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IEA BESTEST IN-DEPTH DIAGNOSTIC CASES FOR GROUND COUPLED HEAT TRANSFER RELATED TO SLAB-ON-GRADE CONSTRUCTION

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With
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ABSTRACT

A set of validation test cases are presented for comparing the results of mid-level detailed ground-coupled heat transfer models typically used with whole-building energy simulation software to verified detailed numerical ground-coupled heat transfer models. A new validation methodology development is also presented that uses an analytical solution for verifying detailed numerical models for overall correctness and proper application. The verified models then form the basis for developing a secondary mathematical truth standard based on their results versus the analytical solution in the initial case, and versus each other as the test cases progress incrementally.

INTRODUCTION

The development of practical procedures and data for tool evaluation and improvement is part of an overall validation methodology that the National Renewable Energy Laboratory (NREL) (Judkoff et al. 2008/1983; Judkoff and Neymark 2006); the International Energy Agency (IEA) (Bloomfield 1999); and the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) (ASHRAE 2005; ANSI/ASHRAE 2007) have been developing for many years.

Importance of Ground Heat Transfer

Ground-coupled heat transfer is an important component of thermal analysis in buildings with a high ratio of ground-coupled floor area to volume. Such buildings include detached residential construction (common in the US), along with warehouses, shopping malls, and other commercial buildings. 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. Based on simulations, typical slab-on-grade floor heat loss can range from 15% to 45% of the annual heating load. This result depends on a wide variety of parameters, including climate, above-grade thermal properties of the building, presence of slab and/or perimeter insulation, and the ground heat transfer model used for the calculation. Estimates of the range of disagreement among models used for calculating uninsulated slab-on-grade heat transfer are 25% to 60% or higher for simplified models versus detailed models, depending on the models being compared, building characteristics, and climate. (Neymark et al. 2008)

Brief History of Ground Heat Transfer Modeling

During the early 1990s computers were substantially less powerful than they are today; such computers typically allowed only the use of simplified models for calculating ground heat transfer. Such simplified models were based on one-dimensional (1-D) steady-state conduction or 1-D dynamic thermal diffusion modeling using a limited amount of mass.

Because of recent improvements to computers, the state-of-the-art in ground heat transfer modeling has improved. Consequently, a number of mid-level detailed models have been developed and applied to building energy simulation software, including the following examples of models tested in this work:

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- BASECALC – produces quasi-3-D analysis by combining two dimensional (2-D) finite element simulations with corner correction factors (Beausoleil-Morrison 1996)
- BASESIMP – correlation method based on more than 100,000 BASECALC simulations (Beausoleil-Morrison and Mitalas 1997)
- EnergyPlus – monthly 3-D numerical analysis in a preprocessor (Bahnfleth and Pedersen 1990; Clements 2004; Crawley et al. 2004)
- EN ISO 13370 – European standard below-grade heat transfer calculation methodology applying a 3-D heat loss component varied monthly and a 1-D heat loss component varied hourly; VA114 applies this method, however, the 3-D heat loss component varies daily. (ISO 1998; VABI 2007)

Recent ground heat transfer simulation improvements include the development of stand-alone 3-D detailed numerical models that have also been integrated with whole-building energy simulation programs. Such models used in this work include TRNSYS's 3-D finite difference model (Thornton 2007) and the GHT 3-D finite element model that interfaces with SUNREL-GC (Deru 2003). Two detailed models not linked to whole-building simulation programs, but used as stand-alone models in this project, were developed using FLUENT (Nakhi 2007; Fluent 2007) and MATLAB (Crowley 2007; The MathWorks 2007).

Evolution of BESTEST Ground-Coupled Heat Transfer Test Cases

The Building Energy Simulation Test and Diagnostic Method (BESTEST) ground-coupled heat transfer test cases have evolved in parallel with model development. The initial IEA BESTEST (Judkoff and Neymark 1995a) ground-coupled heat transfer test case was developed when simplified tools were predominant. This test case included a half basement, did not define all boundary conditions that would be required for use by detailed models, and had a wide range of disagreement among the results. Because of its cursory nature, this was the only case from IEA BESTEST excluded from ASHRAE Standard 140.

