Slab-on-grade foundation and edge wall element design — frost protection and simplified heat loss calculations

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SUMMARY

This paper presents an alternative to the method for calculating heat loss to the ground suggested in international standard EN-ISO 13370 "Thermal performance of buildings — Heat transfer via the ground — Calculation methods". This standard, proposed through CEN, proved to be quit complex, time-consuming, yet not especially accurate. It is absolutely essential that the design engineer understands the different aspects that govern the magnitude of heat loss from a slab-on-grade, and the consequences a reduced heat loss can have for frost protection for shallow foundations in cold climates.

To verify the results for this alternative and simplified method, we have to compare it with real field conditions and not only results from approximate numerical transient computer simulations based on more or less ideal assumptions.

Contrary to other elements included in the building envelope, occupants have direct physical contact with the floor surface. Consequently, to ensure low heat loss and high floor surface temperature, the demand for floor insulation, or low U-value for the floor, ought to be calculated in a similar fashion to U-values for the wall, ceiling, etc. for the building construction itself. The physical and thermal properties for the ground materials are affected by temperature, frost penetration, moisture, ground water table, flow of liquid moisture, etc. This makes it rather difficult to predict. Also snow cover, vegetation and percolation of surface water all affect, and even out, fluctuations in ground temperatures over the year. For a well insulated slab-on-grade, the fluctuations in heat losses are limited to a rather narrow zone near the floor perimeter. We can therefore assume, with sufficient accuracy, to have a uniform temperature below the floor insulation. The approximate 1-dimensional heat flow through the floor slab can then be calculated using simplified formulae by hand. The dynamic heat loss is reduced to a perimeter linear thermal bridge problem attached to the floor/wall/ring-wall junction. For a well-insulated slab-on-grad construction, the heat loss from this thermal bridge can be rather insignificant compared to the more stationary heat loss to the ground. This paper also presents examples how to reduce this thermal bridging problem to a minimum and how to prevent frost problems in cold climate for this rather frost-sensitive construction.

1. Introduction

New national building codes, and growing use of floor heating systems, are advancing the need for new design criteria for slab-on-grade foundations. Since most of the efforts have concentrated on improving the insulation standard of the above-grade building envelope, heat loss from the buildings via the ground has gained importance. Prevention of cold floor surfaces is of great importance, and will extensively improve the indoor climate. To reduce heat loss from the floor slab to the ground, it is necessary to increase the insulation thickness and minimize thermal bridges, particularly between the wall/floor junctions. In this area, around the floor perimeter where we have the highest heat loss, it is important to have a proper design in combination with effective heating systems to prevent cold floor surface, cold radiation and cold downdraught from windows. This enables the use of low temperature radiation heating systems, for instance wall or ceiling heating, with no need to concentrate heating surfaces at the building envelope.

In well-insulated shallow foundations, for instance slab-on-grade, the heat loss from the ground slab is low, and in cold climate not sufficient to prevent frost penetration underneath or inside the ring-wall. The resulting low temperatures can cause frost heave in susceptible ground, and in general frost problems for the water supply pipes situated inside the ring-wall. As a result, low ground temperatures will lower the surface floor temperature near the building perimeter.

The building envelope U-value is normally linked to the ambient outdoor temperature. For slab-on-grade foundations, however, this is not the case. The temperature in the ground below the slab insulation some distance in from the slab perimeter is rather constant over the year. Significant temperature fluctuations in the ground only occur near the building perimeter and outside it. Thermal inertia, and especially latent heat and liquid or diffusion moisture flow in humid materials, acts to reduce peak temperature fluctuations in the ground. The peak heat loss from the slab-on-grade has about a one-month time lag. Only the ring-wall element has direct contact with the outdoor temperature. It therefore requires rather complicated simulations to determine the heat loss from a slab-on-grade and the need for frost protection, with or without floor heating. The new European Standard for calculating heat transfer via the ground (EN-ISO 13370) does not fully take into account thermal bridging problems associated with floor heating, nor does it address frost protection related issues or the coupling between soil heat and moisture transfer. Measures that prevent frost problems, for instance a horizontal insulation layer, will also influence the heat loss. The mean U-value as presented in the building code or Standard for the whole floor area cannot be used as design criterion. Buildings with a larger footprint have a lower mean ground floor U-value, but the ground slab heat loss near the building perimeter is more or less independent of the size of building.

