SIMPLIFIED METHOD FOR UNDERGROUND HEAT TRANSFER CALCULATION

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ABSTRACT

A simplified heat transfer calculation method for underground buildings is developed. The method is based on the results from the ITPE method and is suitable for seasonal heat loss calculation. The simplified method consists of a set of equations for estimating the monthly total heat flow between an underground building and ground as a function of a wide range of variables such as building dimensions, insulation configurations, and soil thermal properties. The equations are designed to accept continuously variable input values. The simplified method predictions are tested against the ITPE results. The agreement between the correlations and the ITPE method is found to be within 10 percent for annual means, amplitude, and phase angle of total building heat loss.

INTRODUCTION

The energy performance of the above-grade portion of buildings is generally well understood. Hourly prediction of heat transfer from walls exposed to ambient air has helped improve the thermal efficiency of building envelopes. Unfortunately, the attention to earth-coupled heat transfer has lagged behind other building components.

A quantitative understanding of earth-coupled heat transfer is required to accurately predict and thus improve the overall energy performance of an underground building. Several authors proposed simplified methods for ground-coupled heat transfer analysis. Most of the proposed methods are based on numerical solutions such as the finite difference or finite element technique. The numerical solutions are used by some authors to develop easy-to-use manual-type methods. For instance, Ship [1982], Yard et al. [1984] and Akridge [1981] have generated their methods from solutions based on two-dimensional finite difference techniques. The most comprehensive method based on numerical solution is that of Mitalas [1983, 1987], who analyzed a total of 39 slab-on-grade floor configurations, in addition to 40 deep basements and 21 shallow basements. Using the results of two dimensional finite element analysis, Mitalas presented a set of correlations that calculate the monthly foundation heat loss for commonly used insulation configurations.

Recently, Krarti and Choi [1996] developed closed form equations to predict monthly ground-coupling heat transfer for basements and slab-on-grade floors. These equations are generated using the Interzone Temperature Profile Estimation (ITPE) technique. The ITPE technique, developed by Krarti et al. (1988) was used to develop two- and three-dimensional solutions to steady-state and transient heat conduction equation to estimate heat loss/gain from a variety of building foundation configurations (Krarti et al., 1990, and Claridge et al., 1994). Because it combines analytical and numerical techniques, the ITPE method benefits from both. Its numerical nature allows the method to treat several realistic problems, while its analytical formalism reduce significantly the computational effort.

Currently, no simplified design method for foundation heat loss calculation can handle earth-sheltered buildings. In this paper, the simplified heat loss calculation method of Krarti and Choi [1996] is extended to underground buildings. The method proposed in this paper is based on the results from the general ITPE solution developed in Choi [1997]. This general ITPE solution has been validated against numerical and empirical data. The results of the ITPE solution are used to generate closed form correlations for the underground building total heat loss predictions. This design tool is easy to use and requires straightforward input parameters with continuously variable values including building dimensions, insulation *R*-values, insulation configurations, indoor temperatures, ground surface temperatures, and soil thermal properties. In this paper, over 360 underground building configurations are used to generate the correlations. First, the general calculation procedure of the proposed design method is presented. In particular, the correlations are provided for each underground building insulation configuration. Then, a validation analysis is provided by comparing underground building total heat loss predictions obtained by the simplified method and those determined from the general ITPE solution. Finally, an example is presented to illustrate how the simplified method can be used to estimate the monthly underground building heat transfer.

GENERAL CALCULATION PROCEDURE

Most of the existing ground heat transfer calculation methods recognize that the annual ground-coupled heat loss, $Q_{(t)}$, varies sinusoidally with time:

$$Q_{(t)} = Q_m + Q_a \sin(\omega t + \phi) \qquad (1)$$

where, Q_m, Q_a, and ϕ are constants that are function of input parameters such as building dimensions, soil properties, and insulation *R*-values. In Eq. 1, Q_m is the annual mean heat loss, while Q_a and ϕ characterize the annual ground-coupled heat loss amplitude, and phase lag between total underground building heat loss and soil surface temperature.

