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Thermal performance of three deep basements: a comparison of measurements with ASHRAE Fundamentals and the Mitalas method, the European Standard and the two-dimensional FEM program

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Abstract

The comparison of four methods for the calculation of deep-basement heat loss is presented along with measured data for three basement types. The Mitalas method was found to give results in best agreement with measured data followed by the finite element method (FEM) program, the European Standard and the ASHRAE Fundamentals method.

The studied methods, with the exception of the European Standard of which the physical background was unknown, were chosen because each of them is also representative of a particular physical model of decreasing complexity in the above order. Therefore, differences in presented results yielded by these methods provide insight about differences one can expect when using 3-D, 2-D and/or 1-D physical models for the calculation of deep-basement heat loss.

The sensitivity of studied methods to input parameters representing various thermal properties of soils and temperature boundary conditions was investigated also.

1. Introduction

More attention is being focused on below-grade heat loss with an increasing thermal performance of the building. Numerous methods have been developed, whose accuracy may be questioned, as they were seldom verified with measured data. Even in the cases where they were verified, the measurement and calculation methods were usually performed by the same author.

It seems reasonable to suggest verifying methods for the prediction of basement heat loss by comparing them with measurements available from independent authors. This study presents a comparison of measurements with calculations for three types of deep basements.

The measurements for two basement configurations, one insulated outside along the upper part of the wall and one with down-and-out insulation on the upper part of the basement exterior, were conducted at the Tohoku University, Sendai, Japan [1].

For the third type of basement the experimental data available from the NRC in Ottawa, Canada, [2] were used. The basement was deep, with full-height inside insulation and an uninsulated floor.

Because of the rather complicated geometries of basement insulation, a two-dimensional program based on finite element method (FEM) program and Mitalas method [2] were used for a comparative study with data measured at Tohoku University. Two more simple methods were added for comparison with data from NRC Canada: the widely used ASHRAE Fundamentals method [3–5] fully based on Latta and Boileau [6], and the new European Standard [7], which will soon become approved [8].

In addition, the influence of input data — temperature boundary conditions and soil properties

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— on predicted heat loss was studied for all three basement configurations.

2. Previous studies

The type of basement for which measured data were available from NRC, Canada [2], will be referred to as model A, Fig. 1. Because of the simple insulation configuration, it has attracted attention in many comparison studies as briefly reviewed below.

The two types of basements, Figs. 2 and 3, in which thermal performance was experimentally investigated at Tohoku University, Japan [1], represent rather complicated configurations for computation, and no comparison studies were available from the literature.

The most-often cited method for calculation of residential basement heat loss is probably that of Mitalas [2, 9, 10]. The Mitalas method implements 2-D and 3-D physical models of the basement. At the time of its introduction in 1982/3 [2, 9], this method was found to give results different from the other methods which were entirely based on 1-D and/or 2-D treatment of basement heat transfer. Studying model A and uninsulated basements, Parker [11] showed that the Mitalas method [9] gives uniformly greater annual heat loss than the methods of ASHRAE Fundamentals [3], F-factor [11], Yard [12] and DAGT [13].

In an extensive study considering type A of deep basements, McDonald *et al.* [14] compared two variations on the Latta-Boileau method [6] with methods from Mitalas [9], Yard *et al.* [12], Akridge *et al.* [13], Shipp [15] and Swinton *et al.* [16]. Significant differences among all methods were reported, irrespective of their mathematical background, in the case of uninsulated walls and floors. However, agreement was found in predicted annual basement heat loss through well-insulated basement walls of model A for the methods of Yard [12], Mitalas [9] and Shipp [15], which are of a similar mathematical background, based on two-dimensional (in ref. 9 partly three-dimensional) numerical programs.

Most of the simpler calculation methods were developed on the basis of precalculation of unit heat transfer rates using numerical programs. The tool probably most often used was a two-dimensional, finite-difference heat conduction program developed in the Underground Space Center [17], further denoted ESHD after Yuill and Wray [18]. This program was also used for studies of large earth-sheltered structures [19, 20] and for the generation of foundation heat flux data by Shen *et al.* [21], which were — using the procedure described by Huang and others [22] — incorporated in DOE 2.1c.

An innovative tool for analysis of basement heat loss, the semi-analytical ITPE technique, was introduced by Krarti and others and described in a series of papers, e.g., refs. 23–26.

The comparison of the Mitalas method, ESHD program and two-dimensional ITPE technique was performed by Yuill and Wray [18] for basement model A and slab-on-grade basements. The basement model A was considered in three cases. Insulation was heavy ($R=3.5$ m^{2}K/W) and the floor was uninsulated. The results showed good agreement in the wall and floor heat loss in all cases except for

