Heat flow measurements in freezing soils with various freezing front advancing rates

MASAMI FUKUDA

The Institute of Low Temperatures Science, Hokkaido University, Sapporo, Japan

Field observations at the Tomakomai Forest experimental station (Hokkaido), during the winters of 1975-1976 and 1976-1977, were undertaken to determine the relationship between the rate of frost heave and the speed of progression of the freezing front, and to measure the associated thermal flux. The poor relationship between the observed and calculated thermal flux values is attributed to insufficient knowledge of soil moisture conditions. Laboratory procedures are described which measure frost heave and soil moisture by the gamma ray attenuation method.

Études sur le terrain à la station forestière expérimentale de Tomakomai (Hokkaido), durant les hivers 1975-76 et 1976-77, pour déterminer la relation entre les taux de soulèvement par le gel et la vitesse de progression du front de congélation, et pour mesurer le flux thermique correspondant. Le manque d'accord entre les valeurs observées et calculées du flux thermique est attribué aux connaissances insuffisantes des conditions d'humidité. On décrit des méthodes de laboratoire permettant de mesurer le soulèvement par le gel et de surveiller les profils de teneur en eau par la méthode d'atténuation des rayons gamma.

Proc. 4th Can. Permafrost Conf. (1982)

Introduction

During the heaving process of soils, heat flow is coupled with moisture flow as water migrates upwards. The amount of undercooling at the freezing front is determined by the flux of heat through the soil and by the freezing front. The heat conducted away through the frozen soil comes from three sources: First, the heat conducted to the freezing front from below; secondly, latent heat from soil water *in situ*; and thirdly, latent heat from water migrating to the freezing front. Thus it is essential to establish the heat balance equation at the freezing front and to verify the equation by experimental studies in order to understand frost-heaving processes.

The author conducted both field measurements of heat flow through unfrozen and frozen layers during soil-freezing and laboratory measurements. From the comparison of the results, the author attempted to verify the heat balance equation.

Field Observations at Tomakomai

Instrumentation

For the study of frost heaving a field site was selected in the Tomakomai experimental forest, Hokkaido. A concrete waterproof basin (5 by 5 m wide, and 2 m deep) was filled with a test soil, Tomakomai silt (Figure 1). The water level within the basin was controlled artificially so that a sufficient amount of water was supplied to the soil for frost heaving to occur. During freezing, temperature profiles were obtained by strain-gauge type sensors at depths of 0, 5, 10, 20, 30, 40, 60, 80, 100, and 150 cm below the surface of the test basin. Frost penetration was determined by thin transparent pipes filled with a methylene-blue dye solution in water (this dye remains blue in an unfrozen state and turns colourless in a frozen state). Time-elapsed measurements of frost penetration at the test site were also done. Heave was monitored by displacement detectors connected to a data-logging system. From these measurements, time-variable heave rates and rates of advance for the freezing front were obtained.

Heat-flow sensors were buried at depths of 10, 20, 30, 40, 50, and 100 cm from the ground surface. Heat-flux values were recorded at 30-minute intervals by the data-logging system. At the 0°C isothermal line in the ground, estimated as the freezing front, heat flows both in and out were measured under various conditions.

Results and discussion

Typical features of frost heave are shown in two sets of observed results from the experimental site. The first set is a record of changes in level of the surface and in depth of the freezing front with the lapse of time during the 1976-1977 season (Figure 2). Two different types of soil were tested. These differences affected the total amounts of heave and the maximum depths of ground freezing. Type I soil is more susceptible to frost than type II soil. Water content profiles of both frozen soil types showed an identical tendency, namely, that water accumulated in certain frozen layers. For example, water content profiles of type II soil on January 7 and March 8, had the maximum peaks at the depths between 10 and 20 cm (Figure 3). A similar tendency for type I soil was also observed. Below the freezing front, water contents were considerably smaller than in the upper frozen layer. This means that water in the soil was redistributed after freezing and that the water accumulating occurred at the upmost layer (Figure 4). Comparison of the