2. Examples of well-insulated slab-on-grade foundations

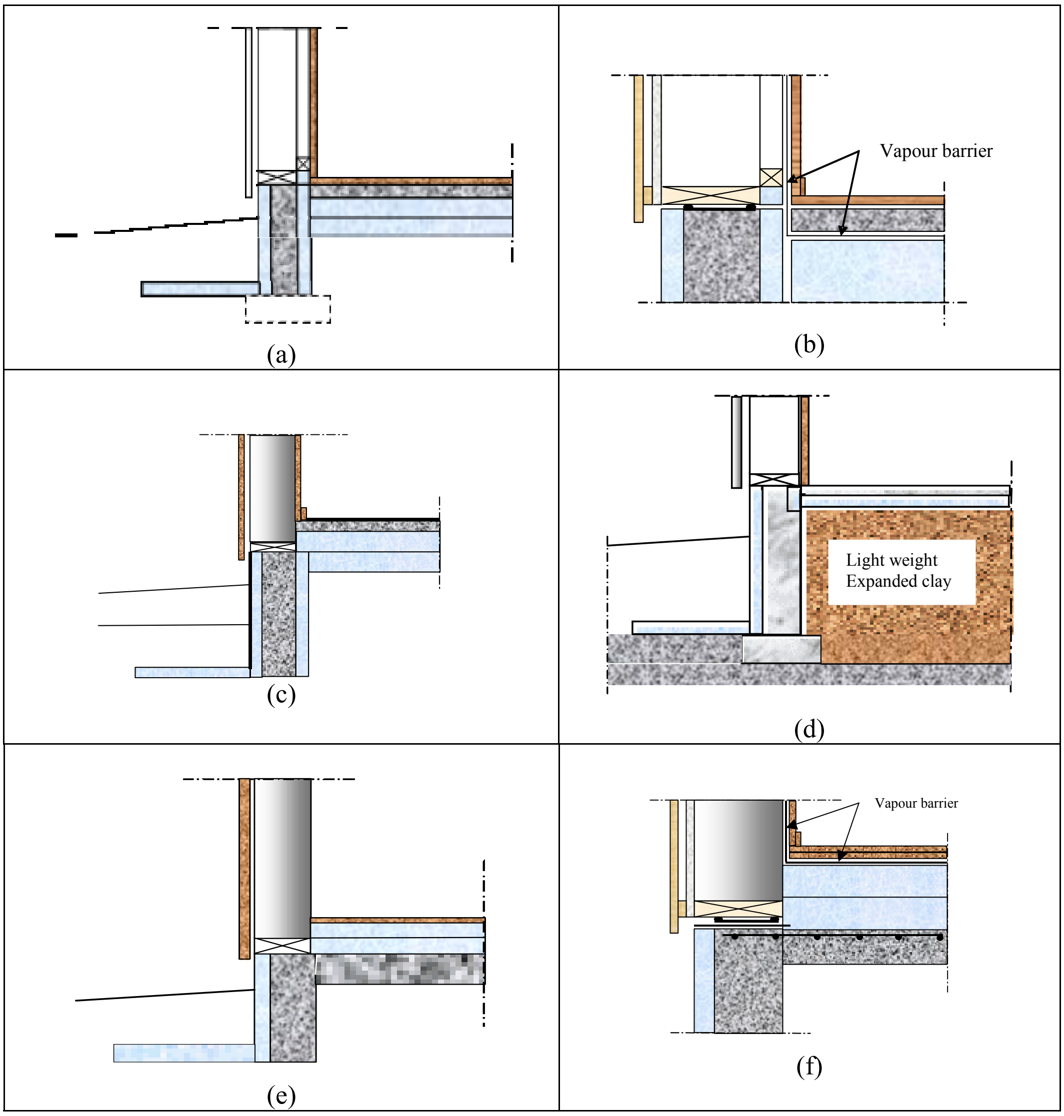


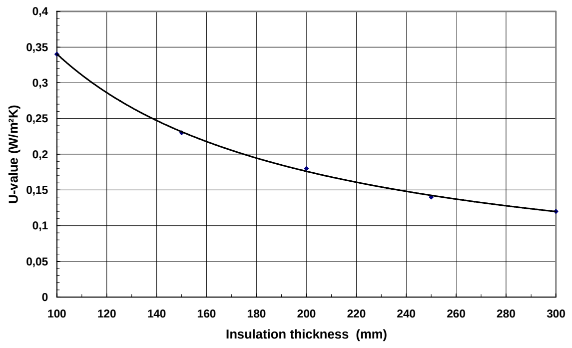
Figure 1. *Examples of slab on ground foundations with no thermal bridging problems at the wall/floor junction.*

