depth of the frost front below the slab will be reduced significantly. Frost heave must be considered in the design process for a modern Swedish slab-on-grade.

INTRODUCTION

In Sweden the insulation thickness below a slab-on-grade has increased significantly since 1999. Today it can be up to 300 mm below the middle section of the slab and at the edge beam it is up to 150 mm. The reason for this is to reduce the heat loss from the foundation. However, measurements have shown that up to two-thirds of the heat loss through the slab, for a single-family house, passes through the edge beam (Roots 2001). The thermal resistance of the edge beam is rather low in comparison with the rest of the slab. One reason for using less insulation at the edge beam is to reduce the frost front penetration, i.e., the thinner insulation thickness results in an increasing perimeter heat loss.

In another Nordic country, Norway, a different method to prevent frost heave is used. The foundation has a large shaft depth. This construction is not used in Sweden since the building contractors claim that the construction is much more expensive than traditional Swedish foundations.

In both Sweden and Norway, modern foundations are well insulated, with an insulation thickness up to 300 mm below the slab. In Sweden, the insulation thickness has increased because floor heating is commonly used as a primary heat source in newly produced single-family houses. Extra insulation is used to reduce the extra ground heat loss caused by the floor heating system.

A study by Adamsson et al. (1973) shows that frost heave can occur below slab-on-grade foundations. As expected, the depth of the frost front penetration is greater for a building located in the north of Sweden. In the study the insulation thickness below the slab is thin, approximately 0.08 m. Today the insulation thickness is much greater. The results in that study are therefore not representative of a modern slab-on-grade. The frost penetration depth is assumed to be more severe in modern slab-on-grade.

There are many other studies on frost heave. However, no references have been found that deal with frost heave in a foundation with insulation thickness up to 300 mm below the slab.

In this paper an alternative slab design is studied to explore the effect on the frost penetration depth for buildings located in northern and southern Sweden. The insulation thickness below the slab is varied between 100 mm and 300 mm. Outside the slab, frost protection insulation is mounted with varying width and thickness. The paper also includes a study of a slab-on-grade with a floor heating system to see if it gives a reduced risk for frost heave, i.e., if the extra heat loss due to the floor heating system significantly reduces the frost front penetration below the slab.

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FREEZING OF A MATERIAL—THEORETICAL MODEL

Under winter conditions, when water freezes and expands in a soil such as clay or silt, a phenomenon known as frost heave can occur. The expansion of the freezing zone in the ground results in the upward movement of structures. In spring, as the ground thaws, an excess of water is produced; this excess reduces the effective stress in the soil and results in a loss of bearing capacity.

The process of a growing ice crystal closely approaches a soil particle, the water separating them is reduced to a thin film, and further growth of the crystal can only take place as molecules of water enter this film. If the soil particle is small and the crystal growth slow, water molecules have time to enter between the ice and the particle and the growing crystal will exclude the particle. This process, referred to as "segregation," leads to the formation of ice lenses in the soil that contribute significantly to the level of heave. On the other hand, if the soil particles are large and freezing is rapid, water cannot freely move into the layer between the ice crystals, the ice gradually surrounds the particle, and the heave associated with segregation is reduced.

When a material is freezing, a phase change occurs within the material. Water is transformed to ice. The thermal conductivity and the thermal capacity will change with temperature. We have a nonlinear thermal problem. For the two-dimensional nonlinear isotropic case, the heat equation governing the thermal process in the ground is

$$C(T) \cdot \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\lambda(T) \cdot \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda(T) \cdot \frac{\partial T}{\partial y}\right),$$

where

C = thermal capacity (J/m^{3}K),

T = temperature (°C),

λ = thermal conductivity, isotropic (W/mK),

x,y = coordinates (m), and

t = time (s).