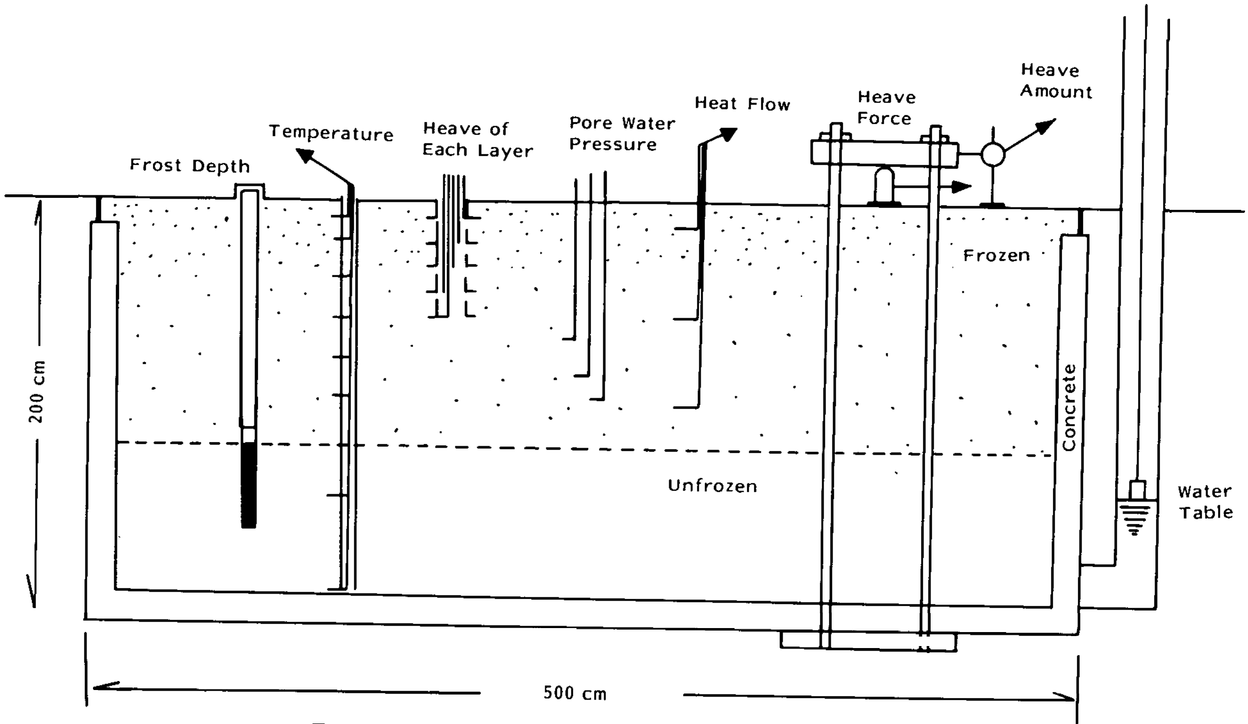

FIGURE 1. Cross section of frost heave test basin at Tomakomai.

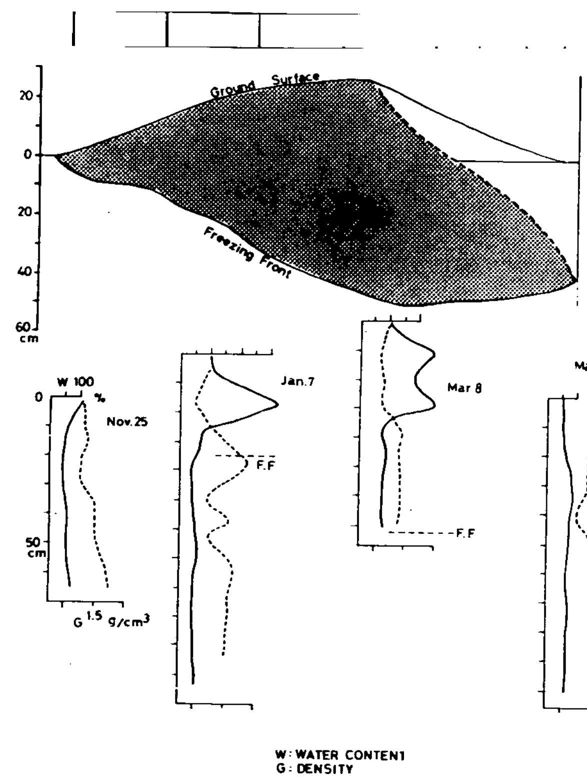

FIGURE 2. Results of soil freezing and heaving at test site I (Soil type I), 1976-1977.

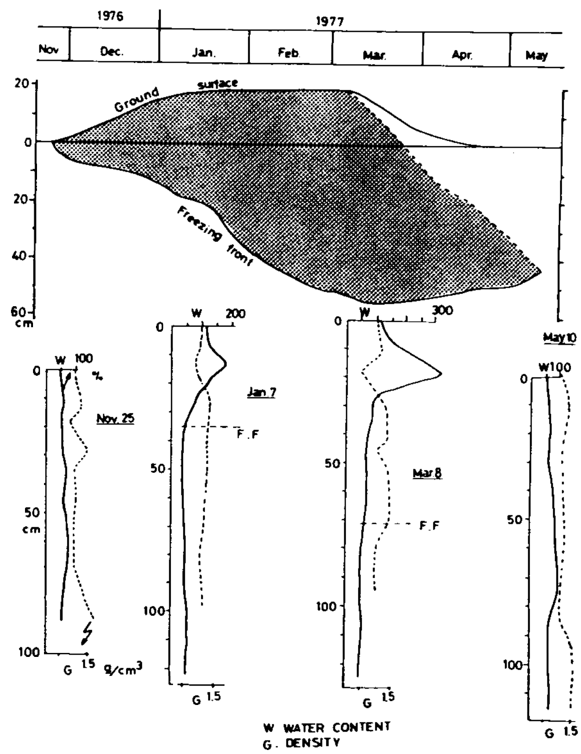

FIGURE 3. Results of soil freezing and heaving at test site II (Soil type II), 1976-1977.