The simplified calculation procedure proposed in this paper allows to estimate total underground building heat losses for common insulation configurations and building geometric shapes. In addition, the proposed calculation procedure handles all soil types.

Figure 1 illustrates an underground building with common insulation configurations. The parameters of the model include:

a. Soil climate
- Soil thermal conductivity, k_s
- Annual mean of ground surface temperature, T_{sm}
- Annual amplitude of ground surface temperature,

T_{sa}, T_{sm} and T_{sa} could be referenced from Kusuda and Achenbach [1965].

b. Underground building physical dimensions:
- Width of underground building , *w*
- Length of underground building, *l*
- Height of underground building, *h*
- Depth of underground building, *d*
- Length of extended roof insulation, *e*

Figure 1 shows the various physical dimensions of a typical earth-sheltered building.

c. Insulation configuration:
- Insulation placement, *Uniform (**FU**), roof (**RF**), roof with extension (**RE**), roof with partial wall (**PW**), roof with full wall (**FW**)*
- Insulation *R*-values (or its thermal conductivity and its thickness)

d. Indoor temperature, T_i

Using the parameters described above as independent variables, correlations for the annual mean Q_m, the annual amplitude Q_a, and the annual phase lag ϕ of underground building heat loss were developed from a set of results obtained from the general ITPE solution (Choi, 1997). These correlations are the basis of the simplified method proposed in this paper. The correlations are presented in the following sections.

CORRELATIONS FOR UNDERGROUND BUILDING HEAT TRANSFER CALCULATION

To determine simplified correlations for annual heat loss from underground buildings, 360 underground building configurations were used: 60 cases for uninsulated building, 60 cases for uniform insulation, 60 cases for roof insulation, 60 cases for extended roof insulation, 60 cases for roof and 1-m upper wall insulation, and 60 cases for roof and full wall insulation. The insulation *R*-value is selected to represent a wide range of values used throughout the United States. The *R*-values of the insulation levels used in this analysis are:

a. No insulation
b. *R*-5 (*R*SI=0.87 m^2K/W)
c. *R*-10 (*R*SI=1.74 m^2K/W)
d. *R*-15 (*R*SI=2.60 W/m^2K)
e. *R*-20 (*R*SI=3.48 W/m^2K)
f. *R*-25 (*R*SI=4.35 W/m^2K)

The selected geometric characteristics of the underground building width, length, and height are as follows:

a. Building width, w = 10, 20, 40-m
b. Building length, l = w x (1.0, 1.5, 2.0)
c. Building height, h = 3, 6, 9-m
d. Building depth, d = 0.5, 1.0, 2.0, 4.0-m
e. Roof Insulation extension, e= *0.0, 0.25, 0.5, 1.0, 2.0-m*

Nonlinear regression analysis is performed to develop simplified correlations of the seasonal variation of the total underground building heat loss. Three set of equations are developed for mean Q_m, amplitude Q_a, and phase angle ϕ of the annual underground building heat loss. Different correlations are determined for each of the six insulation configurations: ***FU*** (Uniform), ***RF*** (roof), ***RE*** (roof with extension), ***PW*** (roof with 1-m upper wall), ***FW*** (roof with full wall), ***NO*** (no insulation).

The correlations are based on three major factors that are consistent with the factors derived for the slab-on-grade floor and basement foundations developed by Krarti and Choi (1996): the location factor (***LF***), the configuration factor (***CF***), and the insulation factor (***IF***). These correlations are provided in the following sections.