Let T_f denote the temperature in the material when it is fully frozen.This temperature is different in different materials. In clay, a considerable part of the water may be unfrozen at a temperature closely below 0°C. The reason for this is that the water is stored in small pores, where lower temperature is required to freeze it. The material is unfrozen at 0°C. It is assumed that the major part of the water in the material is frozen at –1°C, then the freezing process will take place in the interval 0 to (–1°C). We will assume that the freezing process is linearly distributed within this interval. The energy per volume unit is called E and the change of energy, ΔE, associated with a change of temperature, is equal to ΔT. We have the following three cases in the freezing process (Eftring 1990):

$$\Delta E = \begin{cases} C_0 \cdot \Delta T & T > 0 \\ \dfrac{L}{-T_f} \cdot \Delta T & T_f \le T \le 0 \\ C_f \cdot \Delta T & T < T_f \end{cases}$$

where

ΔE = change of internal energy in the material (J/m^3) and

L = latent heat in a phase change of a material (J/m^3).

The freezing process is illustrated in Figure 1.

The process of frost heave also depends on the moisture content of volume in the soil and the latent heat of the water. The latent heat for freezing of water is 330 kJ/kg. The relation between the moisture content per volume in a material, w (kg/m^3), and the latent heat is

$$L = w \cdot 330 \cdot 10^3 \ \text{(J/m}^3\text{)}.$$

In the simulation the freezing penetration depth is assumed to follow the –1°C isotherm. By plotting the –1°C isotherm we can see if there is a risk for frost heave and damage of a building.

Case Studies

A modern slab-on-grade in Sweden has 0.1-0.3 m insulation thickness in the middle section below the slab. At the edge beam, the insulation thickness is around 0.1 m (see Figure 2). Below the insulation there is a drainage layer placed on the pit base slab. As long as the frost penetration does not go deeper than this depth, i.e., the depth to the soil, the foundation is safe for frost heave.

In order to reduce the frost penetration depth near the foundation construction, a frost protection insulation can be used. Figure 3 illustrates how the insulation is mounted outside the slab in the soil, with a thickness d and a width d_{frost}.

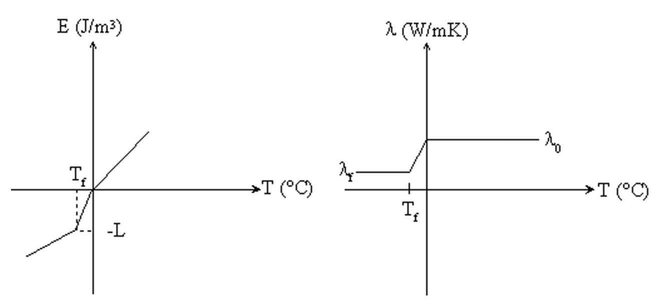

Figure 1 *The relationship between the internal energy, E, in the material and the temperature is shown at left. At right the relationship between thermal heat conductivity and temperature is given. The thermal conductivity for unfrozen soil is λ_o and for fully frozen soil is λ_f and linearly interpolated in the freezing interval. The parameter* L *is the latent heat.*

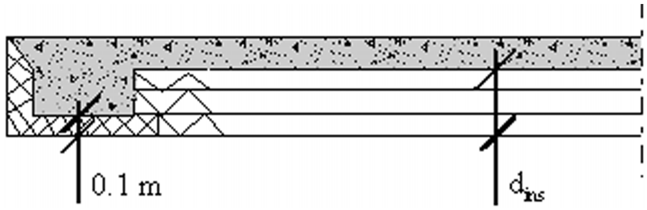

Figure 2 *The insulation thickness in a modern slab-on-grade in Sweden. The edge beam insulation thickness is 0.1 m and the thickness at the middle section is* d_{ins}.

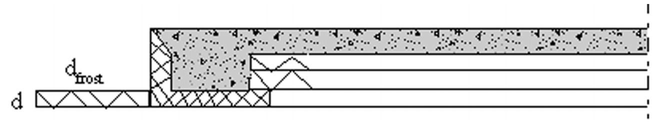

Figure 3 *The heat loss and using frost protection insulation can reduce the frost penetration. The insulation is placed outside the slab, with the thickness* d *and the width* d_{frost}.