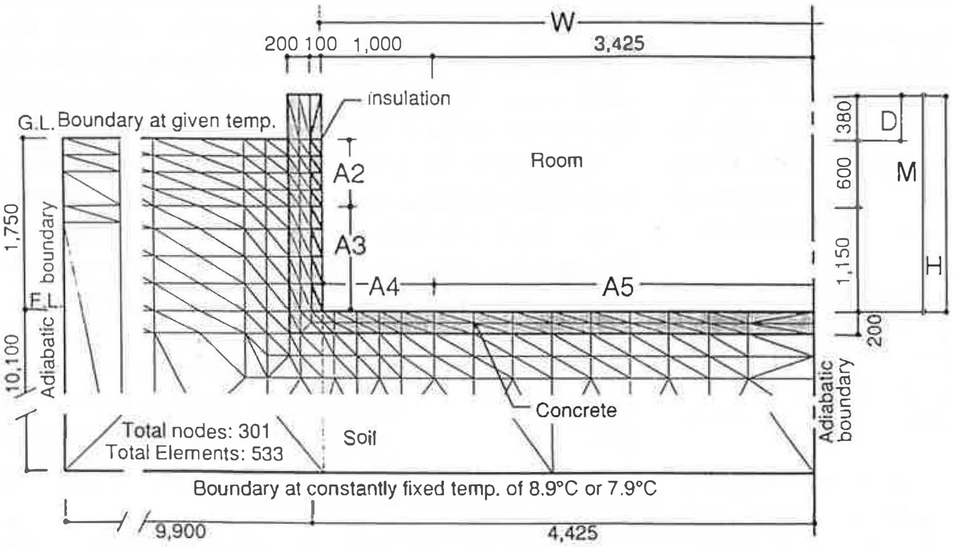

Fig. 1. Basement A for FEM computation modeled after an actual test basement A [2].

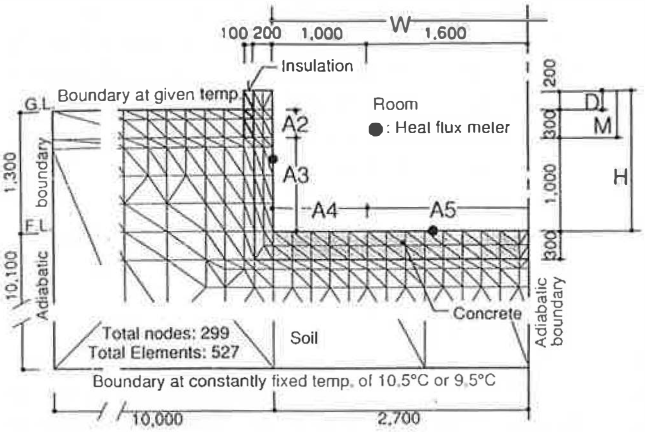

Fig. 2. Basement C for FEM computation modeled after actual test room "C" [1].

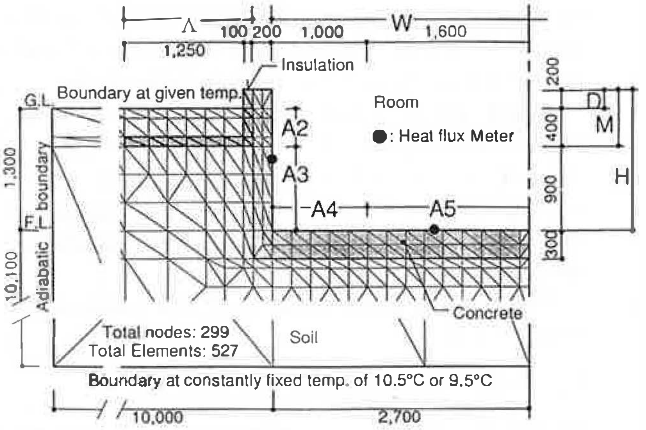

Fig. 3. Basement D for FEM computation modeled after actual test room "D" [1].

floor heat loss predicted by the 2-D ESHD program, which was significantly lower.

A comparison between a two-dimensional and three-dimensional ITPE technique and Mitalas method conducted by the authors of the ITPE technique for the type A of basement is given in ref. 27. The 3-D ITPE method was found to give results closer (with heat loss higher) to the data calculated and measured by Mitalas [2] than the 2-D ITPE method.

The agreement was poorer in ref. 27 than in the study [18] between the 2-D ITPE technique and the Mitalas method for a type A of basement of a similar size but with a lower value of wall insulation than in ref. 18.

The results presented in refs. 14 and 27 suggest that differences similar to those in floor heat loss in ref. 18 can be expected for uninsulated walls when comparing the Mitalas method with the 2-D numerical program. This indicates that the heavy insulation was probably the key factor in improving agreement in predicted wall heat loss among the Mitalas method, ESHD program and ITPE technique in ref. 18.

The literature survey suggests that significant differences between methods can be expected to be caused by the dimensional character of the physical model. The observed differences in predicted heat loss decrease with the decrease in total heat loss, i.e., with increasing insulation.

This idea will be investigated here comparing methods based on physical models of different complexity and comparing them with measured data for three types of deep basement.

3. Description of measured data and calculation methods

3.1. Measured data from NRC, Canada

The total measured heat loss for basement A, Fig. 1, was published by Mitalas [2]. Detailed measured data were not available to us in numerical form. However, the measured monthly heat loss profiles presented here were calculated using relations and constants obtained by a close fit to the original measured data presented in the same publication.

3.2. Measured data, Sendai, Japan

The semi-underground test house was built on the university campus in Sendai, located in the northern region of the main island of Japan. The test house has two separate rooms C and D with basement configurations (Figs. 2 and 3) corresponding well to alternatives 9 and 10, respectively, in ref. 10.

The heat fluxes through the wall and floor were measured by local flux meters. The total energy consumption was measured as well, as the local wall and floor heat flux meters characterize only one-dimensional heat loss. The method used to determine total heat loss and its separation into wall and floor heat loss is described in detail in Matsumoto *et al.* [1].