ANNUAL MEAN OF UNDERGROUND BUILDING HEAT LOSS

As mentioned earlier, 360 underground building configurations were used to develop correlations for heat loss from underground buildings. Using non-linear correlation software, the annual mean of the underground building heat loss is found to be best determined using the following correlation:

$$Q_m = LF \times CF \times IF \qquad (2)$$

where,

$$LF = C1 \times k_s \times (T_i - T_{sm})$$

$$CF = \frac{l \times w}{d} \times e^{C2 \times \frac{w}{l}} \times e^{C3 \times h + C4 \times d}$$

$$IF = 1 \qquad \text{for NO}$$

$$IF = e^{C5 \times H_r} \qquad \text{for RF}$$

$$IF = e^{C5 \times H_r + C6 \times H_e \times e} \qquad \text{for RE}$$

$$IF = e^{C5 \times H_r + C6 \times H_w} \qquad \text{for PW and FW}$$

$$IF = e^{C5 \times H_r + C6 \times H_w + C7 \times H_f} \qquad \text{for FU}$$

with
H_r = Ratio of U-value of roof to soil conductivity, m^{-1}
H_e = Ratio of U-value of extended roof insulation to soil conductivity, m^{-1}
H_w = Ratio of U-value of wall to soil conductivity, m^{-1}
H_f = Ratio of U-value of floor to soil conductivity, m^{-1}

The coefficients C_i, i=1,2,..,7 of the correlation described above are provided in Table 1. The R^2 values of all the correlations are also shown in Table 1. It should be mentioned that the U-values used in the calculation of the H-values listed above include the conductance of the air, the envelope material, and the insulation.

To validate the correlation given by Eq. (2), a set of 60 underground building configurations -not part of the original set used in the determination of the correlation coefficients- was selected to compare the predictions of the simplified method with those of the general ITPE solution. Figure 2 shows the results of this comparison analysis. As it is apparent from Fig. 2, the simplified method agree well with the general solution. The prediction ratio of the simplified method relative to the ITPE model is 0.958 ± 0.091 for the annual mean of the total underground building heat loss.

ANNUAL AMPLITUDE OF UNDERGROUND BUILDING HEAT LOSS

Based on the 360 underground building configurations used in the previous section, the correlations to estimate the annual amplitude of underground building total heat loss are found to be:

$$Q_a = LF \times CF \times IF \qquad (3)$$

where,

$$LF = C1 \times k_s \times T_{sa}$$

$$CF = \frac{l \times w}{d} \times e^{C2 \times \frac{w}{l}} \times e^{C3 \times h + C4 \times d}$$

$$IF = 1 \qquad \text{for NO}$$

$$IF = e^{C5 \times H_r} \qquad \text{for RF}$$

$$IF = e^{C5 \times H_r + C6 \times H_e \times e} \qquad \text{for RE}$$

$$IF = e^{C5 \times H_r + C6 \times H_w} \qquad \text{for PW and FW}$$

$$IF = e^{C5 \times H_r + C6 \times H_w + C7 \times H_f} \qquad \text{for FU}$$

with
H_r = Ratio of U-value of roof to soil conductivity, m^{-1}
H_e = Ratio of U-value of extended roof insulation to soil conductivity, m^{-1}

H_w = Ratio of U-value of wall to soil conductivity, m^{-1}
H_f = Ratio of U-value of floor to soil conductivity, m^{-1}

Table 1 provides the values of the coefficients C_i, i=1,2,..,7 and the R^2 values of all the correlations that provide the amplitude Q_a as function of the insulation and the geometric characteristics for the underground building. Note that the form of the equations for the factor CF, IF, and CF is the same for both annual mean and annual amplitude of the underground building heat loss. Figure 3 illustrates the scatter diagram between the predictions from the simplified method with those from the ITPE model for the same set of 60 underground building configurations used in Fig. 2. The prediction ratio of the simplified method relative to the ITPE model is 0.988 ± 0.042 for amplitudes. Thus, the proposed simplified method agree well with the ITPE model when used to predict the amplitude of the annual variation of total underground building heat losses.

