Coupling soil heat and mass transfer models to foundations in whole-building simulation packages

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Abstract

The availability of greater computing resources in the last few decades has lead to the development of sophisticated models to account for heat transfer from building foundations. Some of these models have been integrated into popular whole-building simulation packages to account for dynamic interactions between buildings and adjacent soils. This paper discusses how this soil-building coupling has been implemented in previous models. The possibility to couple the moisture and air transfer evaluated by some newer soil models is also investigated. Finally, a convenient and potentially more accurate coupling method is proposed.

1 Introduction

Use of complex models to simulate foundation heat losses is relatively recent. In the not so distant past, the considerable computational efforts required did not make precise foundation modelling attractive while the complexity and cost of whole-building simulations limited their use to larger commercial buildings where basement zones represent a small fraction of the space and are rarely conditioned. Many less demanding methods to approximate foundation heat losses were, and still often are, used: some examples are the ASHRAE simplified method (Boileau & Latta 1968), based on heat transfer paths, and the Mitalas (1983) method, based on shape factors. Bahnfleth (1989) provides detailed reviews of many older foundation models.

Improvements in available computational resources and development of simpler user interfaces eventually resulted in simulations being used for smaller applications where foundation heat losses are important: Beausoleil-Morrison & Mitalas (1997) cite a study where it was found that foundation heat losses account on average for 24 % of the losses of energy efficient houses. This lead to the development of more complex foundation models, some of which were implemented in whole-building simulation software: for example Krarti et al. (2001), Krarti & Ihm (2009), Zoras et al. (2002), and Nakhi (1995) performed such integrations. Under the framework of IEA SHC/ECBCS Task 34/43 (Neymark & Judkoff 2008), many models were compared regarding the evaluation of heat transfer from slab on grade foundations, including: BASESIMP (Beausoleil-Morrison & Mitalas 1997), a polynomial model incorporated in the ESP-r (Clarke 2001) software; a finite difference model (TESS 2004) implemented in TRNSYS (Klein et al. 2010); a finite element model (Clements 2004) implemented in EnergyPlus (Crawley et al. 2001); and other models not implemented in whole-building simulation packages. These models all account for heat transfer by pure conduction in soil around foundations.

Recently, the realism of foundation modeling has risen with the introduction of models taking into account both energy and moisture transfer in soils as well as other complex phenomena such as ground freezing, convective and radiative heat transfer, precipitations at the ground surface, etc.: examples include models developed by Janssen (2002), Deru (2003), Chuangchid et al. (2004), dos Santos & Mendes (2006), and Ma et al. (2009). None of these models were integrated into whole-building analysis software.

The models enumerated in this review differ considerably regarding the foundation types (basement, slab on grade, crawlspace), the phenomena (latent energy, radiation, precipitation, etc.), and the insulation configurations (fully or partially insulated) they can model, as well as the methodologies (polynomial, numerical, etc.) used, and even their accuracy. Another aspect in which they can differ is in the way they are coupled with buildings, or not, during simulations. According to Krarti & Ihm (2009), annual heating/cooling loads can be overestimated by 20% for a typical ranch house if ground coupling is not fully integrated with the building model. Assuming a constant space temperature in a foundation model when the temperature in a basement space is allowed to float (the space is not conditioned), or when thermostat setbacks are used to reduce energy consumption, can also lead to considerable error in evaluated foundation heat transfer. It is therefore important that foundation models be fully coupled to dynamically account for interactions with the building and its operation.

Coupling multi-dimensional soil heat (and sometimes mass) transfer models to one-dimensional wall or zone models present in whole-building simulation packages is not trivial. Information, and therefore accuracy, is lost in the dimensional conversion. This article discusses how some of the enumerated models have been integrated in simulation software. These methods are presented, critiqued and, when possible, compared. Coupling of the air and moisture transfer evaluated by some soil models, as well as the influence of soil property variations usually evaluated by these models, are also addressed. A coupling technique, with the aim of reducing the loss of information during communication between models, is also proposed and evaluated. Finally, coupling of soil models to partially insulated foundations is discussed.

2 Some notions of Heat, Air, and Moisture (HAM) transfer in soils

In order to discuss the possible couplings between soils, foundations, and buildings, equation systems must be established. This section describes the soil HAM transfer equations most encountered in the literature; which are based on the mechanistic approach developed by Philip & de Vries (1957). This text is by no means an exhaustive development or complete review. Readers interested in more details should consult specialized texts such as Hillel (1998).

Most soil heat and moisture transfer models assume a non-deformable soil matrix consisting of solid particles. The voids between the particles, named pores, are filled with pure water and air: some specialized models, not addressed here, may consider solutes concentrations in the liquid, and so water movement by osmosis. Under these conditions, the only forces intervening in an unsaturated soil system are gravity, adsorption of water by solid particles, capillarity (surface tension), and air pressure. Since basements are rarely located in the water table, only unsaturated soils are discussed here.