HERS BESTEST (Judkoff and Neymark 1995b), is designed to test simplified tools commonly used with residential modeling, and includes cases designed to test simplified ground heat transfer models for slab-on-grade and basement configurations. The ground coupling results set within HERS BESTEST also displayed a wide range of disagreement among the simplified models that were tested. Because of the simplified nature of the tests, running HERS BESTEST with detailed models would require modeling assumptions not documented in the test specification, thus causing variations among results.

As described above, several building energy software producers have developed relatively detailed ground-coupled heat transfer models and integrated them 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 Solar Heating and Cooling Programme (SHC) Task 22 to develop a BESTEST-type method to test and diagnose the more advanced ground-coupled heat transfer models. The SHC Task 22 cases tested various relatively realistic slab-on-grade and basement constructions. (Deru et al. 2003) The cases were defined to test the following aspects of ground-coupled heat transfer models for slab and basement construction: building/ground/atmosphere interaction, solar radiation/ground interaction, variation of surface coefficients, variation of geometry, effect of insulation, interaction of the building with deep ground conditions, and the ability to model a walkout basement.

Preliminary results from the Task 22 project for cases that isolate the effects of the ground heat transfer models (e.g., no windows, near-adiabatic above-grade construction) are shown in Figure 1. The results indicate some large disagreements among the detailed ground-coupled heat transfer models linked to whole-building energy simulation software, even after a major algorithmic limitation was fixed in one of the programs. 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. Disagreements may be caused by legitimate differences in modeling methods, algorithmic or input errors, or model use outside its intended range.

Based on these unresolved disagreements, the researchers concluded that before proceeding further with the Task 22 test cases, or with other realistic test cases, in-depth diagnostics had to be developed to resolve or better understand the causes of differences found during the SHC Task 22 work.

In parallel with the Task 22 work, ASHRAE published a compilation of analytical solutions (Spitler et al. 2001) that included a 3-D steady-state analytical solution for a slab-on-grade related heat transfer problem with rectangular geometry originally developed by Commonwealth Scientific and Industrial Research Organization (CSIRO), Australia (Delsante et al. 1983). This spawned the idea to design a test suite beginning with the CSIRO

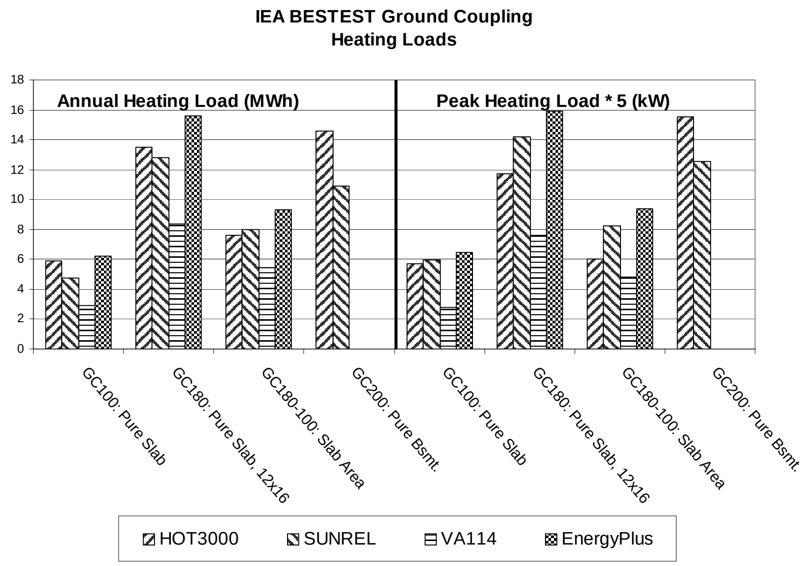

Figure 1. Results from IEA SHC Task 22 test cases isolating ground-coupled heat transfer effects (Deru et al. 2003)

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.

THE NEW IEA-34/43 ANALYTICAL VERIFICATION TEST CASES

A set of idealized in-depth diagnostic analytical verification test cases was developed for use in validating ground-coupled floor slab heat transfer models. (Neymark et al. 2008) The test cases were developed in collaboration with IEA SHC Task 34 and Energy Conservation in Buildings and Community Systems (ECBCS) Annex 43 (IEA 34/43). The logic for the cases may be summarized as follows:

- Identify or develop exact analytical solutions that may be used as mathematical truth standards for testing detailed numerical models using parameters and simplifying assumptions of the analytical solution.
- Apply a numerical solution process that demonstrates convergence in the space and time domains for the analytical-solution test cases and additional test cases where numerical models are applied.
- Once validated against the analytical solutions, use the numerical models to develop reference results for test cases that progress toward more realistic (less idealized) conditions, and that do not have exact analytical solutions.
- Check the numerical models by carefully comparing their results to each other while developing the more realistic cases, and make corrections as needed.
- Good agreement for the set of numerical models versus the analytical solution – and versus each other for subsequent test cases – verifies them as a secondary mathematical truth standard based on the range of disagreement among their results.
- Use the verified numerical-model results as reference results for testing other models that have been incorporated into whole-building simulation computer programs.

