Sample Chapter

Performance Based Building Design 1. From Below Grade Construction to Cavity Walls.

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0 Introduction

0.1 Subject of the book

This is the third book in a series on building physics, applied building physics and performance based building design:

- Building Physics: Heat, Air and Moisture
- Applied Building Physics: Boundary Conditions, Building Performance and Material Properties
- **Performance Based Building Design 1**
- Performance Based Building Design 2

Both volumes apply the performance based engineering rationale, discussed in 'Applied Building Physics: Boundary Conditions, Building Performance and Material Properties' to the design and construction of building elements and assemblies. In order to do that, the text balances between the performance requirements presumed or imposed, their prediction during the design stage and the technology needed to realize the quality demanded.

Performance requirements discussed in 'Applied Building Physics: Boundary Conditions, Building Performance and Material Properties', stress the need for an excellent thermal insulation in cold and cool climates and the importance of a correct air, vapour and water management. It is therefore logical that Chapter 2 starts with a detailed overview of insulation materials, waterproof layers, vapour retarders, airflow retarders and joint caulking, after Chapter 1 recaptured the performance array at the building assembly level. In the chapters that follow the building assemblies that together shape a building are analyzed: foundations, basements and floors on grade, the load bearing structure, floors and massive facade systems. Each time the impact of the performance requirements on design and construction is highlighted. For decades, the Laboratory of Building Physics at the K. U. Leuven also did extended testing on highly insulated massive facade assemblies. The results are used and commented.

0.2 Units and symbols

The book uses the SI-system (internationally mandatory since 1977). Base units are the meter (m), the kilogram (kg), the second (s), the Kelvin (K), the ampere (A) and the candela. Derived units, which are important, are:

Unit of force:	Newton	(N);	$1\ \text{N} = 1\ \text{kg} \cdot \text{m} \cdot \text{s}^{-2}$
Unit of pressure:	Pascal	(Pa);	$1\ \text{Pa} = 1\ \text{N/m}^2 = 1\ \text{kg} \cdot \text{m}^{-1} \cdot \text{s}^{-2}$
Unit of energy:	Joule	(J);	$1\ \text{J} = 1\ \text{N} \cdot \text{m} = 1\ \text{kg} \cdot \text{m}^2 \cdot \text{s}^{-2}$
Unit of power:	Watt	(W);	$1\ \text{W} = 1\ \text{J} \cdot \text{s}^{-1} = 1\ \text{kg} \cdot \text{m}^2 \cdot \text{s}^{-3}$

For the symbols, the ISO-standards (International Standardization Organization) are followed. If a quantity is not included in these standards, the CIB-W40 recommendations (International Council for Building Research, Studies and Documentation, Working Group 'Heat and Moisture

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5 Building parts on and below grade

5.1 In general

The term on and below grade relates to all building parts other than foundations that demand excavation: walls between grade and footing, crawl spaces, basements and floors on grade. All have their own complexity. Construction of the first three proceeds in excavation with soil stability rendering building more difficult. Heat transfer develops three-dimensionally. Parts below the water table have to withstand water heads.

Chapter five first discusses performance evaluation before analysing construction aspects typical for below and on grade building parts.

5.2 Performance evaluation

5.2.1 Structural integrity

5.2.1.1 Static stability

Foundation walls, crawl spaces and basements transmit and distribute the vertical and horizontal load exerted by the building to and over the foundations. Furthermore, they withstand soil pressure and for parts below the water table, they withstand water heads. On sloped sites, below grade building parts also act as retaining walls, with soil friction and passive soil pressure on the sides away from the slope guaranteeing equilibrium (Figure 5.1). For basements partly below the water table, the weight of the building must compensate upward water pressure. Otherwise, building and basement have to be anchored in the soil with piles (Figure 5.2) or one must ballast the basement, for example by constructing a double floor with gravel in between. In buildings founded on footings, building sections with basement may settle less than those without. Larger soil decompression thanks to deeper excavation and smaller load per m^2 of basement floor are the reasons. A good choice on compressible soil therefore is to found parts outside the basement deeper or to design footings and basements as stiff entities.

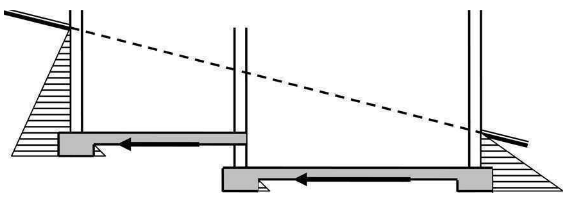

Figure 5.1. Below grade building parts acting as retaining wall.