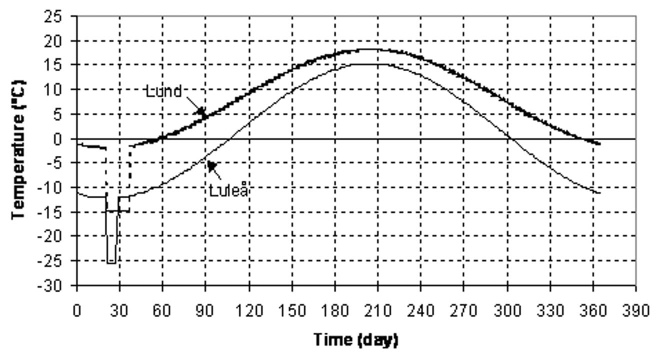

Figure 4 *Outdoor temperature variation in Luleå and Lund.*

The temperature in the slab can also affect the frost front below the slab. Higher slab temperature means an increased heat loss to the ground. This may reduce the frost front penetration below the slab.

Based on the discussion above, the following cases are of interest:

- Varying insulation thickness in the middle section, d_{ins}, 0.1-0.3 m
- Varying width of frost protection insulation, d_{frost}, 0-1.2 m
- Varying insulation thickness of the frost insulation, d, 0.1-0.2 m
- Different locations, Luleå and Lund, cities in northern and southern Sweden, respectively
- Indoor temperature 20°C and 25°C

The daily average outdoor temperature in Luleå, T_e, is assumed to follow

$$T_e = 1.5 + 13.7 \cdot \sin\left(2 \cdot \pi \cdot \frac{(t - 113.5)}{365}\right) \qquad t < t_1 \text{ and } t > t_1 + t_2$$

$$T_e = -25.4°\text{C} \qquad t_1 < t < t_1 + t_2$$

where t is time in days from the beginning of the year. After 22 days the temperature will decrease to –25.4°C during seven days. This corresponds to t_1 equal to 22 days and t_2 equal to 7 days. Similarly, the outdoor temperature in Lund is assumed to follow

$$T_e = 8 + 10 \cdot \sin\left(2 \cdot \pi \cdot \frac{(t - 113.5)}{365}\right) \qquad t < t_1 \text{ and } t > t_1 + t_2$$

$$T_e = -15°\text{C} \qquad t_1 < t < t_1 + t_2$$

Here, t_1 is 22 days and t_2 is 15 days. The outdoor temperatures in Lund and Luleå are shown in Figure 4.

The simulations are performed with a typical Swedish slab-on-grade, as shown in Figures 2 and 3. The thermal characteristics of soil below the slab, the material in the foundation, and resulting frost depth in the ground far away from the building, are summarized in Table 1.

In the simulations a self-developed program is used. A two-dimensional model of the slab-on-grade is used. The construction is divided into cells and the forward difference method is used to solve the heat conduction equation. Boundary conditions are applied on the inside and outside surfaces of the slab-on-grade and on the surface of the soil outside the slab.

RESULTS AND DISCUSSION

Many factors have to be considered to determine if there is a risk for frost heave in a slab-on-grade. The type of soil, the slab design, and the insulation thickness are examples of important factors. In the following, one way for judging the risk will be used. A frost front passing below the edge beam will be considered risky. However, when evaluating the risk, one has to consider the depth on the pit base slab, i.e., the foundation depth. A drainage layer may reduce the risk for frost heave as long as it consists of a nonsusceptible material.

