COMPARISON OF DOE-2.1E WITH ENERGYPLUS AND TRNSYS FOR GROUND COUPLED RESIDENTIAL BUILDINGS IN HOT AND HUMID CLIMATES

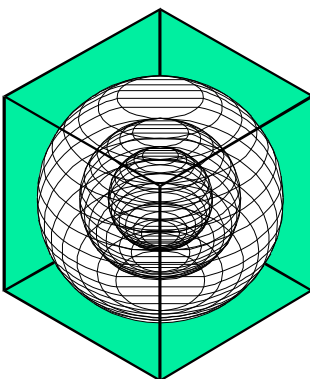## STAGE 1
"Literature Survey on Slab-on-grade Heat Transfer Models of DOE-2, EnergyPlus and TRNSYS"

A Report

Simge Andolsun
Charles Culp, Ph.D., P.E.

December 2011
(Revised June 2013)

ENERGY SYSTEMS LABORATORY

Texas Engineering Experiment Station

The Texas A&M University System

Disclaimer

This report is provided by the Texas Engineering Experiment Station (TEES). The information provided in this report is intended to be the best available information at the time of publication. TEES makes no claim or warranty, express or implied that the report or data herein is necessarily error-free. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement, recommendation, or favoring by the Energy Systems Laboratory or any of its employees. The views and opinions of authors expressed herein do not necessarily state or reflect those of the Texas Engineering Experiment Station or the Energy Systems Laboratory.

Table of Contents

1. Organization of the Report

This report consists of two sections. The first section is the introduction to the significance of the topic. The second section is a literature survey on the primary assumptions and calculation methods of the slab-on-grade heat transfer models in DOE-2, EnergyPlus and TRNSYS programs.

2. Introduction

Foundation heat transfer is a significant load component for low-rise residential buildings. For a contemporary code or above code house, ground-coupled heat losses may account for 30%–50% of the total heat loss [1]. Ground coupling is a hard-to-model phenomenon, because it involves three-dimensional thermal conduction, moisture transport, longtime constants and heat storage properties of the ground [2]. Over the years, many slab-on-grade models have been developed. Some used simplified methods for slab-on-grade load calculations [3-5]; whereas others developed more detailed models [6]. Comparative studies on ground coupled heat transfer models of current simulation tools showed a high degree of variation for slab-on-grade buildings. For an uninsulated slab-on-grade building, the range of disagreement among simulation tools is estimated to be 25%-60% or higher for simplified models versus detailed models [2].

This report summarizes and compares the slab-on-grade heat transfer calculation methods and related primary assumptions of three commonly used energy modeling programs i.e. DOE-2.1e (DOE-2), *EnergyPlus* and *TRNSYS*. *DOE-2* has been used for more than three decades in design studies, analysis of retrofit opportunities and developing and testing standards [7]. The international residential code compliance (IC3) calculator developed by the Energy Systems Laboratory is also based on DOE-2 program. In 1996, the U.S.D.O.E.[1] initiated support for the development of *EnergyPlus*, which was a new program based on the best features of *DOE-2* and BLAST [8]. The idea of shift from *DOE-2* to *EnergyPlus* raised questions in the simulation community on the differences between these two simulation programs [7, 9, 10]. Currently, *TRNSYS* is gaining increasing recognition in the field of building energy simulation.

Slab-on-grade heat transfer is an area that *DOE-2*, *EnergyPlus* and *TRNSYS* programs differ from each other significantly. *EnergyPlus* calculates z-transfer function coefficients to compute the unsteady ground coupled surface temperatures [13]; whereas *DOE-2* sets the temperatures of the ground coupled surfaces as steady [14]. TRNSYS' slab-on-grade model is a more advanced, multi-zone slab-on-grade heat transfer model which was based on detailed 3-D finite difference calculations [2, 11, 12]. In this era of constant development in slab-on-grade heat transfer calculations, it is important to research and understand the differences between the newly emerging models and the earlier ones in order to make more reasonable load estimations for low-rise residential buildings. This research will help us understand the primary differences between the slab-on-grade models of DOE-2, EnergyPlus and TRNSYS programs. Thus, we will make reliable conclusions to update/improve the slab-on-grade heat transfer calculation methods we use in IC3.