3. Thermal transmittance (U-value) for the floor construction

A newly completed comprehensive parameter study [1] shows that the total heat loss from a well-insulated slab can be calculated with sufficient accuracy by dividing it into a 1-dimensional steady state heat loss through the slab floor and a linear 1 or 2-dimensional dynamic thermal bridge heat loss through the wall/floor junction. For a well design slab and edge wall element (Figure 1), the dynamic thermal bridge heat loss is small and can also be considered being 1-dimensional. 1-dimentional heat flow calculations can use simplified formulas suitable for hand calculation. This means that, independent of the thermal properties of the soil, the ground below the floor slab can be considered to have a uniform temperature. Like other elements on the building envelope, this will simplify and give a unique definition of the U-value for the floor construction. Neglecting the thermal resistance of the soil, the average U-value for the slab can then be calculated as:

$$U_{floor} = 1 / \Sigma R \quad (W/m^2K) \qquad (1)$$

where ΣR is the total thermal resistance of the floor construction (floor insulation and superstructure).



Floor-insulation (mm)	100	150	200	250	300
U-value (W/m²K)	0.34	0.23	0.18	0.14	0.12

Average U-value for the slab and thickness of floor insulation. The thermal conductivity for the floor insulation is 0.036 W/m²K an internal surface heat transfer resistance 0.13 m²K/W. The floor insulation has direct thermal contact with the ground.

U-value = 0.15 W/m²K ≈ 230 mm Insulation

***Figure 2**. U-value for an insulated concrete slab construction. (Neglecting thermal soil resistance).*

4. Frost protection

Heat loss from slab-on-grade, and necessary measures to prevent frost problems, are linked intrinsically together. Thick slab insulation and ring-wall insulation will naturally only supply the ground with a small amount of heat from the floor to prevent frost penetration through, or underneath, the ring-wall. In frost-susceptible ground, we cannot accept frost penetration beneath the ring-wall foundation. But in general, frost penetration through the foundation ring-wall element will give a higher heat loss and can result in frozen water and sewage pipes inside the ring-wall and must therefore be prevented.

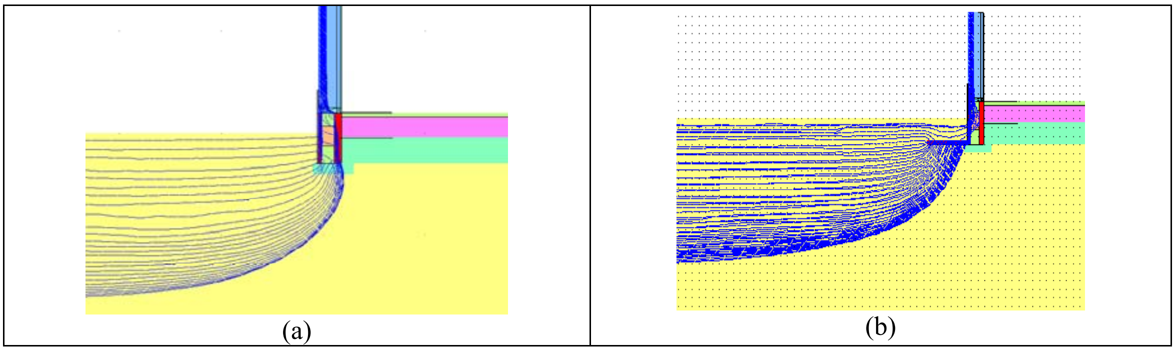

(a) (b)

***Figure 3**. Frost penetration development (Oslo climate) every 5 days during the freezing season in silty soil. Without (a) and with (b) horizontal field-insulation.*

