COMPARISON OF A GROUND-COUPLING REFERENCE STANDARD MODEL TO SIMPLIFIED APPROACHES

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ABSTRACT

The transfer of energy from the ground to buildings through slabs and basements has long been a point of large errors in simulations. Work to increase the accuracy of this ground-coupled heat transfer was started under IEA Task 34/43. Detailed models of the ground heat transfer process were developed in TRNSYS for the IEA task work and refined further after for project work. The detailed models created for TRNSYS will be discussed in the context of the IEA task work as well as in comparison to the simplified methods used in mainstream energy modeling.

INTRODUCTION

The calculation of the energy transfer between the ground and a building through a slab or basement has long been a source of errors in simulation programs and has led to large differences in the results of different programs. One of the tasks undertaken as part of International Energy Agency (IEA) Solar Heating and Cooling (SHC) Programme Task 34 and IEA Energy Conservation in Buildings and Community Systems (ECBCS) Programme Annex 43 (Neymark 2008) was to develop test cases for the ground-coupled heat transfer problem and have different simulation packages converge on an 'acceptable' solution. TRNSYS was one of the software packages participating in the task and a fully 3-dimensional finite-difference model of the ground was developed to calculate the building-to-ground energy transfer. This model was determined to be one of three "reference standards" in the IEA task (along with Fluent and MATLAB) as the model results were found to match closely with an analytical solution and other reference standard models and was capable of running the full suite of test cases. After the completion of the IEA task, the model was further refined to simplify user input and better handle complex geometries. With the increased accuracy in the ground-coupled heat transfer came increased complexity of use and increased run times. To determine the importance in using a detailed ground-coupled heat transfer model, results from the detailed model are compared to several simplified methods for calculating the building-to-ground energy transfer.

IEA ANNEX 34/43 TASK

As above-grade components of the building thermal fabric become more energy efficient, the heat transfer between the building and the ground becomes relatively more important. Ground-coupled heat transfer is a complex phenomenon that involves three-dimensional (3-D) thermal conduction, moisture transport, long time constants, and the heat storage properties of the ground. Typical slab-on-grade floor heat loss can be a significant percentage of the annual heating load for many applications. This percentage depends on a wide variety of parameters, including climate, above-grade thermal properties of the building, presence of slab and/or perimeter insulation, etc.

Several relatively detailed ground-coupled heat transfer models have been developed and are being integrated with whole-building energy simulation computer programs. However, there is little to no quantitative information about the accuracy of these new models, or about how well they compare to each other or to previously developed, simpler models. Furthermore, it is extremely difficult and expensive to collect good empirical data on ground-coupled heat transfer phenomena because of the disturbance to the earth and to temperature profiles resulting from the construction of a building and placement of sensors, the long time constants associated with large ground mass, and the variability in field conditions. For these reasons, NREL collaborated with the previous IEA SHC Task 22 to develop a BESTEST-type method to test and diagnose the more advanced ground-coupled heat transfer models. The cases were defined to test the following aspects of ground-coupled heat transfer models:

- interaction of the building with the atmosphere through the ground
- effects of solar radiation on ground-coupled surfaces
- effects of calculated versus constant surface heat transfer coefficients
- slab-on-grade geometries with and without insulation
- basement geometries with and without insulation

- interaction of the building with the deep ground conditions
- walkout basement construction.

Preliminary results indicated some large disagreements among the detailed ground-coupled heat transfer models linked to whole-building energy simulation software. However, the sources of these disagreements could not be readily determined because the cases were designed to be relatively realistic, not diagnostic, and there was no mathematical or empirical truth standard. Based on these unresolved disagreements, it was concluded that, before proceeding with other realistic test cases, in-depth diagnostics had to be developed to resolve or better understand the causes of differences found.

In parallel with the Task 22 work, ASHRAE published a compilation of analytical solutions (Spitler 2001) that included a 3-D steady-state solution for a slab-on-grade heat transfer problem with rectangular geometry originally developed by Commonwealth Scientific and Industrial Research Organization (CSIRO), Australia. (Delsante 1983) This spawned the idea to design a test suite beginning with the CSIRO analytical solution, which would then step methodically toward more realistic boundary conditions and parametric assumptions. Furthermore, if detailed stand-alone 3-D numerical models were applied to the test cases using a solution process that demonstrates convergence, and good agreement was verified, those numerical models could be established as quasi-analytical solutions. Such solutions would provide a powerful secondary mathematical truth standard, based on their range of disagreement, for checking other ground-coupling models typically used with whole-building energy simulation programs.