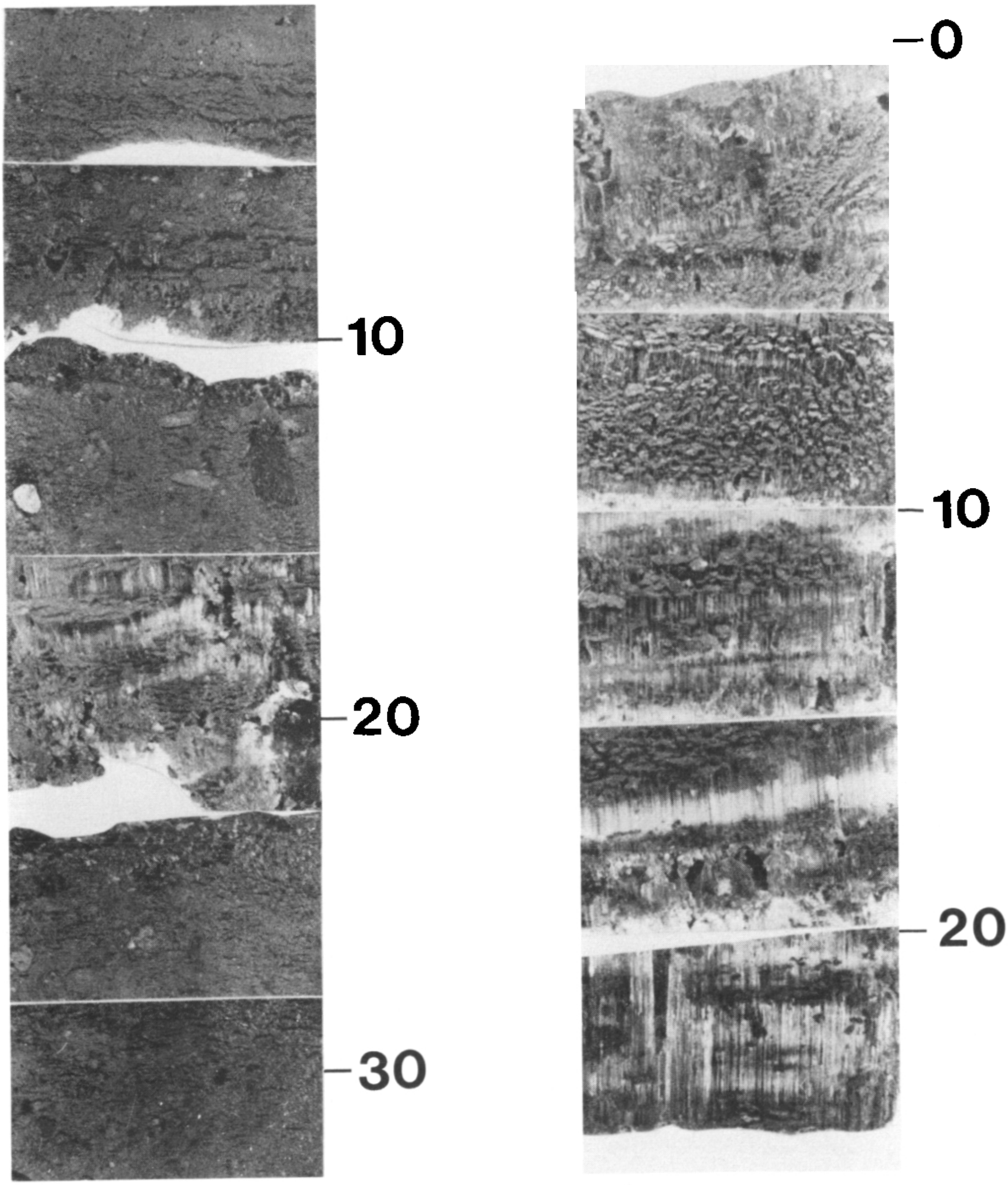

FIGURE 4. Cross sectional photos of frozen soil: (Right) type I soil, (left) type II soil.

redistributed water content profile with the photos shows that the layers of high water content correspond to the ice lenses in the frozen layers. Similar features in the frozen soil were observed in other winter seasons. To explains such a water redistribution, heat flow measurements were carried out in the field.

A typical result is illustrated with data from the 1975-1976 season (Figures 5 and 6). The accumulated degree days were about 600 degree Celsius days and the maximum depth of frozen ground was 60 cm. The maximum heave was 25 cm above the original ground surface. At a depth of 20 cm, the value of heat flow was measured as 20.9×10^{-5} W/cm^2 on January 15. On the next day the value of heat flow in-