ANNUAL PHASE LAG OF UNDERGROUND BUILDING HEAT LOSS

The phase lag ϕ, between the total underground building loss and the soil surface temperature variation can be estimated from Eq. 4.

$$\phi = \frac{C1 \times e^{C2 \times d + C3 \times h + IF}}{d^2} \qquad (4)$$

with,

$IF = 0$ for NO

$IF = C4 / (H_r \times w)$ for RF

$IF = C4 / (H_r \times w + H_e \times e)$ for RE

$IF = C4 / (H_r \times w + H_w)$ for PW

$IF = C4 / (H_r \times w + H_w \times h)$ for FW

$IF = C4 / (H_r \times w + H_w \times h + H_f \times w)$ for FU

The predictions of the annual phase lag using the simplified method agree fairly well with those obtained from the ITPE model as illustrated in Fig. 4. The same set of 60 underground building configurations of Fig. 2 was used in Fig. 4. The ratio of the simplified method relative to the ITPE model is 1.134 ± 0.354. The ratio of annual phase lags is higher than those obtained for means and amplitudes. Nonetheless, it does not induce a severe error in total underground building heat loss prediction.

EXAMPLE CALCULATION

To illustrate the use of simplified method, an example is presented for an underground building with roof insulation located in Chicago, IL.

Step 1. Provide the required input data:

- Dimensions:
  - Underground building width, w = 20-m
  - Underground building length, l = 30-m
  - Underground building height, h = 6-m
  - Underground building depth, w = 2-m
  - No roof insulation extension, e=0-m
- Soil thermal conductivity: k_s = 1.0 W/m K
- Insulation: H-value of the roof, H_r = 0.5 m^{-1} (R-10). The floor and the walls are uninsulated.
- Temperatures:
  - Indoor temperature, T_i = 20 °C
  - Annual Mean of soil surface temperature, T_{sm} = 10.56 °C (Chicago, IL)
  - Annual amplitude soil surface temperature, T_{sa} = 12.77 °C (Chicago, IL)

Step 2. Calculate Q_m, Q_a, and ϕ values:

First, from Eqs. 2, 3 and 4, the annual mean, amplitude, and phase angle of the total underground building heat loss are calculated with the coefficients C_i, i=1,2,...,5 extracted from Table 1 for the case of the underground building with roof insulation (***RF***). The results are summarized in Table 2.

- Example calculation of LF, CF, and IF for the total underground building heat loss.

$$LF = C1 \times k_s \times (T_i - T_{sm})$$
$$= 0.494 \times 1.0 \times (20 - 10.56) = 4.66$$

$$CF = \frac{30 \times 20}{2} \times e^{0.224 \times \frac{20}{30}}$$
$$\times e^{0.004 \times 6 + 0.444 \times 2} = 867.02$$

$$IF = e^{C5 \times hr} = e^{-0.644 \times 0.5} = 0.72$$

Table 2. The annual total underground building heat loss with roof insulation (***RF***)

	Mean	**Amp.**	**ϕ**
LF	4.66	8.88	-
CF	867.02	315.59	-
IF	0.72	0.93	-
Simplified	2902 (W)	2606 (W)	0.43 (rd)
ITPE	3052 (W)	2588 (W)	0.45 (rd)

Using Eq. 1, the annual variation of the total underground building heat transfer can be obtained. Figure 5 shows the comparison of the annual variation of total underground building heat loss using both the simplified method and the ITPE model.

SUMMARY AND CONCLUSIONS

The simplified method, developed by Krarti and Choi (1996) to calculate annual heat loss from slab-on-grade floors and basements, has been extended to handle earth-sheltered buildings. With this extension, the proposed simplified method provides more flexibility than any existing design tools for foundation heat transfer calculation. In deed, the simplified tool can deal with any typical values of thermal conductivity, water table depth, foundation size, foundation type, and insulation R-value and length. In addition, the simplified method is easy to use and requires only a limited number of computations to obtain the monthly variation of foundation heat loss/gain.

The simplified method predicts the annual mean and amplitude of the underground building heat losses within 10 percent of the general ITPE solution. An example is given to illustrate how the simplified method can be used to determine the annual mean, annual amplitude, and annual phase lag of the underground building heat loss.

