Implementation of ground response functions in TRNSYS for faster ground coupling calculations

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ABSTRACT

This paper presents a method that uses ground response functions to model annual or multi-annual building foundation heat transfer. The ground response functions can be obtained from detailed 3-dimensional calculations. They only depend on ground properties and the geometry of building surfaces in contact with the ground, so the same set of functions can be applied when simulating different building construction details, operation strategies, or HVAC systems, without any loss of accuracy. The paper describes the implementation of the proposed method in TRNSYS and its application to typical small residential buildings with slabs-on-grade and basements in the Canadian context. The developed TRNSYS component will be made available as an open-source contribution.

Keywords: simulation, ground coupling, transfer function, TRNSYS, residential buildings.

INTRODUCTION

Heat transfer to the ground from basements or slabs-on-grade can represent a significant share of a small residential building's heat losses, and therefore needs to be accurately simulated. In the case of TRNSYS, different methods are available to model a building's heat transfer to the ground, from simple (constant or scheduled) boundary temperature assumptions to full 3-D ground models. The latter, however, are often slow to run and can increase the total simulation time of a single-family home from a few seconds to several minutes.

The work presented in this paper describes a new ground-coupling method implemented in TRNSYS to strike a balance between accuracy and computational efficiency. The method can model the transient heat exchange between typical residential buildings (with a slab-on-grade or basement) and the ground.

LITERATURE REVIEW

Existing methods to model transient heat transfer between buildings and the ground can be broadly classified in 3 categories: simplified methods, regressions and correction factors, and 2-D or 3-D models.

Simplified approaches assume constant or scheduled ground temperatures at the building surface-to-ground interface. Sometimes soil layers are included in the building surface to account for some capacitance of the ground. Regression and "correction factor" approaches include the simple ASHRAE method (ASHRAE, 2021), the C-factor and F-factor methods used in EnergyPlus (US DOE - BTO, 2023), and the Mitalas method (Mitalas, 1983). These methods implement simplified monthly approximations of the ground behaviour, with 1-D approximations, correction factors, or regressions that account for particular geometries and sometimes particular construction details. BASESIMP (Beausoleil-Morrison & Mitalas, 1997) is an example of a more complex modelling approach based on regressions. The model is more accurate than the methods mentioned above, but it is restricted to a set of precalculated foundation configurations.

Many 3-dimensional and 2-dimensional thermal models have been developed for general purposes. Some examples are Heat2 and Heat3 (buildingphysics.com) or COMSOL (comsol.com). THERM (LBNL, 2013) is an example of a 2-dimensional model specifically designed to model thermal bridging and window frames. TRNSYS includes a 3-dimensional model for the ground coupling of slab-on-grades in the standard library (Klein et al., 2023, Type 49), but more flexible models with multi-surface capabilities are only available through the TESS libraries (TESS, 2023, Types 1244, 1255, and 1256 in the Ground Coupling library). Those models require defining the ground volume "noding" (discretization grid), and can provide an excellent accuracy with fine meshing, at the cost of high computing times. EnergyPlus can optionally be coupled with Kiva (Kruis, 2015), which relies on 2-D approximations for fast calculations with good accuracy, and can also be used in full 3-D mode.

One key issue in developing ground-coupling models for whole-building simulation programs is the location of the boundary between the "building model" and the "ground model". Pinel and Beausoleil-Morrison (2012) present a nomenclature for the different method to place the boundaries, and a comparison between these methods. Indoor coupling places the boundary between the "ground" and the "building" at the inside surface of the slabs or basement walls. Outdoor coupling places the boundary between the "ground" and the "building" at the outside surface of the slabs or basement walls. The outdoor coupling can be modified to adjust the heat flux transferred from the outside wall or slab surface to each node in the ground by a factor depending on the temperature difference between that particular node and the zone. The correction factor is designed so that the average heat flux is the same, but each node receives an adjusted heat flux, larger if the node is further away from the zone temperature than its neighbours.