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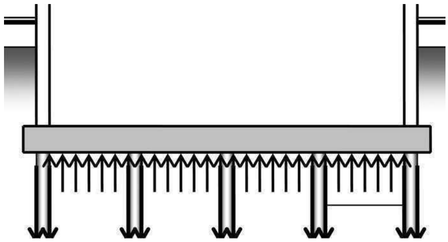

Figure 5.2. Piles used as soil anchor.

5.2.1.2 Strength and stiffness

Basements walls and floors have to withstand axial compression and bending, for the walls by the building above, the soil and, below the water table, by water heads (Figure 5.3), for the floors by the soil, own weight, dead weight, live load and, below the water table, by water heads. In the last case, the lowest basement floor experiences upward water pressure, given by $p = 10\,000$ h (N/m^2), where h is the height of the water table above the floor's underside. Greater height quickly increases the pressure. The consequence are field moments in the floor slab with tension in the upper part and support moments below all basement walls with tension in the lower part. Large spans even demand construction as beam raster. Foundation floors finally are subjected to a strong upward bending by soil pressure, induced by the overall building load.

In massive basement walls the axial load usually gains from bending. That keeps the load's eccentricity within the wall's kern, making masonry applicable. Basements including several floors or basements bearing skeleton constructions, however, can experience such large bending moments that reinforced concrete construction is the only way out. In the recent past, precast reinforced concrete basements have taken over an ever-larger market share in residential construction.

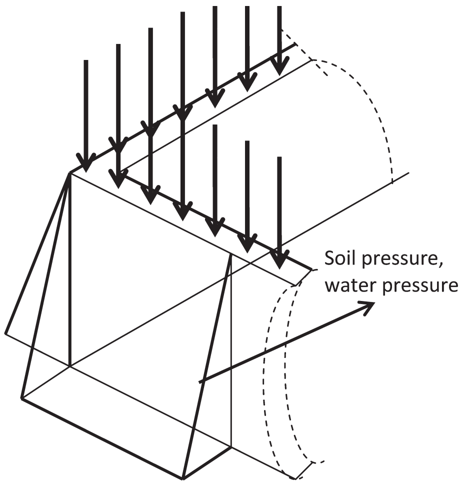

Figure 5.3. Loads on basement walls.

5.2.2 Building physics, heat, air, moisture

5.2.2.1 Air tightness

Problems caused by insufficient air tightness mainly involve ground floors above ventilated crawl spaces. Vents coupling the crawl space to outdoors allow outside air inflow while the draft prone ground floor links the crawlspace to all residential spaces above, which in turn are coupled to the outside through leaks and ventilation grids.

In the case that extract ventilation is applied, air is drawn from the crawl space across the ground floor leaks into the residential space above. That flow is compensated by an identical inflow of outside air into the crawlspace. In other words, floor leaks and vents in the crawl space form a series circuit (Figure 5.4). In case both have the same air permeance exponent b, air leakage can be described as:

$$G_a = \left[\frac{1}{a_{fl}^{1/b}} + 1 \Bigg/ \left(\sum_{i=1}^{n} a_{i,\text{clsp}} \right)^{1/b} \right]^{-b} \Delta P_a^b \tag{5.1}$$

where a_{fl} is the air permeance coefficient of the floor in kg/(s · Pa^b), a_{clsp} the air permeance coefficient of a ventilation opening in the outer wall of the crawl space in kg/(s · Pa^b) and ΔP_a the pressure difference along the path outdoors/crawlspace/living space above in Pa.

Also thermal buoyancy may move air from the crawlspace into the living space above. In windless weather, stack flow equals:

$$G_a = \left[\frac{1}{a_{fl}^{1/b}} + 1 \Bigg/ \left(\sum_{i=1}^{n} a_{i,\text{clsp}} \right)^{1/b} + 1 \Bigg/ \left(\sum_{j=1}^{m} a_{j,\text{inlet}} \right)^{1/b} \right]^{-b} \Delta p_t^b \tag{5.2}$$

where a_{inlet} is the air permeance coefficient of the air inlet grids in the outer wall of the residential space in kg/(s · Pa^b). Thermal stack Δp_t is thereby approximated by:

$$\Delta p_t = 0.043 \left[h_{c,fl}\, \theta_c + h_{fl,rs}\, \theta_i - \left(h_{c,fl} + h_{fl,rs} \right) \theta_e \right] \tag{5.3}$$

with θ_c the temperature in the crawlspace, θ_i the temperature in the living space above, $h_{c,fl}$ the vertical distance between the ventilation openings in the outer crawl space wall and the floor's mid-plane and $h_{fl,rs}$ the vertical distance between the floor's mid-plane and the air inlets in the living space.