Moisture transfer equation

Moisture transfer is evaluated by considering three mechanisms for water migration: liquid movement under potential (Ψ) gradients (Darcy's law), diffusion of vapor in the air contained in the pores under concentration (C_v) gradients (Fick's law), and vapor transported by air movement under pressure (P_a) gradients. This water movement influences the volumetric water content (or wetness), θ (m_w^3/m^3), of a soil region. Water content (θ) and vapor concentration (C_v) can be related to potential (Ψ) and temperature (T) for specific soils. So application of the continuity principle on the water flux, $\overrightarrow{F}_w$ (kg/m^2s), from these mechanisms and grouping of the resulting terms in capacity and diffusion coefficients yield an equation of the form:

$$\begin{aligned}\rho_w \frac{\partial \theta}{\partial t} &= C_{T,w}\frac{\partial T}{\partial t} + C_{\Psi,w}\frac{\partial \Psi_m}{\partial t} \\ &= -\nabla.\overrightarrow{F}_w = \nabla.\left[D_{\Psi,w}\nabla\Psi_m + D_{T,w}\nabla T + D_{P,w}\nabla P_a + D_{g,w}\overrightarrow{y}\right]\end{aligned} \tag{1}$$

Where:

- ρ_w (kg/m^3) is the density of water;
- t (s) is the time and y (m) represents the vertical position;
- Ψ_m (J/kg_w) is the matric potential, a negative potential (suction) representing the work done to overcome interactive capillary and adsorptive forces binding water to the matrix when it flows away from the point under consideration;
- T (K) is the temperature while P_a (Pa) is the air pressure;
- $D_{\Psi,w}$ ($kg\,s/m^3$), $D_{T,w}$ ($kg/m\,s\,K$), $D_{P,w}$ (s), and $D_{g,w}$ ($kg/m^2 s$) are diffusion coefficients affecting potential, temperature, air pressure and gravity while $C_{T,w}$ ($kg/m^3\,K$) and $C_{\Psi,w}$ ($kg\,s^2/m^5$) are capacity coefficients associated with temperature and matric potential variations.

Note that the diffusion and capacity coefficients are functions of potential and temperature so Equation 1 is non-linear. Their development can be easily found in the literature and so will not be repeated here. Also note that the matric potential unit (J/kg_w) is one of three different units encountered in the practice: many practitioners use either the Pascal (*Pa*) or the meter of water (m_w) and the corresponding units for the capacity and diffusion coefficients.

Another potentially important quantity for coupling soil and building models is the vapor content of the air contained in the pores. Since the vapor and liquid phases of water in the pores should be in equilibrium, the relative humidity (*RH*) of this pore air is:

$$RH = \frac{P_v}{P_{v,sat}} = \frac{C_v}{C_{v,sat}} = \exp\left(\frac{\Psi_m}{R_w T}\right) \tag{2}$$

Where:

- P_v and $P_{v,sat}$ (Pa) are the vapor pressure and the vapor pressure at saturation;
- C_v and $C_{v,sat}$ (kg_w/m_a^3) are vapor concentrations;
- R_w is the specific gas constant of water vapor ($461.5\,J/kg\,K$).

Air transfer equation

Air transfer can be evaluated by applying the continuity principle to the air flux, $\overrightarrow{F}_a$ ($kg/m^2 s$), resulting from pressure gradients. Transforming the resulting variables to forms compatible with the variables used in Equation 1 results in an equation of the form:

$$C_{\Psi,a}\frac{\partial \Psi_m}{\partial t} + C_{T,a}\frac{\partial T}{\partial t} + C_{P,a}\frac{\partial P_a}{\partial t} = -\nabla.\overrightarrow{F}_a = \nabla.\left[D_{P,a}\nabla P_a\right] \tag{3}$$

Where $C_{\Psi,a}$ ($kg\,s^2/m^5$), $C_{T,a}$ ($kg/m^3\,K$) and $C_{P,a}$ (s^2/m^2) are capacity coefficients while $D_{P,a}$ (s) is a diffusion coefficient.

Most models do not include this air balance equation and the air pressure term in Equation 1. This is justified by the fact that air movement transports little energy: its thermal capacity ($\rho\, Cp$) is about 3200 times smaller than the one of water. Nevertheless, air can transport significant amounts of moisture, affecting soil properties. Furthermore, air movement can create considerable thermal dispersion, and so increase apparent thermal conductivity, in coarser gravels used in percolation trenches sometimes present around foundations; so Equation 3 should be solved when modelling foundations using this type of moisture management system.

Energy equation

Analysis of soil physics generally considers only thermal energy. Heat moves in soils by conduction, convection, and long wave radiation. This affects the energy stored in the soil: in the form of sensible heat, latent heat, and heat of wetting (energy contained in the adsorptive forces bounding water to the solid matrix). Heat transfer is dominated by conduction for most soils and conditions. Long wave radiation and thermal dispersion can become important for soils with large pores, like gravels used in percolation trenches. These are usually treated as contributions to the soil thermal conductivity (λ_{eq}) and so do not affect the form of the energy balance equation. Meanwhile, all heat storage terms can be expressed as functions of potential and temperature. So applying the continuity principle to the heat flux, $\overrightarrow{F}_h$ (W/m^2), resulting from heat conduction and transport (convection) by water and air flows, results in an equation which can take the form:

$$C_{T,e}\frac{\partial T}{\partial t} + C_{\Psi,e}\frac{\partial \Psi_m}{\partial t} = -\nabla.\overrightarrow{F}_h = \nabla.\left[D_{\Psi,e}\nabla\Psi_m + D_{T,e}\nabla T + D_{P,e}\nabla P_a + D_{g,e}\overrightarrow{y}\right] \qquad (4)$$

Where $C_{T,e}$ (J/m^3K) and $C_{\Psi,e}$ (kg/m^3) are capacity coefficients while $D_{\Psi,e}$ ($kg/m\,s$), $D_{T,e}$ ($W/m\,K$), $D_{P,e}$ (m^2/s), and $D_{g,e}$ (W/m^2) are diffusion coefficients.

Possible boundary conditions

Equations 1, 3, and 4 form a three equations system with three unknowns: Ψ_m, P_a and T. So any boundary conditions set could involve values for these variables or their first derivatives. Direct values of potential at boundaries are rarely available and must be converted from boundary conditions of vapor pressure (P_v), relative humidity (RH), or vapor concentration (C_v) using Equation 2. Air pressure values at boundaries are often available. Temperature or temperature gradient boundary conditions are also relatively common.

