Assessment of Apparent Soil Thermal Conductivity

R.L. Sterling, Ph.D., P.E.

ABSTRACT

This paper describes the current status of the development and documentation of a data base of soil thermal properties and a methodology for the estimation of site-specific apparent soil thermal conductivity for building design purposes. The data base is compiled from available laboratory and field data. The methodology is being developed to provide guidance in selecting reasonable thermal conductivities even when detailed site and soil information is not available. The emphasis of the paper is on a discussion of the necessary site and soil parameters at different levels of estimation accuracy and on the economics of the assessment process relative to the cost impact of misclassification. Building foundation heat transfer is the principal application considered.

INTRODUCTION

Soil thermal conductivity has been extensively studied since the 1940s, when Kersten (1948) published the thermal conductivity measurements for a wide range of soil types under frozen and unfrozen conditions. The principal areas in which studies of thermal conductivity have been pursued are in agriculture and soil science in relation to plant viability and growth, in the electric power industry in relation to the heat loss from buried electric lines, in civil engineering in relation to the effect of frost on road and airfield pavements, and in building science to estimate the heat loss from buried structures and building foundations. An excellent review of the factors affecting the thermal conductivity of soils and calculation methods proposed by various authors is given in Farouki (1986).

Despite many studies, a designer or researcher is faced with a difficult task in selecting reasonable or moderately conservative values for use in his or her analysis. Kersten's original data were still reproduced in the last *ASHRAE Handbook—Fundamentals* (ASHRAE 1989), but the table gave only selected values for certain specific soil types. Many researchers (including Kersten) have provided equations for estimating soil thermal conductivity from soil parameters such as textural class and moisture content plus other data such as soil density, soil mineralogy, and the shape of soil grains. However, the variability of soils and the complexity of the heat transfer processes do not allow these models to give accurate estimates of thermal conductivity for all soil types and thermal/moisture conditions. In many cases, the required detailed soil information needed as input to the model is physically or financially unavailable when estimates must be made. Also, a single measurement of a particular soil parameter such as soil moisture content does not establish how that parameter might vary over an annual cycle.

This paper is based on a research project funded by ASHRAE (project No. 701-RP) to mitigate some of these difficulties and, specifically, to prepare and document a data base and methodology for the determination of site-specific soil thermal properties for inclusion in the *ASHRAE Handbook—Fundamentals*. This data base was to be based on available laboratory and field data and was to provide guidance in selecting reasonable thermal conductivities even when detailed site and soil information is not available. An important aspect of the charge was to attempt to reduce the ambiguity in selecting reasonable thermal conductivities so that individuals faced with the same estimation problem would not arrive at widely differing estimates.

This paper focuses on the estimation of the apparent thermal conductivity of soils for building foundation heat transfer problems.

COMPLEXITY OF SOIL HEAT TRANSFER

Despite the desire to simplify the estimation of soil heat transfer parameters, the nature of the heat transfer processes occurring simultaneously in the soil makes this a difficult task (see references for more complete discussions). The overall heat transfer in a soil results from the combination of the following heat transfer processes:

Conduction	•	conduction through the soil grains
	•	conduction through water and/or ice in the soil voids
	•	conduction through moist air in the soil voids
	•	contact resistances at grain/grain contacts
Convection	•	convection/advection within soil pores in both the air and water
Radiation	•	radiation in the soil voids
Mass transfer	•	transport of moist air and water with its associated heat content driven by external water and/or vapor pressure gradients, gravity, and thermal convection in the moist air and water
Phase change	•	storage/release of the latent heat of evaporation or freezing of water

Raymond L. Sterling is an associate professor in the Department of Civil and Mineral Engineering and director of the Underground Space Center, University of Minnesota, Minneapolis.

The complexity of the processes involved are not yet amenable to a complete micro-scale analysis. In many analyses, the soil is treated as a solid medium transferring heat solely by conduction. In this case, the thermal properties used for this assumed continuous medium must incorporate the impact of the various modes of transport on the overall heat transfer. Because of this lumping of effects into a single parameter, the term *apparent thermal conductivity* is preferred and is used to describe the thermal conductivity of a solid material that would give the same rate of heat transfer as the soil in question.

DATA BASE

One approach to building confidence in the selection of apparent thermal conductivity values for soils is to prepare a data base of soil thermal conductivity values for a wide range of soil types and conditions. This effort has been undertaken during the past year using an extensive literature search. All types of thermal property data were entered into the data base for soils, rocks, and minerals. As of the date of preparation of this paper, 6,390 data points have been entered from approximately 90 references (Sterling, in preparation).

A number of problems were encountered in assembling this data base:

- Well-characterized field data are scarce. Laboratory data are more plentiful and typically better characterized.
- Some of the data in the literature are for artificially prepared soils and porous media, which are not very representative of normal soil types.
- Soil thermal conductivity data come from several different disciplines that use different soil parameters to characterize soil conditions. On occasion this requires estimation in the conversion of the data to common units (for example, in converting moisture contents by volume to moisture contents by weight when the soil density is not given).

The current data base contains 6,390 data entries, but only 3,998 of these are original data, the remainder being data cited from other sources. Of the 6,390 data points, 5,873 are from laboratory measurements and only 517 are in-situ measurements or estimates of field thermal conductivity. There are 6,210 values of thermal conductivity, 772 values of specific heat, and 563 values of thermal diffusivity included in the data base. The number of data points relating to soil and rock are 4,777 and 1,613, respectively.