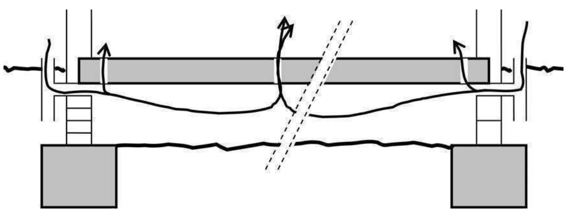

Figure 5.4. Floor leakages between crawlspace and ground floor.

Example

Consider a one storey high detached house with floor area 120 m^2. On top of the operable windows in the living space, 0.12 m^2 of air inlet grids are mounted 2 m above the ground floor mid-plane. The crawlspace has 0.4 m^2 of vents just below the ground floor ($h_{c,fl}$ = 0.2 m). Temperatures are 0 °C outside and 20 °C inside while wind velocity is zero. Thermal stack so equals ≈ 0,043 · 2.2 · 20 = 1.89 Pa. Air flow across the air inlet grids and the vents is given by $A\sqrt{2\,\rho_a/1.5}\,\Delta p_t^{0.5}$ in kg/(s · Pa^b) with ρ_a air density (≈ 1.2 kg/m^3), 0.5 the air permeance exponent (b) and $A\sqrt{2\,\rho_a/1.5}$ the volumetric air permeance coefficients, equal to:

Crawlspace	0.422 $m^3/(s \cdot Pa^b)$
Residential space	0.126 $m^3/(s \cdot Pa^b)$

The volumetric air permeance coefficient of the ground floor is $p\,A/100\,\sqrt{2/(1.5\,\rho_a)}$ ($m^3/(s \cdot Pa^b)$), with *p* the ratio in percentage between floor leakage and total floor area. The air permeance exponent (b) is also 0.5. The resulting airflow in m^3/h from crawl space to residential space is shown in Figure 5.5. While negligible below a floor leakage area of 0.002%, airflow quickly increases to stabilize once the leakage area exceeds 0.4%. Of course, that percentage depends on the air permeance of the vents and inlet grids

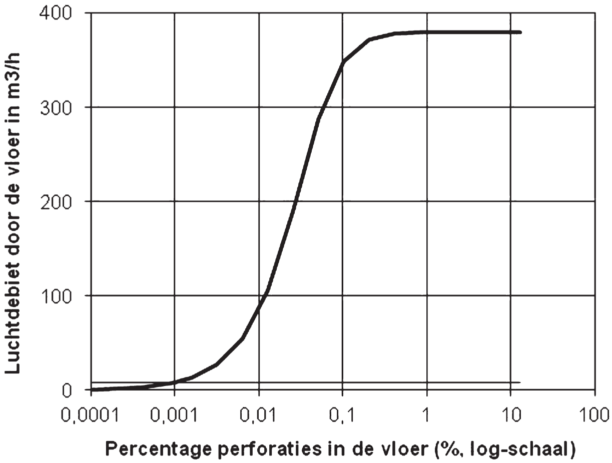

Figure 5.5. Airflow in m^3/h from crawl space to living space.
The dashed line shows the maximum leakage value imposed by the Dutch building ordinance.

The consequences of air inflow from the crawl space into the living space can be annoying. In case the crawlspace is moist, considerable water vapour may co-infiltrate. In radon-loaded soils, the same holds for radon. Air from the crawlspace may smell, etc.