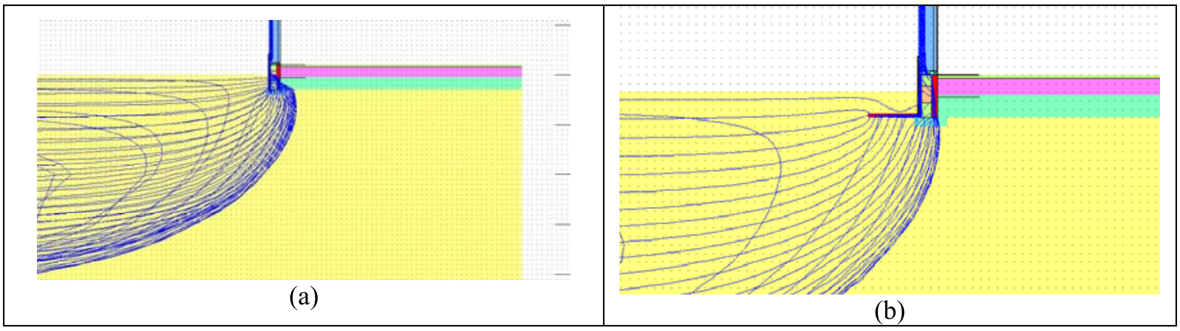

(a) (b)

***Figure 4**. Frost penetration development (Oslo climate) every 5 days during the freezing season in rocky ground. Without (a) and with (b) horizontal field-insulation.*

Figure 3 shows the result of dynamic calculation of the frost penetration every five days during the freezing season for the slab-on-grade construction (Figure 1a) in frost-susceptible ground (silt) for Oslo climate (frost index 25000 h°C, annual mean outdoor dry bulb air temperature 6.0°C). For Oslo climate the maximum frost depth in silt is about 1.7 m. The thickness of the slab insulation is 200 mm. In Figure 3a it is clear that frost penetrates underneath and inside the lower part of the ring-wall foundation. This will undoubtedly lead to frost heave problems. The foundation must therefore have frost-protection. The simplest way to do this is to use some horizontal insulation in the ground outside the ring-wall (Figure 3b). This ‘field insulation’ has a width of 0.6 m and thickness 50 mm. This is sufficient to prevent frost penetration beneath the ring-wall for Oslo climate.

Figure 4 shows a similar dynamic calculation for rocky ground. In this case there is extensive frost penetration beneath and inside the ring-wall (Figure 4a). The frost penetration inside the ring-wall will lead to higher heat loss and frost problems for pipes inside the ring-wall. Fortunately, the presence of frost beneath the ring-wall causes no problems in rocky or non frost-susceptible ground materials. Nevertheless, to prevent frost penetration inside the ring-wall, we can still use field insulation. As seen in Figure 4b, the use of horizontal field-insulation is effective also in rocky areas to prevent frost penetration inside the lower part of the ring-wall. The horizontal insulation also reduces the peak heat loss in a 0.5 m wide zone by approximately 8 % independent of the ground materials. According to steady-state calculations, the effect of the field insulation has practically no influence on the heat loss from the slab-on-grade constructions.

Table 1 lists minimum values of insulation to prevent frost penetration through, and under the ring-wall, in frost-susceptible ground. The ring-wall has an external and inner insulation of the same thickness, and the slab insulation is 200 mm thick. As design climatic load, we have used a correlation between frost index and annual mean temperature that is representative for Norway. In cold climates it is necessary to use a rather wide horizontal field-insulation to prevent frost underneath the ring-wall foundation. To prevent thermal bridging across the top of the ring-wall in colder climates, it is convenient to increase the inner insulation. This will not affect the frost protection. The insulation thickness given in Table 1 is also sufficient to prevent frost penetration during periods with three days design temperature. The geological FEM software package *Temp/W* was used for the numerical calculations.

Table 1 Ring-wall with outer and inner insulation with same thickness

Frost index [h°C]	Annual mean temperature [°C]	Horizontal field-insulation thickness [mm]	Horizontal field-insulation width [mm]	Ring-wall insulation thickness [mm]
15 000	6.0	50	300	50 × 2
20 000	6.0	50	400	50 × 2
25 000	6.0	50	500	50 × 2
30 000	4.0	50	800	50 ×2
35 000	3.0	50	900	50 ×2
40 000	1.5	70	1 000	50 ×2
45 000	1.0	70	1 200	50 × 2
50 000	0.5	100	1 300	100 × 2
55 000	0.5	100	1 700	100 × 2
60 000	0.5	100	1 900	100 × 2

Rocky ground

For rocky ground materials we have assumed a thermal conductivity of 3.5 W/mK and volumetric heat capacity 2×10^3 kJ/m³K. There is no water content in the upper part of the ground. In rocky and non-susceptible soil types we can permit frost to penetrate below the ring-wall foundations, but we want to prevent, if it is possible, frost penetrating the ring-wall.