The adjustment does not take into account factors such as solar radiation or longwave heat transfer inside the zone, but it allows to mitigate the main disadvantage of the outdoor coupling method. The authors conclude from their comparison tests that the modified outdoor coupling performs better than the other methods.

PROPOSED APPROACH

The method adopted in this paper is inspired by the "*g-functions*" used to model the response of geothermal boreholes, which have been used successfully for a long time (Eskilson, 1987) and are still the subject of very active research (see e.g. Spitler et al. (2020), which states that "In fact, at present, they are the only feasible way to simulate a ground-source heat pump system in a whole-building energy simulation"). The *g-functions* are part of the family of response/transfer functions heavily used in building performance simulation programs: several tools, including TRNSYS, rely on conduction transfer functions for 1-D conduction through walls (Stephenson & Mitalas, 1971). Response functions are also used in design methods such as the Radiant Time Series Method (RTSM) (ASHRAE, 2021). Wentzel & Claesson (2004) proposed step response factors for foundation heat losses as part of a broader approach to model buildings with dynamic thermal networks (Claesson, 2003; Wentzel, 2005), but to the authors knowledge the method has not been implemented in a whole-building simulation program.

The method described in this paper relies on a TRNSYS component model capable of exchanging information with the multizone building model (Type 56) through the outdoor coupling method: placing the boundary between the ground model and the building model at the outside surface of slabs and basement walls. The TRNSYS component implements response functions to model the ground transient behaviour and calculate the boundary temperature of surfaces in contact with the ground, taking into account the heat fluxes calculated by the building model and the influence of ambient conditions on the ground temperature.

The modelling approach requires response functions to be precalculated before being used in the simulation. Similarly to the g-function approach for geothermal boreholes, this approach divides the problem in two distinct steps: generating the response functions with detailed model(s), and using the response function for fast, fully coupled simulations. Although the generation of the response function can be achieved with different tools, the approach presented in this paper includes a method to generate them within TRNSYS, using

preliminary simulations with the existing ground-coupling components such as Type 49 (Klein et al., 2023) and Type 1244 (TESS, 2023).

Generating the Ground Step Response factor ($gsrf$): example of a slab

In the proposed approach, the $gsrf$ must be obtained from a detailed 3-dimensional heat transfer model. This is a time-consuming process, but it must only be done once for a particular geometry and set of ground properties. Changing building construction or operation details (e.g. setpoints, HVAC system), or the weather data, does not require recomputing the $gsrf$. In the case of a slab-on-ground, there is only one building surface in contact with the ground, i.e. the slab. The relevant $gsrf$ will provide the response of the surface boundary temperature (T_{bnd}) to a unitary step in heat transfer through the slab.

$$gsrf_{slab} = T_{bnd}(t) \text{ for } \dot{q} = step(t) \quad (1)$$

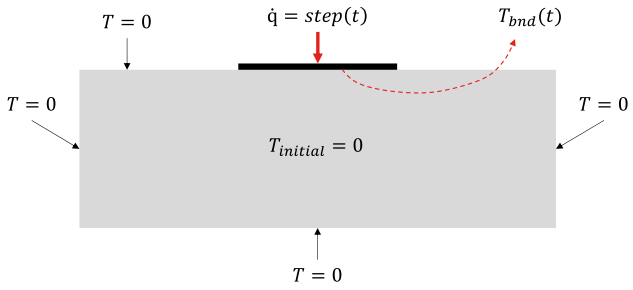

Figure 1: Boundary conditions to generate the slab response function to a step in heat input

Using the Ground Step Response Function

Once the $gsrf$ has been obtained, the response of the boundary temperature of the slab can be calculated for any time-varying heat input. The principle to do so is simply to consider that a signal can be expressed as a series of steps where the value of each step is the derivative of the heat input (i.e. the change in heat input over a time step in a discretized approach):

$$T_{bnd}(t) = \sum step_i \cdot gsrf(t - t_i) = \sum \left.\frac{d\dot{q}}{dt}\right|_{t_i} \cdot gsrf(t - t_i) \quad (2)$$