The minimum temperature, which was set to 20 °C in the test house, was controlled by auxiliary electric heating equipment during an entire year. When this temperature was reached, heating was stopped. This temperature was often exceeded in the summer period due to solar radiation. There was no air-conditioning and the temperature fluctuated when, due to solar radiation, it exceeded 20 °C. In the course of the year this fluctuation increased mean annual indoor air temperature in room C by about 0.55 °C and in room D by about 0.46 °C. This increase was also accounted for in the heat loss calculation, as it was assumed that released heat was stored in the soil mass surrounding the basement. Therefore, mean annual indoor air temperatures for rooms C and D were considered as 20.55 °C and 20.46 °C respectively.

3.3. Mitalas method

This method can be classified as a steady-state method with a time-varying component. For calculation, the below-grade part of the deep basement is divided into four segments. Total heat loss is given as a sum of instantaneous heat fluxes through these segments during the considered period. In equations for their determination, a set of factors is used. These were precalculated using 2-D and 3-D numerical heat condition programs and fine-tuned on the basis of measurements [2].

3.4. ASHRAE Fundamentals method

The rate of heat loss for basement walls in the ASHRAE Fundamentals method [3–5] is not given in implicit form by equation, but is tabulated for one type of soil conductivity and several levels of basement wall insulation following values in Latta and Boileau [6]. To make a comparison for insulation resistance and soil conductivity from measurements, [1, 2], the explicit formulations for the calculation of wall heat transfer rate were used. They were obtained following discussion of the method by Labs [28] and its verbal description in refs. 5 and 6.

The interpolated tabulated values of floor heat rate in ASHRAE Fundamentals were used to determine floor heat loss [29].

Annual heat loss was calculated as the sum of the monthly loads, which were calculated as the hourly load found by the heat rate multiplied by the corresponding temperature difference and by the number of hours in the month.

3.5. FEM program

An unsteady-state computer program for calculation of below-grade heat loss based on the two-dimensional finite element method with triangular simplex elements [30, 31] was prepared by Matsumoto [32]. The time differential of temperature was incorporated using the difference analog method described by Wilson and Nickell [33].

3.6. European Standard

The latest draft version of the new European CEN and ISO Standard [7] was available. The document has not been superseded by any other European Standard. According to information from the convener [8] of the TC89/WG5 group preparing the standard, no substantial changes are expected, but a future version could contain some small amendments. Results supporting proposal of the standard regarding deep-basement heat loss calculation had not yet been published when this study was prepared.

In ref. 7, the average rate of heat transfer is calculated as follows:

$$\phi = L_s(T_i - T_e) - L_{pi}A_i \cos\left(2\pi\frac{m-1+\alpha}{12}\right)$$
$$+ L_{pe}A_e\left(2\pi\frac{m-1+\beta}{12}\right)$$

where L_s is the steady-state thermal coupling coefficient (W/K), L_{pi} = internal periodic thermal coupling coefficient (W/K), L_{pe} = external periodic thermal coupling coefficient (W/K), α, β = phase terms (months), $\beta = 1$ is recommended, T_i = annual average internal temperature (°C), T_e = annual average external temperature (°C), A_i = amplitude of variations in monthly mean internal temperature (°C), A_e = amplitude of variations in monthly mean external temperature (°C), m = month number ($m = 1$ for January to $m = 12$ for December). The coefficients L_s, L_{pi} and L_{pe} depend on the perimeter of the floor (P), area (A), and depth of basement floor below ground level (H).

The steady-state heat transfer coefficient L_s is determined by:

$$L_s = AU_{bf} + HPU_{bw}$$

where U_{bf} and U_{bw} are related to floor and wall heat transfers respectively. The values of U_{bf} and U_{bw} are calculated from further equations, which express the dependence of U_{bf} and U_{bw} on basement size, insulation, and soil thermal properties.

The thermal coupling coefficients L_{pi} and L_{pe}, due to temperature variations over an annual cycle, consist of two terms, one related to the walls of the basement and the other related to the floor of the basement. In our study, the indoor air temperature was considered constant and therefore the L_{pi} term was omitted.

4. Input data for calculations

4.1. Temperature boundary conditions

The annual ground surface temperature amplitude and mean annual ground temperature for Ottawa, Ontario, Canada [2], and Sendai, Japan [1], were considered for the comparison of methods with measurement, Table 1, run 1.

When calculating basement heat loss, ground temperatures, T_G, for most localities have to be estimated using climatic models and/or substituted

[redacted]

[redacted]

TABLE 1. Variable condition parameters for calculations

Modeled basement	Basement A				Room C and Room D			
Run series number	Run 1	Run 2	Run 3	Run 4	Run 1	Run 2	Run 3	Run 4
Ground surface temperature (°C)								
Mean	8.9	7.9	8.9	8.9	10.5	9.5	10.5	10.5
Amplitude	11.4	11.4	11.4	11.4	10.4	10.4	10.4	10.4
Thermal conductivity of soil (W/mK)[a]	0.8–0.9 (0.88[b])	0.8–0.9 (0.88[b])	1.2–1.35 (1.275)	1.8–2.0 (1.90)	0.8–0.9 (0.85)	0.8–0.9[a] (0.85)	1.2–1.35[a] (1.275)	1.8–2.0[a] (1.90)
Heat capacity per unit volume of soil[d] (×10^6 J/m^{3}K)	2.63[b]	2.63[b]	3.00	2.20	2.30	2.30	3.00	2.00
Thermal diffusivity of soil (×10^{-6} m^2/s)	0.335	0.335	0.425	0.864	0.37[c]	0.37[c]	0.425	0.864

[a] Couple of values noted with hyphen is one of three options for Mitalas method [2, 10]. The first term is conductivity for soil above a floor slab and the second is that for soil below the slab. For the other methods, value in parentheses is used instead of the couple.