The CSIRO analytical solution was the only 3-D analytical solution with rectangular surface geometry found, and formed the basis for the test cases. This analytical solution is for a steady-state condition. The new test cases use an idealized un-insulated slab-*in*-grade configuration. This simplified configuration is required by the CSIRO analytical solution, appropriate for developing robust ground-coupling test cases, compatible with the tested programs, and facilitated the development of accurate model results by minimizing chances for input errors. The test cases, as they step away from the analytical solution, test parametric sensitivities to variation of floor-slab aspect ratio, slab area, water table depth (constant deep ground temperature depth), slab-interior and ground-exterior surface heat transfer coefficients, and slab and ground thermal conductivity. The cases use steady-state and harmonic boundary conditions as applied within artificially constructed annual weather data, along with an adiabatic above-grade building envelope to isolate the effects of ground-coupled heat transfer. Because the zone heating load is driven exclusively by the slab heat losses, it is equal to the slab conduction heat loss. This is convenient for testing programs that may not readily disaggregate floor conduction losses in their output.

There were only three participating stand-alone 3-D numerical models (FLUENT, MATLAB and TRNSYS) that showed excellent agreement with the analytical solution and each other for the remaining cases. These verified numerical-model results form a secondary mathematical truth standard based on their range of disagreement and were therefore deemed "reference standards".

Seventeen test cases were designed to use the results of verified detailed numerical ground-coupled heat transfer models as a secondary mathematical truth standard for comparing the results of simplified and mid-level detailed ground-coupled heat transfer models typically used with whole-building energy simulation software.

TRNSYS MODEL

TRNSYS is a modular system simulation tool that has been widely used in the study of buildings, renewable energy technologies, and HVAC systems. The program was originally written by the Solar Energy Laboratory at the University of Wisconsin; but recently is maintained, supported, and distributed by a consortium of international companies and government agencies. TRNSYS Version 16.1 was used for the most recent analysis as well as an extended library of TRNSYS components written by Thermal Energy System Specialists (TESS) LLC of Madison, WI. The ground coupling models used for this analysis are part of the commercially-available TESS ground coupling library for TRNSYS.

The particular model used for this analysis is part of a larger suite of slab-to-soil heat transfer models written by TESS for the TRNSYS simulation package that differ only in application. The core solution algorithm used for the suite of models is identical.

In the IEA test procedure, the slab, soil, and foundation walls have identical thermal properties with no insulation beneath the slab or on the edges of the slab. The slab is assumed to be very thin and surrounded by adiabatic walls. The radiant exchange from the slab to the zone is ignored. With the slab having the same thermal properties as the soil, being very thin, and communicating with the zone through convective exchange only, one of the simpler models was able to be used for these tests. The model chosen simulates an exposed floor with a conductive covering that isolates the zone air from the soil. In these test cases, the resistance of the covering was set very small to mimic the test conditions.

The routine models the heat transfer from a horizontal surface to the soil beneath the surface. The heat transfer is assumed to be conductive only and moisture effects are not accounted for in the model. The model relies on a 3-dimensional finite difference representation of the soil and solves the resulting interdependent differential equations using a simple iterative method. The governing differential equations imposed by the energy balance on each soil node are solved using an implicit methodology; assuring that the solution is stable over all ranges of simulation timesteps.

Due to its implicit formulation, the model allows very high surface heat transfer coefficients (i.e., addresses large Biot Number issues) without the calculation instabilities that plague many of the other soil models currently being studied. This can be seen by the almost identical results from a constant surface temperature condition and a high heat transfer coefficient condition. Each of the soil nodes at the surface conducts to the "local surface temperature" and not directly to the ambient or zone temperature. The "local surface temperature" is typically calculated from an energy balance on a massless, opaque plane located between the air and the soil node. This solution methodology requires another set of coupled iterative calculations within the model - but allows quite a bit more freedom with the model - a requirement for a well-formulated TRNSYS model. The local surface temperature can be calculated from an energy balance (as just described), or from a long term average surface temperature correlation (Kusuda), or provided to the model as an input (for example from a swimming pool model or parking lot model, etc.)