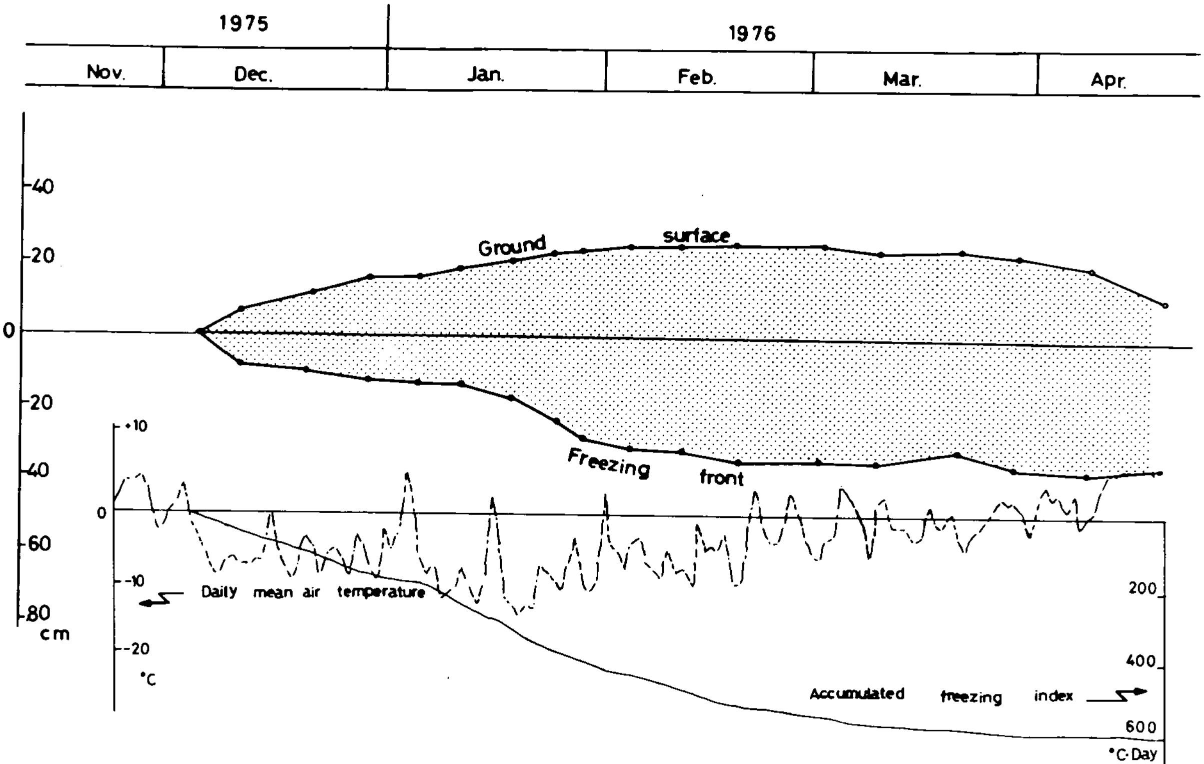

FIGURE 5. Results of soil freezing and heaving at test site III (Soil type I), 1975-1976.

creased to 71.06 × 10^{-5} W/cm^2. The data of the depth of the freezing front indicated that during these periods the freezing front passed the depth of 20 cm. The increase in heat flow was due to the released latent heat at the freezing front and two measured flux values corresponded to the heat flux into, and out of, the freezing front. It is expressed by the following heat balance equation (Chalmers and Jackson 1970).

$$[1] \qquad K_f \frac{\partial \theta f}{\partial x} - K_u \frac{\partial \theta u}{\partial x} = P_w L_w v + P_s L_s \frac{dx}{dt}$$

where K_f, K_u = thermal conductivities of the frozen and the unfrozen soil, respectively;

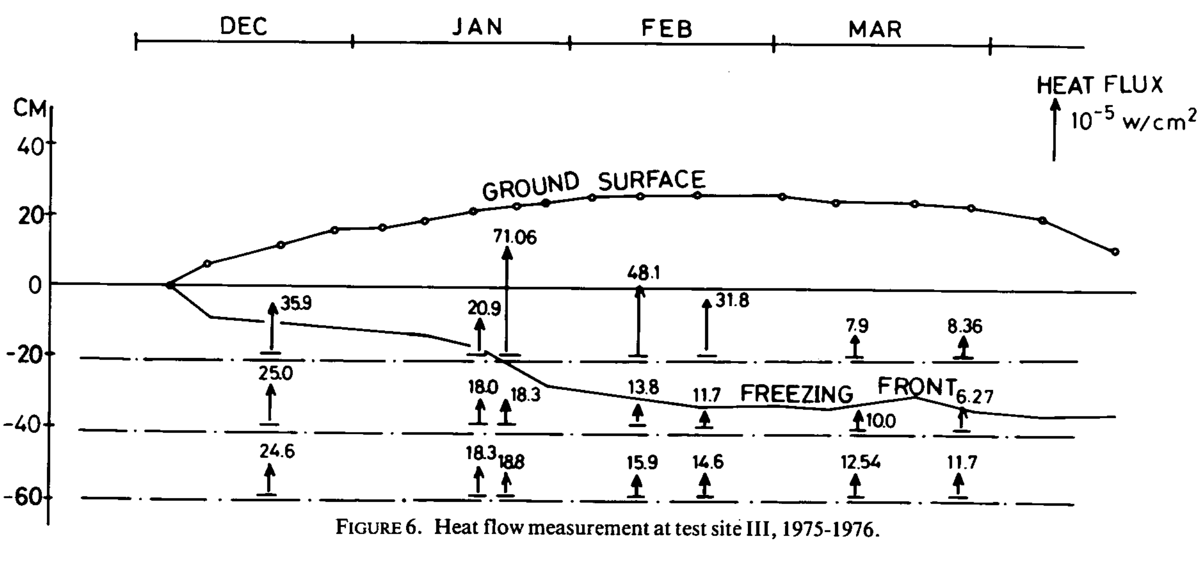

FIGURE 6. Heat flow measurement at test site III, 1975-1976.