3. Literature Survey on Slab-on-grade Models of DOE-2, EnergyPlus and TRNSYS

DOE-2, EnergyPlus and *TRNSYS* select from multiple slab-on-grade models. This report covers the most advanced slab-on-grade models of *DOE-2*, *EnergyPlus* and *TRNSYS*. The *TRNSYS* slab-on-grade model covered in this report is currently accepted as the closest model to a "truth standard" in slab-on-grade heat transfer modeling [2].

3.1. Winkelmann's slab-on-grade model

In 1988, Huang et al. [15] calculated the perimeter conductance per perimeter foot for slab-on-grade floors using a two-dimensional finite-difference program and presented their findings with their paper published in ASHRAE Transactions. In 2002, Winkelmann [16] revised the work of Huang et al. [15] in the Building Energy Simulation User News and described how to use their results in a *DOE-2* model. The GCHT method referred to as "Winkelmann's method" in this report is based on the descriptions from Winkelmann [16]. In this method, it is assumed that the heat transfer occurs mainly in the exposed perimeter of the floor slab since this region has relatively short heat flow paths to the outside air. Instead of using the U-value of the floor, an effective U-value is entered for the floor construction that represents the heat flow through the exposed perimeter. A new construction is also assigned for the floor that has an overall U-value equal to the entered effective U-value. This new construction accounts for the thermal mass of the floor construction when custom weighting factors are specified in *DOE-2*. The new floor construction consists of the three layers shown in Figure 1. Underneath the fictitious insulating layer, the new construction faces the deep ground temperatures provided from the weather file. These temperatures are the outside air temperatures delayed by three months [16].
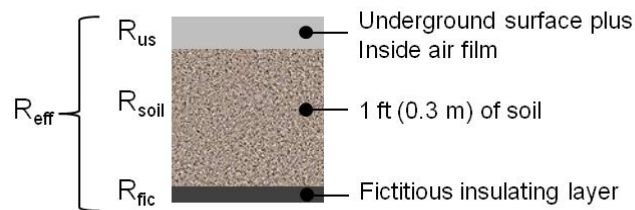

Figure 1. Underground construction layers of the Winkelmann's [16] slab-on-grade model.

Winkelmann's slab-on-grade model is based on the findings of 2-D finite difference calculations conducted by Huang et al. [15] in 1980s. Huang et al. [15] calculated daily heat fluxes at each interior node point of a representative one-foot vertical section of the foundation and surrounding soil. They then derived the total heat fluxes through the 28 x 55 feet foundation of the prototypical house by multiplying the fluxes at each node point of the vertical section by the length of that nodal condition.   The resultant foundation fluxes for the 65 different below-grade configurations in the 13 cities were stored as utility files of the average hourly heat fluxes through the building-to-ground interface [15]. These fluxes were stored for 123 three-day periods of the year to fit the memory limitations of the Function feature in DOE-2.1C LOADS. Linear interpolations were then done between the sequential three-day average fluxes in *DOE-2* in order to produce smoothly varying fluxes for each hour [15].

The daily floor heat fluxes that Huang et al. [15] obtained from the 2-D finite difference program were calculation assuming 70°F constant zone air temperature all year. The 70°F was the default indoor air temperature that DOE-2 LOADS uses (T_{LOADS}). Huang et al. [15] found that there is a linear relationship between the variation in underground heat flux ($\Delta Q = Q_{mod} - Q_{LOADS}$) and the variation in the constant indoor air temperature ($\Delta T = T_{mod} - T_{LOADS}$). They defined the slope of this linear function as the effective conductivity of the slab ($U_{effective}$) and calculated them for all slab configurations using Equation 3.

$$U_{effective} = (Q_{mod} - Q_{LOADS})/[(T_{mod} - T_{LOADS}) \times A] \quad \text{(Equation 3)}$$