The soil volume surrounding the slab in the x, y and z directions is referred to as the near field. The near field soil is assumed to be affected by the heat transfer from the slab into the soil. Nodes contained in the near-field can vary in size in all three dimensions, typically becoming larger as they get farther from the edges/corners of the slab or as they get farther from the surface. The user controls the size and number of the nodes by providing parameters to the model for the noding algorithm. The user also controls the size/volume of the near field by providing parameters to the model specifying the distance away from the edge of the slab that the soil is unaffected by the slab (far-field distance) and the distance beneath the slab that the soil is unaffected by the slab (deep earth distance). The temperature of the far-field nodes can be calculated based on an energy balance (not a function of the near field temperatures but solely of the surface and deep earth temperatures) or can be specified by the Kusuda correlation (temperature is a function of the time of year and distance below the surface). The deep earth temperature can be an input to the model (for high water movement for example) or calculated from the Kusuda approach.

The near field is in turn surrounded by the far field, which is assumed to be an infinite energy sink/source (energy transfer from the near-field to the far-field does not result in a temperature change of the far-field). Like the near field nodes, the sizes of the far-field nodes typically increase as they get further from the soil surface. The boundary between the near field and far field may also be specified as adiabatic. The soil beneath the near field (and below the deep earth boundary) is also assumed to be unaffected by the slab and may also be specified as a conductive or an adiabatic boundary.

ANALYTICAL TEST CASE

This case is based on Delsante et al. (1983; see also Spitler et al. 2001), which calculates steady-state heat flow using fundamental 3-D heat transfer analysis of a semi-infinite solid. Figure 1 shows the boundary conditions at the upper surface of the semi-infinite solid and describes a rectangular floor surface bounded by a concentrically rectangular perimeter surface of finite width that separates the rectangular floor surface from the exterior ground surface. The concentrically rectangular surface may be thought of as the base of a wall that separates the interior floor surface from the exterior ground surface.

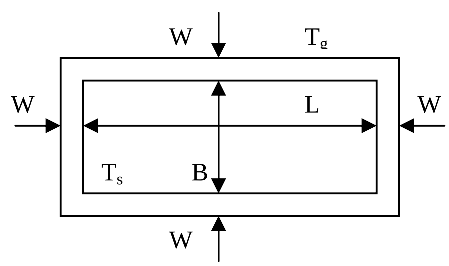

Figure 1 Floor Geometry

The following boundary conditions and assumptions are applied:

- Slab length (L) = slab width (B) = 12 m
- Perimeter boundary width (W) = 0.24 m
- Interior floor surface temperature (T_s) is constant and everywhere = 30 °C.
- Exterior ground surface temperature (T_g) is constant and everywhere = 10 °C.
- Linear variation between T_s and T_g over a perimeter surface boundary of finite width (W) is imposed only at the surface of the ground (this avoids a discontinuity at the interior/exterior boundary).
- Semi-infinite solid: the ground surface extends outward infinitely in all horizontal directions from the perimeter surface boundary defined in Figure 1, and the ground extends infinitely downward from all points on the infinite horizontal surface

(including from the surfaces of Figure 1 and beyond).

- Deep ground boundary condition at infinite soil depth = T_g = 10 °C.
- Thermal conductivities of slab and soil = 1.9 W/m K.
- There is no radiative exchange.

With these given conditions, the steady-state heat flow through the slab is 2433 W and the TRNSYS, FLUENT and MATLAB models were all able to produce agreement within 1% of the analytical solution.

IMPROVED TRNSYS MODEL

The IEA task was limited to single-zone, slab-on-grade construction and rectangular geometries and the TRNSYS model took advantage of symmetry to model only one quarter of the slab and ground in the model. However, these restrictions do not work as well when applied to most buildings being simulated. They may be slab-on-grade, slab-in-grade, or have a basement or partially exposed basement; they are not often shaped like rectangles and have more than a single-zone above the slab. A more flexible model that could handle the different conditions and geometries was needed if it was to be useful. Thus, the TRNSYS model was expanded to handle the more complex geometries and constructions using the same numerical techniques that were used in the model developed for the IEA task work.