Flux of water ($\overrightarrow{F}_w$), air ($\overrightarrow{F}_a$), and/or heat ($\overrightarrow{F}_h$) in the direction normal to a boundary are also commonly available and easily usable: these flux respectively replace the right side of Equations 1, 3, and 4 at the specific boundary.

Variations of soil thermal properties

Since soils are combinations of solid particles, water, and air, their thermal properties can vary considerably depending on the proportion of each constituent and the phase of the water. For example, the thermal capacity of water being much higher than that of air, it is evident that the water content affects the capacity of the soil system. Similarly, water tends to act as a thermal bridge between solid particles, so its presence increases the soil thermal conductivity. Figure 1 presents thermal conductivities (λ_{soil}) as a function of temperature, for dry and saturated Fairbanks sand, evaluated using relationships and data provided by Côté & Konrad (2005). As can be seen, water content and freezing have large influences on thermal conductivity.

Because of the strong influence of water content, there are diurnal variations of properties close to the ground surface: water tends to migrate upward during the night and downward

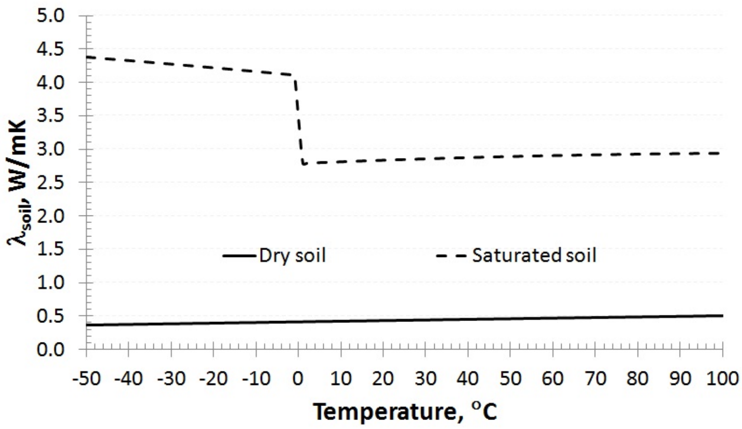


Figure 1: Thermal conductivity of Fairbanks sand

during the day. Seasonal variations are also present as water flows upward during cooler seasons and freezing occurs. Precipitations also cause some aleatory variations. The presence of a basement zone itself could cause properties to vary as water tends to migrate away from this warmer region. So the thermal properties of soil around foundations vary in space and time.

3 Zone and wall models in whole-building simulation packages

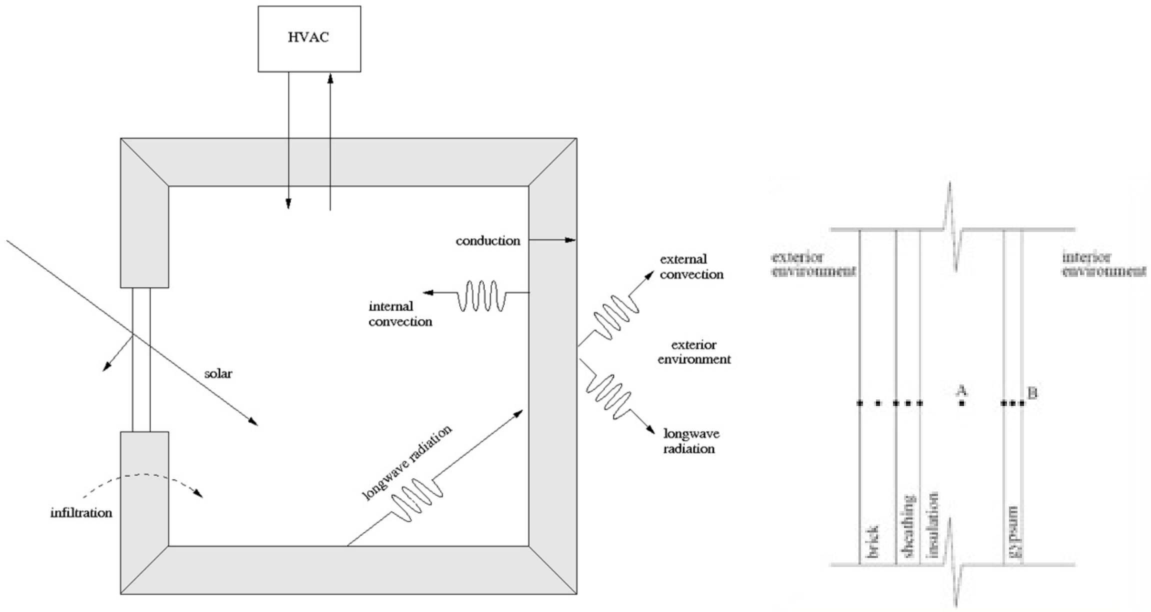
This section provides a short overview of how zones and walls are treated in whole-building simulation packages. This information is required to identify locations and variables with which coupling can be accomplished. Three of the main simulation software are discussed: TRNSYS, EnergyPlus and ESP-r. This section is not an exhaustive description so readers interested in more information should consult specialized documents such as TRANSSOLAR (2010) for TRNSYS, LBNL (2011) for EnergyPlus, and Nakhi (1995) for ESP-r.

Zones are treated similarly in all three simulation packages. As shown in Figure 2(a) for ESP-r, zone models perform energy balances accounting for heat transfer by convection from wall surfaces, incoming/outgoing energy from infiltration and ventilation air, internal gains, long wave and solar radiation exchanges, thermal mass, and inputs from the HVAC systems. When performing HAM analysis, zone models also perform balances of air and moisture flows. So properly modelling a basement zone in a soil model requires the addition of many calculation capacities already present in whole-building simulation packages. It is therefore simpler to define basement zones in building models and couple soil/foundation models to these zones.