Data fields are provided to allow the separation of data for more rigorous analysis. For instance, reported or assumed thermal conductivity values were entered even if the original source was not available or cited, but these can be screened from the data base using a logical field on whether the data are original or not. This screening prevents double counting of thermal conductivity data from the same source. The organization of the structure of the data base is shown in Table 1. Unfortunately, some of the fields did not acquire much useful data from the literature search, particularly the fields relating to site data. It is planned to both update and make available this data base for reference or analysis.

A few samples of the data that can be abstracted from the data base are shown in Figures 1 through 4. For ease of reference, the data are overlain on the soil thermal conductivity regions presented in Figure 8. Figure 1 illustrates all the original laboratory data on apparent soil thermal conductivity subdivided by whether the soil is frozen or unfrozen, and Figure 2 shows similar data for field soils subdivided by the type of conductivity measurement. Unusual soils and other porous media tested have been removed from the data, but the plots still show a wide range of conductivity at all moisture contents. In Figures 3 and 4, the soil data have been subdivided into granular soils (Figure 3) and clays (Figure 4) and classified according to soil density. When specific soil types are selected, the data fall more closely into the anticipated ranges, but it is clear that the respective chart regions do not fully encompass the relevant data.

ESTIMATION PROCEDURES

The data base by itself is not an estimation procedure. It merely provides a reference for developing a particular estimate or assessing the reasonableness of estimation methodologies. It is perhaps easiest to approach the concept of estimation of soil thermal properties by first looking at what could be involved in an idealized system and then discussing the current developments and procedures that are steps toward this process. A chart illustrating the potential organization of an expert system for providing thermal conductivity estimates is shown in Figure 5. Such a system would allow the integration of pre-stored data (e.g., climatic parameters for the U.S. to be combined with project data specific to a particular use or site). An explanation facility providing definitions, discussion of influences on the thermal properties of soils, and access to the full data base could be provided. The expert system infers answers to questions posed by the user using selected reference data, the problem data, and a set of rules for decision making (termed an *inference engine*). Information available in this manner would organize the flow of information and sequence of decisions based on the user's immediate needs. It would allow extensive documentation and background information if the user wished to examine the basis for the information provided.

A description of four suggested levels of procedures for estimation is shown in Table 2. It is not possible within the constraints of this paper to fully present each methodology. Equations for estimations of soil thermal conductivity are

TABLE 1
Soil Thermal Properties Data Base Structure

GROUPING	DATA FIELD	REMARKS
Thermal data	Apparent thermal conductivity* Thermal diffusivity* Specific heat* Heat capacity	
Source information	Original data? Is source of data listed? Data from graph (or cited value)? Data from graph data point?	Separates out measured data Is primary source listed? Separates out interpreted data Are data points marked? (Note 3)
Measurement data	No. of measurements per data point Type of conductivity measurement Soil temperature for measurement Measurement time*	 Keyword list Average or initial as appropriate
Site information	Location Sample date Sample depth* Site type Site drainage Local surface slope Gutters used on building? Area is paved?	For field data; City, state, country City, suburban, rural Rapid, medium, poor Keyword list
General classification information	Field data? Soil data (or rock)? Frozen soil?	Separates field data from lab data Separates soil data from rock data Separates frozen soil data from unfrozen
Soil information	Soil type description Soil classification Bulk unit weight* Grain size distribution Specific volume Porosity Permeability*	Descriptive terms Classification by scheme % clay, % silt, % sand, % gravel
Moisture content information	Moisture content* Percent saturation Type of measurement Is m/c estimated (or measured)?	By weight or volume Keyword list Separates out inferred moisture data
Other information	Publication reference Memo field	Link to bibliographic reference Other pertinent information - gives page no. and graph or table for the data point

Notes:
1. * indicates several fields are used to allow data entry in different units.
2. A field followed by a ? is a logical field
3. For graphs without indicated data points, a minimum number of data points are inferred that would define the curve presented.

reviewed and compared in Farouki (1986). The recommended procedures will be available from ASHRAE by the time of publication of this paper (Sterling, in preparation).

The estimation problem is influenced by the following principal issues:

- the nature of the problem under consideration,
- determination of the soil zones for which different thermal properties should be considered (zonation), and
- determination of any appropriate variation in thermal properties with time (temporal fluctuations).