The drawback of the expanded geometry was the need for a much more complex noding algorithm for the matrix, a description of which nodes were ground, wall, air, etc and to which zone that portion of the slab or basement was assigned. An automatic mesh-generating program was created which when given the vertices of the various walls and zones would derive the necessary node sizes to perform the calculations. The determination of the different vertices was still a cumbersome process and, recently, a Google Sketch-Up™ plugin has been created that calculates the vertices and the meshing based on the drawing of the slab or basement.

COMPARISON TO SIMPLIFIED MODELS

The advantage of the detailed numerical models for ground-coupled heat transfer is the increase in accuracy in the calculations. However, this increase in accuracy comes with a large penalty in increased computational time. There are a number of commonly used simplified approaches for calculating the heat transfer of slabs and basements. The key question concerning these simplified methods is if they are accurate enough in their calculation of the heat transfer to be used in place of a detailed numerical model.

Results from a few of these simplified methods were compared to results from the detailed TRNSYS model for a couple of configurations.

To test the different methods, a model of a basic residence was created which included three occupied zones and an unoccupied attic zone. Figure 2 shows an image of the building modelled and Figure 3 shows the floor plan of the three occupied zones. The exterior walls were modelled as face brick over insulated studs with an overall u-value of 0.588 W/m^2 K, the ceiling as insulated with an overall u-value of 0.228 W/m^2K and the roof as an un-insulated shingle roof with an overall u-value of 1.818 W/m^2K. The windows were modelled as double pane with argon gas in a vinyl frame (U-value = 2.0 W/m^2K, SHGC=0.33, VT=0.588). The slab was modelled as a 0.1 m concrete slab with carpet and includes 1.2 m deep footers on the edges of the slab. The different slab insulation cases modelled are discussed later in this paper.

Figure 2Building Modelled

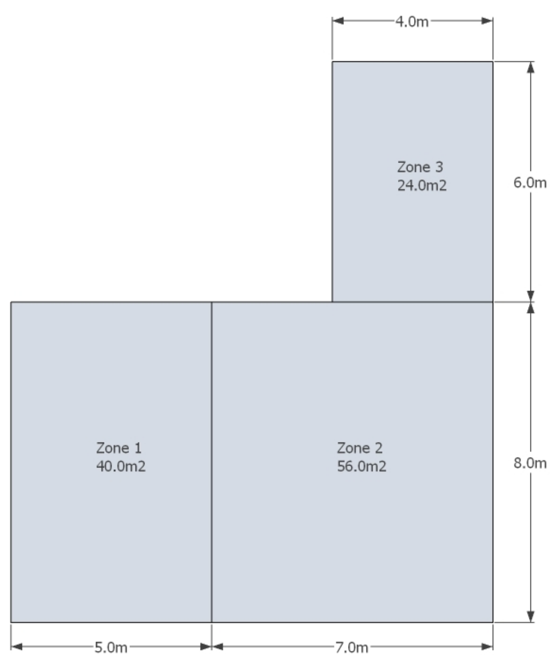

Figure 3 Floor Plan

The infiltration rates were set to a constant 0.21 air changes per hour in the occupied areas and 1.5 air changes per hour in the attic zone. The internal gains were set at 170 kJ/day/m^2 with a daily schedule as shown in figure 4 (ASHRAE 2001a).

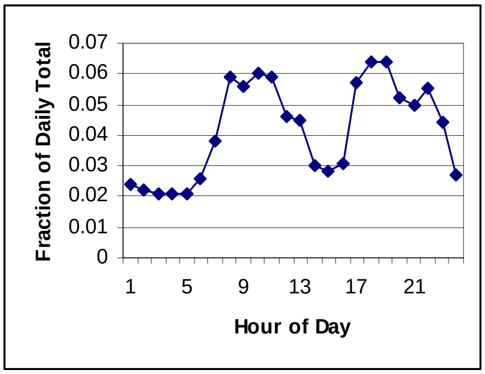

Figure 4 Internal Gains Schedule

Three different slab insulation cases were considered. The first was a completely un-insulated case as shown in Figure 5. The second case included insulation vertically on the inside of the footer and in the gap between the slab and the footer as shown in Figure 6. The insulation was modelled as R=0.88 m^2K/W. The final case was insulation horizontally under the slab as shown in Figure 7. The insulation in this case was modelled as R=1.76 m^2K/W.