$\frac{\partial \theta_f}{\partial x}, \frac{\partial \theta_u}{\partial x}$ = temperature gradients in the frozen and the unfrozen layer, respectively;

P_w, P_s = densities of water and ice, respectively;

L_w, L_s = latent heats of water and soil, respectively;

v = rate of flux of water transferred to the freezing front; and

$\frac{dx}{dt}$ = advancing rate of the freezing front.

The left side of the equation is assumed to represent the residual of the heat conducted out of, and into, the freezing front, which is equal to latent heat. This is separated into two parts. The first is due to the latent heat of water which flowed into the freezing front; the second is due to the latent heat of water frozen *in situ*. When measured values are substituted into the equation, the value of 50.1×10^{-5} W/cm^2 is obtained. The heaving rate and the advancing rate of the freezing front during this period were estimated as 1×10^{-6} cm/s and 6×10^{-6} cm/s, respectively. Hence, estimated values of latent heat of water either redistributed or frozen *in situ* were 33.4×10^{-5} and 50.1×10^{-5} W/cm^2. The sum of these two values is 83.5×10^{-5} W/cm^2 and corresponds to two terms of the equation. Consequently, the estimated value does not agree with the measured value. This is mainly due to the lack of water content values at that time period.

The results of other observations made during the 1977-1978 season are shown (Figures 7 and 8). For example on January 11, the measured value of latent heat was $Q_2 - Q_1 = 6.48 \times 10^{-4}$ W/cm^2. However, the estimated value, based upon the heaving rate (2×10^{-6} cm/s), the freezing advancing rate (2×10^{-6} cm/s), and water content (0.3 cm^3/cm^3), was 8.35×10^{-4} W/cm^2. In another case on January 27, the measured value was $Q_2 - Q_1 = 8.18 \times 10^{-4}$ W/cm^2. Using a value for the heaving rate of 2×10^{-6} cm/s, a freezing advancing rate of 3×10^{-6} cm/s and a water content of 0.3 cm^3/cm^3, the value of 10.5×10^{-4} W/cm^2 was estimated. Again, in these two cases, the estimated values do not agree with the measured values. These disagreements are mainly due to insuffcent data on water content and flux of water. For verification of equation 1, field observation gave general features of soil heaving such as either water accumulation or ice lenses. From this point of view, a relevant laboratory experiment for soil freezing is called for, in order to determine in a non-destructive manner the water-content profile.

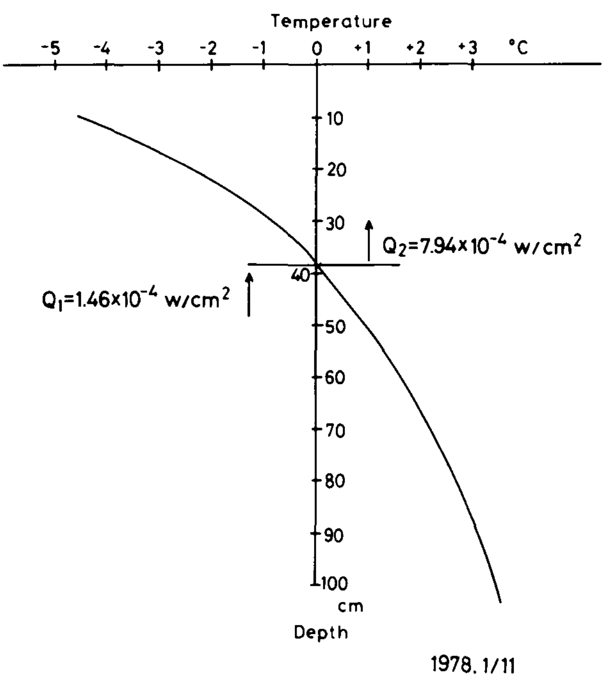

FIGURE 7. Heat flow measurement and temperature profile at test site III, January 11, 1978.

