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ABSTRACT

One of the most complex configuration to model in detail, both in the dynamic simulation of buildings and in the analytical quasi steady-state calculations, is the thermal dispersion through the walls and the floor in contact with the ground. The problem consists in determining the boundary conditions of the external wall surface directly exposed to the soil, whose temperature cannot be considered undisturbed. Different studies, both experimental and numerical, have been carried out in the last decades in order to determine the ground boundary conditions, some of which have been used to elaborate the technical standard EN ISO 13370. This standard gives some indications about the conditions to be considered in the use of quasi steady-state methods and within the dynamic simulation. The evaluation of the simulation software in the specific context of the ground heat transmission, has also driven the IEA to define a specific series of validation cases, the BESTEST In-depth ground coupled heat transfer tests.

The present research aim is to test implement reliable calculation procedures for the thermal dispersion through the building envelope towards the ground, in dynamic simulation modelling systems. In this work, a test case of the EN ISO 13370 standard has been modelled with FEM codes, both in steady-state conditions and also in periodic external conditions. Different types of floor have been considered, with different thickness and position of the insulation layer. The results have been compared with those calculated following the prescriptions of the standard EN ISO 13370.

1. INTRODUCTION

In the last decades, the enhancement of the energy performance of buildings has led to an average increase of the thickness of the thermal insulation layer of the envelopes. Therefore, the ground heat losses – traditionally considered of minor importance – have become more and more significant for the building energy balance assessment. In fact, the surface relevant to the heat exchange towards the ground represents a large portion of the total building envelope. This external surface belongs to walls and floor directly in contact with the ground and its detailed numerical modelling become complex when referred both to dynamic simulations and to analytical quasi steady-state calculations. In particular, a difficult step in the analysis is the determination of the boundary conditions to be assigned to the surfaces in contact with soil (i.e., external walls, floor) whose temperature cannot be considered as undisturbed.

Hagentoft (1988), Claesson and Hagentoft (1991), Hagentoft and Claesson (1991) have developed accurate calculation methods for evenly insulated floors. In these studies the heat transfer through the floor in contact with the ground is modelled using a conformal mapping in the complex plane, assuming a semi-infinite ground layer and a floor with definite width. The solution is derived for steady-state, periodic and single-step boundary conditions in temperature. When the external wall itself is used as thermal protection, the same authors derived an analytical solutions for the steady-state ground heat loss for buildings with only perimeter insulations (Hagentoft, 2002a, 2002b). Furthermore, the complexity of the underground structures has been analysed by Hagentoft (1996a, 1996b) also considering the presence of aquifers.

The technical standard EN ISO 13370:2007 (European Committee for Standardization, 2007a) provides methods for the calculation of heat transfer coefficients and heat flow rates for building elements in thermal contact with the ground, including slab-on-ground floors, suspended floors and basements. The standard defines an equivalent thermal transmittance of a floor, which depends on its characteristic dimension (i.e., the ratio between the area of the floor and half its perimeter), on its total equivalent thickness (i.e., sum of the actual floor thickness and the product between the floor thermal resistance and the soil thermal conductivity) and on the thermal conductivity of the soil. This technical standard gives also some indications about the conditions to be considered in the use of quasi steady-state methods and within the dynamic simulation. An interesting aim of the research in this field, is the test and implementation of reliable calculation procedures for the thermal dispersion through the building envelope towards the ground, in dynamic simulation modelling software, such as TRNSYS and EnergyPlus.

In this paper, the slab on ground case - proposed by the standard EN ISO 13370:2007 - has been modelled with finite elements methods (FEM) codes in a 3D approach. Different kinds of floor have been considered, with different thickness and position of the insulation layer and also different shape (aspect ratios) of the building have been taken into account. Sinusoidal external solicitations of one day period (periodic stabilized regime) have been considered for the simulations in order to take into account the effect given by the thermal diffusivity of the soil. The deviations between the dynamic and the steady state modelled boundary conditions have been assessed, resulting negligible for all the considered configurations. Therefore, steady-state regime has been finally assumed for the FEM simulations. The comparison of the predictions of the technical standard and the modelling results has been carried out through a detailed assessment of floor losses.

2. METHODS

In the following paragraphs the standard calculation procedure of EN ISO 13370:2007 and the detailed modelling approach are described. As test case the slab-on-ground has been chosen with a 20 cm thick floor slab, and variable thickness of the insulation layer (5-10 cm). This is assumed as polystyrene having thermal conductivity of 0.04 W m^{-1} K^{-1}, density of 40 kg m^{-3} and specific heat capacity equal to 1470 J kg^{-1} K^{-1}. Two positions (internal or external side) and three different kind of soil (clay, sand or rock) have been considered. Moreover, the shape of the floor has been also varied considering a square floor (i.e., 1:1 aspect ratio, defined as the ratio between the floor sides) and three different rectangular shapes (with 1:4, 2:4, 3:4 aspect ratios).