This calculates the boundary temperature response to a heat input at a particular time step (t) as a function of the successive steps and the $gsrf$. This is the mathematical equivalent of a convolution product (noted *):

$$T_{bnd}(t) = \left.\frac{d\dot{q}}{dt}\right|_{t_i} * gsrf(t - t_i) \quad (3)$$

The convolution has several interesting properties: it is commutative ($gsrf$ could be evaluated at t_i and the derivative of the heat input at $(t - t_i)$), but the derivatives can also be swapped (Cimmino, personal communication):

$$T_{bnd}(t) = \dot{q}(t - t_i) * \left.\frac{d\ gsrf}{dt}\right|_{t_i} \quad (4)$$

In the following, the right side of the last equation in (4) will simply be written as:

$$T_{bnd}(t) = \left\{\dot{q} * \frac{d\ gsrf}{dt}\right\}(t) \quad (5)$$

The convolution theorem (Wikipedia) offers an elegant and fast method to solve a convolution product, by stating that "under suitable conditions the Fourier transform of a convolution of two functions is the element-wise product of their Fourier transforms". The solution uses three steps: 1) take the Fourier transform of each function, 2) multiply these Fourier transforms elementwise, and 3) take the inverse Fourier transform of the result to get the convolution product. The method was proposed in (Marcotte & Pasquier, 2008) for geothermal boreholes:

$$T_{bnd}(t) = \left\{\dot{q} * \frac{d\ gsrf}{dt}\right\}(t) = \mathcal{F}^{-1}\left(\mathcal{F}(\dot{q}) \cdot \mathcal{F}\left(\frac{d\ gsrf}{dt}\right)\right) \quad (6)$$

Computing the Fourier transform of discrete functions, even for large sizes, can be performed extremely fast thanks to highly optimized libraries such as the Intel oneAPI Math Kernel Library (Intel, 2024). The "Fast Fourier Transform" (FFT) functions of oneMKL are used in the current TRNSYS Type implementation.

Impact of the ambient conditions

The impact of ambient conditions can be expressed using a $gsrf$ function as well, which would express the ground surface temperature response to a heat input

from the ambient air. The heat input includes solar radiation, convection from the ambient air, and long-wave radiation exchange with the sky. It must be calculated during the simulation using the current ambient conditions and the current surface temperature, which is often approximated by the surface temperature at the previous time step.

An alternative method used in the current version of the implemented TRNSYS component is to pre-calculate the impact of the ambient conditions on the boundary temperature of the slab, T_{bnd}, when the heat flux input from the slab, $\dot{q}$, is a constant null. In this "undisturbed temperature" scenario, T_{surf} is determined for each simulation timestep, t, using either a pre-computed temperature profile such as the commonly used Kusuda profile (Kusuda & Achenbach, 1965), or detailed model taking into account the heat balance at the surface. The latter approach is illustrated in Figure 2, where T_0 is a constant "deep-earth" temperature boundary to the detailed model, and $T_{surf}(t)$ and $T_{bnd}(t)$ are the calculated outputs.

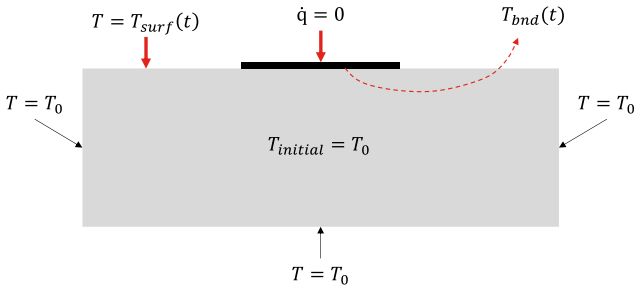

Figure 2: Impact of ambient conditions

Precomputing the impact of ambient conditions requires changing the precomputed values whenever the weather data file is changed, but it allows for faster simulation runs. This paper adopted the precomputed response. Unlike the $gsrf$ described above, the result of this step is not a function relating the boundary temperature $T_{bnd}(t)$ to another variable, but a calculated value:

$$T_{bnd}(t) = T_{bnd,ambient}(t) \tag{7}$$

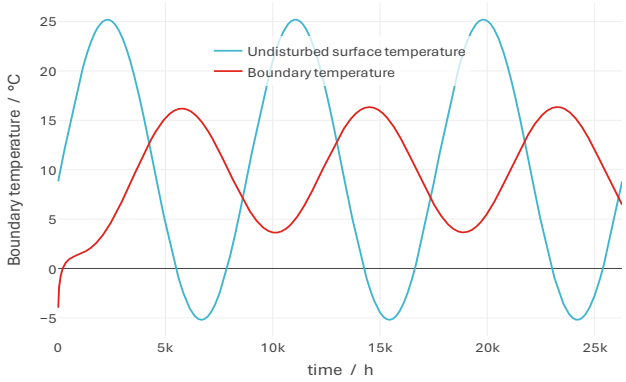

Figure 3: Precomputed boundary temperature with the impact of ambient conditions. The undisturbed surface temperature is shown for reference, to highlight the fact that the boundary temperature resulting from "no flux" conditions at the slab is not the undisturbed temperature

Combined heat injection & ambient conditions

The boundary temperature resulting from the combined effects of ambient conditions and heat input through the slab is obtained by summing the two responses:

$$T_{bnd}(t) = \underbrace{\left\{\dot{q} * \frac{d\ gsrf}{dt}\right\}(t)}_{\text{impact of boundary heat transfer}} + \underbrace{T_{bnd,ambient}(t)}_{\text{impact of ambient conditions}} \tag{8}$$

The heat input at the boundary surface, $\dot{q}$, is obtained from the building model (i.e., Type 56 in TRNSYS), so the ground response function (GRF) model must iterate with Type 56, shown in Figure 4.

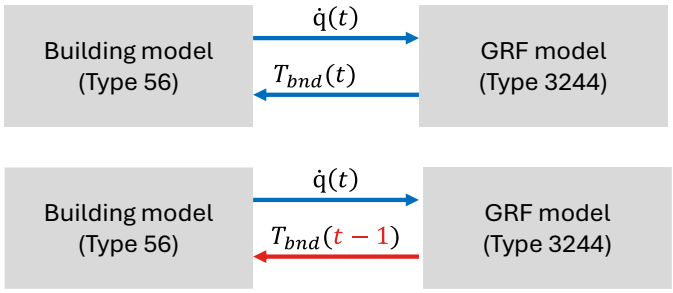

Figure 4: Information exchange between the building and ground-coupling components, iteratively (top) or with a delay (bottom) if convergence issues occur.

Generalization to multiple surfaces

When several surfaces are present, such as in the case of a basement, the response of the boundary temperature

of a given surface will be influenced by ambient conditions and the heat input at that particular surface, as well as heat input at other surfaces. This is illustrated in Figure 5 for three surfaces, showing that the heat input on surface 1 will have an impact on the boundary temperature at surface 1 (as in the slab-on-grade case), but also on surfaces 2 and 3. And conversely, heat inputs on surfaces 2 and 3 will also have an impact on the boundary temperature at surface 1.

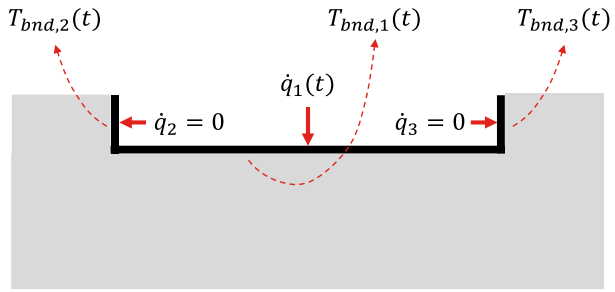

Figure 5: Multiple responses of boundary temperatures to a heat input on one of the surfaces