Equation (5.2) suggests three measures that limit air inflow: (1) not venting the crawlspace, (2) no air inlets and perfect air-tightness of the residential enclosure, (3) airtight ground floor. The second kills living space ventilation, which is unacceptable. The first demands a warm crawlspace whereas the third seems the most logical choice, though difficult to realize. It is more realistic to limit crawlspace air inflow to a value that avoids mould growth in the residential spaces above. Additional conditions then become a well-insulated envelope ($R_{opaque} \geq 2$ $m^2 \cdot K/W$, no problematic thermal bridging), outside air ventilation equal to the value required by law or standard and monthly mean vapour release indoors not exceeding the indoor climate class 3/4 vapour pressure threshold. For example, the Dutch building ordinance limits air inflow from the crawlspace to 0.072 $m^3/(m^2 \cdot h)$. Implementation in Figure 5.5 shows that value requires a floor leakage ratio below 0.001%.

Where are the leaks in floors above crawlspaces found? Timber decks may have open joints between planks. With prefabricated floors and concrete slabs, heating, water supply pipes, discharge pipes and electrical wiring passages create leaks if not well sealed. Prefabricated floors without concrete topping sometimes suffer from leakage at the supports.

5.2.2.2 Thermal transmittance

For floors on grade, floors above basements, floors above crawlspaces, basement and crawl-space floors and walls in contact with the soil the concept of a 'thermal transmittance' is not applicable anymore. The temperature field in the soil in fact is three-dimensional whereas thermal transmittances presume one-dimensional temperature fields. The concept nevertheless is retained, now called reduced thermal transmittance ($U_{red,fl}$) and given by:

$$U_{red,fl} = a\,U_{o,fl} \tag{5.4}$$

with 'a' a reduction factor and $U_{o,fl}$ the thermal transmittance as if the underside of a floor on grade, a heated basement floor and its outer walls were facing the outside environment and, as if the underside of a floor above unheated basements and crawlspaces were facing an inside environment. The problem then becomes to calculate that factor.

Software

The best method is use software. The tools for three-dimensional heat transport in soils with constant thermal conductivity are quite simple. Figure 5.6 shows the results for a heated basement with a 25 cm thick concrete floor and 20 cm thick concrete walls. Thermal conductivity of the concrete is 2.2 $W/(m \cdot K)$, of the soil 2 $W/(m \cdot K)$. Reduction factors are 0.077 for the floor and 0.23 for the walls. When the floor and walls consisted of light-weight concrete, $\lambda = 1$ $W/(m \cdot K)$, the values should have been 0.088 for the floor and 0.29 for the walls. Or, reduction decreases with better insulation of the basement floor and walls.

A better choice is to use software that considers combined heat and moisture transfer in the soil. That way, enthalpy displacement is included. Figure 5.7 gives an example. With a thermal transmittance of 0.7 $W/(m^2 \cdot K)$ for the basement floor and the walls, reduction factors reach 0.26 and 0.62 respectively.

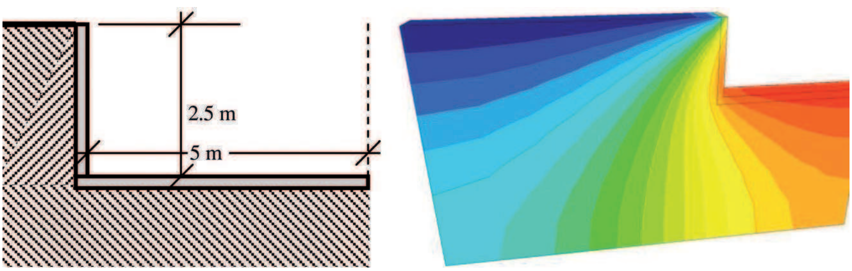

Figure 5.6. Heated basement with concrete walls and floor (20 °C inside, 0 °C outside), isotherms in the soil (calculated with software for steady state three-dimensional heat transport, the soil with thermal conductivity 2 $W/(m \cdot K)$).