Table 2 Ring-wall with outer and inner insulation with same thickness

Frost index [h°C]	Annual mean temperature [°C]	Horizontal field-insulation thickness [mm]	Horizontal field-insulation width [mm]	Ring-wall insulation thickness [mm]
15 000	6	50	500	50
20 000	6	50	800	50
25 000	6	60	1 000	50
30 000	4	70	1 800	70

To prevent frost penetration inside lower part of the ring-wall in colder climate, with a frost index above 30 000 h°C, the width of the horizontal field-insulation must exceed 2.0 m. Normally in colder climates we can take into account some snow cover, which effectively reduces frost penetration in the ground. The task for the horizontal field-insulation is mainly to prevent frost penetration in a period before we have snow cover. Alternatively we can frost-protect pipes inside the ring-wall with trace heating or use a deeper ring-wall.

5. Simplified calculation of heat loss from a well insulated slab-on-grade

5.1 Background

Standard EN-ISO 13370 is a rather comprehensive method for determining heat loss from a slab-on-grade via the ground. Nevertheless the calculation method is not particularly accurate, and gives no answers on how to prevent frost problems in cold climates. Steady-state calculations give little or no credit to the use of a horizontal field-insulation with regards to heat loss. In general, ground materials are not homogeneous but consist of a mixture of different materials with different thermal properties. In periods with high rain intensity or melting snow it is rather common to allow surface water to percolate through the Macadam layer beneath the slab insulation (Figure 5). This will cool down the ground materials beneath shallow foundations. It is therefore difficult to predict with any confidence the thermal properties of the soil materials.

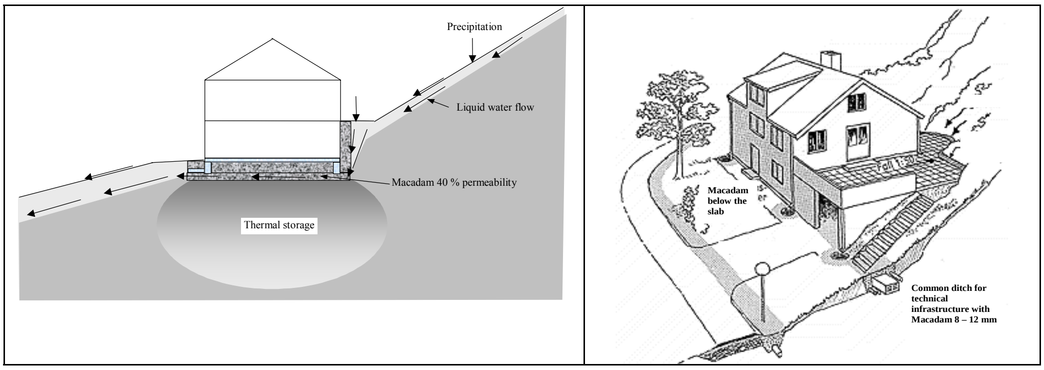


Figure 5. *Thermal storage in the soil underneath the slab is highly dependent on moisture content and liquid moisture flow. The Macadam or crushed rock layer under the floor slab and foundation, and internal and external ditches, all serve as a storage and waterway for rainwater.*

Because of a considerable energy surplus in summer, we are primarily interested in determining the heat loss during the heating season. However, compared to specific heat loss from well-insulated walls, thick floor insulation will result in a relatively small heat loss and heat loss fluctuation over the year (Figure 6). Irrespective of building size, it is important to have sufficient slab insulation in the perimeter zone. For large buildings it is not always necessary to have the same insulation thickness over the whole floor area. Consequently we cannot always operate with an average insulation thickness for the whole floor area.