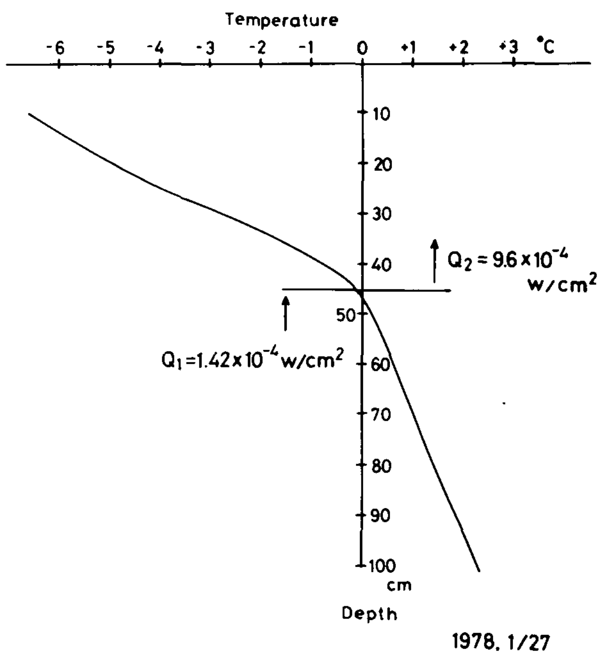

FIGURE 8. Heat flow measurement and temperature profile at test site III, January 27, 1978.

Heat flow measurement under a constant freezing front advancing rate

Experimental procedure

The attenuation of a gamma beam is the most powerful technique for studying frost heaving phenomena associated with soil freezing (Fukuda *et al.* 1980; Hoekstra 1966; Jame and Norum 1976; Loch and Kay 1978). Attenuation of gamma radiation during transmission through soil has been developed and used for three decades as a non-destructive method for determining water content and dry-bulk density in other fields of study such as swelling processes of clay soil. The author employed a single gamma source method with 350 mic ^{137}C as the source. The length of soil sample was determined as 10 cm based upon a similar calculation done by Gardner *et al.* (1972). Overall accuracy of the water content determination was ± 2 per cent or less.

The soil sample was frozen from the top by a freezing plate attached to the top of the sample, in which a cooling fluid circulated. If the cooling fluid temperature was constant, such as $-5°C$, the rate of the freezing front advance was found to alter. However, the rates of freezing front advance measured under field conditions were almost constant in the time scale of a few days. Generally, the measured rates in the small soil column were 100 times larger than in the field. Thus it was desirable to conduct the soil freezing experiment with constant rate of freezing front advance.

For this reason, the experiment of soil freezing with a constant rate of the freezing front advance was undertaken. The experimental procedure was as follows. Temperature profiles of the soil column were measured at certain time intervals. By applying linear or multiple regression to the temperature profile, the 0°C position was estimated. The movement of the 0°C position was monitored and the rate of movement was calculated. If the rate of movement was greater than the value at which it was initially set, the cooling rate on the cold end was changed. The cooling rate was controlled by the on–off of the magnetic valve through which cold brine was supplied to the cooling plate. The monitored rate of movement was compared with the desired value, and the results of the comparison were fed back to the adjuster of the valve. A small computer was employed as the controller (Figure 9).