In Table 1 the thermal properties of the soil and the floor slab are reported.

2.1 EN ISO 13370:2007 procedure

The slab-on-ground floors are defined by the technical standard as any kind of floor consisting of a slab in contact with the ground over its whole area, whether or not supported by the ground over its whole area, and situated at the level (or near the level) of the external ground surface (Figure 1).

Table 1: thermal properties of the soil and the floor slab

	soil	
	thermal conductivity ($W\ m^{-1}\ K^{-1}$)	**heat capacity per volume** ($J\ m^{-3}\ K^{-1}$)
clay	1.5	3.0×10^6
sand	2	2.0×10^6
rock	3.5	2.0×10^6

	floor slab
	thermal conductance ($W\ m^{-2}\ K^{-1}$)
no insulation	1.25
5 cm insulation	0.49
10 cm insulation	0.30

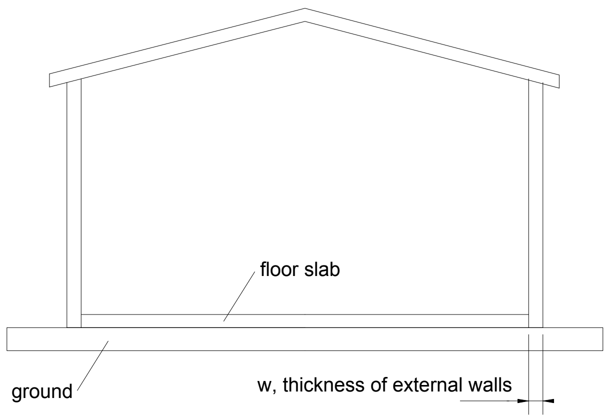

Figure 1: Schematic diagram of slab-on-ground floor according to EN ISO 13370:2007

The floor slab may be without insulation layer, or evenly insulated (above, below or within the slab) over its whole area. A correction on the thermal transmittance is also foreseen by the technical standard if the floor has horizontal or vertical edge insulation. The thermal transmittance depends on the characteristic dimension of the floor, B' (i.e., area of the floor divided by half the perimeter) given by Equation (1), and on the total equivalent thickness, d_t given by Equation (2).

$$B' = \frac{A}{0.5P} \tag{1}$$

$$d_t = w + \lambda\left(R_{si} + R_f + R_{se}\right) \tag{2}$$

The characteristic dimension B' assumes the following values for the test cases: 5 m (4:4 aspect ratio), 4.95 m (3:4 aspect ratio), 4.71 m (2:4 aspect ratio) and 4 m (1:4 aspect ratio). See also Table 2 and Figure 2 for the dimensions of the test case and thus the size of the floor slab (A, P).
The thermal resistance of dense concrete slabs and thin floor coverings may be neglected. Hardcore below the slab is assumed to have the same thermal conductivity as the ground, and its thermal resistance should not be included. The thermal transmittance U is computed using either Equation (3) for the case with $d_t < B'$ (i.e., not insulated and moderately insulated floors), or Equation (4) for the case with $d_t > B'$ (i.e., well-insulated floors)

$$U = \frac{2\lambda}{\pi B' + d_t} ln\left(\frac{\pi B'}{d_t} + 1\right) \tag{3}$$

$$U = \frac{\lambda}{0.457 \cdot B' + d_t} \tag{4}$$

The steady-state ground heat transfer coefficient H_g between internal and external environments is then obtained using Equation (5).

$$H_g = AU + P\Psi_g \tag{5}$$

The linear transmittance relevant to the thermal bridges (i.e., Ψ_g relevant to the wall-floor junction) has been evaluated firstly considering EN ISO 14683:2007 (European Committee for Standardization, 2007b) – with thermal bridges C1, C3 and C4 type – and then applying the finite element modelling procedure in agreement with EN ISO 10211:2007 (European Committee for Standardization, 2007c) (see paragraph 2.1).

2.1 Finite elements modelling

The slab on ground test case has been discretized using a 3-dimensional geometry. Taking advantage of the geometry symmetries, only a quarter of the building has been modelled in agreement with the standard procedure. The Partial Differential Equations (PDE's) discretization and solution procedure has been carried out by means of finite elements approach. The temperature values of the external and internal air have been assumed as boundary conditions.