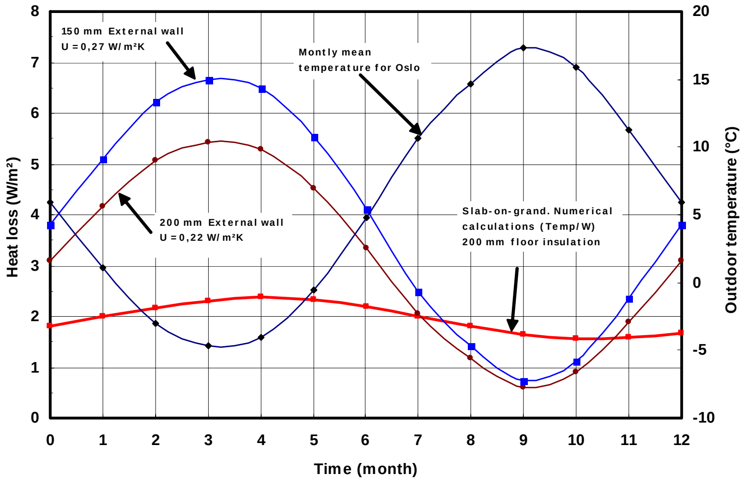


Figure 6. *Calculations of mean specific heat loss from external walls over the year compared to similar heat loss from a slab-on-grade with 200 mm floor insulation (U-value 0.17 W/m²K) and floor area 100 m². Oslo climate.*

5.2 Method description

5.2.1 Energy calculation, 1-dimentional heat loss to the ground

In the alternative simplified method, the problem is split up into two separate calculations: one 1-dimentional steady state heat loss through the floor slab to the ground, and 1 or 2-dimensional dynamic heat loss through the wall/floor junction to the external air. With sufficient ring-wall insulation to prevent frost penetration (Table 1 and Figure 1), the dynamic heat loss due to thermal bridging across the wall/floor junction can be small and negligible in regard to energy calculations.

With a uniform temperature in the ground below the floor insulation, the average steady state heat loss Q_{floor} can be calculated as:

$$Q_{floor} = U_{floor} \cdot A \cdot \Delta T_0 \quad \text{(W)} \qquad (2)$$

where A = Internal floor area (m)
U_{floor} = U-value for the floor construction, see Equation (1)
$\Delta T_0 = (T_{internal} - T_m)$

Internal temperature $T_{internal}$ is normally set to 20°C and as reference temperature in the ground T_m we can for a building with small or medium footprint use the local year mean temperature (Oslo $T_m = 6.0°C$).

Example:

$U_{floor} = 0.17$ W/m²K (200 mm floor insulation, 50 mm concrete and 15 mm parquet)
$T_m = 6.0°C$ (Oslo climate)
$A = 100$ m²

$$\Rightarrow \quad Q_{floor} = U_{floor} \cdot A \cdot \Delta T_0 = 0.17 \cdot 100 \cdot (20 - 6) = 238 \text{ W} \quad \text{or } 2.4 \text{ W/m}^2$$

Heat loss over the heating season (6 months)

$$Q_{heating\ season} = Q_{floor} \cdot 24 \cdot 6 \cdot 30/1000 = 1028 \text{ kWh} \quad \text{or } 10.3 \text{ kWh/m}^2 \text{ floor area}$$