This approach represents an important methodological advance to extend the analytical verification method beyond the constraints inherent in classical analytical solutions. It allows a secondary mathematical truth standard to be developed in the form of a set of stand-alone detailed numerical models (quasi-analytical solutions). Once verified against all available classical analytical solutions, and compared with each other for cases that do not have exact analytical solutions, the set of verified numerical models can be used together to test other models as implemented in whole-building simulation programs. This allows for much greater enhanced diagnostic capability than the purely comparative method, and it allows somewhat more realistic boundary conditions to be used in the test cases than are possible with pure analytical solutions.

The CSIRO analytical solution (Delsante et al. 1983) was the only 3-D analytical solution with rectangular surface geometry we found (see Figure 2), and formed the basis for the test cases. This analytical solution is for a steady-state condition. We investigated the possibility of finding or developing a

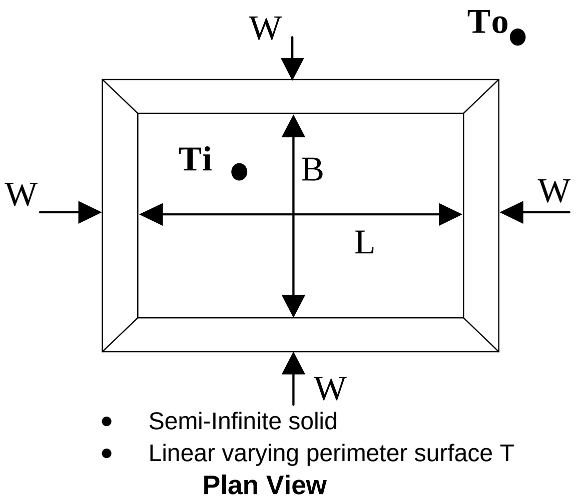

Figure 2. Schematic of CSIRO steady-state analytical solution case with rectangular geometry (Delsante et al. 1983; Spitler et al. 2001)

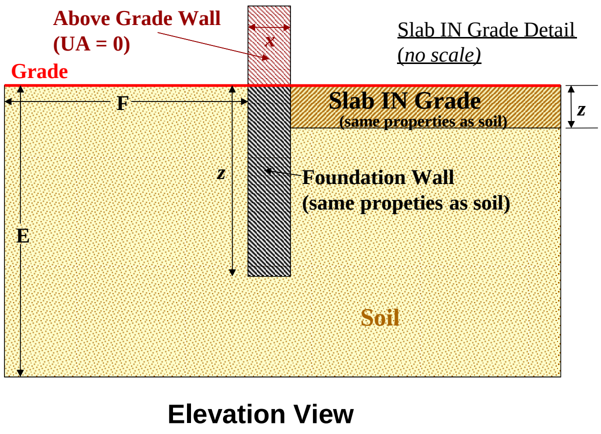

Figure 3. Slab-in-grade geometry idealization

comparable 3-D solution for a harmonic boundary condition. However, we did not find a ready-made solution, and several applied mathematicians advised that such a solution would be difficult, if not impossible, to derive.

The new test cases use an idealized uninsulated slab-*in*-grade configuration (see Figure 3). This simplified configuration is required by the CSIRO analytical solution, is appropriate for developing robust ground-coupling test cases, is compatible with the tested programs, and facilitated the development of accurate model results by minimizing chances for input errors. These cases, as they step away from the analytical solution, also test parametric sensitivities to variation of floor-slab aspect ratio, slab area, water table depth (depth of constant ground temperature), 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 (see Figure 4) to isolate the effects