Walls are treated by default as one-dimensional entities in all three simulation engines. ESP-r provides multi-dimensional modelling capacities for specified zones. These wall models include many functionalities, like the capacity to model active layers and phase change materials as well as access to different databases of common materials and walls. So, again, it is convenient to avoid modelling foundation walls and slabs in soil models and leave this task to building simulation packages in order to avoid reproducing already existing functionalities.

Heat conduction through walls is evaluated using transfer functions (Stephenson & Mitalas 1971) in TRNSYS and a finite volume (Patankar 1980) approach in ESP-r. EnergyPlus uses transfer functions by default but offers the possibility to switch to a numerical approach. All of these approaches to modelling offer appropriate temperature and heat flux boundary conditions which can be used to connect soil models.

Moisture flow through walls is treated in TRNSYS using a buffer storage model, which considers walls as moisture flow resistances with surface and deep moisture buffers. In ESP-r, and when using the EnergyPlus capacity for numerical calculations, moisture transfer is eval-



(a) Zone (b) Wall

Figure 2: Zone and wall models in ESP-r

uated using a more complete differential equation accounting for all layers composing a wall as well as the effect of moisture content on thermal properties: treatment of this non-linear behavior requires a finer mesh than the one, shown on Figure 2(b) for ESP-r, typically used for heat conduction calculations. Note that ESP-r does not provide multi-dimensional modelling capacities for moisture transfer as it does for heat conduction. These approaches can, in theory, provide access to sufficient data to complete coupling with soil models but it is not known by these authors at this time if/how these variables are available for connections: the TRNSYS buffer model, for example, can use relative humidities computed by soil models as boundary conditions at the external surfaces of walls but does not provide complementary outputs, like moisture flows, to use as boundary conditions in soil models.

Air flow through building envelopes is evaluated by default in all three software using one zone infiltration models. These models can not provide information on conditions at specific surfaces. All three packages provide access to multi-zones airflow networks which generally use air pressure as a boundary condition to evaluate air flow through external walls. Such networks could, in theory, be used to couple the air flow equation but, again, it is not clear at the present if the capacity to provide/access the required information exists: for example, these networks evaluate air pressure on external surfaces from ambient weather data and it is not clear if a pressure evaluated by a soil model could be provided directly instead.

4 Thermal coupling

The previous two sections established the type of equation systems solved by soil and building models and identified variables usable as boundary conditions for these equations. The following three sections (thermal, moisture and air couplings) review how the coupling between soils and buildings has been treated in existing models and, when possible, compare these methods. They also attempt to improve on this previous work by proposing a ”universal” method that takes advantage of lessons learned from these comparisons.

Many authors, including Krarti et al. (2001), Krarti & Choi (1997) and Zoras et al. (2002), used different techniques to convert results from soil/foundation models into equivalent walls and slabs transfer functions to incorporate directly as foundations into building models. These transfer functions account for transient heat conduction in the foundations and adjacent soil. This practice is technically closer to an integration than a coupling of different models performing calculations and exchanging information dynamically. It is applicable only to simulation packages using transfer functions and to model heat conduction.

Nakhi (1995) coupled a soil model to a house in ESP-r by creating a dummy zone, with a geometry corresponding to the one of his soil model, in his building. He used three-dimensional walls to provide data exchange between this zone (and so the soil model) and adjacent (coupled) building zones as well as other boundaries. This gave the soil model access to powerful utilities within ESP-r, like the shading analysis tool which provided the soil model with information about shading from the building and trees at the ground surface. This method requires multi-dimensional walls/zones and is therefore only usable with pure conduction models in ESP-r.

Comparison of universal coupling methods

The objective of this analysis, is to compare couplings that can be considered "universal", i.e., that link inputs and outputs of soil/basement models to inputs and outputs of walls/zones in building models and can therefore be implemented in any simulation package. In order to effect this comparison, a simplified model is used. The model, shown on Figure 3, is a steady state two-dimensional finite volume (Patankar 1980) representation of a basement zone, a wall, and the adjacent soil. The dimensions and boundary conditions are indicated on the schematic. The thermal conductivities are $3\,W/mK$ for the soil and $2.8\,W/mK$ for the concrete wall. A situation is also studied where the top $0.4\,m$ of soil are frozen and have a thermal conductivity of $4\,W/mK$: this should reflect how couplings behave when soil properties vary. The zone is maintained at $20°C$ and exchanges heat with the interior surface of the wall by convection only. In the following discussion, the solution of this problem treated as a single domain is referred to as the Base Case. Results for this Base Case are compared with results for cases separating the problem in two domains, one resolved by a two-dimensional soil model and the other by a one-dimensional building model, coupled using different methods.