If $gsrf_{ij}$ denotes the step response function characterizing the impact of heat input on surface i on the boundary temperature at surface j, the general expression for the boundary temperature at a given surface i becomes:

$$T_{bnd,j}(t) = \underbrace{\sum_i \left\{ \dot{q}_i * \frac{d\, gsrf_{ij}}{dt} \right\}(t)}_{\text{impact of boundary heat transfer}} + \underbrace{T_{bnd,ambient,j}(t)}_{\text{impact of ambient conditions}} \quad (9)$$

For a typical basement with 5 surfaces, this would result in $5^2 = 25$ Ground Step Response Functions, and 25 uses of the FFT convolution per time step or iteration.

Fortunately, symmetries reduce the number of calculations, and some $gsrf_{ij}$ functions can be neglected. This is illustrated in Figure 6 for a conventional rectangular basement.

The full $gsrf$ matrix has 25 elements. Symmetries impose that the boundary temperature of surfaces 1 and 2 ("Front" and "Back") must be equal. The same is true for surfaces 3 and 4 ("Left" and "Right"). In the overall $gsrf$ matrix, columns 2 and 4 can be ignored, the boundary temperature outputted by the component can just be set equal to that of the symmetrical surface. This is indicated in the matrix by coloring the corresponding $gsrf$ in light grey.

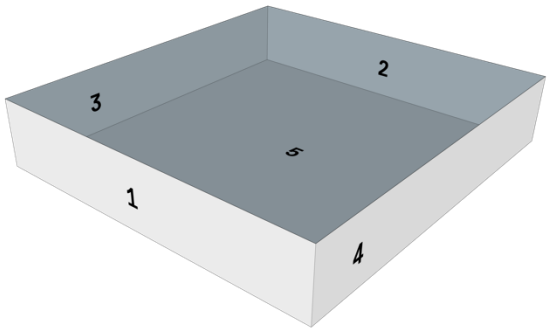

Figure 6: Conventional rectangular basement with 5 surfaces in contact with the ground

Furthermore, the impact of a heat injection on surface 1 (front) or 3 (left) on the boundary temperature of surface 5 (bottom) is very small, and can be neglected, because the "easy" path for the heat (or cold) out of the ground is towards the surface, not under the slab. The corresponding $gsrf$ are set to zero and colored in green in the table. The same holds true for the relationship between surfaces 1 and 2 on one side, and 3 and 4 on the other. This cancels another set of functions, which are set to 0 and colored in light blue. This leaves 9 $gsrf$ to evaluate. For typical basement sizes and ground properties, initial tests have shown that a heat injection on surface 1 has a negligible impact on surfaces 3 or 4, and this is true for any "around the corner" couples of surfaces. These are indicated as "$gsrf_{ij} \approx 0$" in the table and colored in light orange.

After accounting for symmetries and null (or approximately null) response functions, the number of $gsrf$ to consider is reduced to 5.

In the developed component, the user must define the number of surfaces, $n_{surfaces}$, and by default $n_{surfaces}^2$ $gsrf$ are expected. But the user must also define the symmetries (removing columns of the matrix) and can optionally specify null response functions. In a case similar to this example, the data file should include 5 response functions, and not 25.

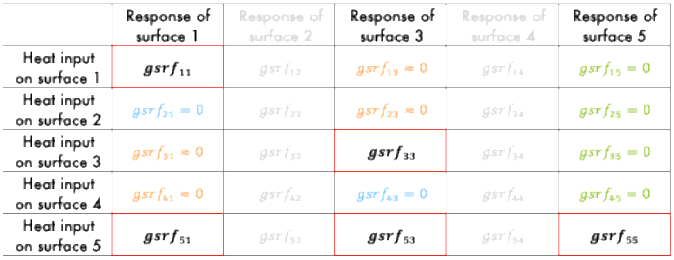

Figure 7: Ground Step Response Function matrix for a rectangular basement with functions that do not need to be considered due to symmetries and simplifications

RESULTS: WHOLE-BUILDING TEST CASE

The proposed method was tested on two variants of a single-family detached house: one with a slab-on-grade, the other a full basement. The model parameters are selected to represent a building complying to the Canadian National Building Code (Canadian Commission on Building and Fire Codes, 2022). Heating and cooling systems are idealized.