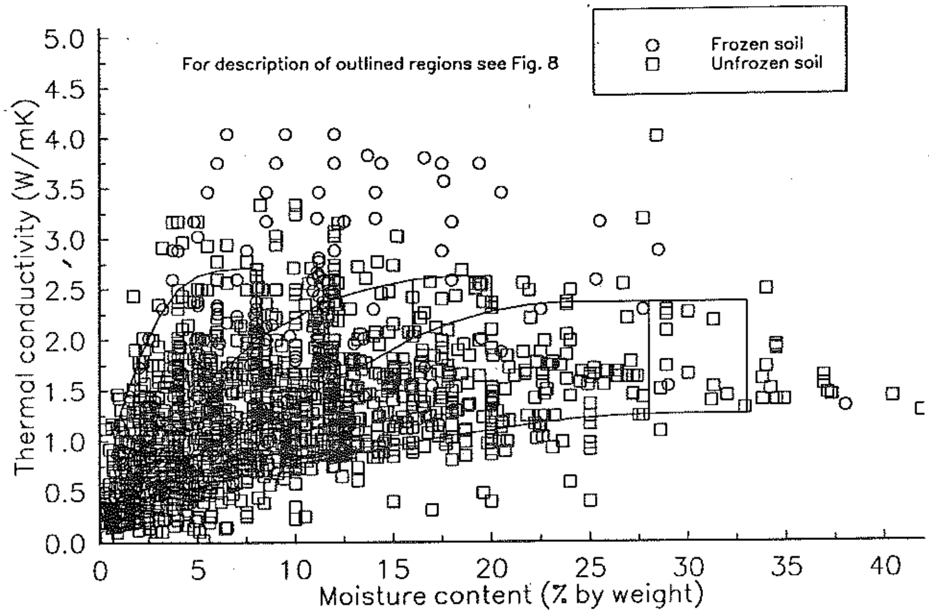

Figure 1 *Frozen and unfrozen soil data from laboratory tests.*

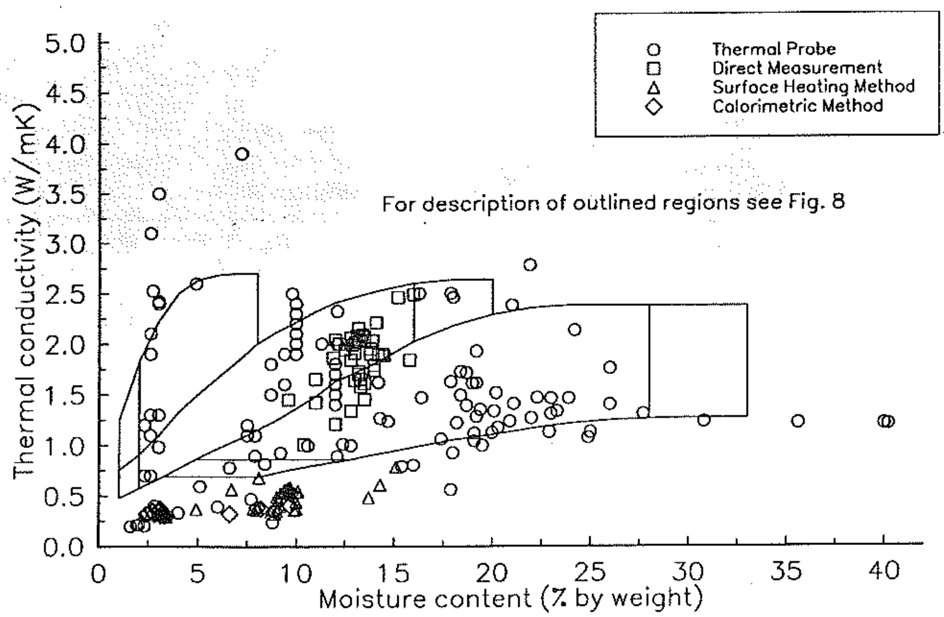

Figure 2 *In-situ data by type of measurement.*

Nature of Problem

Because of the temporal and zonal variation of soil thermal properties and the coupled dependence of heat and moisture transfer mechanisms on the soil temperature and heat transfer rate, the nature of the application for which the thermal properties are needed influences the selection of appropriate values of thermal conductivity. Table 3 provides a listing of the more common types of ground heat transfer applications. These divide into the broad categories of cases where

- a moderately conservative high value is required for assessing the maximum likely heat flow rate from or to a structure,
- a moderately conservative low value is required for assessing the minimum likely heat flow rate from or to a structure,
- a best estimate is required for comparative studies or because the choice of a conservative value is not possible,
- a single estimate of conductivity is acceptable for the affected zone of ground and is not assumed to vary with time, and