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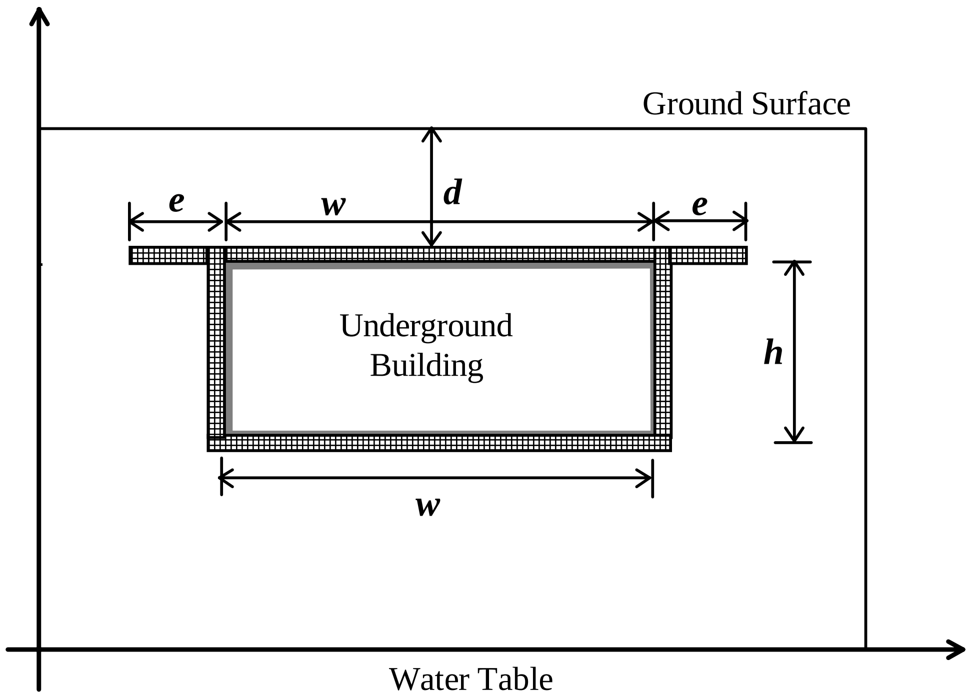

Figure 1. An underground building model with various insulation configurations.

Table 1. Coefficients and R^2 values for Underground Building

	Insulation Type								
	NO			RF			RE		
Coeff.	Q_m	Q_a	ϕ	Q_m	Q_a	ϕ	Q_m	Q_a	ϕ
C1	0.733	0.930	1.131	0.494	0.695	0.356	0.188	0.830	0.521
C2	0.117	0.024	0.482	0.224	0.028	0.742	0.209	0.014	0.642
C3	0.019	0.007	-0.056	0.004	0.006	-0.030	0.051	0.007	-0.044
C4	0.275	-0.019	-	0.444	-0.002	2.710	0.454	0.031	2.686
C5	-	-	-	-0.644	-0.136		0.861	0.106	
C6	-	-	-	-	-		-0.119	-0.087	
C7	-	-	-	-	-		-	-	
R^2	0.981	0.999	0.874	0.942	0.994	0.931	0.924	0.984	0.889
	Insulation Type								
	PW			**FW**			**FU**		
Coeff.	Q_m	Q_a	ϕ	Q_m	Q_a	ϕ	Q_m	Q_a	ϕ
C1	0.161	0.688	0.664	0.103	0.678	0.784	0.086	0.863	1.253
C2	0.195	0.020	0.592	0.136	0.013	0.493	0.144	0.013	0.481
C3	0.051	0.023	-0.020	0.057	0.023	0.008	0.060	0.013	-0.035
C4	0.458	0.067	1.408	0.440	0.070	1.296	0.450	-0.006	-1.979
C5	0.572	0.664		0.657	0.677		0.798	0.131	
C6	0.107	-0.641		0.528	-0.642		0.103	0.746	
C7	-	-		-	-		0.458	-1.086	
R^2	0.935	0.995	0.889	0.959	0.995	0.839	0.965	0.966	0.830