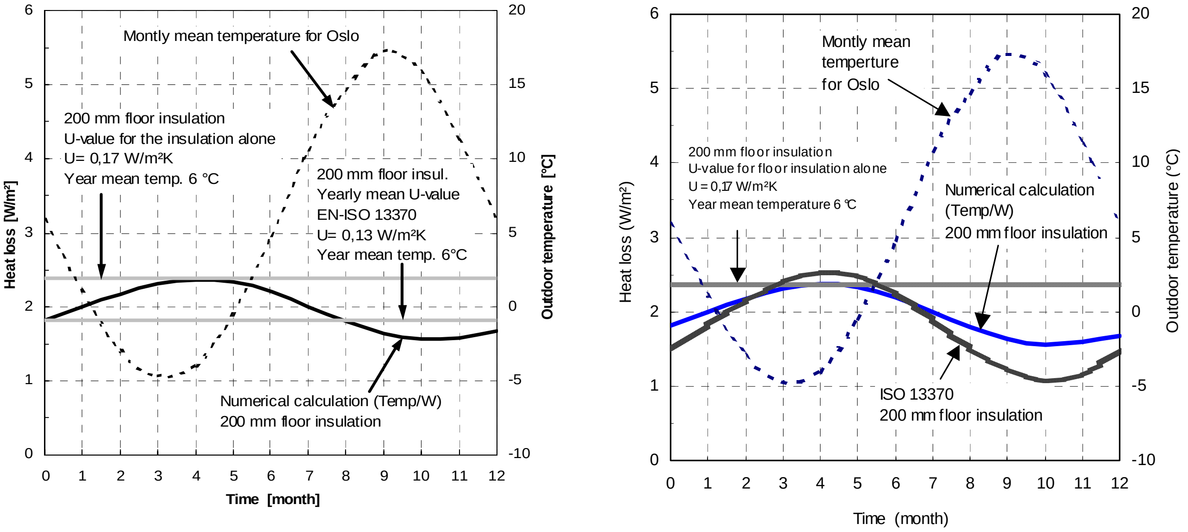


Figure 7*. Different methods of calculating heat loss from the slab-on-ground construction (Figure 1a) over the year. In the diagram to the left only steady state yearly heat loss from the EN-ISO 13370 is counted for. To the right it is corrected for seasonal variations. The numerical calculations (Temp/W) take into account the soil's latent heat and dependence of thermal conductivity on temperature.*

In Figure 7 it is interesting to notice that when we in the numerical calculations take into consideration more realistic field conditions [phase change of moisture (latent heat) and variation in heat conductivity with temperature], it tends to level out the heat loss fluctuations over the year. And we still have not taken into account the liquid moisture flow in the soil materials that even moreso tend to level out temperature fluctuations in the soil. Normally we will have heavy rainfall that can lead to flooding in autumn and a lot of surface water in the spring during the snow-melting period. This surface water can penetrate the permeable soil materials especially near the building perimeter (Figure 5).

Building a larger footprint can result in an inner zone with lower heat loss (Figure 8). However, to calculate with a lower heat loss, the soil materials have to be homogeneous and well documented with no liquid moisture flow and ground-water-table at least 2 m below soil surface. Because it will take years to build up a thermal storage in the soil it is advantageous, also for buildings with large footprints to have the same insulation thickness as required for the outer area. In Norwegian climatic conditions, with a yearly mean soil temperature varying from 2 ~ 7°C, we can use 12±1°C as a default value for the inner zone reference soil temperature [1].

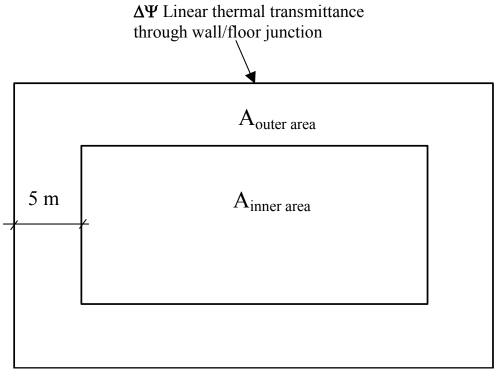


Figure 8*. For buildings with a large footprint >> 100 m², the floor area can be split into an outer and inner area with different heat losses. It is nevertheless normally advantageous to have the same insulation thickness over the whole floor area.*

5.2.2 Calculation of the design heat loss

For design heat loss Q_e calculations, it can be necessary to take into account the dynamic linear heat loss due to thermal bridging across the wall/floor junction (Figure 9). The linear thermal transmittance ψ in W/mK can also with good approximation be considered a 1-dimensional problem. The following simplified method can then be used for calculation of the linear transmission heat losses Q_{dynamic}:

$$Q_e = Q_{\text{floor}} + Q_{\text{dynamic}}$$

$$Q_{\text{dynamic}} = \psi \cdot P \cdot | T_{\text{external}} - T_m | \quad [\text{W}]$$

where P = Building perimeter [m]
T_{external} = Local design temperature (Oslo, –20°C)
$\psi \approx (1/\Sigma R) \cdot a \quad [\text{W/mK}]$
ΣR is the total heat resistance for the 1 (2)-dimensional heat flow (Figure 9).
a = thickness of the floor superstructure (concrete slab) above the floor insulation [m]