Luleå

In Luleå the design frost depth is 2.3 m for undisturbed soil (far away from the building). For a slab-on-grade the insulation thickness below the slab has an influence on the frost penetration depth. When the insulation thickness increases, the frost penetration goes deeper below the slab (see Figure 5). With the thinnest insulation thickness of 0.1 m below the middle section of the slab, the penetration depth below the slab

Table 1. The Thermal Characteristics of Soil Below the Slab and the Material in the Foundation Used in the Simulations (H Represents the Frost Depth in Undisturbed Soil)

	λ_o (W/mK)	λ_f (W/mK)	C (J/m^{3}K)	C_f (J/m^{3}K)	L (J/m^{3}K)	H (m)
Soil	1.86	2.79	$2.29*10^6$	$1.8*10^6$	$7.488*10^7$	
Insulation	0.04	0.05	$1*10^5$	$1*10^5$	$1*10^4$	
Concrete	1.7	1.7	$2.23*10^6$	$2.23*10^6$	$5*10^7$	
Luleå						2.3
Lund						1.1

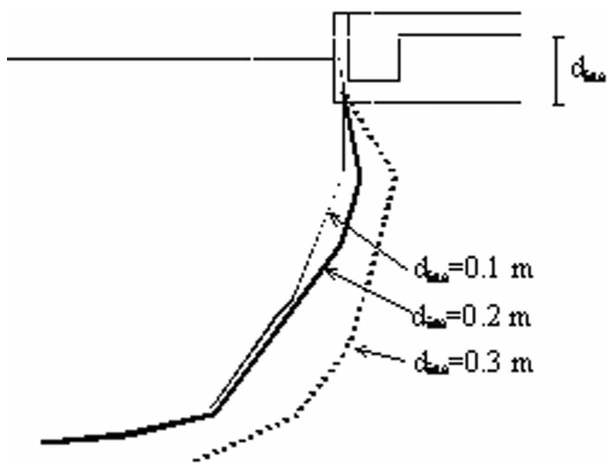

Figure 5 *The isotherm –1°C, the frost front, is plotted for varying insulation thickness below the middle section of the slab. The city is Luleå, and indoor temperature is 20°C.*

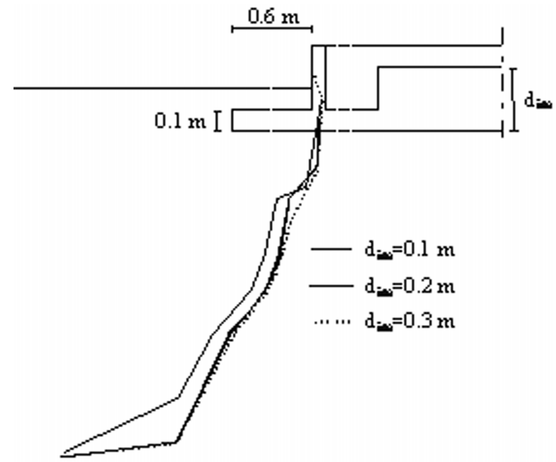

Figure 6 *The isotherm –1°C, the frost front, is plotted for different insulation thickness below the middle section of the slab and with frost insulation. The city is Luleå, and indoor temperature is 20°C.*

is smallest. However, this construction is a risky construction with respect to frost heave. In the corners, the frost front will go even deeper and this may cause damage to the building. The results indicate that the insulation below the slab, when the edge beam is not altered, has a large impact on the frost front depth. In well-insulated slab-on-grade the risk for frost heave must be taken into account in the design of the building.

When a frost protection insulation—width of 0.6 m and thickness of 0.1 m—is used, the frost penetration depth decreases, as illustrated in Figure 6.

In order to further reduce the frost penetration depth, the width of the frost insulation is increased to 1.2 m. The frost penetration depth is significantly reduced with frost insulation that has the width of 1.2 m, as illustrated in Figure 7.

In the following example, the frost insulation thickness is increased to 0.2 m (see Figure 8). There is only a small reduction of the frost front depth, i.e., the frost insulation thickness in the example has a minor influence.

In order to check the influence of the slab temperature, simulations with two different interior temperatures, 20°C and 25°C, have been performed. The higher indoor temperature represents the floor heating case. The results in Figure 9 show that the slab temperature for a normal slab has a minor influence on the frost front depth below a slab.

With frost insulation, the temperature of the slab has a minor influence on the frost front in a well-insulated (0.3 m thickness) slab-on-grade. The results in Figure 10 indicate that the frost front is nearly the same in the case with an indoor temperature of 20°C or 25°C. This means that a slab-on-grade with a floor heating system may not reduce the frost front location below the slab.