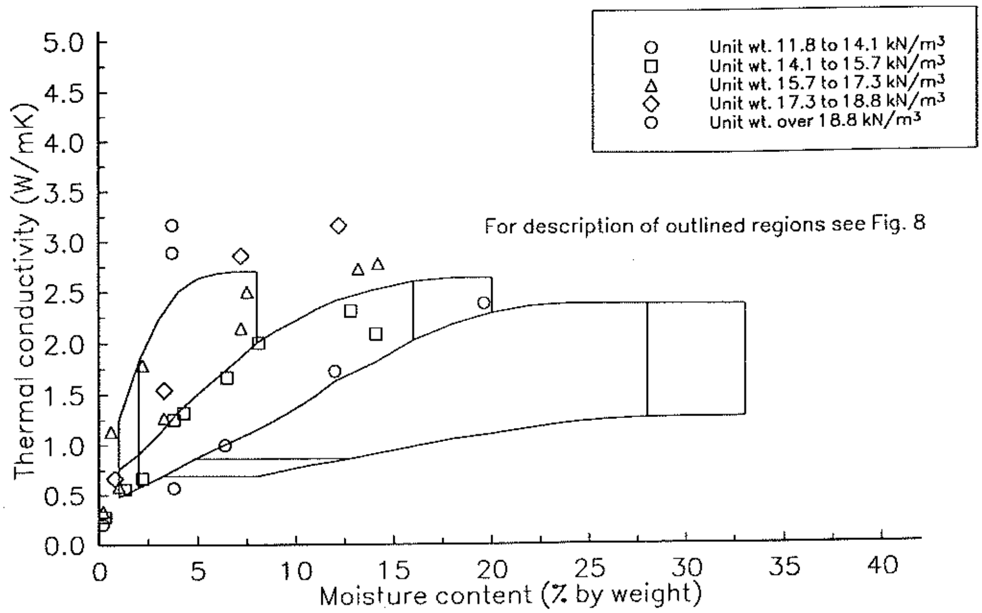

Figure 3 ***Granular soils by unit weight groupings.***

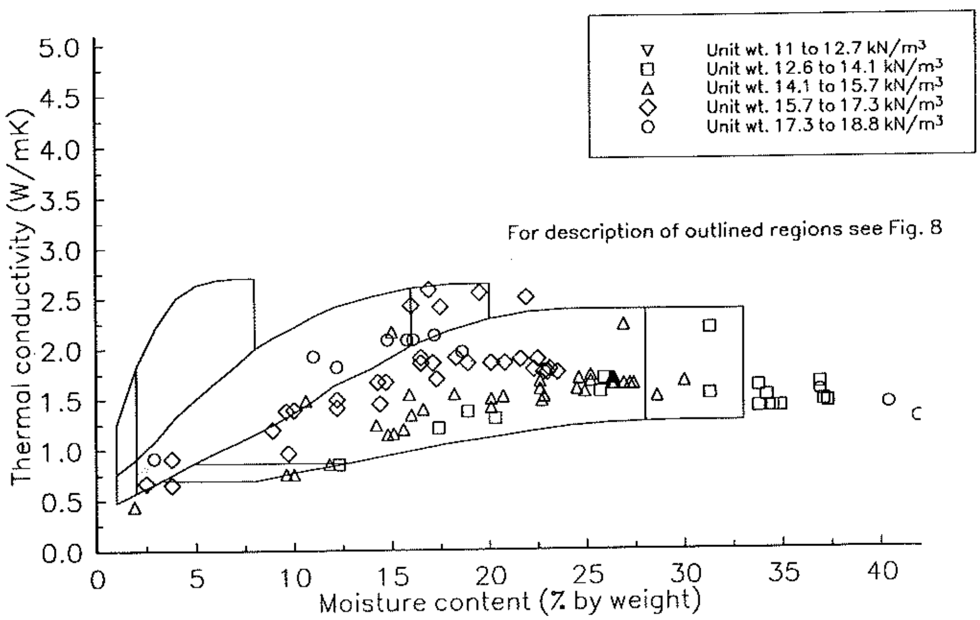

Figure 4 ***Clays by unit weight groupings.***

- conductivity estimates corresponding to ground zonation and temporal variations in ground conditions are required for critical and/or annualized studies.

The criticality of the estimate, the economic impact of a poor estimate, and the availability of data all influence the level of estimation that is necessary and possible for the problem under consideration.

ECONOMIC IMPACTS ON THE ESTIMATION PROCEDURE

Obtaining the best estimate of soil thermal conductivity is subject to the usual constraints of available time and budget and whether a better estimate will have a critical impact on the project in question. Many of these issues can only be resolved by design judgment, but the question of how much should be spent to improve an estimate of thermal conductivity to allow the most cost-effective choice of insulation configuration is amenable to analysis and is an important one. Similar issues have been addressed in geotechnical site investigations, and the problem is termed the "cost of misclassification." Since the actual value of soil thermal conductivity and resulting heat transfer is not directly affected by the designer wrongly estimating its value, the cost of misclassification comes from using a less than optimum insulation configuration based on an erroneous assumption about soil thermal conductivity. This can be formally stated as

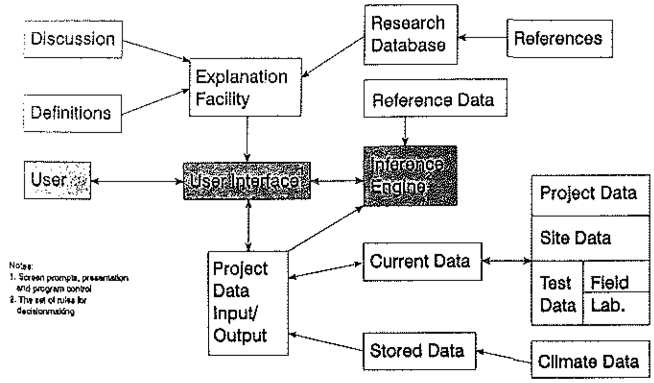

Figure 5 *Organization chart for an expert system for estimation of soil thermal properties.*

TABLE 2
Levels of Estimation for Apparent Soil Thermal Conductivity

Level	General Description	Available or Required Parameters	Methodologies
1	Average value, typical range or conservative values for design	Purpose of analysis General project, site & climate data No geometric or temporal zonation	Use general purpose figures and tables
2	Improved estimate with some soils data available	Purpose of analysis, project, site & climate data Soil type, density, moisture content Simple ground zonation	Refine figure and tabular estimates Search data base for similar conditions Use regression equations e.g. Kersten, or simple physical models eg. Woodside and Messmer.
3	Good non-field estimate. Detailed soils data is available or specified for collection Use detailed models or laboratory tests and infer field conductivity	Detailed soil properties, including mineralogy and shape of soil grains, soil pore size, anticipated heat flux rate, etc. Field moisture data, ground zonation and temporal zonation to match accuracy of models	Semi-realistic physical models of heat transfer in unsaturated porous media, e.g. deVries, or semi-empirical methods eg. Johansen. Simulation of small representative element of soil
4	Direct field measurement or back analysis of thermal properties	Expected geometric and temporal variation of soil thermal properties to guide location and time(s) of measurement	Thermal needle or other thermal disturbance methods Back analysis of ground temperature data

TABLE 3
Ground Heat Transfer Applications

Applications	Information sought
Building foundations	Peak heat loss or gain Annual energy use Potential for frost damage
Ground heat exchange systems	Max. or min. heat exchange potential Hourly, diurnal or annual performance
Buried electric power transmission lines	Minimum value of heat dissipation
Pipelines	Max. and annual energy loss for hot pipelines Max. and annual energy gain for cold pipelines
Agriculture	Growing season estimation Max. and min. temperature in root zone

$$\$MC = \$LC1 - \$LCA$$

where

$MC = present worth of the cost of misclassification;

$LC1 = present worth of the life-cycle cost of the insulation strategy, which is the minimum life-cycle cost option for the assumed soil properties; and

$LCA = present worth of the life-cycle cost of the insulation strategy, which is the minimum life-cycle cost for the actual soil properties.

