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Publisher's version / Version de l'éditeur:

Géotechnique, 13, 3, pp. 241-249, 1963-09

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BY
W. G. BROWN

REPRINTED FROM
GÉOTECHNIQUE, VOL. 13, NO. 3, SEPTEMBER 1963, pp. 241-249.
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RESEARCH PAPER NO. 194
OF THE
DIVISION OF BUILDING RESEARCH

PRICE 25 CENTS

OTTAWA
SEPTEMBER 1963

NRC 7570

16503

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THERMAL MODEL TESTS FOR PROBE CONDUCTION ERRORS IN GROUND-TEMPERATURE MEASUREMENT

by

W. G. BROWN, D.Sc.(Tech.), M.Sc.*

SYNOPSIS

Several reduced scale models of probes for ground-temperature measurements were tested in the laboratory to determine heat conduction errors. Actual field conditions were simulated by applying a sudden temperature change to the model ground surface, and temperatures at equivalent field depths of up to several feet were measured. The size scale of the models was nominally 1:10 and times of 1 or 2 hours represented 4 to 8 days in the field. With probes of conventional design containing bundles of thermocouples the errors were found to range between approximately 1° to 3°F for depths less than about 3 ft. For most probes, errors of less than 0.1°F would be expected for depths greater than 5 ft.

On a fait des essais en laboratoire avec plusieurs modèles réduits de sondes de mesure de température du sol afin de déterminer les erreurs de conductivité. On a reproduit les conditions actuelles sur le terrain en provoquant un changement de température brusque à la surface du sol du modèle et on a mesuré les températures à des profondeurs équivalentes à plusieurs pieds sur le terrain. L'échelle de modèle était de un dixième, et des durées de 1 ou 2 heures représentaient 4 à 8 jours sur le terrain. Avec des sondes de conception conventionnelle comprenant des faisceaux de thermocouples on a noté des erreurs allant d'environ 1° à 3° F pour des profondeurs de moins de 3 pieds environ. Pour la plupart des sondes, on s'attendrait à des erreurs de moins de 0.1° F pour des profondeurs de plus de 5 pieds.

INTRODUCTION

When temperature sensing devices are inserted into the ground from the surface, either as separate probes or in groups inside tubes or on supports, some temperature error results because the thermal properties of the probe are generally different from those of the ground. Whether this error is significant depends on the cross-sectional area of the probe and the depth to which it is inserted.

There are two basic types of ground-temperature measurement. In the first, spot measurements are made by sudden and temporary insertion of the probe. Errors associated with this method are covered extensively by Cunningham and Rohsenow (1960).¹ In the second method, which will be treated here, the probe remains permanently in place and measurements are made continuously or periodically to record, for example, the effects of diurnal or annual weather changes.

The mathematical complexities that arise in considering probes of practical shape rule out an analytical approach to the problem. In place of the analytical approach, however, the method of models offers several advantages: size and time reductions, and the opportunity to apply a uniform temperature change at the ground surface. The present study was intended only to investigate the errors occurring at shallow depths on two probes of a type used by the Division of Building Research, National Research Council. Along with tests on two other probes of arbitrary design the results indicate the general magnitude of errors to be expected. In addition, the tests offer another example of the usefulness of models in problems of heat exchange in the ground (compare Brown, 1958).

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¹ The references are given on p. 249.

EQUIPMENT AND PROCEDURE

Scale

The model probes were intended to simulate field prototypes measuring temperatures within a few feet of the ground surface. By choosing a length scale of approximately 1:10 it was possible to build a small laboratory apparatus in which tests of only 1 or 2 hours' duration would yield the same information as field tests requiring from 4 to 8 days (i.e. for the same soil the time scale is 1:100). With a length scale of 1:10 the 36-gauge (0.005-in. dia.) copper-constantan thermocouples used throughout would represent wires of 0.05-in. diameter commonly used in field installations of this type.

Auxiliary equipment

The four probes were inserted in the central region of an 18 in. $\times$ 18 in. $\times$ 12 in. box of fine sand at the corners of a $4\frac{1}{4}$ -in. square. At the centre of this square thermocouples were inserted horizontally at depths of 1, 2, and 3 in. to measure the true sand (ground) temperature.* On top of the box and in contact with the sand an open copper tank was installed as a receptacle for ice water for use in obtaining a sudden change in boundary temperature. The probes were inserted into copper sockets in the 0.125-in.-thick bottom of the copper tank and the whole tank and box arrangement was turned on its side for filling with sand. Side filling, accompanied by vibration, ensured good contact of the sand with the copper tank.