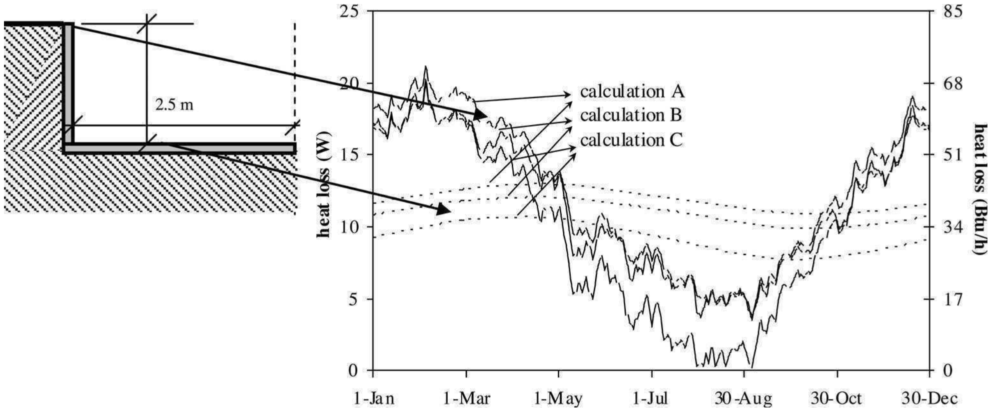

Figure 5.7. Heated basement (20 °C inside, 0 °C outside), heat losses to the soil. A is the reference. In B moisture content in the soil equals the annual mean. C considers the equivalent temperature outdoors. The curves with highest amplitude represent heat flow across the walls, the other heat flow across the floor.

Standard EN ISO 13370

Floor on grade

Calculation starts with the characteristic floor dimension:

$$B' = 2\ A_{\mathrm{fl}}/P \quad \text{(m)} \tag{5.5}$$

where A_{fl} is floor area and P the part of the floor perimeter facing the outdoors, called the free perimeter (Figure 5.8). The floor is then replaced by an equivalent soil thickness (d_{t}):

$$d_{\mathrm{t}} = d_{\mathrm{fw}} + \lambda_{\mathrm{gr}} \left(\frac{1}{h_{\mathrm{e}}} + R_{\mathrm{T,fl}} + \frac{1}{h_{\mathrm{i}}} \right) \quad \text{(m)} \tag{5.6}$$

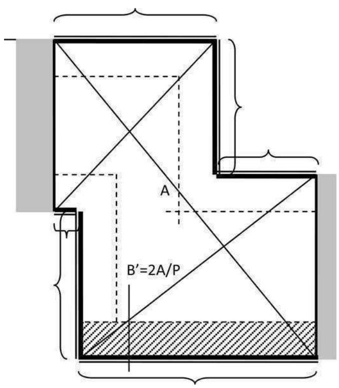

Figure 5.8. Floor on grade, characteristic dimension. Braces show the part of the perimeter facing outdoors, while the hatched surface gives the horizontal width of the horizontal perimeter insulation.

where d_{fw} is the average width in m of the foundation walls under the free perimeter, λ_{gr} the thermal conductivity of the soil in W/(m · K), $R_{T,fl}$ the thermal resistance of the floor in $m^2 \cdot K/W$, h_i the surface film coefficient indoors, 6 $W/(m^2 \cdot K)$), and h_e the surface film coefficient outdoors, 25 $W/(m^2 \cdot K)$. If thermal conductivity of the soil is unknown, the following values are proposed:

Soil	**Thermal conductivity W/(m · K)**	**Volumetric heat capacity $J/(m^3 \cdot K)$**
Clay or silt	1.5	$3 \cdot 10^6$
Sand or gravel	2.0	$2 \cdot 10^6$
Homogeneous rock	3.5	$2 \cdot 10^6$

Finally, the reduction factor is calculated, its value depending on the ratio between the equivalent soil thickness and the characteristic floor dimension (see Figure 5.9):

$$\begin{aligned} d_t < B'&: \; a = \frac{1}{U_{o,fl}}\left(\frac{2\,\lambda_{gr}}{\pi\,B' + d_t}\right)\ln\left(\frac{\pi\,B'}{d_t}+1\right) \\ d_t \geq B'&: \; a = \frac{1}{U_{o,fl}}\left(\frac{\lambda_{gr}}{0.457\,B' + d_t}\right) \end{aligned} \tag{5.7}$$

Without perimeter insulation, calculation comes to a halt. If perimeter insulation is applied, reduced thermal transmittance turns into:

$$U_{red,fl} = a\,U_{o,fl} + 2\,\frac{\psi}{B'} \quad (W/(m^2 \cdot K)) \tag{5.8}$$

with ψ a negative linear thermal transmittance along the free perimeter, a value depending on the equivalent soil thickness of the perimeter isolation:

$$d' = \lambda_{gr}\left(R_{ins} - \frac{d_{ins}}{\lambda_{gr}}\right) \quad (m) \tag{5.9}$$

and given by:

$$\psi = -\frac{\lambda_{gr}}{\pi}\left[\ln\left(\frac{D}{d_t}+1\right) - \ln\left(\frac{D}{d_t + d'}+1\right)\right] \quad (W/(m \cdot K)) \tag{5.10}$$