The obtained $U_{effective}$ values were entered into the DOE-2 input file as the U-value of the floor construction. These values were then used in the SYSTEM part of DOE-2 for correcting the floor heat fluxes calculated in the LOADS part of DOE-2 to account for the constant zone air temperatures different than 70°F. For slabs, the floor heat transfer calculations of Winkelmann's model is complete after this correction and no further correction is made to take the varying indoor temperatures into consideration. The other known limitation of Winkelmann's model is that the 2-D finite difference calculation of Huang et al. [15] was made on a rectangular prototype building with unequal sides. Thus, the suggested $U_{effective}$ values are expected to be somewhat off for different slab shapes.

3.2. *Slab* model of EnergyPlus

Slab is a preprocessor program of *EnergyPlus* that calculates monthly ground temperatures for single zone slab-on-grade buildings using a 3-D numerical analysis [6, 17]. *Slab* was originally developed by Bahnfleth [6], and further modified by Clements [17].

The current state of the *Slab* program is based on a calculation method that uses area to perimeter length (A/P) as the length scale to correlate the average heat flux for L-shaped and rectangular floors. The other significant parameters in this model are the thermal conductivity of the soil, ground surface boundary conditions and shading of adjacent soil. The mathematical basis of this model is a boundary value problem on the three-dimensional heat conduction equation. The boundaries of the system are interior slab surface, far-field soil, deep ground and ground surface. This boundary value problem is solved in Cartesian coordinates by a Fortran program that implements the Patankar-Spalding finite difference technique [18]. The three-dimensional domain of the model is discretized by an irregular grid into 10,000 cells. The minimum grid spacing is 4in (0.1m) near the ground surface and slab boundaries. The user is expected to define the domain dimensions and grid spacings, weather data file (TMY), soil and slab properties, ground surface properties, slab shape and size, deep ground boundary condition, evaporative loss at ground surface (evapotranspiration) and building height for shadowing calculations. *Slab* has an automated grid sizing function which sets the solution domain according to a modified Fibonacci sequence to provide grid flexibility. *Slab* also automatically calculates the undisturbed ground temperature profile for initialization purposes. The three dimensional calculations of *Slab* are integrated with one-dimensional heat conduction calculations of *EnergyPlus* through iteration.

According to Bahnfleth [6], ground surface condition is the most significant boundary condition for the floor heat transfer and evapotranspiration is a significant parameter for this boundary. The *Slab* program of *EnergyPlus* models a potential evapotranspiration case which accounts for a number of naturally occurring situations, most often through the action of vegetation [6]. In this model, grasses and other similar ground cover, when well watered, are assumed to transpire moisture into the atmosphere at near the potential rate even when the ground surface is relatively dry [6]. According to Bahnfleth [6], the potential evapotranspiration model of *Slab* takes these processes into account and brackets the range of boundary evapotranspiration effects. This model is, therefore, claimed to be a useful asymptotic model that does not require specification of moisture conditions at the surface [6].

3.3. TRNSYS slab-on-grade model

The *TRNSYS* system simulation program has a commercially available ground coupling library written by Thermal Energy System Specialists (TESS) LLC of Madison, WI [12]. The *TRNSYS* slab-on-grade model used for this study i.e. the Type 49 model is part of a larger suite of these ground coupling models

that are identical in core solution algorithm but differ in application [11]. The Type 49 model calculates floor heat transfer by iterating with the Type 56 (Multizone Building) model of the *TRNSYS* program [12]. The Type 56 model calculates the above ground building loads by assigning the slab/soil interface temperatures calculated by the Type 49 model [12]. The Type 49 model calculates the slab/soil interface temperatures using the QCOMO output produced by the Type 56 model [12]. The QCOMO output of the Type 56 model defines the energy flow to the outside of a surface [12]. This energy flow includes convection to air and longwave radiation to other surfaces or sky [12].