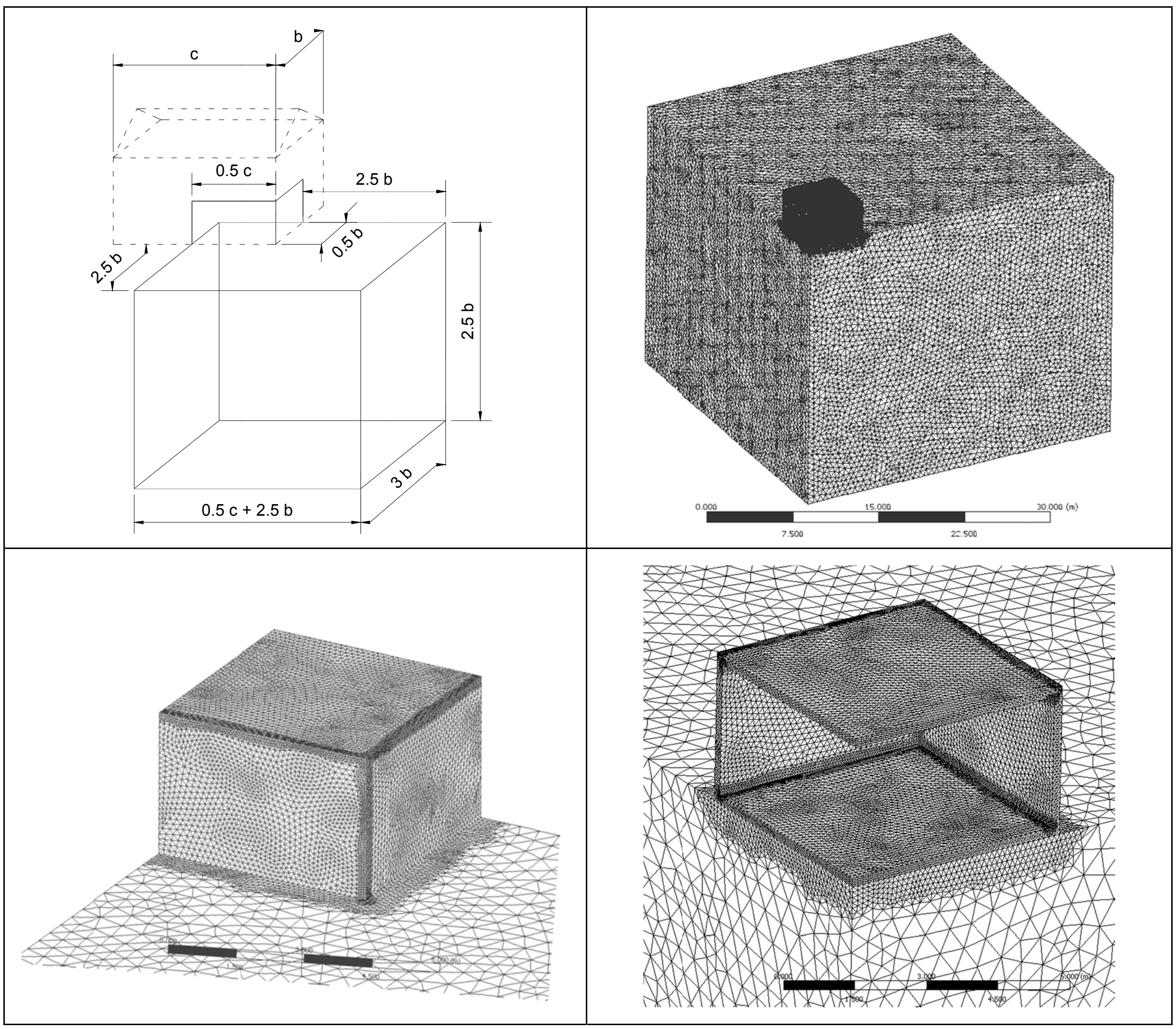

Figure 2: 3-dimensional model according to EN ISO 10211:2007 (top left, see Table 2) and FEM model geometry and mesh (top right and bottom).