The truth standard for test cases is TRNSYS Type 1244, a 3-D finite difference model that was part of the ASHRAE Standard 140 "Ground coupling" test cases, and was considered as one of the reference models for test cases where an analytical truth standard was not available (ASHRAE, 2023b). Type 1244 is described in more detail in the documentation for the TESS libraries (TESS, 2023).

Type 1244 is also used to generate the response functions needed by the developed component, Type 3244, so the results comparison will assess the ability of the developed component to accurately reproduce the transient heat transfer that was encapsulated in the response functions, rather than assessing the accuracy of the response functions themselves.

Aggregated error indicators

The table below presents selected error indicators for the basement example (ASHRAE, 2023a). The $CV(RMSE)$ is the root-mean-square error normalized by the mean value, while the $NRMSE$ is normalized by the variable range (maximum value – minimum value), which is more appropriate for temperatures. The $NMBE$ is normalized by the mean value for heat transfer rates (indicated as $MBE/mean$) and by the range for temperatures (indicated as $MBE/range$).

Table 1: Aggregated error indicators, basement case

Heat transfer rate		
	$CV(RMSE)$ [%]	$MBE/mean$ [%]
Front	0.4	0.2
Left	0.4	0.2
Bottom	1.5	0.6
Total	1.4	0.5
Boundary temperatures		
	$NRMSE$ [%]	$MBE/range$ [%]
Front	0.1	-0.1
Left	0.1	-0.1
Bottom	0.4	-0.3

The error indicators seem acceptable given other sources of uncertainty in the calculation of foundation heat transfer. The error is slightly higher for the slab surface (bottom), which is uninsulated (and hence sees a much larger heat transfer).

Transient behaviour

Figure 8 shows that the dynamic profiles of the boundary temperatures and heat transfer rate are well captured by the $gsrf$ model. Both the seasonal pattern and the sharp transients occurring at the end of the heating season are correctly reproduced. The amplitude of the boundary temperature is slightly underestimated, which leads to a slightly underestimated / overestimated heat transfer rate in winter / summer respectively.

Computing times

Computing times are compared to assess the difference between a typical simulation with a state-of-the-art 3-D ground model in TRNSYS and a simulation with the developed fast ground coupling model. Computing times were obtained on a recent laptop equipped with a 13th Gen Intel Core i7-1365U processor (1.80 GHz base frequency) with 32 GB of RAM and a fast SSD, running one simulation at a time to avoid thermal throttling. They are presented for 3-year simulations, allowing for ground preconditioning.

Two values are presented in Table 2 for the reference simulation (using Type 1244): one using the standard complied version and one re-complied with optimized compiler settings. The comparison between the optimized compiler settings and the ground response functions method gives a better estimate of the time

savings from the model itself, as both models are compiled with the same settings.