The cost of refining an estimate by more detailed zonation in analyses and more field testing and/or laboratory studies can then be compared with the present worth of the cost of misclassification.

To provide an indication of how this comparison might look for the design of an individual residence, the data provided by Shen et al. (1988) can be used. They estimated the annual whole-house energy requirement for a single-story house (area of 143 m^2 [1,540 ft^2]) with a full basement using finite-difference ground heat transfer simulations coupled to DOE-2 for the whole-house energy response. They analyzed five different foundation insulation levels ranging from none to RSI-3.52 (R-20 [$h \cdot ft^2 \cdot °F$]/Btu) for the full basement wall height. The analyses were conducted for dry soil conditions with an apparent soil conductivity of 0.86 W/m·K (0.5 Btu/($h \cdot ft^2 \cdot °F$) and for wet soil conditions with a value of 2.57 W/m·K (1.5 Btu/[$h \cdot ft^2 \cdot °F$]. Using an energy cost per kilowatt-hour equivalent to a medium price level of natural gas (from Labs et al. [1986]) an analysis of the life-cycle cost of misclassifying a soil as wet or dry can be made. The results of this analysis for a house in Minneapolis are shown in Table 4. The high thermal conductivity assumption for the soil produces a minimum present worth, 30-year life-cycle cost of $19,611 for the option of RSI-3.52 full wall (the lowest life-cycle cost in the row). The low thermal conductivity assumption produces an equivalent cost of $17,284, but for the RSI-1.76 full-wall option.

Two costs of misclassification can be considered from these data. First, if the soil is assumed to have a low thermal conductivity, the RSI-1.76 full wall option should be chosen for a minimum life-cycle cost. If, in fact, the soil has a high thermal conductivity, the insulation option chosen will produce a life-cycle cost of $19,726 (the figure directly above), which is $115 higher than the optimum that should have been chosen if the soil were known to have a high thermal conductivity ($19,611). Considering the reverse situation, where the soil is assumed to have a high thermal conductivity, the cost of misclassification would be the difference between the minimum cost for a low soil thermal conductivity and the cost of the option chosen under the high assumptions ($17,366 - $17,284). This is a present worth cost difference of only $82; thus, the worst present value cost of misclassification for a house in Minneapolis is estimated to be $115. In fact, if the economical assumptions are changed, it is easy to arrive at the situation in which the most economic alternative among those listed is the same for both high and low soil thermal conductivities. Under such conditions, the cost of misclassification would be zero. The small costs of misclassification come about because there are only small differences in the total life cost over a range of insulation placements near the optimum value. The costs of misclassification in warmer climates are not likely to be more severe than those listed for Minneapolis. Wing insulation placements, however, may show a greater cost of

TABLE 4
Cost of Misclassification

	Thermal Conduct.	Insulation level (RSI)				
		None	0.88 half wall	0.88 full wall	1.76 full wall	3.52 full wall
Annual energy use (kWh)	High	55435	42455	38441	34837	32200
	Low	44821	35218	33109	30091	27835
Annual cost at $0.028/kWh	High	1552	1189	1076	975	902
	Low	1255	986	927	843	779
Present worth of annual cost (1)	High	28519	21841	19776	17922	16565
	Low	23058	18118	17033	15480	14320
Installation cost		0	737	1164	1804	3046
Total present worth	High	28519	22578	20940	19726	19611
	Low	23058	18855	18197	17284	17366

Notes: 1. 30-yr analysis, discount rate 10%, energy cost inflation 5%.
2. High thermal conductivity = 2.57 W/m·K, low = .86 W/m·K.
3. The shaded boxes are the lowest life cycle cost for each conductivity assumption

misclassification than wall placements since they are likely to be affected more by the soil thermal properties.

This analysis shows that it is not an economical proposition to spend much money or effort to determine the actual soil thermal conductivity for an individual house with a conventional heating system. More effort might be warranted for larger buildings, for higher levels of ground heat transfer, and for decisions affecting a larger number of buildings (although this reduces the level of site-specific information possible). Also, the analysis illustrated only addresses the economic costs of selecting an insulation system for minimum life-cycle energy costs in building foundations. Other design issues might have far higher costs of misclassification, e.g., the cost of mispredicting frost heaving of a foundation or the thermal instability of a buried electric transmission line.

As a basis for comparison with the above numbers, the costs of some of the tests used to establish or estimate thermal conductivity of soils were reviewed. Salomone (1988) documented the typical costs of thermal conductivity testing as $150 to $200 for a single thermal conductivity or thermal diffusivity test and approximately $750 to generate a curve of thermal conductivity versus moisture content for a single soil sample in the laboratory. In 1992, a single laboratory moisture content test costs about $10 and a combined density and moisture content evaluation on a split-spoon soil sample costs about $30 when done as part of a normal site investigation procedure for determining acceptable foundation bearing capacities, etc. Moisture content and density data are usually the minimum level of data required for a sample-specific calculation of estimated soil thermal conductivity.

Site Parameters and Ground Zonation

For building/ground heat transfer, the most important zone of soil for which the thermal conductivity must be estimated is adjacent to the building and is the zone in which the heat transfer patterns caused by the building foundation are significantly different from those in a non-building, open-field condition. This zone varies with the size of the foundation, its shape, and its depth as well as the temperature differential between the foundation and the surrounding ground. Figure 6 illustrates a hypothesized set of simple rules to determine a reasonable estimate of the most affected zone of soil around a building foundation. Values for the ground and above-ground climatic parameters are available. Reasonable values for coefficients *a* and *b* are under investigation.