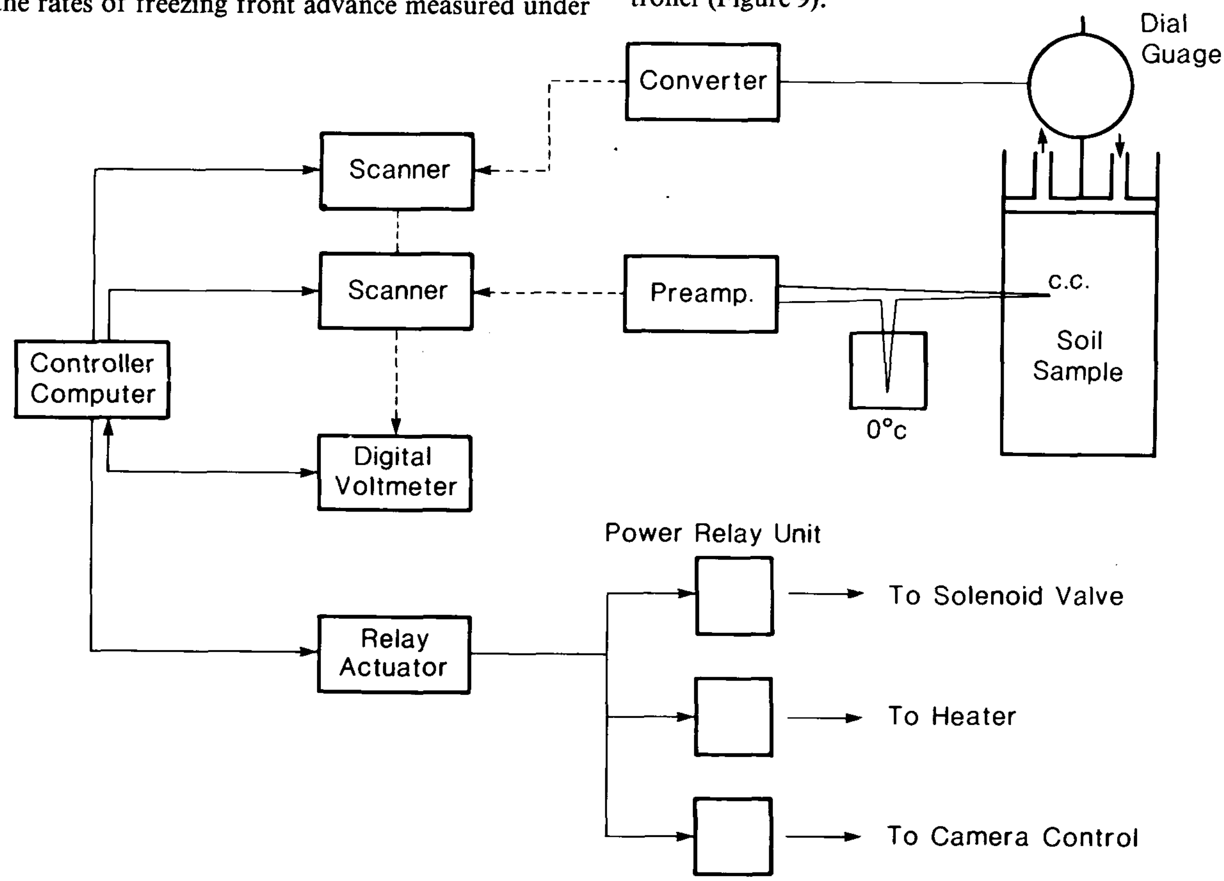

FIGURE 9. Diagram of the controlling system of the experiment.

Water was used as a freezing material. To eliminate convected heat transfer, one per cent agar solute with methylene-blue dye was added. The boundary of the frozen and the unfrozen layer was clearly visible, and the rates of movement were measured by both computer estimation and observation by eye.

The soil column consisted of transparent plexiglas. The column had double-sided walls and the space between the walls was evacuated to insulate the column thermally. Using this system, the temperature profile and the moisture profile were measured.

Results and discussion

The result of the test were plotted. The position of the 0°C thermal line was plotted according to elapsed time (Figure 10). If the advancing rate was constant, a simple line could be drawn. Both the estimated and observed lines plotted as almost straight lines, which indicates that the control system works properly.

The values of freezing front advancing rate are scattered around 0.15 cm/hour which was close to the initially set value (Figure 11). A small-size heat flow sensor (measured 10 by 10 mm) was inserted in the soil sample at a depth of 3 cm. The measured heat flow at 3 cm changed when the freezing front passed that location (Figure 12). During the same time period, water content at 3 cm depth was measured as 0.306 cm^3/cm^3 by the gamma ray attenuation method. The heaving rate was measured also as 0.1×10^{-5} cm/s.

Using equation 1, measured latent heat is equal to $Q_2 - Q_1 = Q_L = 3.51 \times 10^{-4}$ W/cm^2. The first part of the right side in equation is due to the latent heat of water flowing to the freezing front, which is estimated by $\rho wLwv$. The measured heave rate is substituted into v (flux of water). Thus the estimated value is 3.4×10^{-4} W/cm^2. The second part is due to the latent heat of water frozen in situ estimated by

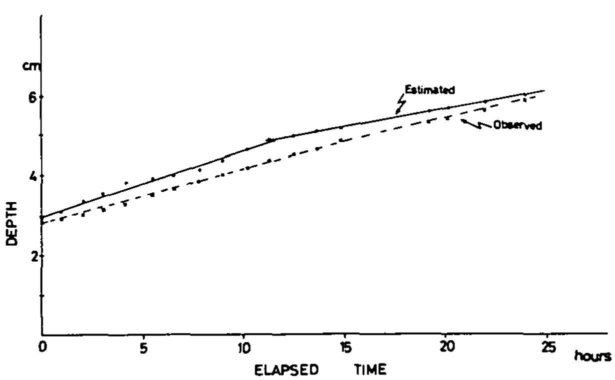

FIGURE 10. Result of a test run using water positions of the 0°C line are plotted.

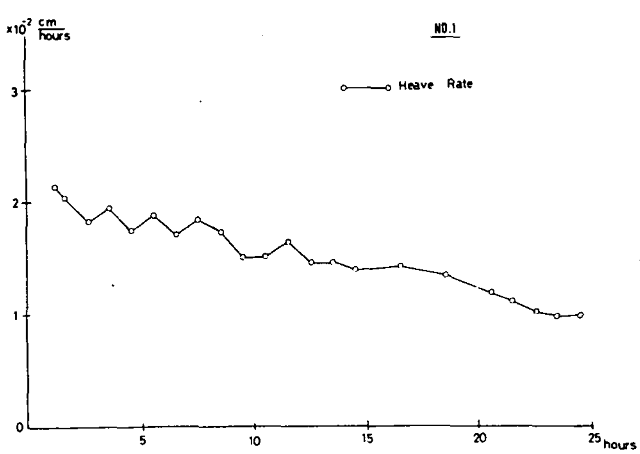

FIGURE 11. Results of a freezing experiment with a constant rate of freezing front advance, test No. 1.