where D is the horizontal width of the insulation strip and d_t the equivalent soil thickness of the floor (Figure 5.8). In case the perimeter insulation is lined vertically against the foundation walls or if these walls are constructed of insulating blocks (R_{ins} and d_{ins} in [5.9]), linear thermal transmittance in terms of mean thermal resistance and thickness of the foundation walls then becomes:

$$\psi = -\frac{\lambda_{gr}}{\pi}\left[\ln\left(\frac{2\,H}{d_t}+1\right) - \ln\left(\frac{2\,H}{d_t + d'}+1\right)\right] \tag{5.11}$$

with H the height of the perimeter insulation or height of the foundation walls.

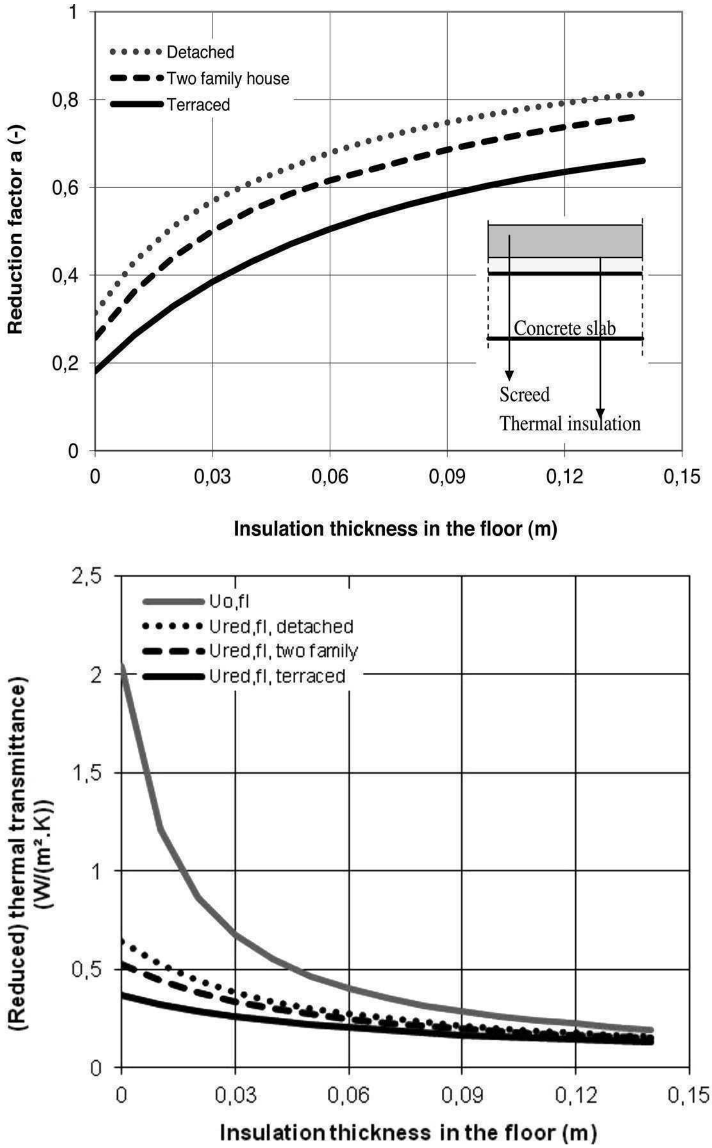

Figure 5.9. Floor on grade, reduction factor and reduced thermal transmittance (EN ISO 13370). Area 77.8 m^2, free perimeter 36 m if detached, 25.2 m if two family and 14.4 m if terraced. Thermal resistance without insulation 0.32 $m^2 \cdot K/W$, thermal conductivity insulation 0.03 $W/(m \cdot K)$, soil 2.0 $W/(m \cdot K)$.