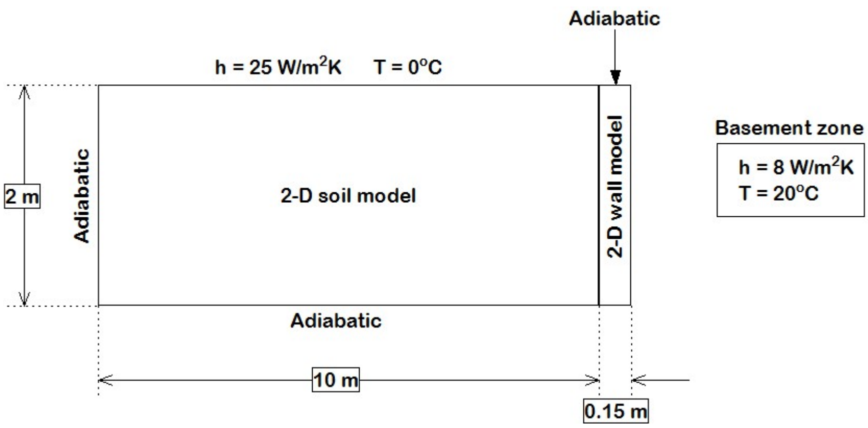


Figure 3: Base case basement approximation

Indoor coupling: As previously discussed, soil and building models can exchange boundary conditions of temperature and heat flux. These two variables seem like natural variables to perform thermal couplings. This first explored coupling method is illustrated in Figure 4. It consists of a two-dimensional domain including the soil and the wall. This model sends the average temperature on the indoor surface of the wall to the zone domain. The zone model returns the corresponding one-dimensional heat flux which is used as a uniform boundary condition in the soil/wall domain. A drawback of this method is that the soil model must include the wall.

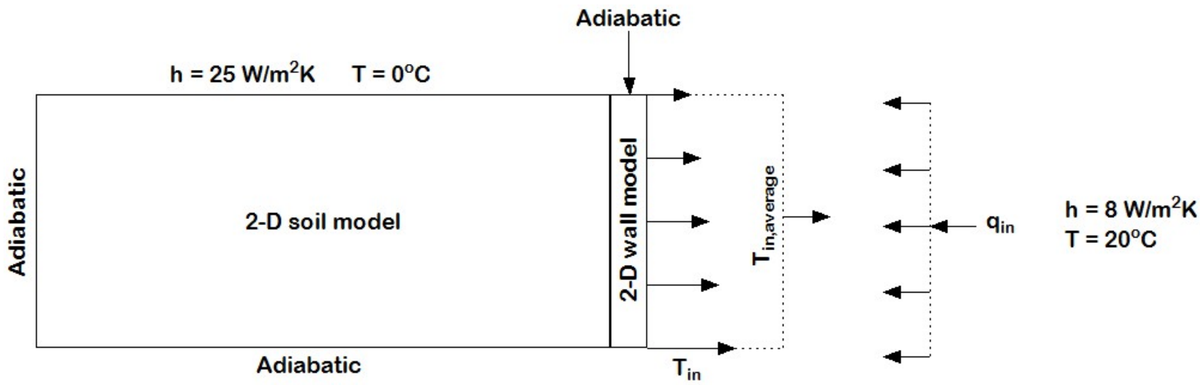


Figure 4: Indoor coupling

Outdoor coupling: The second studied coupling method, previously used by Krarti & Ihm (2009), is illustrated in Figure 5. With this coupling, the two-dimensional domain includes the soil only. The wall and zone are modelled using a one-dimensional domain, similarly to the way whole-building simulation packages treat them. The soil model sends the average temperature on the outdoor surface of the wall to the wall model which returns the one-dimensional heat flux to be used as a uniform boundary condition in the soil domain.

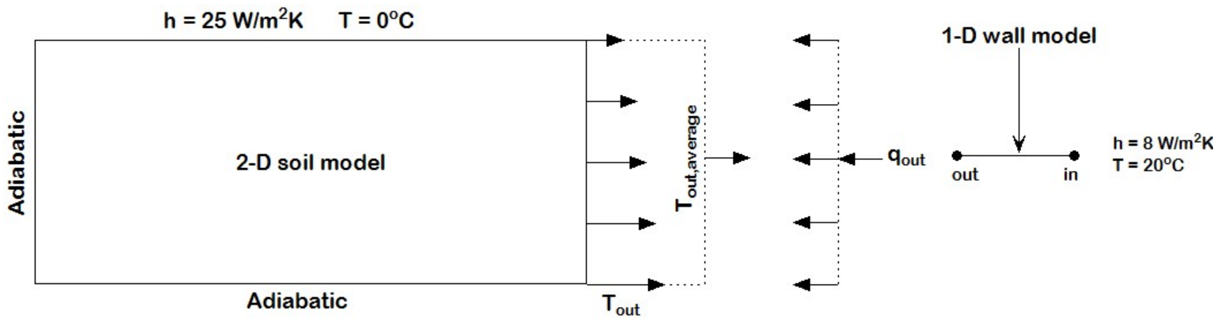


Figure 5: Outdoor coupling

In-Out coupling: This third coupling method, previously used by TESS (2004), is illustrated in Figure 6. The wall is modelled in both a two-dimensional soil/wall domain and in the one-dimensional wall/zone domain. The soil/wall model sends the average temperature on the outside surface of the wall to the the wall/zone model which returns the temperature on the inside surface to be used as a uniform boundary condition for the soil/wall domain. A drawback of this method is again having to model the wall within the soil model.

Clements (2004) effected a similar coupling where a three-dimensional foundation model sent the average temperatures on the outside surfaces of foundations to EnergyPlus wall models; the reverse coupling was different as EnergyPlus returned the zone temperature which was used by the soil model to approximate the temperatures on the inside surfaces of the walls assuming a heat transfer coefficient accounting for convection and long wave radiation. The BASESIMP (Beausoleil-Morrison & Mitalas 1997) implementation in ESP-r also uses the zone temperature