[b] Measured value [2].

[c] Measured value [32].

[d] Heat capacity of soil is necessary for calculations by European standard method and two-dimensional FEM.

by mean annual air temperatures, T_{AIR}, and/or mean annual solar air temperatures. The difference ($T_G - T_{AIR}$) was found to be about 1 K when studying the influence of elevation on T_G in Central Europe [34], and the same was also reported from Japan [32] and some parts of the USA [14]. Therefore, in a parametric part of the study investigating the influence of temperature boundary conditions on predicted heat loss, a 1 K difference was considered (Table 1, run 2).

4.2. Soil properties

In the Mitalas method, thermal properties of soil are characterized only by its thermal conductivity, λ, with three options, each distinguishing one value of thermal conductivity down to the basement bottom and a slightly higher value above it. For a comparative study with measurement the closest option of soil thermal conductivity $\lambda = 0.8/0.9$ (W/mK) was used for the Mitalas method, while in the ASHRAE Fundamentals method, European Standard and FEM program it was possible to consider the measured value $\lambda = 0.88$ (W/mK). In the latter two methods, the measured value of soil thermal diffusivity was also an input parameter (Table 1, run 1).

In a parametric study of the influence of soil thermal properties on deep-basement heat loss, the mean values of the "upper/lower" soil conductivity in the Mitalas method were considered in the ASHRAE Fundamentals calculation of basement wall heat loss, in the European Standard, and the FEM program. For the European Standard and FEM program, soil conductivity was supplemented by the value of soil thermal diffusivity, Table 1, runs 3 and 4.

The considered alternatives are summarized in Tables 1 and 2.

5. Results

The calculation yielded by the unsteady-state FEM program results in decreasing year-to-year annual heat loss. The progression in annual calculated heat loss for the first five consecutive years was as follows: 100%, 79.7%, 77%, 76.1% and 75.8% for basement A; 100%, 82.54%, 80.86%, 80.34%, 80.17% in the case of model C; and 100%, 76.49%, 74.24%, 73.55%, 73.31% in the case of model D.

The results for a third year were used for comparison, in accordance with measured data.

5.1. Basement A

5.1.1. FEM program, Mitalas method and measurement

There is a good agreement between measured and calculated annual heat loss with the Mitalas method (+4%) while the FEM program predicted slightly lower heat loss (−9%) than measured, Fig. 4.

The lower floor heat loss predictions from the FEM program account for all of the difference between predicted heat loss as calculated by the Mitalas method and the FEM program. This is fully consistent with the findings in the previous studies, that the Mitalas method tends to predict higher heat

TABLE 2. Constant condition parameters for calculations

Modeled basement	Basement A (National Research Council, Ottawa, Canada)				Rooms C and D (Tohoku Univ., Sendai, Japan)			
					Room C		Room D	
Calculation method	Mitalas Method	European Standard	ASHRAE Method	2-D FEM	Mitalas Method	2-D FEM	Mitalas Method	2-D FEM
Calculation model name	Alt. 3[b]			Model A	Alt. 10[b]	Model C	Alt. 9[b]	Model D
Model configuration (m)								
L[a]	9.20	9.20	9.20	(Model is shown in Fig. 1)	6.67	(Model is shown in Fig. 2)	6.67	(Model is shown in Fig.3)
W	8.50	8.50	8.05		5.36		5.36	
D	0.0[c]	0.0[c]	0.0[c]		0.0[c]		0.0[c]	
H	1.75	1.75	1.75		1.30		1.30	
Thickness of wall	–	0.20	–		–		–	
Configuration of thermal insulation (m)								
M	1.75 (full height interior insulation for wall)			See Fig. 1	0.30	See Fig. 2	0.30	See Fig. 3
Λ	–			–	1.10[b]	1.35	1.10[b]	1.35
Area of each segment (m^2)	A2 = 21.24 A3 = 40.71 A4 = 31.40 A5 = 46.80	Wall: 61.95 Floor: 78.20	0.3 m strip of wall: 10.62 (by 5.833) Floor: 78.20	A2 = 21.24 A3 = 40.71 A4 = 31.40 A5 = 46.80	A2 = 7.22 A3 = 24.06 A4 = 20.06 A5 = 15.69	A2 = 7.22 A3 = 24.06 A4 = 20.06 A5 = 15.69	A2 = 7.22 A3 = 24.06 A4 = 20.06 A5 = 15.69	A2 = 7.22 A3 = 24.0.6 A4 = 20.06 A5 = 15.69
Thermal resistance R (m^2K/W) or thermal conductivity λ (W/mK)								
Concrete	–	–	–	$\lambda = 1.63$ ($R = 0.123$)	–	$\lambda = 1.63$	–	$\lambda = 1.63$
Insulation	$R = 1.55$	$R = 1.55$	$R = 1.55$	$\lambda = 0.065$ ($R = 1.55$)	$R = 3.33$	$\lambda = 0.065$ ($R = 3.33$)	$R = 3.33$	$\lambda = 0.065$ ($R = 3.33$)
Thermal diffusivity ($\times 10^{-6}$ m^2/s)								
Concrete	–	–	–	0.83	–	0.83	–	0.83
Insulation	–	–	–	1.39	–	1.39	–	1.39
Indoor film coefficient (W/m^2K)								
For wall	–	8.333[d]	8.0	8.0	–	8.0	–	8.0
For floor	–	7.143[d]	8.0	8.0	–	8.0	–	8.0
Room air temperature (°C)	21.0	21.0	21.0	21.0	20.55	20.55	20.46	20.46

[a] L: length of basement floor. The other symbols are shown in Figs. 1–3.