In the steady-state analysis the boundary temperatures have been a fixed at -5°C for the external air (as usually assumed in the dynamic simulations) and at 20 °C for the internal air, while an equivalent convective thermal condition was imposed for all the internal and external walls surfaces. The equivalent convective coefficients have been calculated in accordance with the technical standard EN ISO 6946:2007 (European Committee for Standardization, 2007d) and are 25 W m^{-2} K^{-1} for the external wall and ground surfaces, while for the internal ones, 7.69 W m^{-2} K^{-1}, 10 W m^{-2} K^{-1} and 5.88 W m^{-2} K^{-1}, for the vertical, the ceiling and for the floor, respectively. Both steady state and time-variable conditions on the external air have been assumed for the simulations. The 3-dimensional heat flux at the ground has been computed at the internal surface of the floor slab.
In order to carry out a sort of sensitivity analysis of the thermal flux to the daily outdoor temperature variation, a dynamic modelling of the slab on ground test cases have been performed using a fictive external forcing temperature of 24 hours period, 15 °C amplitude. Daily variation was considered to evaluate the potential effects on the building dynamic response. Yearly conditions variation are likely to have marginal effects on the hourly analysis allowing to impose the averaged value over longer period (week or month).
According to EN ISO 10211:2007 the scheme of Figure 2 has been assumed for the FEM simulations in order to estimate the linear thermal transmittance associated with the wall-floor junction Ψ_g and also to carry out a detailed simulation of the whole building-ground system. The external size and dimensions of the building and ground volumes have been reported in table 2. The internal floor area is 100 m^2 for all the configurations.

Table 2: Size and dimensions of the building (EN ISO 10211:2007, see Figure 2)

Dimensions	**4:4**		**3:4**		**2:4**		**1:4**	
insulation (m)	**b**	**c**	**b**	**c**	**b**	**c**	**b**	**c**
0.00	10.40	10.40	9.06	11.94	14.54	7.47	5.40	20.40
0.05	10.50	10.50	9.16	12.04	14.64	7.57	5.50	20.50
0.10	10.60	10.60	9.26	12.14	14.74	7.67	5.60	20.60

3. RESULTS AND DISCUSSION

3.1 Steady-state assumption and finite elements modelling

A sample of the results obtained through the FEM simulations in steady state has been reported in figure 3. In particular the temperature field on the internal floor surface has been plotted in order to point out the effect of the ground type, aspect ratio and thermal insulation. The results in terms of temperature and heat flux variations at the floor internal surface - obtained through the FEM simulations in dynamic regime - have been also compared with a steady state case (i.e., average temperature value as boundary condition).
The estimated deviations between the peaks and the average values - in terms of both temperature and heat flux - have been computed by means of the finite element method approach (Figure 4). The maximum deviations on the temperature values have been computed in the case of rock having the highest thermal diffusivity (1.75×10^{-6} m^2 s^{-1}), followed by sand (thermal diffusivity 1.00×10^{-6} m^2 s^{-1}) and clay, whose thermal diffusivity value (5.00×10^{-7} m^2 s^{-1}) is the lowest. As the calculated deviations are lower than 0.1°C for the temperature and lower than 0.5% for the heat flux, steady state boundary conditions have been assumed for the further analysis.
The specific heat flux in steady state conditions has been computed dividing up the heat flow towards the ground - obtained through the finite elements model and evaluated at the internal floor surface - by the floor area and by the difference of temperature (i.e., $|\theta_{int} - \theta_{ext}|$ =25°C) used for the simulations in steady state regime (Equation 6). Figure 5 shows the ground specific heat flux as a function of ground and floor slab thermal properties. The effect of the shape (continuous lines refer to 1:4 aspect ratio and dashed line to 4:4 aspect ratio) and also the position of the insulation layer - either considered on the external (a) or on internal (b) side - have been here taken into account.

$$\varphi_g = \frac{\Phi_g}{A \cdot \left|\theta_{int} - \theta_{ext}\right|} \tag{6}$$