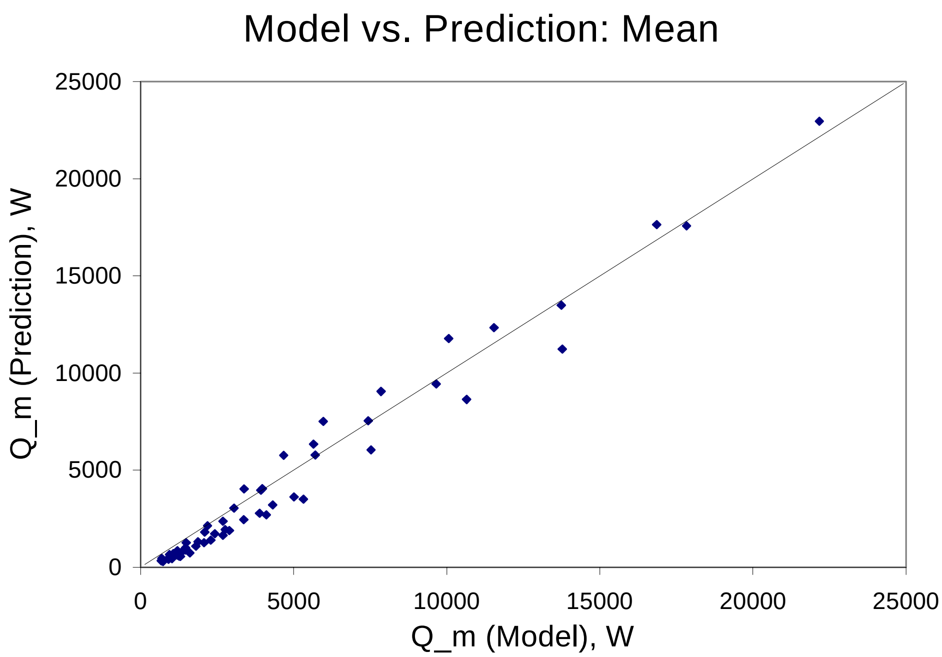

Figure 2 The underground building heat loss mean predictions from simplified method compared to those from the ITPE model.

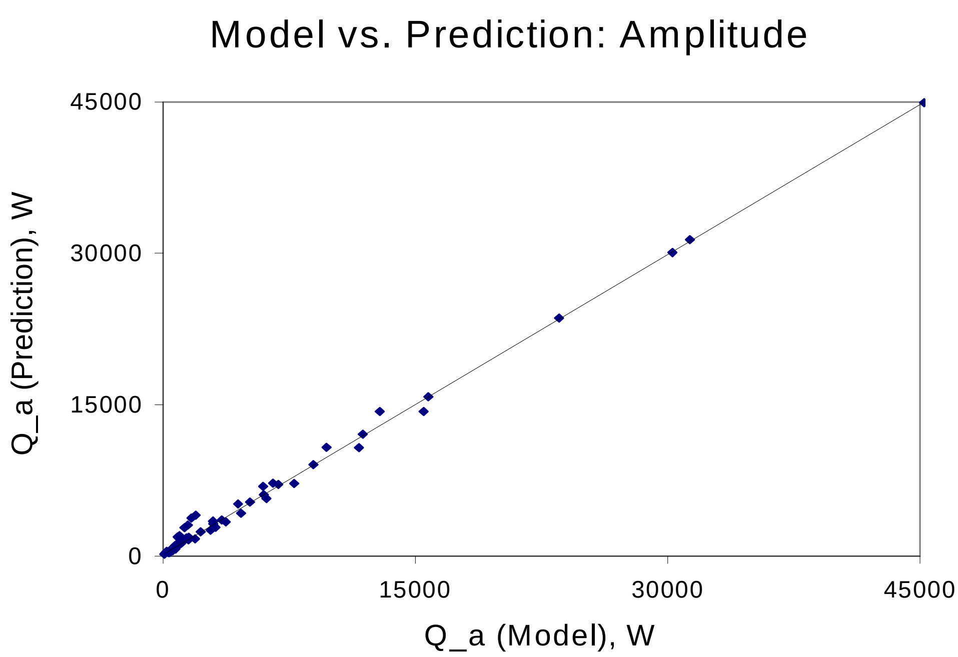

Figure 3 The underground building heat loss mean predictions from simplified method compared to those from the ITPE model.