[b] Designated/determined by Mitalas [2, 10].

[c] Disregarded.

[d] Equivalent to R-values described in European Standard Draft (CEN/TC 89/WG5 N184).

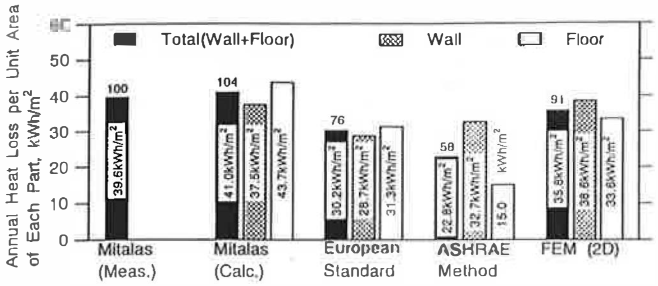

Fig. 4. A comparison of annual heat losses per unit area, for basement A by investigated methods and measurement [2].

losses through uninsulated floors than does the 2-D numerical program.

Other authors observing this discrepancy in results between the 2-D numerical methods and the Mitalas method have suggested that Mitalas multiplied floor heat loss shape factors by 1.5, i.e., that the values of the floor shape factor in the Mitalas method were arbitrarily increased by 50%. However, the only reference to a modification made by Mitalas himself that we have found is his comment [2]: "The values of the floor shape factor were increased by assuming that the conductance between the basement and the lower boundary is 1.5 times the values calculated for the basement model."

This suggests that Mitalas only slightly modified his method on the basis of measurement. Further study by Sobotka *et al.* [35] shows that this modification did not alter substantially the results yielded by the Mitalas method.

5.1.2. European Standard and measurement

The predicted value of the annual heat loss by the European Standard was 23.8% lower than measured.

Discussion of the wall heat loss and the floor heat loss separately for this method is not possible, as the heat transfers through the floor and walls of the basement are interlinked and the two terms U_{bf} and U_{bw} do not precisely represent the heat transfer through the floor and through the walls respectively [7].

The method allows the possibility of different insulation levels being applied to the walls and floor of the basement, but it cannot be used to optimize the insulation configuration. However, this method using only a few parameters to characterize basement heat loss has already — before becoming officially approved — attracted interest, which will probably lead to modifications in the future, e.g., those suggested by Nagata and Matsuo [36].

5.1.3. ASHRAE Fundamentals method and measurement

The total annual heat loss by the ASHRAE Fundamentals method is 42% lower than by measurement, Fig. 4. It is interesting to study the cause of the disagreement of measured data and calculated data by the ASHRAE Fundamentals method.

For this purpose, the heat rate loss per unit area and temperature difference (U-value) for a basement 2.4 m deep and 9 m wide was calculated with the FEM program and compared with the U-value calculated using the ASHRAE Fundamentals approach and German method [37] of a similar character.

Oswald [37] presented data on the soil resistance along the depth of the basement wall, obtained using electroanalogy. Results from Oswald [37] were used here in a way described in detail in ref. 38 to calculate U-values for basement walls, in addition to ASHRAE Fundamentals and the FEM program.

The steady-state temperature boundary conditions (Fig. 5) and soil conductivity $\lambda = 1.16$ W/(mK) were considered to enable comparison with this method [37]. The uninsulated basement, $R = 0$ m^{2}K/W, and thermal resistance of insulation of basement walls $R = 1.55$ m^{2}K/W were considered.

The values of unit heat transfer rate of all three methods differ mostly in the upper part of the wall and at the foot of the basement (Fig. 5). The U values obtained using the ASHRAE Fundamentals method are lowest, except for the upper part of the basement.

The results presented in Fig. 5(a) and (b) show that disagreement in U-values between the ASHRAE Fundamentals method and the FEM program is greater for a strip of floor adjacent to a wall (Fig. 5(b), $R = 1.55$ m^{2}K/W) than for the bottom part of a wall (Fig. 5(a), $R = 1.55$ m^{2}K/W). This explains well the differences between ref. 5 and FEM calculations in predicted annual heat loss per unit area, which were more significant for floor than wall (Fig. 4).

The use of unsteady-state conditions, as well as consideration of the shorter, thermally more unfavorable period (the heating season was considered to be from November to May, inclusively) did not influence significantly the results for U-values of a basement wall by the FEM program with the exception of the basement corner (Fig. 6). The results for U-values of the basement floor are more sensitive to temperature boundary conditions, with U-values derived by all-year unsteady-state calculations being highest (Fig. 6(b)).