$$\Delta_g = \frac{\Phi_g}{\Phi_{tot}} \cdot 100 \tag{7}$$

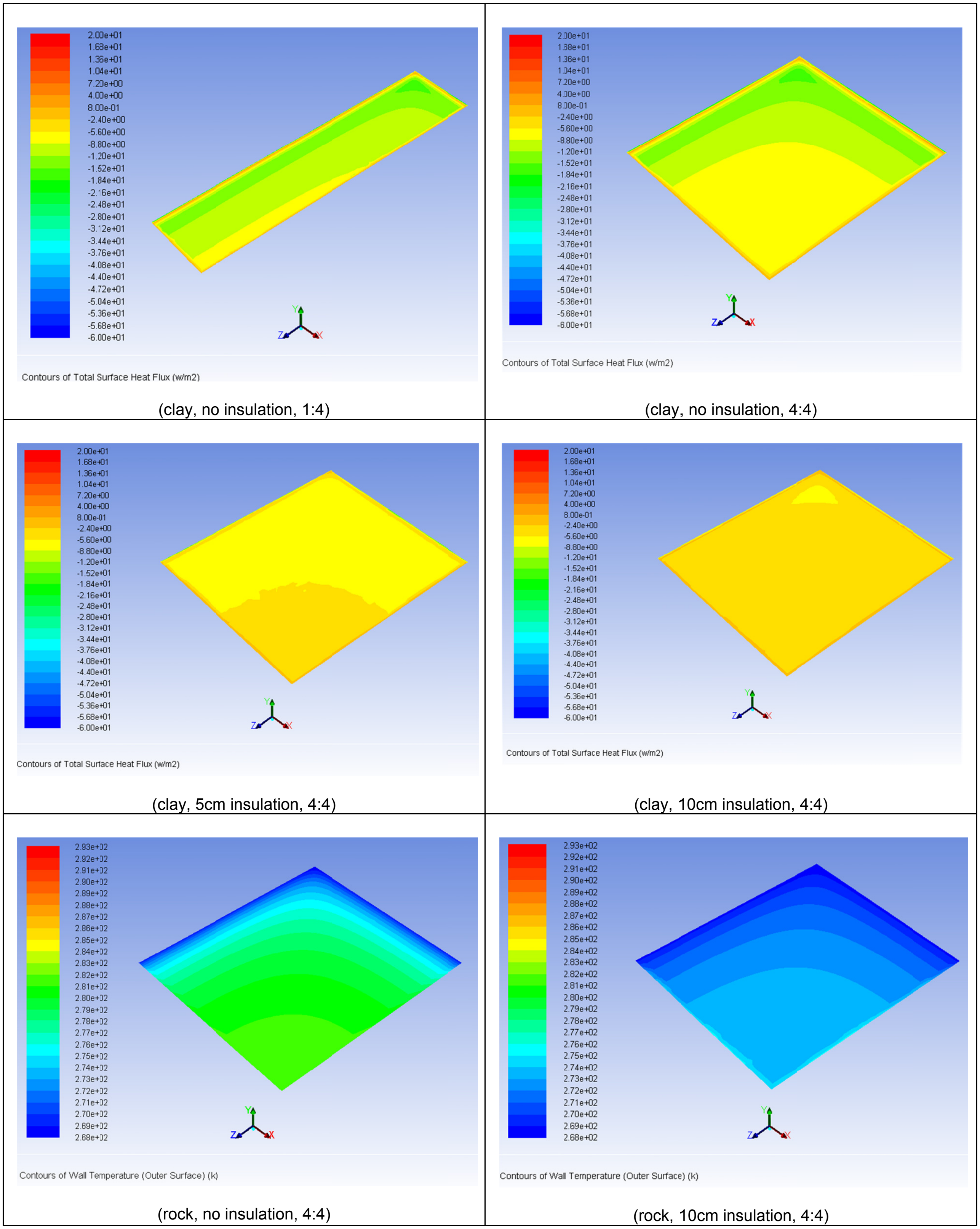

Figure 3: Examples of the results obtained through the FEM simulations

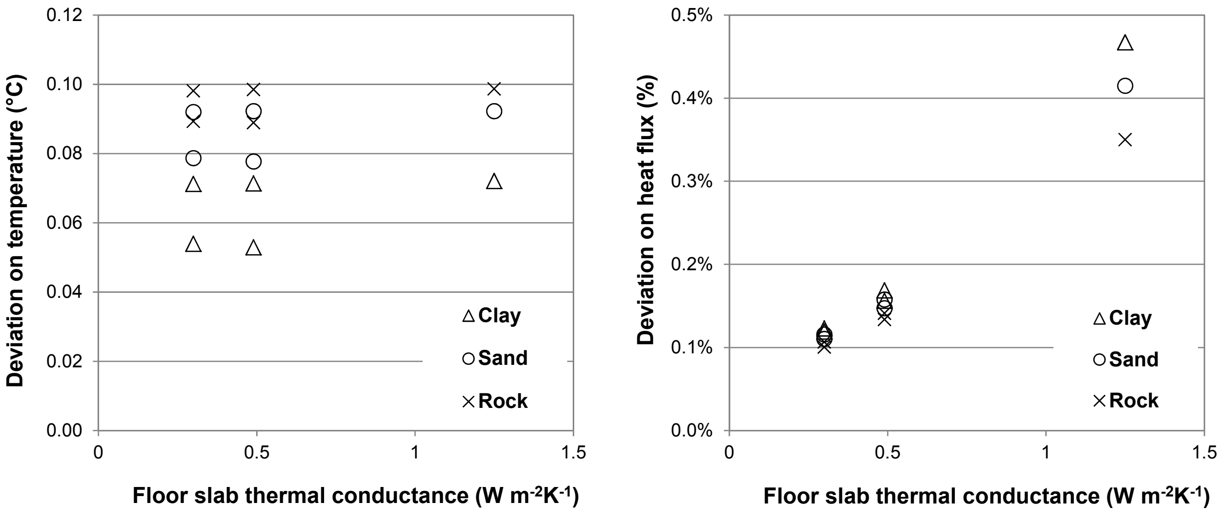

Figure 4: Absolute values of the deviations between the peak and the average values of temperature and heat flux at the ground computed by means of the FEM model in dynamic regime