McDowell et al. [11] presents a concise summary of the *TRNSYS* ground coupling models as follows. According to their descriptions, the *TRNSYS* ground coupling models are multi-zone models and they rely on a 3-dimensional finite difference representation of the soil. These models solve the resulting interdependent differential equations using an iterative analytical method. In these models, heat transfer is assumed to be conductive only and moisture effects are not accounted for. The solution is stable over all ranges of simulation steps and even for very high surface heat transfer coefficients. The soil nodes at the surface do not directly conduct to the zone air or ambient air. Instead, they conduct to a "local surface temperature" that is calculated on a massless, opaque plane located between the air and the soil node. This "local surface temperature" can be calculated from an energy balance, or from a long term average surface temperature correlation (Kusuda), or provided to the model as an input.

In *TRNSYS* slab-on-grade model, the soil volume surrounding the slab is divided into two parts: 1) the near field and 2) the far field. The far field surrounds the near field and it includes the soil beneath the near field and below the deep earth boundary. The deep earth boundary is defined by the deep earth temperatures, which are either calculated from the Kusuda approach or entered by the user. The boundary between the near field and the far field can be defined as adiabatic or conductive. The near field is affected by the heat transfer between the soil and the slab; whereas the far field is not. The user defines the near field entering the number of nodes and the field size/volume. The far field is assumed as an infinite energy sink/source and its node temperatures are calculated either by using energy balance (between the surface and deep earth temperatures) or the Kusuda correlation (temperature is a function of the time of year and distance below the surface).

References

[1] K. Labs, J. Carmody, R. Sterling, L. Shen, Y.J. Huang, D. Parker, Building Foundation Design Handbook, ORNL/Sub/86-72143/1 (1988).

[2] J. Neymark, R. Judkoff, I. Beausoleil-Morrison, A. Ben-Nakhi, M. Crowley, M. Deru, R. Henninger, H. Ribberink, J. Thornton, A. Wijsman, M. Witte, International Energy Agency Building Energy Simulation Test and Diagnostic Method (IEA BESTEST) In-Depth Diagnostic Cases for Ground Coupled Heat Transfer Related to Slab-on-Grade Construction, NREL/TP-550-43388, National Renewable Energy Laboratory, Golden, Colorado, USA (2008).

[3] B.A. Rock, L.L. Ochs, Slab-on-grade Heating Load Factors for Wood-framed Buildings. Energy and Buildings 33 (2001) pp. 759-768.

[4] B.A. Rock, Sensitivity Study of Slab-on-grade Transient Heat Transfer Model Parameters. ASHRAE Transactions 110 (1) (2004) pp.177-184.

[5] B.A. Rock, A User-friendly Model and Coefficients for Slab-on-grade Load and Energy Calculations, ASHRAE Transactions:Research (2005) pp. 122-136.

[6] W.P. Bahnfleth, Three Dimensional Modeling of Heat Transfer from Slab Floors, Ph.D. Dissertation, University of Illinois (1989).

[7] J. Huang, N. Bourassa, F. Buhl, E. Erdem, R. Hitchcock, Using EnergyPlus for California Title-24 Compliance Calculations, Second National IBPSA-USA Conference, Cambridge, Massachusetts, USA (2006).

[8] D.B. Crawley, L.K. Lawrie, C.O.Pedersen, F.C.Winkelmann, M.J.Witte, R.K. Strand, R.J. Liesen, W.F. Buhl, Y.J. Huang, R.H.Henninger, J. Glazer, D.E. Fisher, D.B. Shirey III, B.T. Griffith, P.G. Ellis, L. Gu, EnergyPlus:New, Capable, and Linked. Journal of Architectural and Planning Research 21(4) (2004) pp.292.

[9] S. Andolsun and C.H. Culp, A Comparison of EnergyPlus with DOE-2 Based on Multiple Cases from a Sealed Box to a Residential Building, Sixteenth Symposium on Improving Building Systems in Hot and Humid Climates, Plano, Texas, USA (2008).