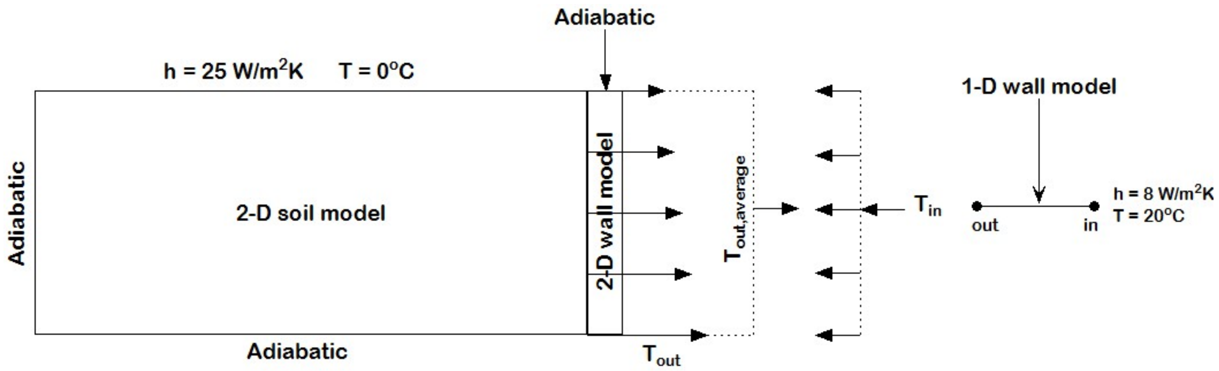


Figure 6: In-Out coupling

as a boundary condition and assumes a combined heat transfer coefficient; BASTESIMP returns heat losses from the foundation (walls/floor) to be used by the zone model. The accuracy of these approaches can not be verified with the simplified model used for the present analysis which also assumes a single coefficient to account for heat transfer in the zone.

Figure 7 presents average heat flux on the outside surface of the wall for the base model and the three coupling methods presented. As can be seen, the couplings behave well when the soil conditions are uniform with a maximum deviation around 4% for the Outdoor coupling. When freezing is assumed, performance degrades slightly with a maximum deviation around 5.5% for the Outdoor coupling. The conditions (temperature and heat flux) on the outside surface of the wall are presented in Figure 8 where the 0 m position is located at the bottom of the domain. As can be seen, significant deviations are observed. So this preliminary simplified analysis seems to indicate that these couplings result in acceptable evaluation of foundation heat losses but should not be used when knowledge of the soil conditions is important.

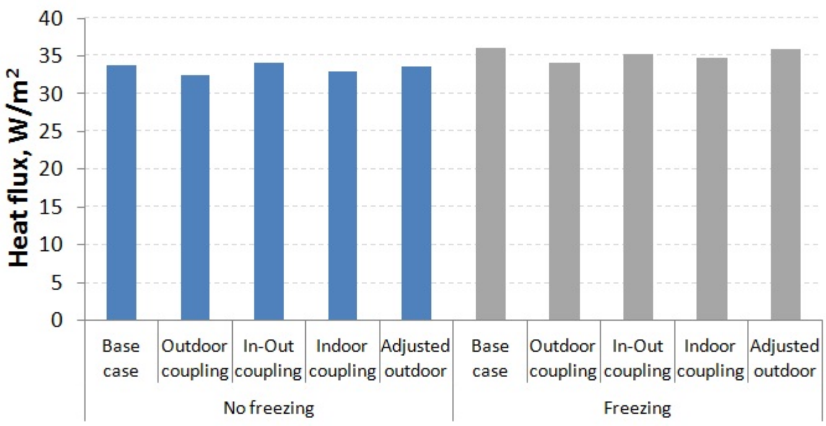
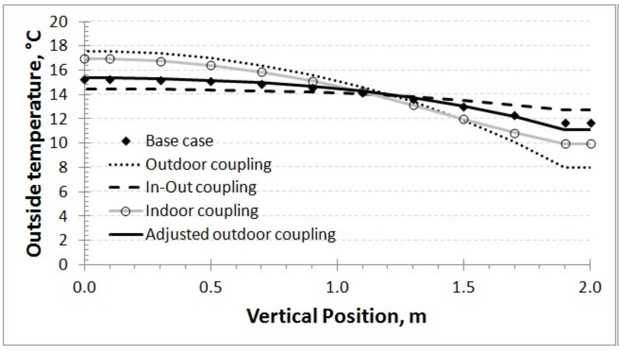


Figure 7: Average heat flux on outside surface of foundation wall

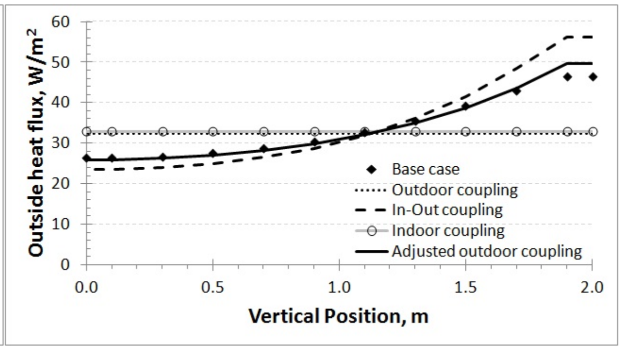
Another set of calculations was performed, assuming an unfrozen soil thermal conductivity equal to $1\,W/mK$ and a frozen soil conductivity of $4\,W/mK$, to assess the effect of highly varying soil properties. Average heat flux are presented in Figure 9. This time, the frozen soil condition results in significant deviations: 16% for the Indoor coupling, 27% for the Outdoor coupling, and 20% for the In-Out coupling. These are not acceptable.