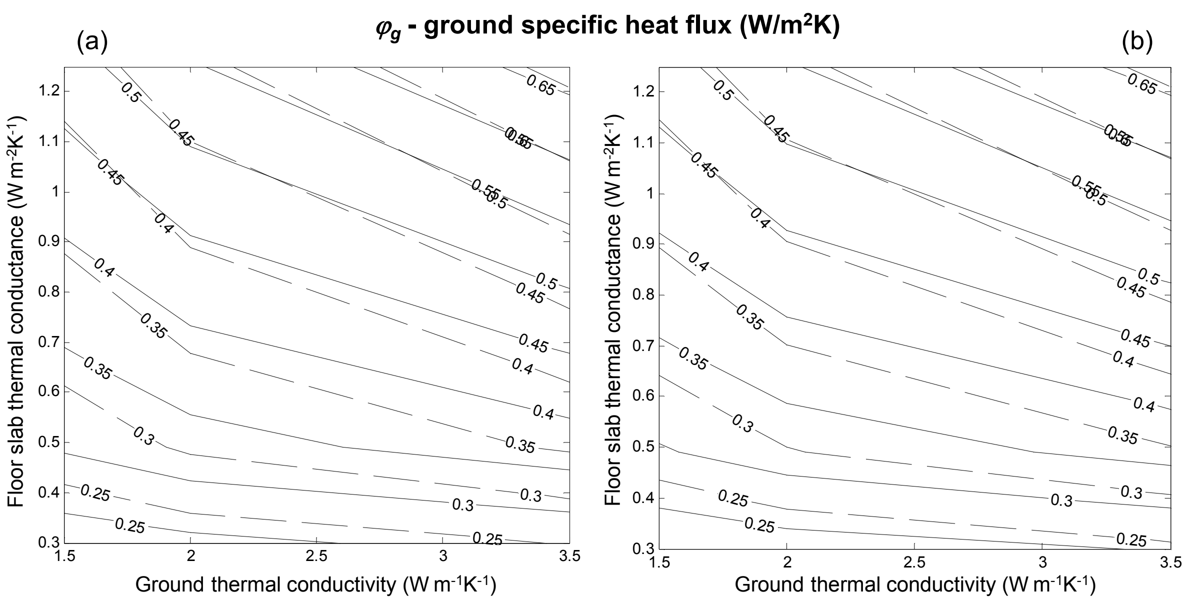

Figure 5: Specific heat flux at the ground computed by the FEM model as a function of ground and floor slab thermal properties: thermal insulation layer either on the external (a) or on internal (b) side (continuous lines refer to 1:4 aspect ratio and dashed line to 4:4 aspect ratio)

Considering the same conditions, the most compact structure (4:4 aspect ratio) is the most efficient as the specific heat flux values are lower than the ones given by the other configurations (see in particular the 1:4 aspect ratio). Furthermore, assuming the same floor slab thermal conductance, the use of an insulation layer on the internal side gives slightly better performances than using the same layer on the external side, since the corresponding specific heat flux is lower. It is also worth to assess the contribution of the thermal losses towards the ground to the whole energy balance of the building. For this purpose the ratio between the heat flux through the floor slab and the total heat flux through the whole building envelope (Equation 7) computed by the FEM model has been plotted in Figure 6 as a function of ground and floor slab thermal properties.