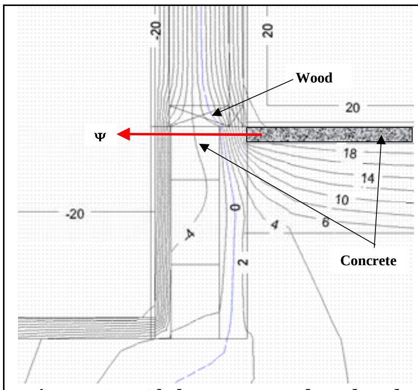


Figure 9a*. Slab-on-ground under design temperature conditions (–20°C) for Oslo climate. Configuration of the isotherms.*

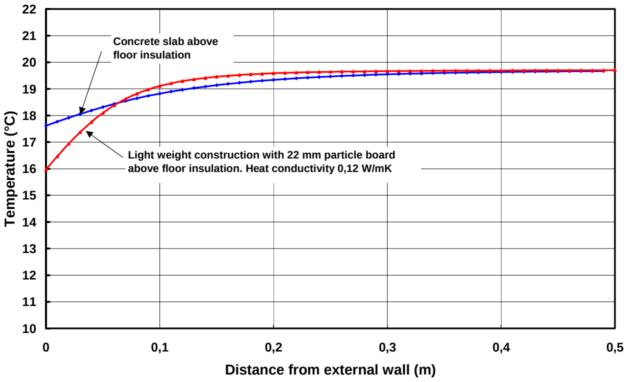


Figure 9b*. The floor surface temperature distribution from the external wall with concrete or a lightweight low conductivity slab construction.*

Calculation example:
The construction in Figure 9 has 100 mm ring-wall insulation. The concrete slab is *a* = 60 mm thick, and the external surface heat transfer resistance is 0.04 m²K/W. The footprint of the building is 100 m², perimeter *P* = 40 m and external design temperature –20°C.

$\Sigma R \approx 0.1 / 0.036 + 0.04 = 2.8 \text{ m}^2\text{K/W}$

$\psi = (1/\Sigma R) \cdot a \;\; = (1 / 2.8) \cdot 0.06 = 0.02 \text{ W/mK}$

$Q_{dynamic} = \psi \cdot P \cdot | T_{design} - T_m | = 0.02 \cdot 40 \cdot | -20 - 6 | = 21 \text{ W}$

$Q_e = Q_{floor} + Q_{dynamic} = 238 + 21 = 259 \text{ W}$

Under design temperature conditions (Oslo climate) the dynamic heat loss due to thermal bridging across the wall/floor junction is 8 %.

The average temperature over the freezing season (6 months) for Oslo climate is about 0°C.
The dynamic heat loss $Q_{dynamic}$ over the heating season (6 months) can be calculated as:

$Q_{dynamic} = 0.02 \cdot 40 \cdot |0 - 6| \cdot 24 \cdot 30 \cdot 6/1000 = 21 \text{ kWh}$

The total heat loss Q_e over the heating season (6 months):

$Q_e = Q_{floor} + Q_{dynamic} = 1028 + 21 = 1049$ kWh where the dynamic heat loss only is 2 % and therefore of minor interest.

If the edge wall element design in principal is in accordance with the examples given in Figure 1, and the insulation thickness is in accordance with Table 1 or 2 for frost protection, the dynamic linear heat loss due to thermal bridging across the wall/floor junction is small and can be neglected both in energy and design heat loss calculations.

6. Conclusion

This paper gives examples of how to design and frost protect well-insulated slab-on-ground constructions and describe an alternative simplified method of calculating heat loss to the ground. This simplified method for heat loss calculation for well-insulated slab-on-grade constructions for energy and power analysis, can with sufficient accuracy be used as an alternative to the more complex and time-consuming method described in standard EN-ISO 13370. For design purposes it is essential to keep things simple to avoid thermal bridging across the wall/floor junction and frost problems. It is also important to note that obstructive complex standardised evaluation methods can prevent further development of new and better solutions. However, to put things in the right perspective, during the heating season the heat loss from a well-insulated slab-on-grade construction is normally about 10 ~ 15 % of the total heat loss from the building. If we roughly assume that the accuracy for the floor heat loss calculations compared to real in site conditions is about 10 ~ 20 %, this will only affect 1 ~ 2 % of the total heat loss for the building during the heating season.

7. Acknowledgements

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8. References

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