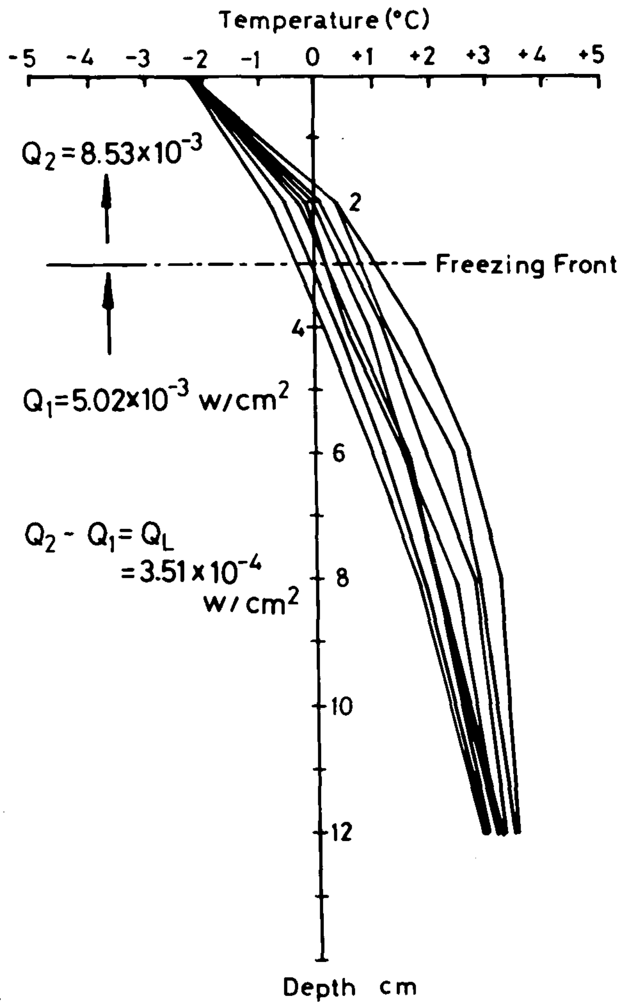

FIGURE 12. Heat flow measurement with a constant rate of freezing front advance, test No. 1.

$\rho s L s \dfrac{dx}{dt}$. The latent heat of soil (Ls) is equal to latent heat of water in soil, which is determined by the water content. Thus the measured water content and freezing advancing rate ($\dfrac{dx}{dt}$) are substituted. The calculated value is 4.01×10^{-4} W/cm^2. The measured value (3.51×10^{-4} W/cm^2) is slightly smaller than the estimated value. However if one compares it with results of the field measurements, the result of the experiment agrees with the heat-balance equation, 1. This agreement is mainly due to proper data of water content in soil by gamma ray attenuation method. The controlled freezing condition such as the constant rate of freezing front advance makes it possible to apply the experimental results using the equation without the limitation of the boundary condition.

Conclusions

During the heaving of soil, heat-flow measurements through the unfrozen and frozen layers were conducted both in the field and laboratory. For the purpose of verifying the heat-balance equation related to moisture transfer in soil, water content profiles were monitored by the gamma-ray attenuation method. The heat flux conducted to the freezing front from soil below was directly measured by a heat-flow sensor. The balanced heat sources at the freezing front are latent heat from soil water *in situ* and latent heat from water migrating into the front. These two values were calculated separately by measurement of the rate of advance of the freezing front the heaving rate, and the water content at certain times. Due to the lack of the water-content measurements in the field, the values of calculated latent heat did not coincide well with the measured values.

The ratio between the latent heat from migrated water and the conducted heat in soil was termed the ice-segregation efficiency, E (Arakawa 1966). If ice segregation takes place will full efficiency, E is equal to 1. If no ice segregation takes place at the freezing front, E is equal to zero. According to the measured values of the experiment, E is equal to 0.8. Such a large efficiency of this soil is reflected in field observations.

For the purpose of verification of the frost-heaving model, the heat- and moisture-balance equations might be established based upon relevant experimental results.

References

ARAKAWA, K. 1966. Theoretical studies of ice segregation in soils, J. Glaciol., vol. 6, pp. 255–260.

CHALMERS, B. AND JACKSON, K.A. 1970. Experimental and theoretical studies of the mechanism of frost heaving. CRREL Res. Report 199, pp. 23.

FUKUDA, M., ORHUM, A., AND LUTHIN, J.N. 1980. Experimental studies of coupled heat and moisture transfer in soils during freezing, Cold Regions Sci. and Technol., vol. 3, pp. 223–232.

GARDNER, W., CAMPBELL, G.S., AND CALISENDORFF, C. 1972. Systematic and random errors in dual gamma soil bulk density and water content measurement, Soil Sci. Soc. Amer. Proc. vol. 36, pp. 393–398.

HOESKSTRA, P. 1966. Moisture movement in soils under temperature gradients with the cold-side temperature below freezing. Water Res. Res., vol. 2, pp. 241–250.

JAME, Y.W. AND NORUM, D.I. 1976. Heat and mass transfer in freezing unsaturated soil in a closed system. *In*: Proc. Edmonton Conf. Soil-water Problems in Cold Regions. Amer. Geophys. Union, pp. 46–62.

LOCH, J.P.G. AND KAY, B.D. 1978. Water redistribution in partially frozen, saturated silt under several temperature gradients and overburden loads. Soil Sci. Soc. Amer. J. vol. 42, pp. 400–406.