Modification to the Outdoor coupling

In light of these results, a coupling that provides a more effective communication between models is required: there obviously is information lost when using one-dimensional walls/zones val-



(a) Temperature



(b) Heat flux

Figure 8: Conditions on outside surface of the wall for different couplings (unfrozen soil)

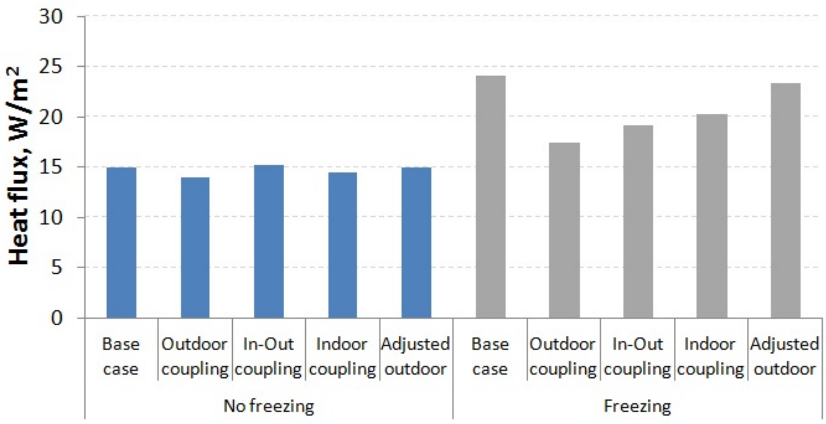


Figure 9: Average heat flux for low unfrozen soil conductivity

ues as uniform boundary conditions in multi-dimensional soil models. Preferably, this coupling should not require modelling of foundations in soil models as this should be the task of the building model. Figure 10 presents a modified version of the Outdoor coupling. With this new coupling, when the wall model returns the heat flux on the outside surface of the wall ($q_{out,1-D}$), this flux is adjusted at each element (i) of the boundary (to obtain $q_{out,i}$) by a factor equal to the ratio of the difference between the zone temperature (T_{zone}) and the boundary temperature at the specific element ($T_{out,i}$) over the difference between the zone temperature and the average boundary temperature ($T_{out,avg}$). This yields:

$$q_{out,i} = q_{out,1-D} \frac{T_{zone} - T_{out,i}}{T_{zone} - T_{out,avg}} \tag{5}$$

Results obtained with this coupling are also shown in Figures 7, 8, and 9 where it clearly out-performs the other studied couplings: showing a deviation from the base case of only 3% when evaluating the average heat flux for the large conductivity variations case of Figure 9. It also follows relatively well the variations of temperature and heat flux along the boundary (Figure 8). It is normal that this coupling performs well for this simplified example since only convection is considered between the zone and the wall so the heat flux is directly proportional to the temperature difference between the zone and the wall element considered. When used in more complete models, where wall temperatures are dependent of other factors which are not directly related to the zone temperature, like solar gains and long-wave radiative exchanges, its performance should degrade. This degradation should be limited as typical basements do not include much glazing and experience relatively low radiative exchanges. This should be verified

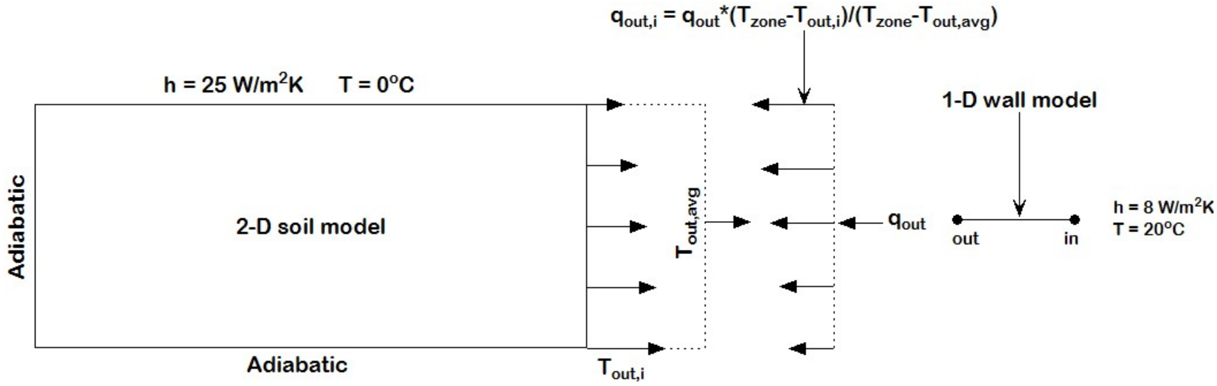


Figure 10: Adjusted Outdoor coupling

with a more complete model than the one used for this preliminary analysis.

Non-continuous insulation

Clements (2004) studied the coupling of partially insulated foundations. According to his results, connecting a three-dimensional soil/wall model with non-continuous insulation to a single wall in a building model, using the temperature at the outside face of the wall as a coupling point, can lead to over-prediction of the heat flux by as much as 63%. He recommends creating two walls in the building model, one representing the insulated portion of the wall and the other representing the non-insulated portion. The coupling is effected by connecting the average temperatures of the corresponding sections of the soil model to the outside of each wall.

Non-continuous insulation is reproduced in the simplified model (Figure 3) used for the present analysis by assigning a thermal conductivity of $0.071\,W/m\,K$ to the top 0.6 m of the studied wall: resulting in a resistance of RSI-2.11 (R-12). The Adjusted Outdoor coupling, including Clement's recommendation, is compared to this model. The resulting coupling is presented in Figure 11. The insulated portion of the wall is numbered 1 while the non-insulated portion is numbered 2. Information is exchanged with the corresponding sections of the soil model sending average external temperatures to one-dimensional wall models which return heat flux which are weighted at each node of each section according to Equation 5.