Two series of tests were made, the second necessitated by breakage of several of the fine 36-gauge thermocouples. In the first test temperatures were recorded on a 16-point Minneapolis Honeywell Brown Recorder, whereas in the second test a Monroe data log was added to print millivolt readings directly on tape. Precision of measurement in both tests was $\pm 0.1^\circ\text{F}$.

Description of probes

The dimensions of the probes investigated are given in Fig. 1. All thermocouples were of butt- or lap-welded 36-gauge cotton-covered copper-constantan wire. The depths at which the thermocouples were installed were measured carefully; measurements before and after placing and removing the sand indicating the precision of location to be within $\frac{1}{64}$ to $\frac{1}{32}$ in. The purpose of extending the probes into sockets in the bottom of the copper tank was to simulate an actual installation in which the probes usually extend above the ground surface.

Probe A.—Brass rod 0.1 in. in diameter, intended primarily as control since the range of errors was not known before the tests. Thermocouples were inserted through holes drilled in the rod at depths of 1, 2, and 3 in.

Probe B.—Birchwood circular dowel 0.25 in. in diameter and 6 in. long, hollowed out to contain five thermocouples at depths of 1, 2, 3, 4, and 5 in. The thermocouples exit at the various depths and make one half-turn in a groove around the dowel.

Probe C.—Thin-walled nylon tubing 0.125 in. outside diameter, 0.096 in. inside diameter, and 12 in. long, containing sixteen bare copper wires (0.006 in. dia.) in transformer oil. Three thermocouples were glued to the outside of the tube at depths of 1, 2, and 3 in.

Probe D.—Thin-walled nylon tubing 0.125 in. outside diameter, 0.096 in. inside diameter, and 12 in. long, containing three thermocouples in air at depths of 1, 2, and 3 in. The

* That no appreciable error occurs due to conduction along the leads will be apparent from the experimental results. In particular Fig. 6 shows that the probes themselves at 4–5 in. depths exhibit negligible error: hence the horizontal thermocouples having lengths of 9 in. cannot exhibit greater errors.

thermocouple leads extend completely through the tube, the constantan wires being above and the copper wires below.

Test procedure

The assembled apparatus was allowed to reach constant temperature (about 72°F) in the laboratory, then a mixture of ice and water was poured quickly into the copper tank and maintained by addition of ice chips as required. Test duration was approximately 2 hours,

Fig. 1. Probe dimensions

during which time the ice-water mix was stirred continuously. The test conditions correspond to the mathematical case of a sudden change in temperature at the surface of a semi-infinite solid.

TEST RESULTS

Contact resistance

A very thin layer of sand and air in immediate contact with the underside of the copper tank has thermal properties that differ from those of the main body of the sand. This occurs because a plane in the sand cuts through particles, whereas at the surface there is simply point contact between the sand and surface. It follows from theory (Carslaw and Jaeger, 1959, pp. 70-72) that in the range of tests encountered here, the contact resistance can be almost perfectly accounted for by assuming all thermo-couples to be buried an extra distance " l " from the surface.

Thermal properties of the sand

With account taken of contact resistance, the theory requires that temperature data for all depths in the sand should correlate on the basis of a plot of the temperature ratio $(T_0 - T)/(T_0 - T_\epsilon)$ versus $t/(x + l)^2$; where T_0 , T and T_ϵ are the initial temperature, temperature at time t and final temperature (32°F), and x is the actual depth of the thermocouple.

By plotting the temperature ratio first against t/x^2 it was possible to determine l by

Fig. 2. True temperature of sand

comparing the test results obtained with the horizontal thermocouples for the depths of 1, 2 and 3 in. The result gave an average value of $l = 0.11$ in. With this value of l the results correlate almost perfectly (Fig. 2). There are slight differences for the two tests due to differences in the sand density.

The thermal diffusivity α of the sand was determined with the help of theory which requires that:

$$\frac{T_0 - T}{T_0 - T_\epsilon} = \operatorname{erfc} \frac{(x + l)}{2\sqrt{\alpha t}} \quad . \quad . \quad . \quad . \quad . \quad (1)$$

for a sudden temperature change from T_0 to T_ϵ at the surface of a semi-infinite solid, where

$\text{erfc} = 1 - \text{erf}$ and erf is the error function tabulated in Carslaw and Jaeger (1959) p. 485. The results gave $\alpha = 0.00985$ sq. ft./hour for Test No. 1 and $\alpha = 0.01045$ sq. ft./hour for Test No. 2.