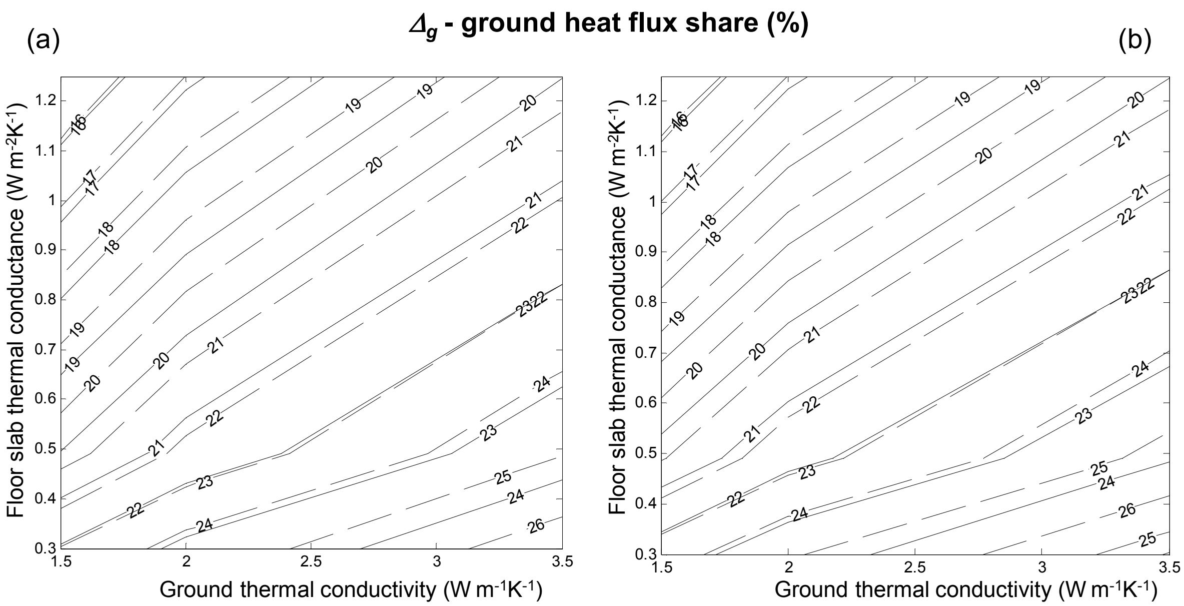

Figure 6: Ground heat flux share computed by the FEM model as a function of ground and floor slab thermal properties: thermal insulation layer either on the external (a) or on internal (b) side (continuous lines refer to 1:4 aspect ratio and dashed line to 4:4 aspect ratio)

This parameter, expressed as percentage, represents the ground heat flux share on the total heat flux exchanged by the building through the envelope. The effect of the shape (continuous lines refer to 1:4 aspect ratio and dashed line to 4:4 aspect ratio) and also the effect of the position of the insulation layer - either considered on the external (a) or on internal (b) side - have been taken into account.

As expected, the contribution of the heat losses towards the ground become more significant as the thermal conductance of the envelope decreases (i.e., the thermal conductance of the whole envelope is constant, thus equal to the floor slab one).

Considering the same conditions, the share of the ground heat flux is lower for 4:4 aspect ratio than the ones relevant to the 1:4 ratio, confirming the higher performance of compact structure regarding the heat exchange to the ground.

Moreover, assuming the same envelope thermal conductance, the use of an insulation layer on the internal side give a slightly higher ground heat flux share than the one obtained using the same layer on the external side.

3.2 Comparison between finite elements modelling and standard procedure

The specific heat flux computed by means of the FEM model is here considered has a benchmark for the assessment of the performance of the EN ISO 13370:2007 standard procedure.

An assessment of the deviations between the specific heat flux at the ground - computed by means of the finite elements model - and the one calculated by means of the EN ISO 13370:2007 standard procedure has been carried out. The linear thermal transmittance relevant to the wall/floor junction has been computed according to EN ISO 10211:2007 through FEM approach.

Figure 7 shows the computed deviations (as absolute values) as a function of floor slab thermal conductance and either aspect ratios (on the left) or ground type (on the right). Dashed lines represent the envelope curves relevant to the maximum and the minimum value for the limit aspect ratios (4:4 and 1:4 respectively).

As a whole, the computed deviations are characterized by small values, always lower than 1%, with a decreasing trend as the floor slab thermal conductance decreases.

Regarding the shape of the building (Figure 7, left side), the higher the slab thermal conductance values, the higher the differences between buildings with low and high aspect ratios. Buildings structures with 4:4 ratio are subjected to higher errors when using the standard procedure, resulting in values up to 0.98%.