The climate of the building site influences the soil temperature, soil moisture content, and whether soil freezing will be a significant concern. Soil moisture is also influenced by the location of the groundwater table, surface drainage impacts, vegetation, and soil permeability. Figure 7 illustrates a hypothetical section of a small building foundation and the potential complexity in assessing relatively homogeneous zones for soil thermal conductivity even when existing soil conditions do not vary laterally across the site. For most building analysis purposes, the assessment of a different soil thermal conductivity for each of these zones is not warranted. However, such potential variations of soil moisture content, soil type, soil density, surface vegetation, and surface drainage impacts within the zone of influence of the building also bring into question the appropriateness of trying to determine the thermal conductivity of a particular zone with any great degree of accuracy. If only one or two representative values are to be used to characterize the soil thermal properties around the foundation, too detailed an estimate implies a false level of accuracy in thermal calculations.

Temporal Variation

It has been hypothesized that the thermal conductivity of soil around building foundations changes in a predictable manner on an annual cycle—with heat loss from the foundation causing a drying of the soil and a decrease in thermal conductivity in the wintertime, which may be accentuated by the cessation of moisture entry through the ground surface in climates where the ground surface becomes frozen. The few cases of monitored data on soil moisture or conductivity variations around building foundations at different times of the year do not confirm that this type of response is necessarily seen. Shen and Ramsey (1981) found that the moisture content of the soil adjacent to an underground wall varied less with time than with depth (fluctuations in soil parameters). Bligh and Smith (1983) found that the soil moisture content was close to its field capacity (the moisture of a soil that has been thoroughly wetted and then drained until the drainage rate has become negligibly small) most of the year, that the influence of rainfall was short-term, and that there was no evidence of soil dryout adjacent to the building. Statistical data for field soil moisture contents are available from agricultural research and are summarized in Salomone and Marlowe (1989). These were used in developing reasonable moisture content cutoff values (field capacity and wilting point) for different soil classes, as shown in Figure 8. Except for short periods after rainfall and during prolonged droughts, the moisture content of a soil will typically lie between its field capacity and its wilting point (the moisture content of a soil below which a plant cannot alleviate its wilting symptoms).

BASIC ESTIMATION OF APPARENT THERMAL CONDUCTIVITY

To conclude this paper some generalized values/relationships of apparent soil thermal conductivity are included (see Figure 8 and Table 5). This information was prepared for the forthcoming edition of the *ASHRAE Handbook—Fundamentals* at an early stage of the research project. These data may change slightly in the final recommendations from the current project but provide a reason-

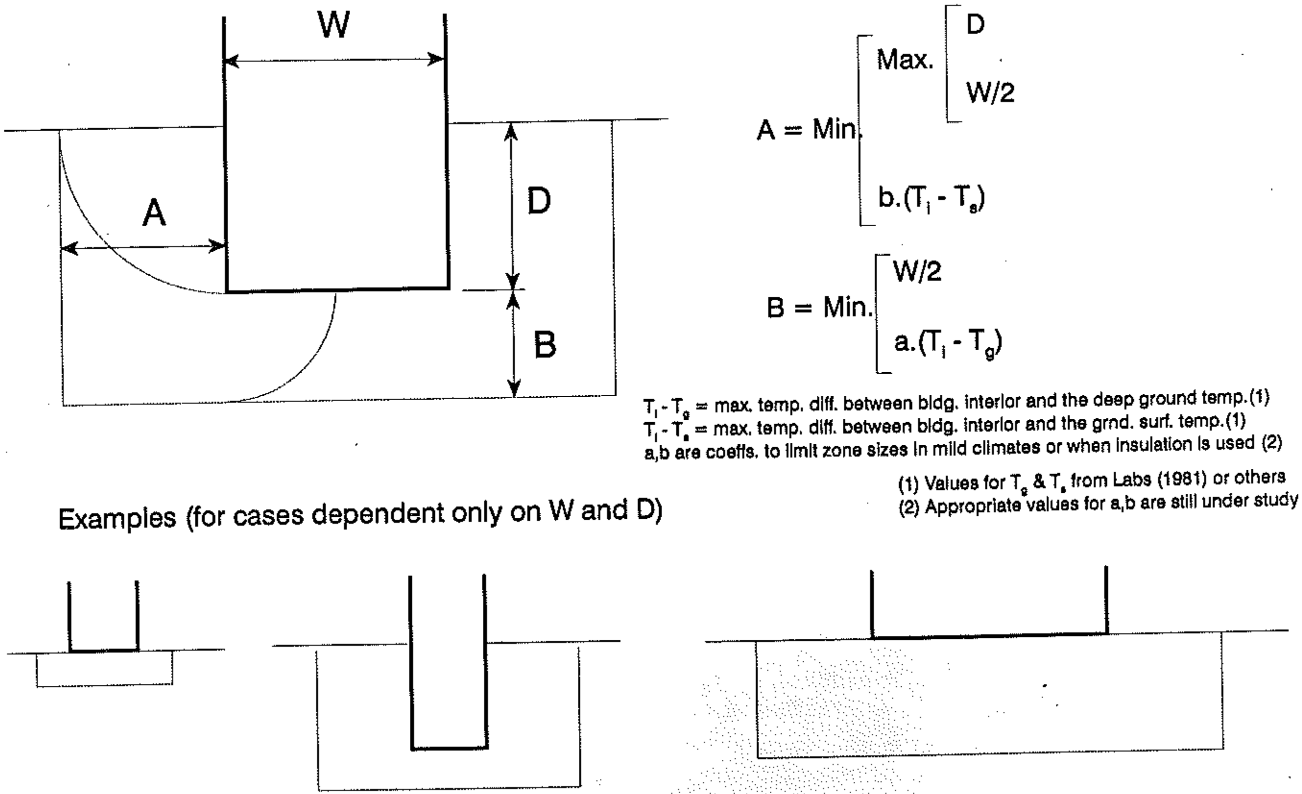

Figure 6 *Proposed approach to assessing a zone of influence of soil properties on building heat transfer.*