Comparison of U-values along the basement wall and floor surface derived by the 2-D FEM program

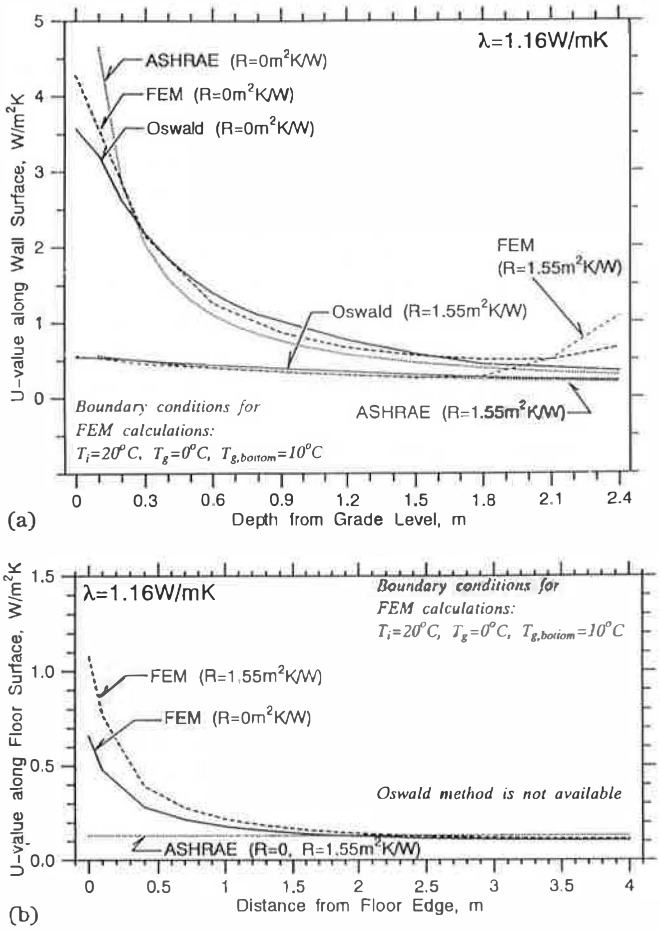

Fig. 5. (a) U-value along a wall surface yielded by FEM program, ASHRAE Fundamentals [4], and Oswald [37] method; steady state-conditions for FEM program. (b) U-value along a floor surface yielded by FEM program and ASHRAE Fundamentals [4]; steady-state conditions for FEM program considered.

with one-dimensional steady-state design by ASHRAE Fundamentals illustrates the following: the main cause of the differences in predicted heat loss is due to the physical model applied to the calculation of heat loss through uninsulated basement parts adjacent to the corners.

Agreement between predicted and measured peak load is better than in annual heat loss, with best results from the FEM program (−0.8%) followed by the Mitalas method (+5.8%) and with almost the same results by ASHRAE Fundamentals [5] (−15.5%) and the European Standard (−15.8%), Fig. 7.

The times when maximum heat loss occurs were correctly predicted by the Mitalas method and the FEM program, compared to a one-month delay generated by the European Standard, Figs. 7 and 8.

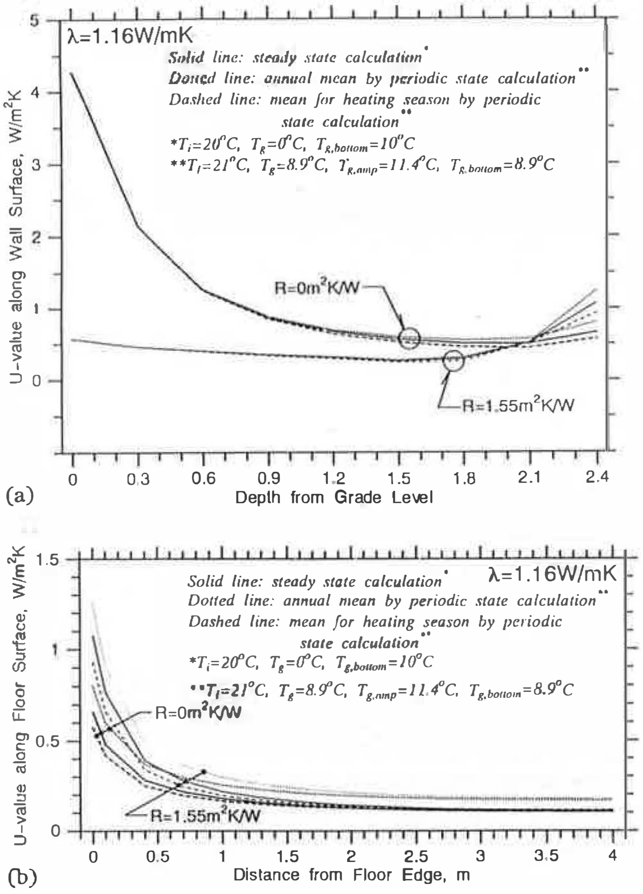

Fig. 6. U-value along wall and floor surfaces yielded by FEM program under various boundary conditions: (a) for wall, (b) for floor.

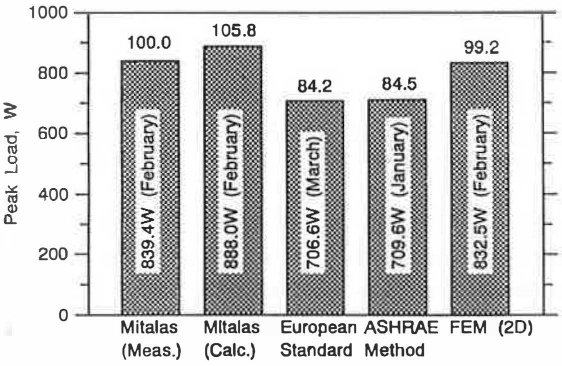

Fig. 7. Comparison of monthly peak load yielded by investigated methods.