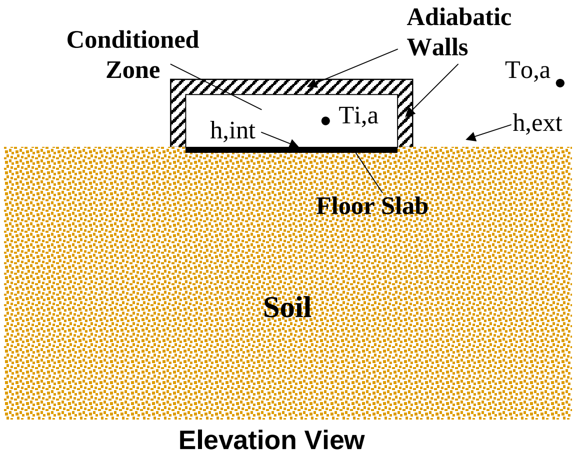

Figure 4. Comparative test base case schematic diagram – to isolate ground heat transfer

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. Various output values – including steady-state, annual total steady-periodic, and annual peak-hour steady-periodic results for floor conduction and zone heating load, along with time of occurrence of peak-hour loads and other supporting output – are compared and used in conjunction with a formal diagnostic method to determine algorithms responsible for predictive differences.

RESULTS

Field trials of the new IEA BESTEST cases were conducted with a number of detailed state-of-the-art numerical models and state-of-the art whole-building energy simulation programs, which contained a variety of ground-coupled heat transfer models from around the world (see Table 1). The field-trial process was iterative in that executing the simulations led to refinement of the BESTEST cases, and the results of the tests led to improving and debugging the ground-coupled heat transfer models.

The agreement among simulation results improved with each iteration of the field trials. Improvements to the simulation programs are evident when initial results (see Figure 5) are compared to final results (see Figure 6). (In these figures verified numerical-model results are shown with blue shaded background and the analytical solution result [Case GC10a] is shown with magenta background.) The figures indicate improvements in the ability to model surface heat transfer interaction, a large slab, a high water table (shallow depth of constant ground temperature), varying slab aspect ratio, and low soil conductivity. Improvements to simulation programs or simulation inputs made by participants were required to have a mathematical and a physical basis, and to be applied consistently across tests. Arbitrary

Table 1. Participating Organizations and Models

Analytical Solution, Case GC10a	Authoring Organization	Implemented by
Delsante, Stokes, Walsh (1983)	CSIRO, Australia	NREL/JNA, [a,b] United States
Verified Numerical Model	**Authoring Organization**	**Implemented by**
FLUENT 6.0.20	Fluent, Incorporated, United States	PAAET,[c] Kuwait
MATLAB 7.0.4.365 (R14)	The MathWorks, Inc., United States	Dublin Institute of Technology, Ireland
TRNSYS 16.1	University of Wisconsin/TESS,[d] United States	TESS,[d] United States
Simulation Program	**Authoring Organization**	**Implemented by**
BASECALC V1.0e	CETC,[e] Canada	CETC,[e] Canada
EnergyPlus 2.0.0.025	LBNL/UIUC/DOE-BT,[f,g,h] United States	GARD Analytics, Inc., United States
ESP-r/BASESIMP	CETC/ESRU,[e,i] Canada/United Kingdom	CETC,[e] Canada
GHT	NREL,[a] United States	NREL,[a] United States
SUNREL-GC 1.14.01	NREL,[a] United States	NREL,[a] United States
VA114 2.20/ISO-13370	VABI Software BV, The Netherlands; CEN/ISO[j,k]	VABI Software BV, The Netherlands

[a]NREL: National Renewable Energy Laboratory, United States
[b]JNA: J. Neymark & Associates, United States
[c]PAAET: Public Authority for Applied Education and Training, Kuwait
[d]TESS: Thermal Energy Systems Specialists, United States
[e]CETC: CANMET Energy Technology Centre, Natural Resources Canada, Canada
[f]LBNL: Lawrence Berkeley National Laboratory, United States
[g]UIUC: University of Illinois Urbana/Champaign, United States
[h]DOE-BT: U.S. Department of Energy, Office of Building Technologies, Energy Efficiency and Renewable Energy, United States
[i]ESRU: Energy Systems Research Unit, University of Strathclyde, United Kingdom
[j]CEN: European Committee for Standardisation, Belgium
[k]ISO: International Organization for Standardization, Switzerland

modification of a simulation program's input or internal code to more closely match a given set of results was not allowed. All improvements were required to be documented and justified in the modeler reports provided with the final report.