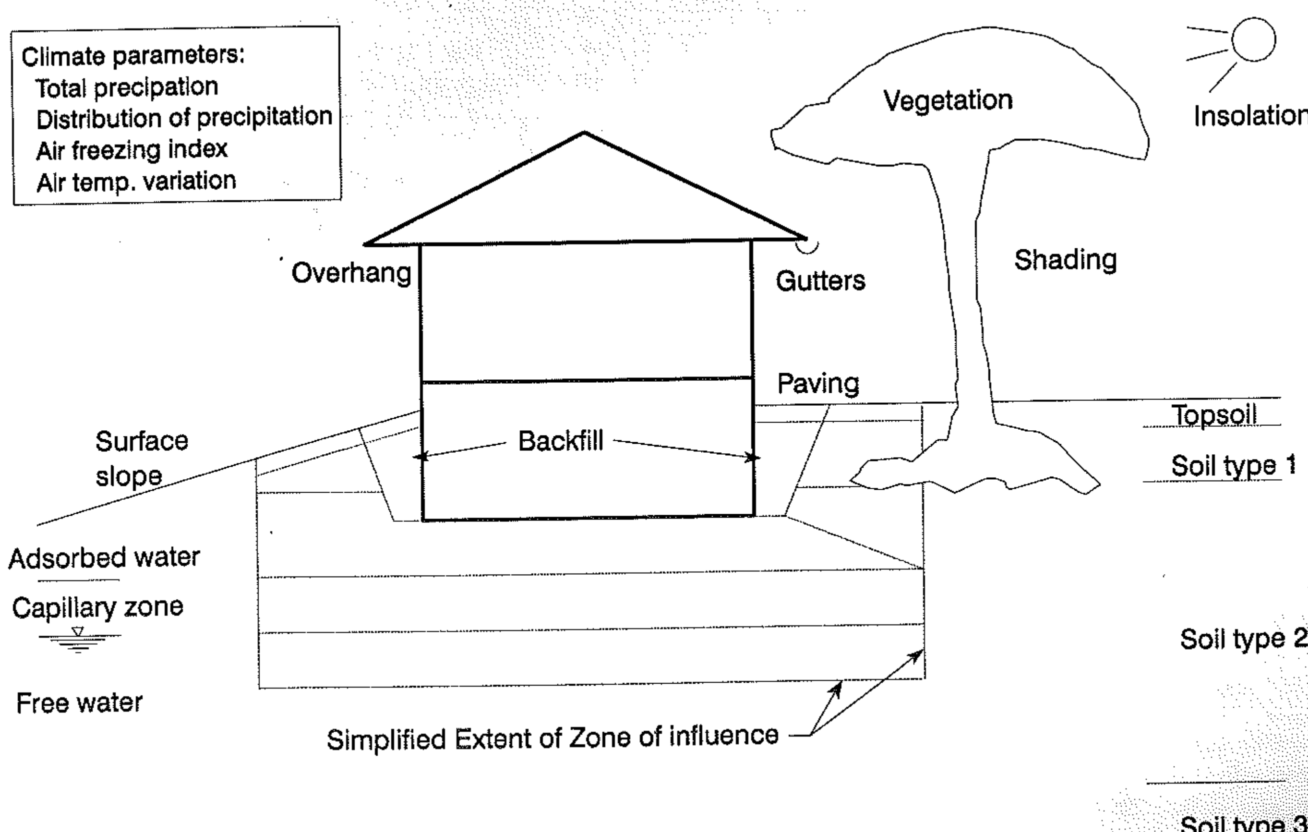

Figure 7 *Potential ground zonation adjacent to a building foundation.*

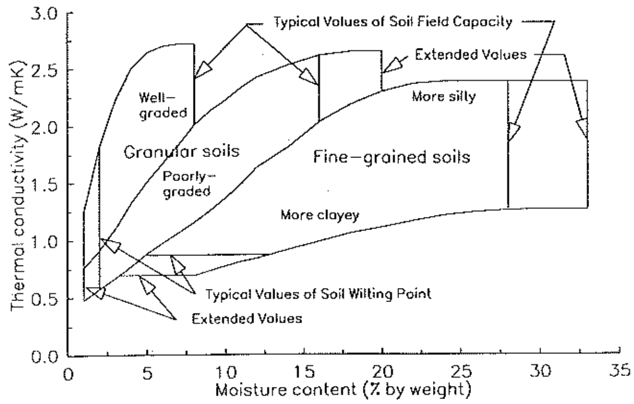

Figure 8 *Anticipated ranges of dependence of apparent thermal conductivity on moisture content for general soil classes based on Salomone and Marlowe (1989).*

TABLE 5
Typical Values of Apparent Thermal Conductivity for Soils (W/m · K)

	Normal range	Recommended values (1)	
		Low (2)	High (3)
Sands	0.60 - 2.50	0.75	2.25
Silts	0.85 - 2.50	1.65	2.25
Clays	0.85 - 1.65	1.10	1.55
Loams	0.85 - 2.50	0.95	2.25

Notes:
1. Reasonable values for use when no site or soil specific data is available.
2. Moderately conservative values for minimum heat loss through soil (from Salomone and Marlowe, 1989).
3. Moderately conservative values for maximum heat loss.

able guide to the variation that might be expected among various soil types at different moisture contents. These data also provide reasonable values to use as conservative estimates for conductivity in heat loss and heat gain problems.