[10] S. Andolsun, C.H. Culp, J. Haberl, EnergyPlus vs DOE-2: The Effect of Ground Coupling on Heating and Cooling Energy Consumption of a Slab-on-grade Code House in a Cold Climate, Fourth National IBPSA-USA Conference, New York, USA (2010).

[11] T.P. McDowell, J.W. Thornton, M.J. Duffy, Comparison of a Ground-Coupling Reference Standard Model to Simplified Approaches. Eleventh International IBPSA Conference, Glasgow, Scotland (2009).

[12] TRNSYS 17 A Transient System Simulation Program, Volume 4: Mathematical Reference, Solar Energy Laboratory, University of Wisconsin-Madison, TRANSSOLAR Energietechnik GmbH, CSTB-Centre Scientifique et Technique du Bâtiment, TESS- Thermal Energy Systems Specialists. (2010).

[13] M. Krarti, P. Chuangchid, P. Ihm, Foundation Heat Transfer Module for EnergyPlus Program, Seventh International IBPSA Conference, Rio de Janeiro, Brazil (2001).

[14] R. Sullivan, J. Bull, P. Davis, S. Nozaki, Z. Cumali, G. Meixel, Description of an Earth-contact Modeling Capability in the DOE-2.1B, Energy Analysis Program 91 (1A) (1985), pp.15-29.

[15] Y.J. Huang, L.S. Shen, J.C. Bull, L.F. Goldberg, Whole-house Simulation of Foundation Heat Flows Using the DOE-2.1C Program, ASHRAE Transactions 94 (2) (1988).

[16] F. Winkelmann, Underground Surfaces: How to get a Better Underground Surface Heat Transfer Calculation in DOE-2.1E. Building Energy Simulation User News 23 (6) (2002), pg.19-26.

[17] E. Clements, Three Dimensional Foundation Heat Transfer Modules for Whole-Building Energy Analysis, MS Thesis, Pennsylvania State University, USA (2004).

[18] S.V. Patankar, Numerical Heat Transfer and Fluid Flow, Hemisphere Publishing Corporation, New York, USA (1980).

Appendix A. Comparison of *Winkelmann's, Slab* and *TRNSYS* slab-on-grade models.