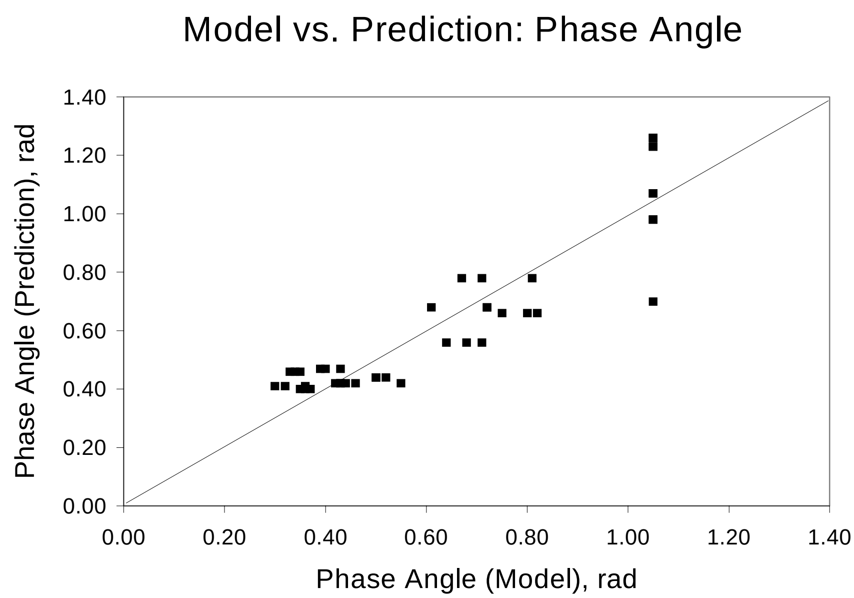

Figure 4 The underground building heat loss phase lag predictions from simplified method compared to those from the ITPE model.

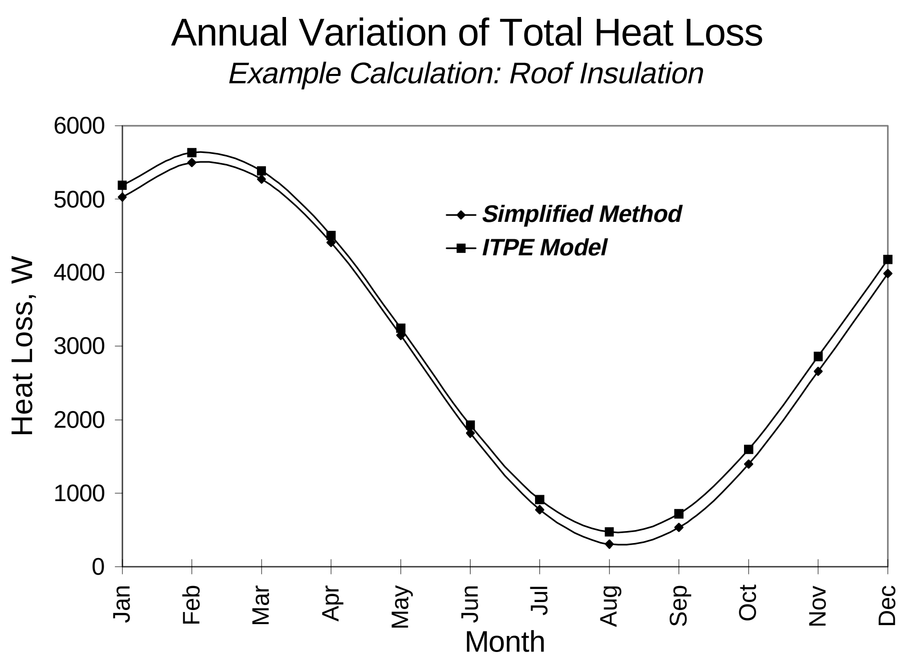

Figure 5 The prediction of the annual variation of the total underground building heat loss prediction from simplified method and the ITPE model.