Figure 8 is an adapted version of the results of testing of a wide range of soil types reported in Salomone and Marlowe (1989). The two limiting curves represent the maximum or minimum curves obtained for granular or fine-grained soils (but excluding unusual soils such as marine clays). The two intermediate curves represent soils with borderline classifications between the general soil classes. The straight lines on the graph are taken from moisture data on field soils from the National Soil Moisture Study, Agricultural Research Service experimental watersheds or plots, a soil data base, and Ratliff et al. (1983). These data were collected and presented in Salomone and Marlowe (1989). The typical values are taken from the median values of wilting point and field capacity measured. The extended values are taken from the 5th percentile values (wilting point) and the 95th percentile values (field capacity). Since the moisture studies included more detailed descriptions of soil type, the limits of the moisture contents have been simplified to straight-line boundaries. The horizontal line limits for fine-grained soils provided a better fit to the data from various soil types midway between clayey and silty soils in the fine-grained region. This figure was prepared as a graphical illustration of the likely soil thermal conductivity dependency on moisture content for various soil types. The extent to which these zones reasonably encompass the data reported in the literature is being tested against the data base. For the purposes of comparison, the zones from Figure 8 are overlaid on the data presented in Figures 1 through 4.

Table 5 lists normal ranges and moderately conservative estimates of apparent thermal conductivity of in-situ soils for use in building design and analysis. These values were selected during compilation of the data base and will be statistically analyzed when the data base is complete.

CONCLUSIONS

The issues involved in assessing the apparent thermal conductivity of a soil for building applications have been reviewed and a methodology for assessment at varying levels of required accuracy has been outlined. The full procedures will be presented in an ASHRAE report. A data base of soil thermal properties also has been described and is available for use by researchers and practitioners.

ACKNOWLEDGMENTS

The support of the American Society of Heating, Refrigerating and Air-Conditioning Engineers and the guidance of Technical Committee 4.4 are gratefully acknowledged. This paper would not have been possible without the assistance of Dr. L. Shen and Dr. L. Goldberg of the Underground Space Center and Dr. S. Gupta of the Department of Soil Science at the University of Minnesota, who provided data, references, and critical comments in developing the data base and estimation approach. Special thanks go to Yiming Sun, a graduate student at the University of Minnesota, who had the unenviable task of carrying out the compilation of the data base, and to J. Christian of Oak Ridge National Laboratory for his encouragement, comments, and suggestions.

REFERENCES

ASHRAE. 1989. *1989 ASHRAE Handbook -- Fundamentals*. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Bligh, T.P., and E.A. Smith. 1983. Thermal conductivity measurements of soils in the field and laboratory using a thermal donductivity probe. Report to U.S. Dept. of Energy, Contract No. DOE/DE-ACOS-80sf11508. Cambridge, MA: MIT Joint Program for Energy Efficient Buildings and Systems.

Farouki, O.T. 1986. *Thermal properties of soil.* Clausthal-Zellerfeld, Germany: Trans Tech Publications.

Johansen, O. 1985. Thermal conductivity of soils. Ph.D. thesis, Trondheim, Norway. *CRREL Draft Translation* 637, 1977.

Kersten, M.S. 1948. The thermal conductivity of soils. *Proc. 28th Annual Meeting Highway Research Board* 28:391-409. Washington, D.C.: National Research Council.

Labs, K. 1981. Regional analysis of ground and above-ground climate. *Report to Oak Ridge National Laboratory,* ORNL/Sub-81/40451/1, for U.S. Department of Energy.

Labs, K., J. Carmody, R. Sterling, L. Shen, and J. Huang. 1986. *Building foundation design handbook,* prepared for Oak Ridge National Laboratory, ORNL/Sub/86-72143/1. Minneapolis, MN: Underground Space Center, University of Minnesota.

Ratliff, L.F., J.T. Ritchie, and D.K. Cassel. 1983. Field-measured limits of soil water availability as related to laboratory-measured properties. *Soil Science Society American Journal* 47(4): 770-775.

Salomone, L.A. 1988. Feasibility study for collecting site soil characterization thermal property data for residential construction. ORNL/Sub/86-04923/1/October. Report to Oak Ridge National Laboratory, Oak Ridge, TN.

Salomone, L.A., and J.I. Marlowe. 1989. Soil and rock classification according to thermal conductivity: Design of ground-coupled heat pump systems. Report to Electric Power Research Institute, Report No. EPRI CU-6482. Chantilly, VA: STS Consultants, LTD.

Shen, L.S., and J.W. Ramsey. 1981. Temperature, heat flux, and moisture measurements at Williamson Hall. Part 1 of Final Report, Energy Conservation by Subsurface Construction. Prepared for Innovative Structures Program, Oak Ridge National Laboratory, by Heat Transfer Laboratory, University of Minnesota, Contract No. 96X-42533.

Shen, L.S., Y.J. Huang, and J. Poliakova. 1988. The effect of soil thermal and moisture properties on building foundation heat loss. *Proc. 3rd. Int. Conf. on Underground Space and Earth Sheltered Buildings,* Shanghai, PRC, Tongji University, Shanghai.

Sterling, R.L., in preparation. Assessment of soil thermal conductivity for use in building design and analysis. Report to American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, Georgia.

deVries, D.A. 1966. Thermal properties of soil. Chapter 7, *Physics of Plant Environment,* 2d ed., W.R. Van Wijk, ed. Amsterdam: North-Holland Publishing Co.

Woodside, W., and J.M. Messmer. 1961. Thermal conductivity of porous media. *Journal Applied Physics* 32(9): 1688-1706.