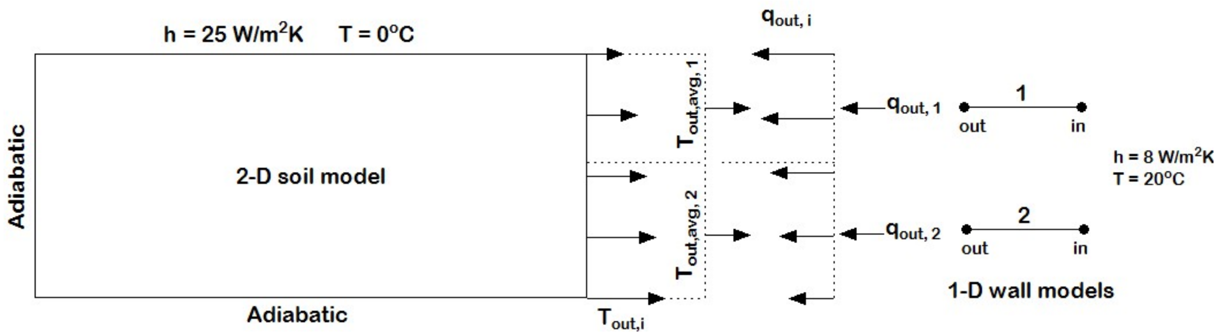


Figure 11: Adjusted Outdoor coupling for non-continuous insulation

Average heat flux at the outside surface of the wall are presented in Figure 12 where almost no differences between the base model and the coupled one can be observed, even when large soil thermal conductivity variations ($\lambda_{unfrozen} = 1W/mK$, $\lambda_{frozen} = 4W/mK$) are applied: the maximum deviation between the base and coupled models is 0.2 %. This indicates that insulated foundations are less sensible to the coupling and to soil properties variations than non-insulated ones. In any case, the combination of Clements' method and the Adjusted Outdoor coupling provides impressive results for this relatively complex situation.

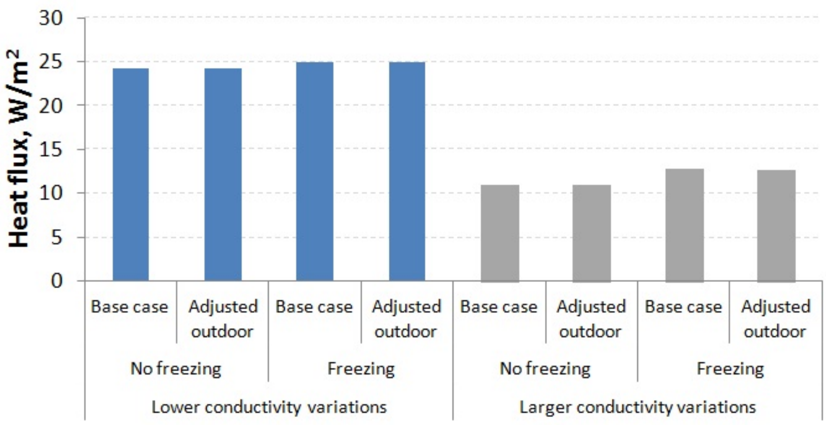


Figure 12: Average heat flux on outside face of partially insulated foundation wall

5 Moisture coupling

Moisture migration follows equations (Darcy and Fick's laws) similar to the heat conduction equation (Fourier's law): although the flow of liquid water in soils is not a diffusion phenomenon, Darcy's law has the form of a diffusion equation. So the analysis of Section 4 is also applicable provided that the wall models in the whole-building simulation package can evaluate moisture flow. The information exchange is relatively simple with HAM models included in the reviewed (Section 3) simulation packages as these models can accept relative humidities evaluated by soil models as boundary conditions and return moisture flux which can be used as boundary conditions for soil models by inserting them directly in Equation 1. The main issue concerns the availability of the required flux information from the HAM model.

Moisture flows through walls are usually small compared to inputs due to ventilation, so ignoring the effect of this coupling on latent loads could be justified. But this coupling also affects condensation in walls, wall thermal properties, and soil modelling accuracy. So its effects may be important and simplifying hypothesis should be validated, for a wide range of situations, against full transient heat and moisture transfer models before being generalized.

6 Air coupling

The air flux VS pressure relationship also has the same form as Fourier's law so the analysis of Section 4 applies. The coupling can be effected relatively simply using multi-zone airflow networks with soil models providing air pressures on external walls and airflow networks returning air fluxes for direct insertion in Equation 3. The main question remains the capacity of air flow networks to directly accept pressure values instead of calculating them from weather data.

7 Conclusions

This paper discusses possible couplings between soil models and foundations in whole-building simulation packages. Such couplings allow models to interact dynamically by exchanging information on conditions at boundary locations. Methods previously used to couple soil heat conduction models are reviewed and, when possible, evaluated using a steady state two-dimensional model of a simplified basement zone-wall-soil representation. It is found that information exchange between multi-dimensional soil models and one-dimensional wall/zone models in simulation software results in loss of important information. A coupling method, using temperature weighted factors to convert one-dimensional information provided by zone/wall models into inputs more appropriate for multi-dimensional soil models, is proposed. This method also has the advantage of accomplishing the coupling on the outer surfaces of foundations, resulting in the zones, walls and floors being modelled in the simulation package where many features are available to simplify this task. The method is evaluated for many situations, including highly varying soil thermal conductivities and non-continuous foundation insulation, and provides good results.

Coupling of the air and moisture transfer evaluated by some soil models is also investigated. Due to the shape of the governing equations, the technique proposed for thermal coupling can also be applied. The required information could easily be exchanged with HAM analysis capabilities already included in reviewed simulation packages (EnergyPlus, TRNSYS and ESP-r). The main questions concern availability of the data required by soil models as outputs from HAM models and acceptance of the data provided by soil models as HAM inputs. Further investigation should be performed and, if required, pertinent data exchange capabilities should be implemented within HAM models.

This work will continue with a more complete three-dimensional transient soil heat and mass transfer model. This model will allow more precise evaluation of the impact of different coupling techniques. A larger range of conditions should be investigated to allow generalization of results and conclusions. A number of possible simplifying assumptions should also be tested.

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