These results indicate that there was initially a 9%–55% disagreement among the cases for the simulated energy consumption results, with substantial scatter among the programs. Here disagreement is the difference between the maximum and minimum results for each case, divided by the mean of the results for each case ((max-min)/mean). These results include two estimates for results that would have occurred before fixes were made during preliminary work of prior IEA SHC Task 22 documented in the final report, which were not previously published; see Figure 5 results for cases GC60b and GC70b. After correcting software errors using BESTEST diagnostics – 24 disagreements were found among the programs, which resulted in 19 fixes so far – the remaining disagreements for the models are 1%–24% with reduced scatter among results. This may be a reasonable range of disagreement, given the complexity of the modeling problem, although a few remaining disagreements that were identified could be addressed later. Agreement is also improved among the detailed numerical models (results shown with blue shaded background), where initial disagreements up to 12% were reduced to 0%–4% for the verified numerical-model results over the course of the project. Remaining disagreements may be attributable to basic modeling differences related to conduction within the ground, the interaction of the ground with ambient air, simplifications such as use of correlation methods or other simplifications in space or time domains, undetected input errors, etc.

Findings

Several important technology advances were made as a result of running the test cases:

- The detailed numerical-methods modelers used the analytical solution to improve their models – e.g., a TRNSYS node meshing refinement (finer mesh near perimeter boundaries) resulted in a 10% results improvement versus the analytical solution; compare results for Case GC10a in Figures 5 and 6.
- There were three participating stand-alone 3-D numerical models that demonstrated convergence with the analytical solution and showed excellent agreement with each other for the remaining cases (see in Figure 6 the results with blue background and the GC10a result with magenta background). These verified numerical-model results form a secondary mathematical truth standard based on their range of disagreement.
- The high level of agreement among the verified numerical models allowed diagnosis of errors in other mid-level detailed models integrated with whole-building energy simulation software; some may have been missed without the secondary mathematical truth standard.

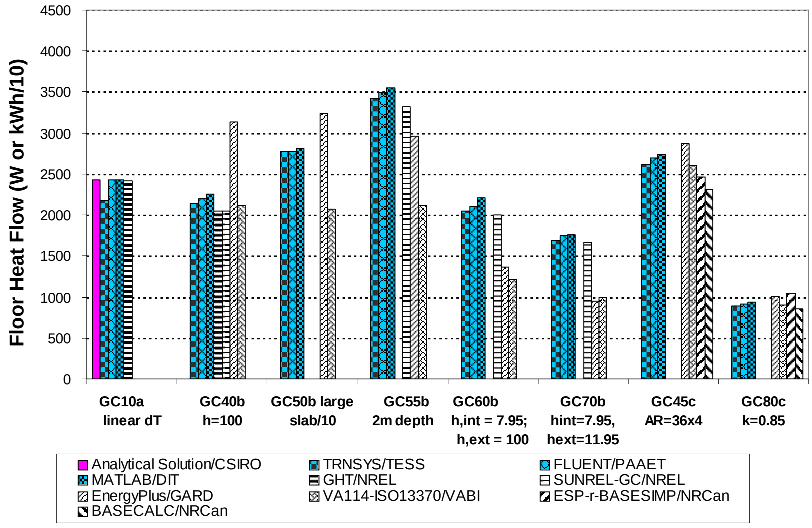

Figure 5. Selected BESTEST slab/ground heat transfer cases – floor conduction, before BESTESTing
(Abbreviations along the x-axis are shorthand for the case descriptions; see Nomenclature section for label abbreviations; see Table 1 for legend description; see Neymark et al. [2008] full case descriptions.)