	Winkelmann's Slab-on-grade Model	*Slab* Model of *EnergyPlus*	*TRNSYS Multizone Slab-on-grade Model*
CALCULATION	1-D conduction heat transfer calculations are made by the energy simulation program. The inputs of these calculations are derived from the findings of an early two-dimensional finite difference study by Huang et al. [19]. The finite difference program simulations yielded daily heat fluxes at each interior node point of a representative one-foot vertical section of the foundation and surrounding soil [19]. The heat fluxes through the foundation are then derived by multiplying the fluxes at each node point of the vertical section by the length of that nodal condition, P [19]. P is the perimeter length for the vertical portions of the section and it is the rectangular annulus at the equivalent nodal distance under the building foundation for the horizontal portions of the section [19]. The resultant foundation fluxes are stored for 123 three-day periods of the year.	Uses a numerical method (Patankar Spalding finite difference technique [22]) to solve a boundary value problem on the 3-D heat conduction equation. The boundaries were 1) interior slab surface, 2) far-field soil, 3) deep ground, 4) ground surface. The ground heat transfer calculation is partially decoupled from the thermal zone calculation. The outside face temperature of the building surface that is in contact with the ground is the "separation plane" for the two calculations. This temperature connects the 3-D ground heat transfer calculations to thermal zone calculations by 1-D conduction heat transfer through the floor.	Uses a simple iterative analytical method to solve the resulting interdependent differential equations of a 3-D finite difference soil model at each time step. In this method, the subroutine solves its own mathematical problem and does not rely on nonstandard numerical recipes that must be attached to the subroutine. This method is time-step independent; therefore, it converges in multi-zone simulations.
PRIMARY	Primary ground coupled heat flux is assumed to occur from the exposed perimeter of the underground construction. The heat flux is correlated with the perimeter length (P). This method represents a two-dimensional approximation of three-dimensional foundation heat flux by ignoring lateral heat flow at the building corners.	The ground coupled heat flux is correlated with the area over perimeter ratio (A/P). Floor heat transfer rates are dependent on both the shape and size of the slab. Thermal conductivity of the soil and ground surface conditions exert a strong influence on floor heat transfer rates, while thermal diffusivity, far-field boundaries and deep ground conditions (in general) do not. Also, It is assumed that it is reasonable to use monthly average ground temperature as the separation plane temperature, since the time scales of the building heat transfer processes are so much shorter than those of the ground heat transfer processes.	This model assumes that the system (including the soil and the slab) consists of cubic nodes which have six unique heat transfers to analyze. The edge of the floor surface is adiabatic i.e. no heat transfer occurs between the edges of the slab and the surroundings.
FLOOR MODEL	An effective U-value (U_{eff}) is assigned to the underground construction to model the heat flow from the exposed perimeter. This U_{eff} value is determined based on the tables provided by Huang et al. [19] for different insulation configurations and foundation depths.	The original U-value of the underground construction is used as it is.	The original U-value of the underground construction is used as it is.
	Fictitious underground constructions are modeled including 1) a 0.3m soil layer and 2) a massless insulation layer and 3) the concrete slab. The soil layer accounts for the thermal mass of the neighboring soil. The insulation layer equalizes the overall U-value of the new fictitious floor construction to the U_{eff} value. Applies only to the floor construction modeled by Huang et al. [19].	The original layers of the underground constructions are used. No fictitious construction layers are modeled. The slab properties (density, conductivity and specific heat), the slab shape (rectangle or L) and size are the important inputs of the model. This floor model applies to any floor construction; however, sometimes shows convergence problems.	The original layers of the underground constructions are used. No fictitious construction layers are modeled. Resistance of footer insulation is the only floor input parameter of the TRNSYS slab-on-grade model, Type 49. The floor construction is defined in the TRNSYS above ground Multi-zone Building Model, Type 56.
SOIL MODEL	Thermal conductivity of the soil up to 0.3m depth is taken into account. The ground surface boundary conditions, the shading of the adjacent soil, slab shape and evaporative loss at ground surface are not taken into account.	Domain dimensions and grid spacings, weather data file (TMY), soil properties (density, conductivity and specific heat), ground surface properties, deep ground boundary condition (zero flux or fixed temperature), evaporative loss at ground surface (on/off), shadowing (on/off) and building height for shadow calculations are the input parameters for the *Slab* model.	The number of nodes and the size/volume of the near field (2-dimensional map of the soil surface), the node temperature calculation method for the far field (energy balance or Kusuda correlation), soil properties (density, conductivity and specific heat), average surface soil temperature (equals to annual average air temperature), amplitude of soil surface temperature (one half of the maximum monthly average air temperature minus one half of the minimum monthly average air temperature), the day of minimum surface temperature are the input parameters of the Type 49 model.
	Ground temperatures are the inputs of Winkelmann's slab-on-grade floor model. These temperatures are the outside air temperatures delayed by three months.	Ground temperatures are the outputs of the *Slab* model. These temperatures are then entered into *EnergyPlus* as inputs. Starting from version 5.0, *EnergyPlus* and *Slab* iterate with each other internally just once.	Ground temperatures are the outputs of the *Type 49* model. These temperatures are used by the *Type 56 model of TRNSYS* to calculate the QCOMO output, which is then used by the Type 49 model. The Type 49 and Type 56 models iterate until their results converge.
	The outermost layer (the insulation layer) of the fictitious underground construction faces the entered ground temperatures.	The actual concrete floor faces the calculated ground temperatures.	The actual concrete floor faces the calculated ground temperatures.
	Ground temperatures are climate specific. In the same climate, the same ground temperatures are entered for all underground constructions (walls and floors).	*Slab* calculates separate, case-specific ground temperatures for each underground surface.	*Type 49* calculates separate, case-specific ground temperatures for each underground surface.