Heated basement or heated space partly below grade

First, the characteristic dimension of the basement or space below grade is calculated with the facade length as free perimeter. The reduction factor for the floor then is:

$$d_\text{t} + H/2 < B'\text{:}\quad a_\text{fl} = \frac{1}{U_\text{o,fl}}\left[\frac{2\,\lambda_\text{gr}}{\pi\,B' + d_\text{t} + H/2}\ln\left(\frac{\pi\,B'}{d_\text{t} + H/2} + 1\right)\right] \tag{5.12}$$

$$d_\text{t} + H/2 \geq B'\text{:}\quad a_\text{fl} = \frac{1}{U_\text{o,fl}}\left(\frac{\lambda_\text{gr}}{0.457\,B' + d_\text{t} + H/2}\right) \tag{5.13}$$

with B' the (mean) equivalent soil thickness of the outer walls (see [5.5]), H the mean height between the floor's underside and grade and d_t the equivalent soil thickness of the floor.

For the walls along the free perimeter, the equivalent soil thickness intervenes:

$$d_\text{t,w} = \lambda_\text{gr}\left(\frac{1}{h_\text{e}} + R_\text{T,w} + \frac{1}{h_\text{i}}\right) \tag{5.14}$$

giving as a reduction factor:

$$\begin{aligned} d_\text{t,w} \geq d_t\text{:}\quad d_\text{t} + H/2 \geq B'\ a_\text{w} &= \frac{1}{U_\text{o,w}}\left[\frac{2\,\lambda_\text{gr}}{\pi\,H}\left(1 + \frac{0.5\,d_\text{t}}{d_\text{t} + H}\right)\ln\left(\frac{H}{d_\text{t,w}} + 1\right)\right] \\ d_\text{t,w} < d_\text{t}\text{:}\quad a_\text{w} &= \frac{1}{U_\text{o,w}}\left[\frac{2\,\lambda_\text{gr}}{\pi\,H}\left(1 + \frac{0.5\,d_\text{t,w}}{d_\text{t,w} + H}\right)\ln\left(\frac{H}{d_\text{t,w}} + 1\right)\right] \end{aligned} \tag{5.15}$$

The reduced heat transmission coefficient of a heated basement then looks like:

$$H_\text{red} = a_\text{fl}\,U_\text{o,fl}\,A_\text{fl} + a_\text{w}\,U_\text{o,w}\,P\,H \tag{5.16}$$

The free perimeter (P) and floor area (A_fl) are measured out to out.

Floor above crawlspace

The reduction factor is given by:

$$a_\text{red} = \frac{1}{U_\text{o,fl}}\left(\frac{1}{U_\text{o,fl}} + \frac{1}{U_\text{red,gr} + U_\text{x}}\right)^{-1} \tag{5.17}$$

with $U_\text{o,fl}$ the thermal transmittance of the floor (calculated with $h_\text{i} = h_\text{e} = 6$ W/(m$^2\cdot$K)), $U_\text{red,gr}$ the reduced thermal transmittance of the bottom and U_x a fictitious thermal transmittance combining crawlspace ventilation with the heat flow across the above grade crawlspace outer walls.

Crawlspace bottom

Characteristic dimension B' of the crawlspace bottom is:

$$B' = 2\, A_{\text{clsp}} / P$$

with A_{clsp} bottom area out to out and P free perimeter. The equivalent soil thickness of the bottom is given by ($h_i = 6$ W/(m$^2 \cdot$ K) and $h_e = 25$ W/(m$^2 \cdot$ K)):

$$d_{\text{gr}} = d_{\text{fw}} + \lambda_{\text{gr}} \left(\frac{1}{h_i} + R_{\text{T,clsp}} + \frac{1}{h_e} \right)$$

where d_{fw} is the thickness of the foundation walls in m and $R_{\text{T,clsp}}$ the thermal resistance of the bottom slab. The bottom's reduced thermal transmittance then becomes:

$$U_{\text{red,gr}} = \frac{2\, \lambda_{\text{gr}}}{\pi\, B' + d_{\text{gr}}} \ln\left(\frac{\pi\, B'}{d_{\text{gr}}} + 1 \right)$$

Crawlspace ventilation and the heat flow across the above grade crawlspace walls

The fictitious thermal transmittance is calculated as:

$$U_x = \frac{2\, H\, U_w}{B'} + 1450\, A_{\text{vent}} \frac{v_w\, f_w}{B'}$$

In that formula H is the mean wall height between grade and the underside of the ground floor, U_w is that wall's thermal transmittance, A_{vent} is the area of vents per meter run along the crawlspace's free perimeter in m^2/m, v_w the annual mean wind speed measured at the nearest weather station in m/s, and f_w the wind shielding factor, equal to:

Situation	**Example**	**wind shielding factor** f_w
Sheltered	City centre	0.02
Average	Suburban, village	0.05
Exposed	Rural, open	0.10