Lund

In south of Sweden the maximum frost depth is approximately 1.1 m. The frost penetration depth may therefore be smaller in comparison with an identical slab on the ground in the north of Sweden.

In Figure 11 the simulated frost penetration depth is shown for a slab-on-grade with varying insulation thickness below the slab. The result shows that the frost does not penetrate below the edge beam. The insulation thickness has a minor influence close to the edge beam. Farther down the curves separate, and the case with the thinnest insulation gives the minimum penetration.

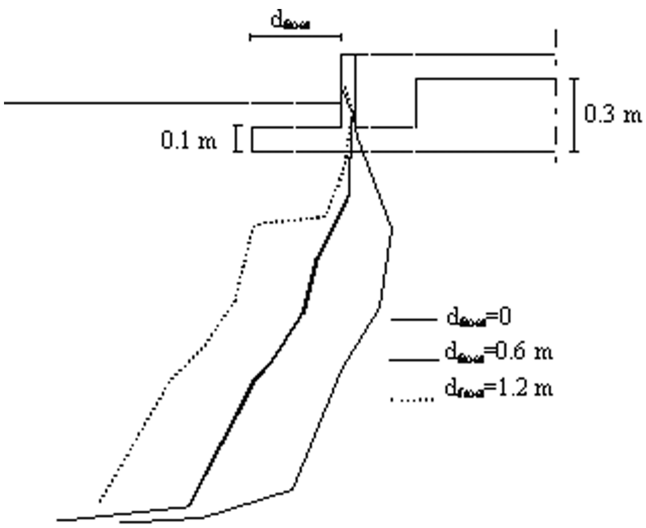

Figure 7 *The isotherm –1°C, the frost front, for different insulation widths of the frost insulation. The city is Luleå, and indoor temperature is 20°C.*

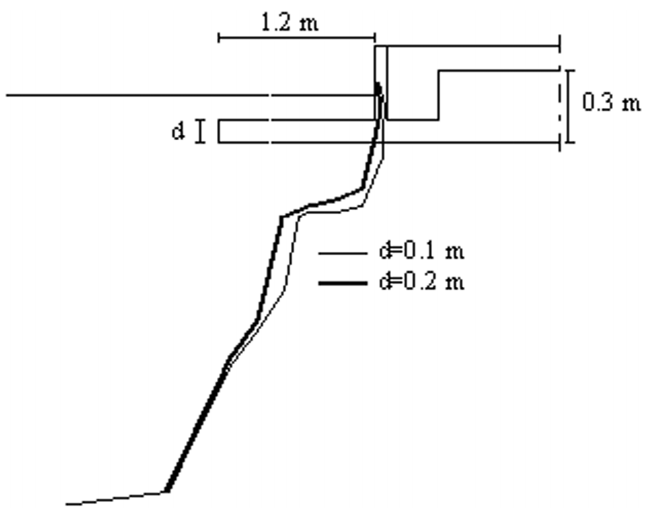

Figure 8 *The isotherm –1°C, the frost front, for different thicknesses of the frost insulation, 0.1-0.2 m. The city is Luleå, and indoor temperature is 20°C.*

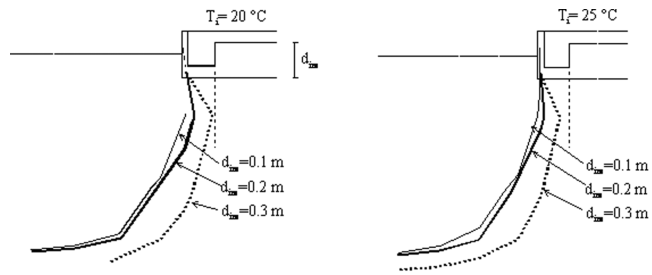

Figure 9 *The isotherm –1°C, the frost front, for different temperatures in the slab and varying insulation thickness. The city is Luleå.*