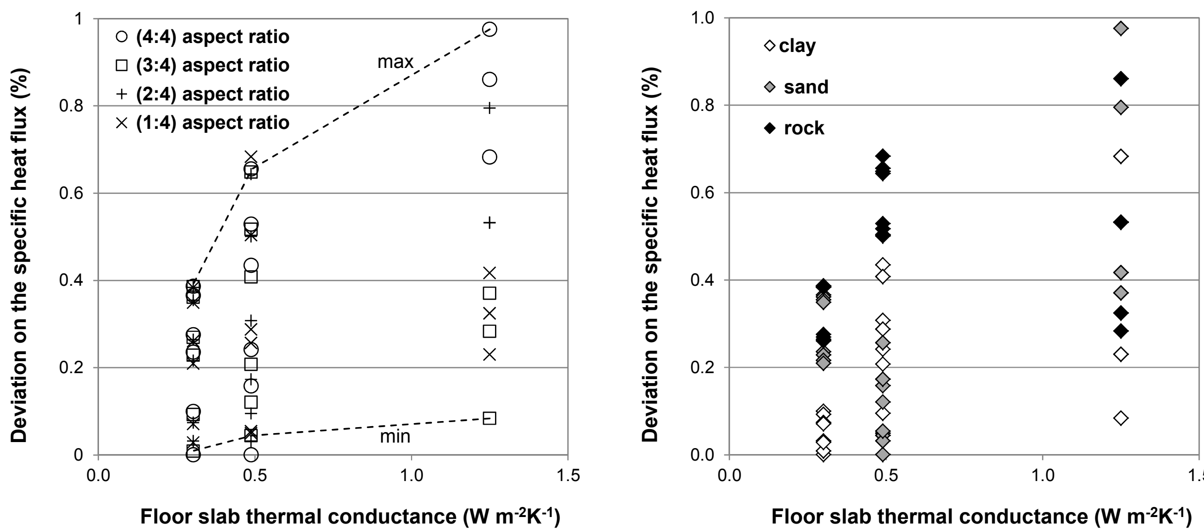

Figure 7: Absolute values of the deviations between the specific heat flux at the ground computed by means of the finite elements model and by means of the EN ISO 13370 procedure (thermal bridges computed according to EN ISO 10211) as a function of floor slab thermal conductance, aspect ratios (on the left) or ground type (on the right). Dashed lines represent the envelope curves relevant either to the maximum or the minimum values for the limit aspect ratios (4:4 and 1:4 respectively).

The variation in the thermal properties of the ground (i.e., varying the kind of soil) also affects the performance of the standard computation if compared with the FEM modelling results (Figure 7, right side). In particular, the maximum deviations have been detected for the rocky and sandy grounds, which are characterized by the higher thermal conductivities. On the contrary, the values of the deviations relevant to the clay soil - which is characterized by the lowest thermal conductivity - are generally lower.

4. CONCLUSIONS

In this paper, the slab on ground case - proposed by the standard EN ISO 13370 - has been modelled with finite elements methods (FEM) codes. Different types of floor have been considered - with different thickness and position of the insulation layer - and also different shapes (aspect ratios) of the building have been taken into account. Sinusoidal external boundary condition on temperature (one day period) have been used to simulate the test system to take into account the effect of the soil thermal properties. The standard procedure of EN ISO 13370 has been also used. For this calculation, the linear transmittance relevant to the wall-floor junction has been evaluated applying the finite element modelling procedure in agreement with EN ISO 10211.
The deviations between the dynamic and the steady state modelling have been assessed. The estimated deviations between the peaks and the average values - in terms of both temperature and heat flux computed by means of the FEM approach - resulted negligible. Therefore, steady-state regime has been finally assumed for the FEM simulations.
The specific heat flux and the share of the ground heat flux on the total heat flux through the whole building envelope have been computed. The effect of the soil and floor slab thermal properties, the effect of the aspect ratio of the building have been considered for the analysis. The more compact, the more efficient the building structure is. The use of an internal insulation layer also gives better performances in terms of specific heat flux, but not in terms of ground heat flux share on the total heat flux through the envelope.
Moreover, the comparison of the predictions of the technical standard and the modelling results has been carried out through a detailed assessment of floor losses. Once again, compact building structure are the more efficient, as they are subjected to lower errors when using the standard procedure.
The variation in the thermal properties of the ground also affects the performance of the standard procedure. As a whole, the lower the soil thermal conductivity the smaller the deviations between the standard and the modelling.

As a further development, it is worth to focus on the implementation of the tested procedures for the thermal dispersion through the building envelope towards the ground, in dynamic simulation codes, such as TRNSYS and EnergyPlus.

NOMENCLATURE

A	area of floor	(m^2)
B'	characteristic dimension of floor	(m)
d_t	total equivalent thickness - slab on ground floor	(m)
H_g	steady-state ground heat transfer coefficient	(W K^{-1})
P	exposed perimeter of floor	(m)
R_f	thermal resistance of floor construction	(m^{2}K W^{-1})
R_{se}	external surface resistance	(m^{2}K W^{-1})
R_{si}	internal surface resistance	(m^{2}K W^{-1})
U	thermal transmittance between internal and external environments	(W m^{-2}K^{-1})
w	thickness of external walls	(m)
λ	thermal conductivity of unfrozen ground	(W m^{-1}K^{-1})
Δ_g	ground heat flux share	(%)
φ_g	specific heat flux through the floor slab	(W m^{-2}K^{-1})
Φ_g	heat flux through the floor slab	(W)
Φ_{tot}	total heat flux through the building envelope	(W)
Ψ_g	linear thermal transmittance associated with wall/floor junction	(W m^{-1}K^{-1})
θ_{ext}	temperature of the external environment	(K)
θ_{int}	temperature of the internal environment	(K)

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