Floor above unheated basement

The reduction factor equals:

$$a_{\text{redl}} = \frac{1}{U_{\text{o,fl}}} \left\{ \frac{1}{U_{\text{o,fl}}} + \frac{A_{\text{bas}}}{A_{\text{bas}}\, U_{\text{red,fl,bas}} + P\left[H\, U_{\text{red,w,bas}} + \left(H_{\text{bas}} - H \right) U_{\text{w,bas}} \right] + 0.33\, n\, V} \right\}^{-1} \tag{5.18}$$

where A_{bas} is the basement area, H_{bas} the height between the underside of the basement floor and the underside of the floor above, H the height between the underside of the basement floor and grade, P the free perimeter, $U_{\text{o,fl}}$ the thermal transmittance of the floor above (calculated with $h_i = h_e = 6$ W/(m$^2 \cdot$ K)), $U_{\text{red,fl,bas}}$ reduced thermal transmittance of the basement floor, $U_{\text{red,w,bas}}$ the thermal transmittance of the basement outer walls, $U_{\text{w,bas}}$ the thermal transmittance of the basement outer walls above grade (calculated with $h_i = 8$ W/(m$^2 \cdot$ K) and $h_e = 25$ W/(m$^2 \cdot$ K)), n the ventilation rate in the basement and V the basement volume out to out.

Basement floor

The characteristic dimension B' is $2\,A_{bas}/P$. Equivalent soil thickness becomes ($h_i = 6$ W/(m$^2 \cdot$ K) and $h_e = 25$ W/(m$^2 \cdot$ K)):

$$d_t = d_{w,bas} + \lambda_{gr} \left(\frac{1}{h_i} + R_{T,fl,bas} + \frac{1}{h_e} \right)$$

with $d_{w,bas}$ the thickness of the basement outer walls in m, and $R_{T,fl,bas}$ the thermal resistance of the basement floor. Reduced thermal transmittance calculates as:

$$d_t + H/2 < B': \quad U_{red,fl,bas} = \frac{2\,\lambda_{gr}}{\pi\,B + d_t + H/2} \ln\left(\frac{\pi\,B'}{d_t + H/2} + 1 \right)$$

$$d_t + H/2 \geq B': \quad U_{red,fl,bas} = \frac{\lambda_{gr}}{0.457\,B' + d_t + H/2}$$

Below grade basement outer walls

Equivalent soil thickness is ($h_i = 6$ W/(m$^2 \cdot$ K) and $h_e = 25$ W/(m$^2 \cdot$ K)):

$$d_{t,w} = \lambda_{gr} \left(\frac{1}{h_i} + R_{T,w,bas} + \frac{1}{h_e} \right)$$

with $R_{T,w,bas}$ the thermal resistance of the basement floor. Reduced thermal transmittance becomes:

$$d_{t,w} \geq d_t: \quad U_{red,w,bas} = \left[\frac{2\,\lambda_{gr}}{\pi\,H} \left(1 + \frac{0.5\,d_t}{d_t + H} \right) \ln\left(\frac{H}{d_{t,w}} + 1 \right) \right]$$

$$d_{t,w} < d_t: \quad U_{red,w,bas} = \left[\frac{2\,\lambda_{gr}}{\pi\,H} \left(1 + \frac{0.5\,d_{t,w}}{d_{t,w} + H} \right) \ln\left(\frac{H}{d_{t,w}} + 1 \right) \right]$$

Method of the perimeter circles

Although a few meters below any excavation soil temperature equals the annual mean outdoors, EN ISO 13370 does not consider that when calculating reduction factors and reduced thermal transmittances. It only does so when stepping to heat fluxes as reduced thermal transmittances are multiplied with the difference between the temperature indoors and the annual mean temperature outdoors. However, when looking at the isoflux lines in the soil, a clear difference is noticed between a perimeter zone where the lines form circles from indoors to grade and a central zone, where the lines plunge vertically into the soil (Figure 5.10).

That allows splitting the heat flow in two parts: a flow straight to the isotherm in the soil some 5 meters below the excavated volume and a circular perimeter flow:

$$\Phi_{CT} = \psi_{per}\;P\left(\theta_i - \theta_e\right) + U_c\;r_{fl}\;A_{fl}\left(\theta_i - \theta_{em}\right) \tag{5.19}$$

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