5.2. *Basements C and D*

In Fig. 9 are the results of comparison of measurements at Tohoku University between the Mitalas method and FEM program for the basement types C and D. It is interesting to notice that, when compared with measurements, the Mitalas method predicted for room C, total heat loss almost within the 10% range (−13%) claimed by the author, and

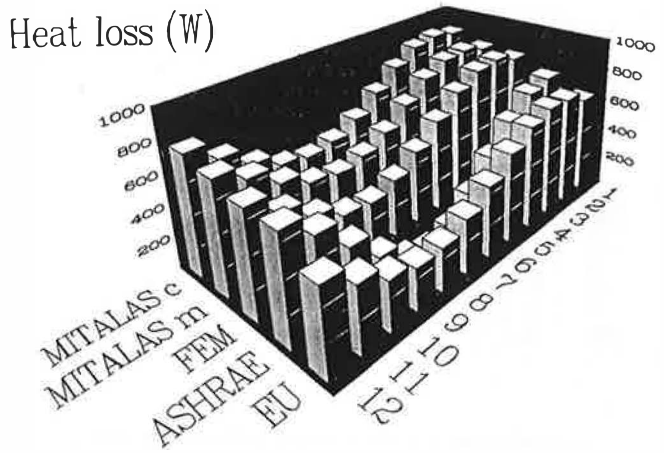

Fig. 8. The monthly heat loss profiles for basement A according to measurement (Mitalas m), calculated by Mitalas method (Mitalas c), FEM program, (FEM), ASHRAE Fundamentals, (ASHRAE) and European Standard.

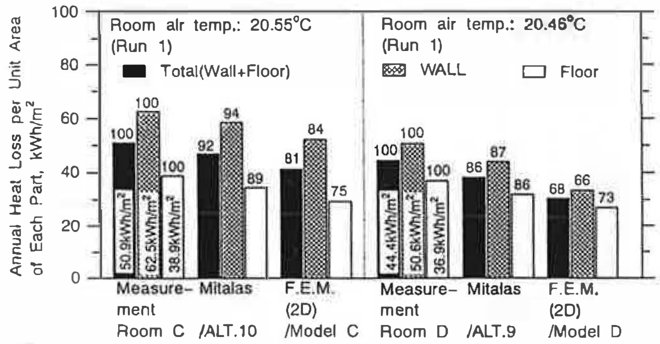

Fig. 9. A comparison of annual heat losses per unit area for basements C and D by investigated methods and measurement [1]. The value shown at the top of a bar indicates proportion to measurement result (%).

for room D within 20% (− 18%). The Mitalas method predicted higher heat loss than the numerical two-dimensional FEM program, which is consistent with findings of the other authors that the Mitalas method tends to give higher predictions than the others.

In the study of basements C and D, there was neither good agreement between total wall nor between total floor heat losses, which were both lowest in the calculations from the FEM program.

A possible reason for differences in both floor as well as wall heat losses can be that, in the currently studied basement configurations, the upper part of the basement wall was well insulated, while the uninsulated lower part caused the differences in total wall heat loss.

The results for basements C and D lend positive support to a new explanation of the discrepancy noticed above and in refs. 11 and 18 between the disagreement in floor heat loss predictions and relatively good agreement in wall heat loss predictions in the case of the basement type A. A likely explanation seems to be that differences are significant for those uninsulated basement sections for which three-dimensional heat losses are encountered by the Mitalas method, e.g., in the studied case one can expect greatest disagreement for uninsulated segments A4 and A5, which was also observed [1].

In the case of basement A, the full height of the wall was insulated. This probably reduced differences in predicted heat loss through wall construction by diminishing the significance of three-dimensional heat transfer through the bottom part of the basement wall, which resulted in increased agreement in predicted wall heat losses by Mitalas and other methods.

The findings presented, supported by discussion of the literature, suggest that dimensions of the physical model are important for calculation of basement heat loss. The results obtained on the basis of 1-D and 2-D physical models of basements underestimate deep-basement heat loss in comparison with 3-D methods, which is especially apparent for its uninsulated parts in the vicinity of corners — the more simple the physical model is, the lower and less accurate is the predicted heat loss.

5.3. *Sensitivity study to input data*

Results from all the methods, obtained under modified temperature boundary conditions (run 2, Table 1) and modified soil thermal properties (run 3 and run 4, Table 1), were compared with respect to the calculated results for the measured input data (run 1, Table 1).

5.3.1. *Temperature boundary conditions*

According to the results in Fig. 10, a 1 K decrease in annual mean soil temperature leads in all investigated methods for basement A to about an 8% increase in predicted heat loss. The influence of 1 K lower mean annual ground temperature on the total annual predicted heat loss for basements C and D causes about a 10% difference of predicted heat loss by the 2-D FEM program and Mitalas method, Fig. 10.

The results obtained for all basement types are in accord with the observation in Mitalas [2], where a 1 K change in annual mean basement air temperature resulted in a 5% to 10% increase in heat loss for various basements.

5.3.2. *Soil thermal properties*

The influence of soil thermal properties on predicted heat loss by each method is studied in Fig. 11.