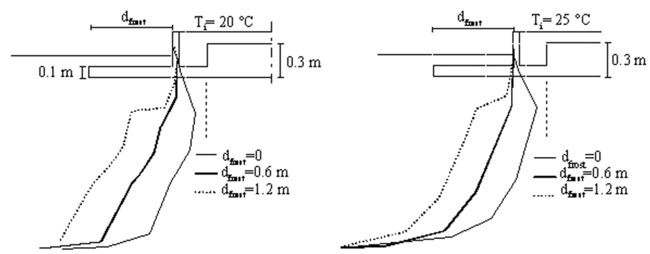

Figure 10 *The isotherm –1°C, the frost front, for different temperatures in the slab and 0.3 m insulation thickness. The city is Luleå.*

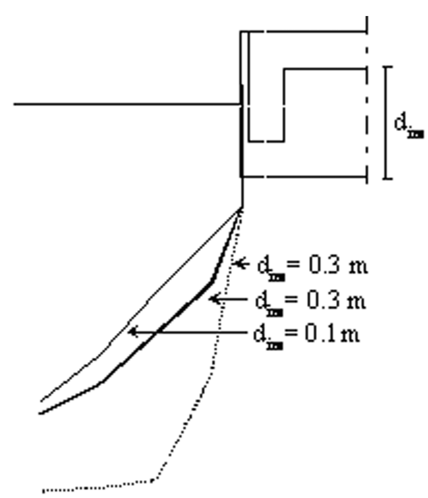

Figure 11 *The isotherm –1°C, the frost front, for different insulation thickness below the slab. The city is Lund, and indoor temperature is 20°C.*

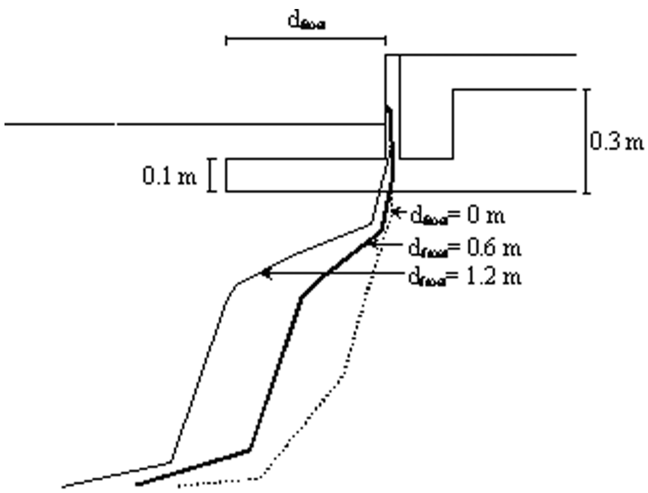

Figure 12 *The isotherm –1°C, the frost front, for different insulation widths of the frost insulation. The city is Lund, and indoor temperature is 20°C.*

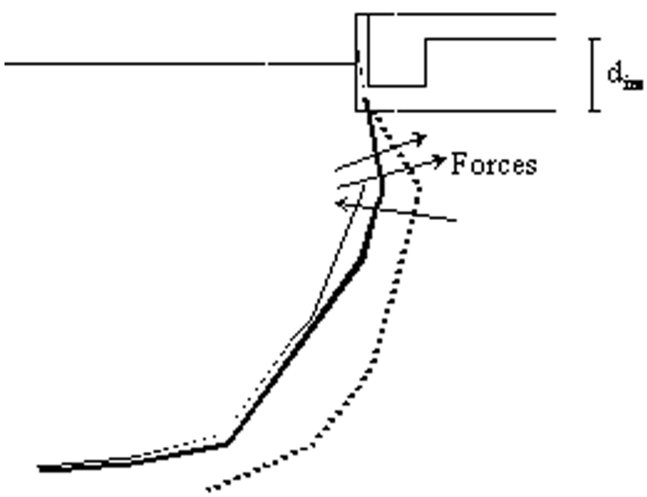

Figure 13 *The direction of the forces due to frost heave that acts on the foundation.*

With frost insulation, the –1°C isotherm, is nearly the same as in the case without frost insulation. However, the frost penetration will be reduced further (see Figure 12).