Figure 5 Un-insulated Slab Configuration

Figure 6 Vertical Insulation Configuration

Figure 7 Horizontal Insulation Configuration

Wherever ground properties were needed in the models, typical properties for heavy, damp soil were used (k = 1.30 W/mK, ρ = 2100 kg/m^3, C_p = 0.96 kJ/kgK).

Three different cities were considered for this analysis. For a cold climate, Minneapolis, Minnesota was used; for a moderate climate, St Louis, Missouri was used; and for a hot climate, Austin, Texas was used. In all cases TMY2 files were used for the weather data.

Rather than include a detailed HVAC system in the model, an idealized heating and cooling system was used. With this method, the amount of energy needing to be added or removed from the zone to maintain a setpoint is calculated. For this model the heating setpoint was 21 °C and the cooling setpoint was 25 °C.

Detailed TRNSYS Model

For each of the three cases, the slab geometry and ground parameters were entered into the full TRNSYS model. Since the TRNSYS model is a finite difference model, the initial temperatures of the various soil nodes make a tremendous difference on the calculated heat transfer. For this reason, it is necessary to run the model for multiple years to build-up an appropriate ground temperature profile in the model. Based on the IEA task work that showed less than a 0.2% change in results after 5 years, it was decided to use a simulation period of 5 years. For each of the cases in each of the cities, the simulation was run for 5 years and all of the results shown are for the 5th year.

ASHRAE 1 Model

The first of the simple models is described in the ASHRAE Handbook of Fundamentals (HOF) chapter on Residential Cooling and Heating Load Calculations (ASHRAE 2001b). The heat flow through the slab is calculated by the following equation:

$$q_{perim} = F_2\, P\, (t_i - t_o) \qquad (1)$$

where

q_{perim} = heat loss through perimeter

F_2 = heat loss coefficient per meter of perimeter

P = perimeter or exposed edge of floor

t_i = indoor temperature

t_o = outdoor temperature

The F_2 factors are given for four different wall and slab configurations. Of course, the configurations that are being modelled here do not exactly match any of the four cases for which the factors are given. There is one case which is a face brick on concrete block with insulation vertically on the inside of the footer and wall. It was decided that this was the case closest to un-insulated and vertically insulated cases. There was no case which included horizontal insulation, so that case was not modelled with this technique. The F_2 factors used in the analysis are shown in Table 2.

Table 1
F_2 Factors(W/m K)

City	Un-insulated	Vertical Insulation
Minneapolis	1.45	0.85
St Louis	1.38	0.81
Austin	1.38	0.81

ASHRAE 2 Model

The second simple model is detailed in the ASHRAE HOF chapter on Energy Estimating and Modeling Methods (ASHRAE 2005). In this model the heat flow through the slab is calculated based on a base design value and an amplitude value. The total heat flow through the slab is then the design amount with the amplitude amount added based on a sine function with a phase delay.

$$q_{slab} = q_{mean} + q_{amp} \sin(\omega(\theta + \phi)) \quad (2)$$

where

q_{slab} = heat loss through slab

q_{mean} = annual-mean heat loss/gain

q_{amp} = heat loss/gain amplitude

ω = annual angular frequency

θ = time

ϕ = phase lag between total slab heat loss/gain and soil surface temperature

The equations for calculating q_{mean} and q_{amp} are well documented in the HOF and are not recreated here. However, there is little guidance on determining the phase lag value. After plotting the heat flow through the slab as a function of the time of year calculated by the detailed model, it was decided to use the same phase lag as is used for the lag between the beginning of the year and the minimum ground temperature.

The method utilizes two parameters based on the location of the insulation for the slab. There are parameters given for the case with horizontal insulation and for basement walls with vertical insulation, but not for slabs with insulation vertically on the footers. So for this model the vertical cases are not considered.