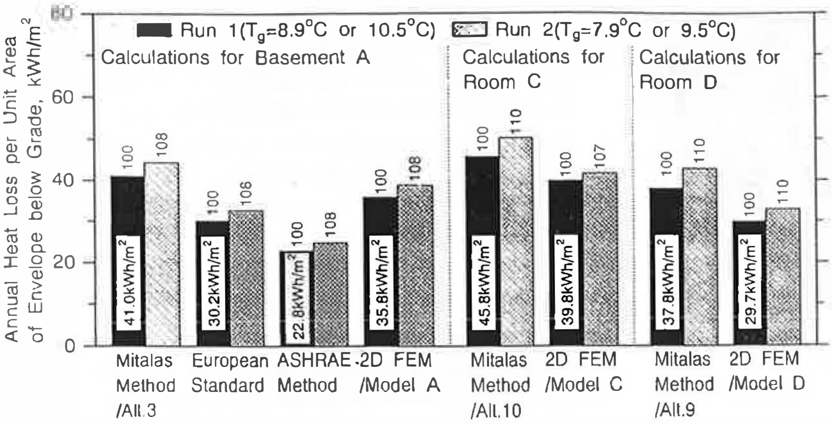

Fig. 10. The influence of 1 K difference in annual mean ground temperature upon change in annual heat loss per unit area. The value at the top of a bar indicates the proportion to the result of Run 1 (%). T_g = annual mean ground temp.

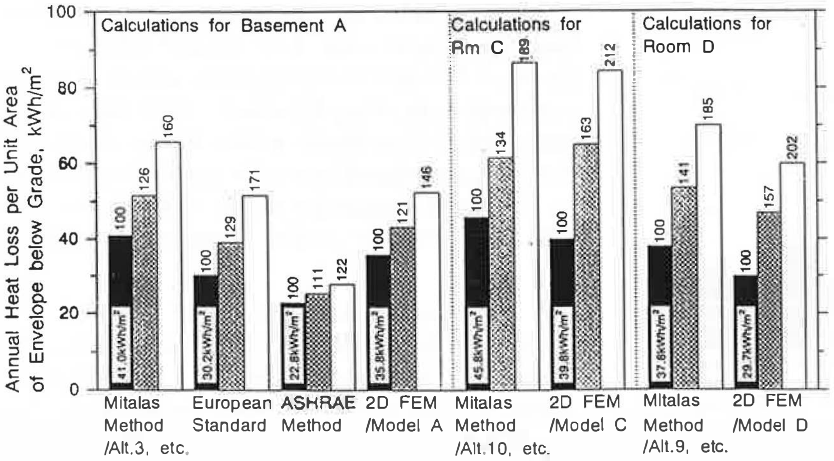

Fig. 11. The influence of soil thermal properties on change in annual heat loss per unit area. ■, Run 1 (λ = 0.8–0.9 or 0.88 W/mK, $c\rho$ = 2.63 MJ/m^{3}K). ⊠, Run 3 (λ = 1.2–1.35 or 1.275 W/mK, $c\rho$ = 3.0 MJ/m^{3}K). □, Run 4 (λ = 1.8–2.0 or 1.90 W/mK, $c\rho$ = 2.20 MJ/m^{3}K). The value at the top of a bar indicates proportion to the result of Run 1 (%). λ = thermal conductivity of soil, $c\rho$ = heat capacity of soil.

When studying basement A, a similar response of the Mitalas method and European Standard to the increase in soil thermal conductivity was found, with 26% and 60% increases for the Mitalas method and slightly higher, 29% and 71% increases, for the European Standard. The results predicted by the FEM method followed a similar trend for run 3, giving an increase of 21%, but results for run 4 varied only 46% from run 1. The response of the ASHRAE Fundamentals method followed the trend of increasing annual mean heating load with increases in soil thermal conductivity, but this dependence was much less significant than for other methods.

To illustrate the influence of soil thermal properties on predicted heat losses, an FEM computation was performed for the basement configurations C and D using on-site measured soil conductivity k = 0.99 W/mK [32]. Results of this calculation presented in ref. 1 showed that a 10% increase in predicted heat loss for room C and a 12% for room D can be obtained in this case by accurate on-site measurement of the thermal properties of soil. This results in a reduced difference between measured and calculated heat loss by the FEM program from 19.1% to 10.9% for room C and from 31.8% to 23.8% for room D.

The soil thermal diffusivity does not influence the annual mean heat loss to the ground in theoretical studies like this, considering the earth-coupled problems isolated from the other thermal processes in the basement. However, soil thermal diffusivity influences the annual course of the basement heat loss. Therefore, when control of the heat loss in the annual course can be provided and counterbalanced, e.g., by solar radiation, the correct prediction of the monthly heat profiles becomes an important issue.

6. Conclusions

The results presented suggest that predictions for deep-basement heat loss by the Mitalas method are in good agreement with measured data for three types of basement configurations, when similar and/ or identical dimensions of the basement are considered in the calculations.

The comparison of the 2-D FEM program with the Mitalas method and measured data suggest that the combined 2-D/3-D model of heat transfer implemented in the Mitalas program can be considered the main reason that the Mitalas method gave results closer to measured data than a program based on a 2-D model.

The investigation of the ASHRAE Fundamentals method using the 2-D FEM program illustrated the shortcomings of the one-dimensional physical model of deep basements which results in lower predicted heat loss, especially around the basement corner.

The comparison with a measurement and sensitivity study presented here gave evidence that use of the European method is adequate for the practical design of a simple basement configuration when soil properties as well as thermal boundary conditions are only estimated.

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