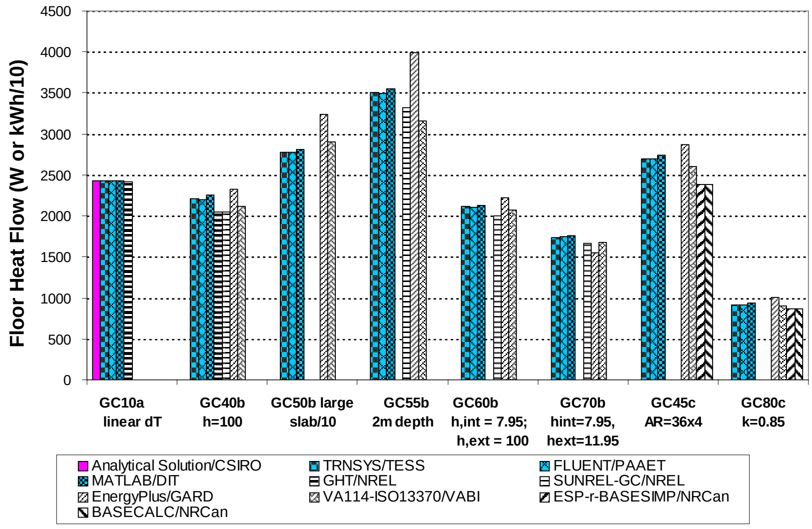

Figure 6. Selected BESTEST slab/ground heat transfer steady-state cases – after BESTESTing
(Abbreviations along the x-axis are shorthand for the case descriptions; see Nomenclature section for label abbreviations; see Table 1 for legend description; see Neymark et al. [2008] full case descriptions.)

- Of 24 found disagreements, 19 were diagnosed and fixed (only 2 of these were input errors), 3 are planned for investigation by the software authors, and 2 were judged as acceptable by the authors of mid-level detailed models (after they had fixed previous disagreements). Several of the found errors affected some individual results by more than 20%; this was after two major problems were fixed as a result of the Task 22 work. A detailed listing of the problems found among the tested models appears in the final report. (Neymark et al. 2008)

Based on results *after* several iterations of BESTESTing, and resulting model improvements, all tested programs now appear to be generally reliable for modeling ground-coupled heat transfer related to slab-on-grade construction, although some remaining disagreements should be addressed. The verified numerical-model results may be used as a reference or benchmark against which other software can be tested. For applications where ground-coupled heat transfer is a major component of a given simulation problem, the superior accuracy of the verified numerical models may justify adapting highly detailed models to more whole-building energy simulation programs, especially as computer hardware continues to improve and the detailed models become more user friendly.

CONCLUSIONS

The major accomplishments of this project were:

- The IEA BESTEST building thermal fabric envelope tests were expanded to include in-depth diagnostic analytical verification test cases for ground-coupled heat transfer related to slab-on-grade construction.

- A formal methodology was developed to facilitate using and verifying numerical models to establish a secondary mathematical truth standard. This method applies to the test case development and to numerical model implementation, and allows quasi-analytical solutions to be developed for more realistic (less constrained) cases than exact analytical solutions allow.
- A set of verified numerical-model results was developed for all test cases, using the newly developed methodology. This represents a secondary mathematical truth standard founded on the range of disagreement of the numerical-model results.
- The accuracy of all models that participated in the field trials of the test cases was improved: 19 errors were diagnosed and fixed; initial disagreement ranges of 9%–55% for the test cases were reduced to 1%–24% by applying the diagnostic logic of the test cases to expose problems with the models; initial disagreement ranges for only the numerical models were narrower (up to 12%), and were similarly reduced to 0%–4% for the verified numerical-model results over the course of the project.

Recommendations

As a result of the successful field trials, this work is planned for adaptation for ANSI/ASHRAE Standard 140. Future work on testing of ground coupled heat transfer models includes revising and rerunning the more realistic IEA SHC Task-22 test ground heat transfer test cases, which were the preliminary cases that led to the IEA-34/43 test cases presented here. To extend the numerical-model based secondary mathematical truth standard as far as possible, transition cases from the IEA-34/43 test suite to the more realistic cases are also proposed.

ACKNOWLEDGEMENTS

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NOMENCLATURE (FOR FIGURES)

AR = 36 × 4: B = 4 m, L = 36 m (for most other cases B = L = 12 m)

B: floor length

E: ground depth (for amount of ground modeled)

F: far-field distance (for amount of ground modeled)

h,ext: exterior surface coefficient

h,in or h,int: Interior surface coefficient

h = 100: h,int = h,ext = 100 W/(m^2K)

h,ext = 11.95: h,ext = 11. 95 W/(m^2K)

h,ext = 100: h,ext = 100 W/(m^2K)

h,int = 7.95: h,int = 7. 95 W/(m^2K)

k = 0.85: thermal conductivity = 0.85 W/(mK) (for most other cases k = 1.9 W/(mK))

L: floor length perpendicular to B

Linear dT: linearly varying perimeter surface temperature

T_i: interior surface temperature

$T_{i,a}$: interior air temperature

T_o: exterior surface temperature

$T_{o,a}$: exterior air temperature

W: perimeter surface width (0.24 m)

2m depth: E = 2 m

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