An alternative way to analyze the influence of the frost heave is to study how the forces act on the foundation. The frost lenses often follow the isotherm. The forces due to frost heave can be considered to act perpendicular to the –1°C isotherm. In Figure 13, the forces due to frost heave have been plotted for the case with varying insulation thickness below the slab. The directions of the forces indicate that it will affect the middle part of the foundation, and the edge beam is not affected (this is usually the load-bearing part). If the middle

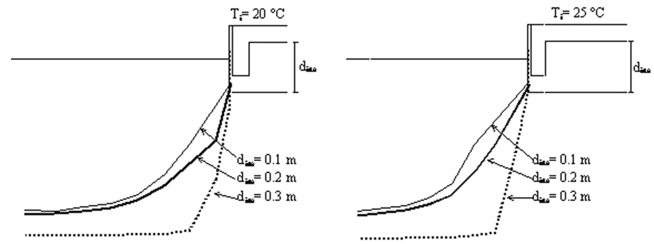

Figure 14 *The isotherm –1°C, the frost front, for different temperatures in the slab and varying insulation thickness. The city is Lund.*

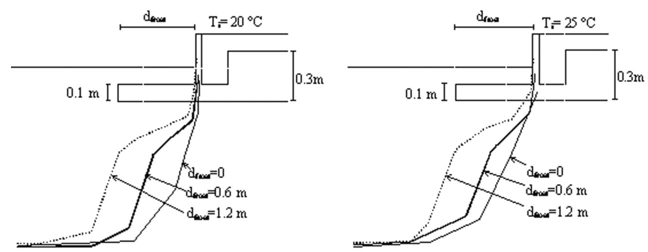

Figure 15 *The isotherm –1°C, the frost front, for different temperatures in the slab and 0.3 m insulation thickness. The city is Lund.*

section of the slab is reinforced, it may be a safe construction. However, the forces can also be divided into a horizontal and a vertical part. The vertical part of the force affects the foundation. The magnitude of the vertical forces depends on depth of the frost front. In the example illustrated in Figure 13, the vertical force is low and the load force from the building is probably larger. This indicates that the vertical frost heave force may not cause any damage on the slab. However, today it is not fully clear how the forces acts on the slab, and it is necessary to further analyze the frost penetration depth and how the forces act on the foundation.

Simulation of a slab with floor heating has been done for indoor temperatures of 20°C and 25°C. In Lund the frost front depth will be affected by the increased temperature of the slab (see Figure 14).

Floor heating, in combination with frost insulation, will also reduce the frost penetration in Lund, which can be seen in Figure 15. The insulation thickness is up to 300 mm below the slab for the cases in Figure 15. Therefore, the extra heat loss from the floor-heated slab will have a minor influence on the frost penetration depth.

CONCLUSIONS

Summarizing, frost heave is complex and many parameters affect the frost front penetration. The simulations show the following:

- Frost heave increases with thicker foundation insulation.
- A higher slab temperature (moderate), due to a floor heating system, has a minor influence on the depth.
- Frost protection insulation reduces the frost front penetration significantly.
- It is important to take the risk for frost heave into account in the design process. Other actions such as drainage layer thickness, frost protection insulation, etc., must be considered in order to prevent frost heave.

The simulations are undertaken in two dimensions. This will not give the most severe, greater frost front penetration. That will occur at the corners of the building, which are most exposed to the external low temperatures. According to Adamson et al. (1973), the frost penetration can be twice as large compared with the midsection of a building. To handle this, the frost protection insulation width should be increased up to a distance of 2.5 m from the corners. On the other hand, in Luleå the ground is very often covered with snow during wintertime. The snow layer represents a thermal resistance that will reduce the frost penetration. This shows that many parameters must be taken into account in order to determine if frost heave will cause damage to a building construction. The results presented here indicate that there is a risk for frost heave in a modern Swedish slab-on-grade, which must be considered in the design process.

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