DOE2 Model

The third simple model was described in the Building Energy Simulation User News as a method of approximating the heat flow through underground surfaces in the DOE2 program (Winkelmann 2002). The technique was modified for use with TRNSYS for this study. This method involves calculating an effective resistance of the underground surface based on the area to perimeter ratio and a factor based on the location and amount of insulation on the surface. For all three of the cases selected here, there are applicable factors provided using this method. With the effective resistance calculated, the method subtracts the actual resistance of the surface plus the resistance of a 0.3 m layer of soil to determine a resistance for a fictitious insulation layer that is then included in the overall surface resistance (see Figure 8).

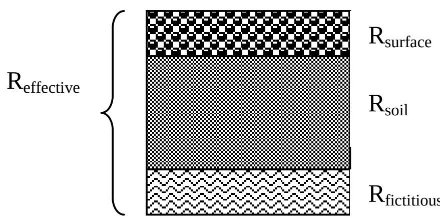

Figure 8 Layer Construction

The heat flow through the slab is calculated based on this new surface resistance and the temperature difference between the zone air temperature and the average monthly outside air temperature delayed by three months.

Simplified TRNSYS Model

The final simplified case is just a different manner of applying the detailed TRNSYS model. When the five year detailed model was run, the temperatures at the boundary of the slab and the soil were recorded hourly. A file of these temperatures from the 5th year was created. The TRNSYS building model was then changed to read in these values and apply them to the boundary of the slab rather than having the detailed model calculate these temperatures at every timestep.

RESULTS

The most obvious measure of comparison between the models is the heat flow through the slab. However, if this is the main measurement of concern, it is likely that the most detailed model available would be chosen to gain as much accuracy as possible. A better question is how do the simplified models compare on calculating the loads of the building. This comparison allows for decisions to be made about the appropriate ground heat transfer model to use when that is not the most important structure being studied. Also, since the simplified methods have been designed for annual load calculations, the comparisons documented here are the total annual heating and cooling load for the building. In all cases the models were applied to the three zones of the building separately, but it is the total building load being shown here. The results are shown in two different formats. The first are graphs showing the annual heating and cooling loads for each of the different methods for each city and each slab configuration in Figures 9-11. In Tables 3-5 the results are presented in percentage difference between the detailed model result and the simplified model results. Again, these are shown for both heating and cooling and for each city and each slab configuration.