Temperature errors due to probes

Having established values for α and l the temperature readings of all probes can be compared with the true sand temperature on a consistent basis by plotting the dimensionless temperature ratio *versus* the dimensionless time, $\alpha t/(x + l)^2$. Results are given for the three

Fig. 3. Probe temperatures at 1-in. depth

depths in Figs 3, 4, and 5. To preserve clarity actual data points are not included; the precision, however, is equal to that of Fig. 2. (Subscripts indicate the test number.)

As would be expected, the brass control rod (probe A) showed the greatest error at all

three depths, as its thermal conductivity was very high. Following the brass rod in order of error magnitude at 1-in. depth were probe B containing five thermocouples, probe C with sixteen copper wires in oil, and probe D with three thermocouples. In the case of probe D, the error was in the opposite direction to that of the other probes, due to a combination of the high insulating value of the air in the tube coupled with heat conduction along the copper and constantan leads.* Since the thermal conductivity of copper is much higher than that of

Fig. 4. Probe temperatures at 2-in. depth

constantan, the gradient in the constantan will be higher than that of the copper in the neighbourhood of the junction. Similarly, this constantan gradient is higher than that in the sand and the result is a measured temperature ratio which is lower than that of the sand. Had the direction of the leads been reversed (i.e. copper wires extending upward) the measured temperature ratio would have been greater than that of the sand.

The magnitude of the errors at the 2-in. depth (Fig. 4) are considerably less than those at 1 in. and errors at the 3-in. depth (Fig. 5) are smaller again. The probes follow the same order in their errors as Fig. 3 except that probes B and C are interchanged. This is due

* The theory for this case is relatively simple and the error can be estimated with the help of the calculation method given by Fishenden and Saunders (1939).

principally to the fact that the number of heat conducting wires in probe B decreases with increasing depth.

In Fig. 6 the results for probe B at 4- and 5-in. depths are compared with the theoretical

Fig. 5. Probe temperatures at 3-in. depth

value for the sand. Within the limits of experimental accuracy there is no appreciable error apparent at these depths.

DISCUSSION

Probes B and C are types at present used in ground-temperature measurement. It is interesting to compare the magnitude of errors which would result with these probes in an actual field installation. With the scale of 1:10, model probe B would represent a field probe consisting of a wood rod 2.5 in. in diameter containing 0.05-in. thermo-couple elements which

measure temperature at 10-, 20-, 30-, 40- and 50-in. depths. Similarly, probe C would represent a 1-in. dia. oil-filled plastic pipe 10 ft long with temperatures being measured at depths of 10, 20, and 30 in. Assuming these probes to be in dry sandy soil ($\alpha = 0.01$) the

Fig. 6. Probe B temperatures at 4- and 5-in. depths compared with true temperature of sand

temperature errors can be determined from Figs 3, 4 and 5. Examples are given in Table 1 for a sudden change of 40°F in ground-surface temperature.

The error in probe B decreases with depth for reasons already given. The error in probe C, on the other hand, has a value of about 1°F at a depth of 30 in. From the rate at which this error decreases with increasing depth, however, it seems apparent that errors of less than about 0.1°F can be expected for depths greater than about 5 ft.

The data for probe A (brass rod) can be used to illustrate the large errors that may occur when even fine wires are inserted vertically from a surface. If, for example, probe A is

Table 1
Temperature errors in probes B and C at different times

Depth : in.	Temperature error in probe B: °F		Temperature error in probe C: °F	
	$t = 10$ hour	$t = 24$ hour	$t = 10$ hour	$t = 24$ hour
10	2.8	3.2	3.4	3.1
20	0.9	0.8	2.1	1.7
30	0.4	0.3	1.2	1.0

considered to be a ten-fold enlargement, then the probe in question would be 0.01 in. in diameter and temperature measurements corresponding to Figs 3, 4 and 5 would be at depths of 0.1, 0.2, and 0.3 in.

CONCLUSION

Most probes of design similar to probes B and C would be expected to exhibit only small temperature errors for depths greater than about 5 ft. For lesser depths, however, errors of several degrees F are possible. For this region other means of arranging thermocouples should be considered.

The data obtained in the tests may be used to determine errors that would result from any prescribed variations of surface temperature. For methods, the reader is referred to Carslaw and Jaeger (1959).

The model method reported here is extremely simple and is recommended for trials of different probe designs prior to field use.

ACKNOWLEDGEMENT

The equipment was constructed by Mr J. J. M. Lavoie of the DBR Building Services Section who also carried out the tests. This Paper is a contribution of the Division of Building Research, National Research Council of Canada and is published with the approval of the Director of the Division.

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