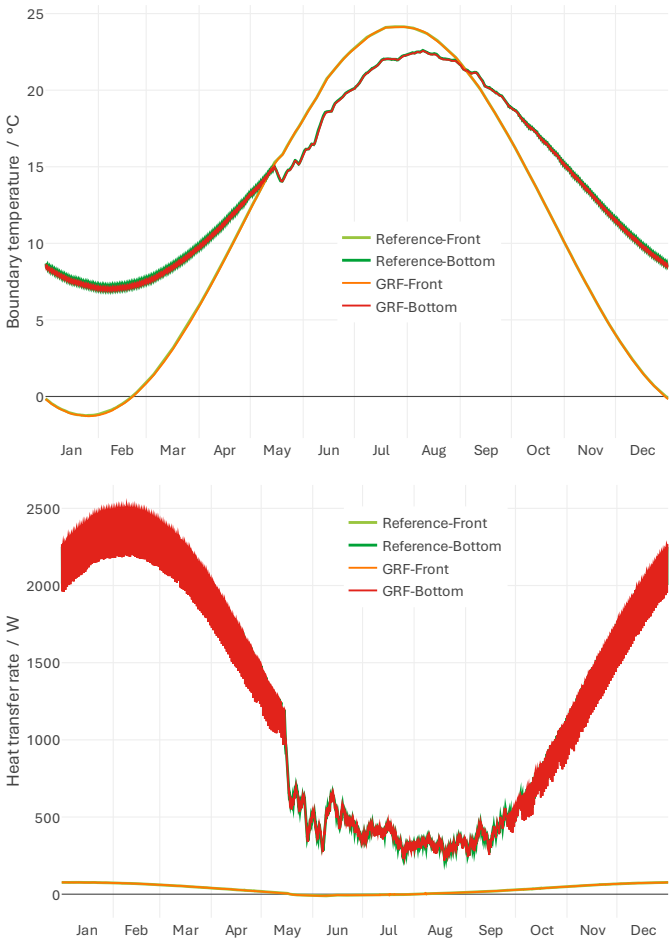

Figure 8: Hourly boundary temperatures (top) and heat transfer rates (bottom) for the basement case

Table 2: Computing times

Slab-on-grade (1 surface)		
	Time [s]	% of Ref (Official)
Reference (Official)	3000	100
Reference (Optimized)	600	20
$gsrf$	30	1
Basement (5 surfaces, with symmetries)		
	Time [s]	% of Ref (Official)
Reference (Official)	5700	100
Reference (Optimized)	1000	20
$gsrf$	140	2.5

The speed-up factor delivered by the $gsrf$ method is 20 for the slab, and 7 for the basement, compared to a reference simulation using the full 3-d model in Type 1244 (with optimized compiler settings). The time to generate the response functions is not included. The assumption is that a typical use case would require generating the transfer functions once, and then running many simulations comparing different building construction details, HVAC systems, and operation parameters. As an indication, the computation time to obtain the $gsrf$ is of the same order of magnitude as the reference simulation (≈ 1000 s).

CONCLUSIONS

This paper demonstrates the feasibility of the ground response functions method to simulate the thermal losses or gains through slabs and basement in TRNSYS accurately with much improved computing times compared to the current situation.

The proposed component delivers a speed-up between 7 and 20 compared to a reference simulation using Type 1244 with optimized compiler settings (identical to those used for the new component).

Generating the ground response functions takes approximately the same time as the reference simulation with Type 1244, but this cost in computing time is acceptable if many simulation variants are run with the same ground response functions.

The model accuracy has been assessed on realistic examples. Aggregated error indicators ($CV(RMSE)$ and $NMBE$) show a very good agreement, with percentage values below 2 %. The graphs presented in the results section also show that the transient behaviour of the surface boundary temperatures and heat transfer rates are correctly reproduced by the model.

LIMITATIONS AND FUTURE WORK

The generation of ground step response functions is a time-consuming process. To alleviate that issue, *g-functions* used to model the response of boreholes in geothermal systems are expressed as dimensionless numbers, which makes them suitable for a series of cases instead of the particular case for which they have been generated. The time is expressed as the dimensionless Fourier number, using the ground thermal diffusivity and the borehole depth in that case. In the case of basement or slab $GSRF$s, it would be

interesting to explore the generalization of calculated response functions by expressing them as a function of dimensionless ratios (e.g. perimeter/area ratio, length/width ratio, etc.) and the Fourier number so the same $GSRF$ could be used for different simulations.

The method to generate the ground response function, whether it relies on TRNSYS or other tools implementing 2-D or 3-D models, could be automated to facilitate the generation of response functions and their transfer to the appropriate data files for Type 3244. The current process is manual.

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