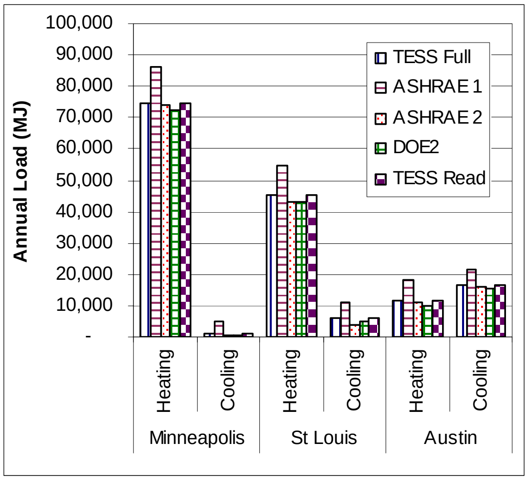

Figure 9 Un-insulated Slab Results

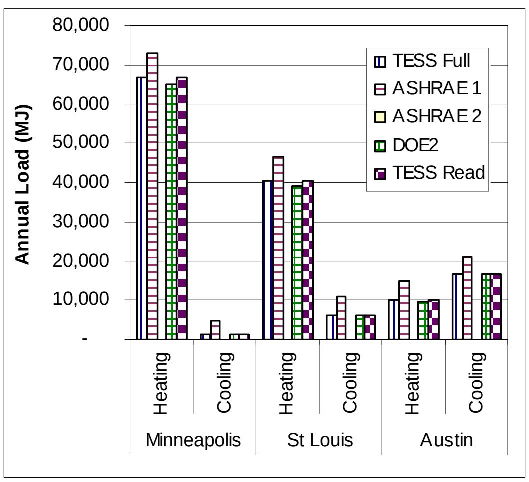

Figure 10 Vertically Insulated Slab Results

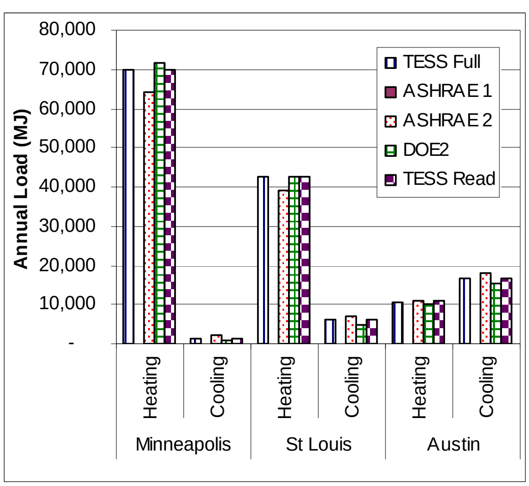

Figure 11 Horizontally Insulated Slab Results

Table 2
Percentage Results for the Un-insulated Slab

	Minneapolis		St Louis		Austin	
	Heating	Cooling	Heating	Cooling	Heating	Cooling
ASHRAE 1	16%	312%	21%	83%	56%	30%
ASHRAE 2	0%	-60%	-4%	-33%	-7%	-5%
DOE2	-3%	-42%	-5%	-21%	-13%	-9%
TESS Read	0%	0%	0%	0%	0%	0%

Table 3
Percentage Results for the Vertically Insulated Slab

	Minneapolis		St Louis		Austin	
	Heating	Cooling	Heating	Cooling	Heating	Cooling
ASHRAE 1	9%	278%	15%	78%	49%	26%
ASHRAE 2	n/a	n/a	n/a	n/a	n/a	n/a
DOE2	-3%	13%	-3%	4%	-3%	0%
TESS Read	0%	0%	0%	0%	1%	0%

Table 4
Percentage Results for the Horizontally Insulated Slab

	Minneapolis		St Louis		Austin	
	Heating	Cooling	Heating	Cooling	Heating	Cooling
ASHRAE 1	n/a	n/a	n/a	n/a	n/a	n/a
ASHRAE 2	-8%	60%	-8%	14%	1%	8%
DOE2	2%	-37%	0%	-18%	-6%	-8%
TESS Read	0%	0%	0%	0%	1%	0%

CONCLUSION

The first ASHRAE method performed the worst in comparison to the detailed model. That is not too surprising because the factors are based on only four different constructions. The second ASHRAE method did reasonably well in heating (within 8%), but had a rather significant error on the cooling load (up to 60%), especially in the colder climate zones. But again, it is only applicable to slabs with horizontal insulation. Another drawback is the necessity of determining the phase delay factor in the equation, without any guidance provided in the HOF. The DOE2 method also did well in the heating load calculations (within 13%), but differed on the cooling load calculations (up to 42%). With the largest table of factors available, the DOE2 is the most widely applicable of these three simplified methods. However, even with the large table of factors, it is quite easy to have a slab construction that does not fit in the table. The determination of the average outside air temperature delayed by three months is also a drawback of the DOE2 method. Not surprisingly, the method of using temperatures produced by the detailed method as inputs to a model without the detailed model produces good agreement. This method allows for the detailed method to be run once and any subsequent simulations that need to be run for system issues can be run much more quickly as long as the building construction and zone control temperatures do not change.

FUTURE WORK

A similar comparison of models for basement heat transfer should be completed.

ACKNOWLEDGEMENT

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NOMENCLATURE

B - slab width

C_p - specific heat

F_2 - heat loss coefficient per meter of perimeter

k - thermal conductivity

L - slab length

P - perimeter or exposed edge of floor

q_{amp} - heat loss/gain amplitude

q_{mean} - annual-mean heat loss/gain

q_{perim} - heat loss through perimeter of the slab

q_{slab} - heat loss through the slab

R - resistance value

SHGC - solar heat gain coefficient

T_g - exterior ground surface temperature

t_i - indoor temperature

t_o - outdoor temperature

T_s - interior slab surface temperature

u-value - heat transfer coefficient

VT - visible transmittance

W - Perimeter Boundary Width

ρ - density

ω - annual angular frequency

θ - time

ϕ - phase lag between total slab heat loss/gain and soil surface temperature

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