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APPLICATION OF TIME–DOMAIN REFLECTOMETRY TO DETERMINE THE THICKNESS OF THE FROZEN ZONE IN SOILS

by T.H.W. Baker and J.L. Davis

ANALYZED

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RÉSUMÉ

La réflectométrie associée au temps est une technique faisant intervenir des impulsions électromagnétiques qui a été utilisée pour mesurer la constante diélectrique des sols à des fréquences variant entre 1 MHz et 1 GHz. La constante diélectrique de l'eau équivaut à 30 fois celle de la glace, ce qui fait qu'il est possible de situer le front de congélation dans les sols. Les résultats d'expériences en laboratoire sont présentés afin d'illustrer l'application de cette technique à la mesure de l'épaisseur de la zone gelée de sols à granulométrie grossière et fine. L'emplacement de la limite de congélation sit[illegible]ciée au temps est comp[illegible] de la température e[illegible]es aux rayons-X.

APPLICATION OF TIME-DOMAIN REFLECTOMETRY TO DETERMINE THE THICKNESS OF THE FROZEN ZONE IN SOILS

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ABSTRACT

Time-domain reflectometry is an electromagnetic pulse technique that has been used to measure the dielectric constant of soils at frequencies between 1 MHz and 1 GHz. The dielectric constant of water is 30 times that of ice, making it possible to delineate the freezing front in soils. Results of laboratory experiments will be presented to show the application of this technique to determine the thickness of the frozen zone in coarse-grained and fine-grained soils. The location of the freezing boundary using time-domain reflectometry will be compared with temperature measurements and interpretations from X-ray photographs.

INTRODUCTION

During the construction and repair of shafts and tunnels, artificial ground freezing has been used to supply temporary structural support and to control water infiltration. In these projects it is necessary to monitor the thickness of the frozen layer for safety and economic reasons. Several techniques have been used including temperature measurement, electrical resistivity, frost-tube, ultrasonic, seismic and radar methods. This paper describes the use of another technique, time-domain reflectometry, to locate the freezing front and to calculate the thickness of the frozen zone.

Time-domain reflectometry was first used by Davis et al. (1976) to measure the apparent dielectric constant of soils. They found that the apparent dielectric constant was strongly dependent on volumetric water content and weakly dependent on soil type, density, temperature (above 0°C) and soluble salt content in the frequency range between 20 MHz and 1 GHz. Topp et al. (1980) proposed an empirical relationship between the apparent dielectric constant and the volumetric water content of soils. Similarly, Patterson and Smith (1981) investigated the relationship between the apparent dielectric constant of frozen soils and unfrozen water content using time-domain reflectometry.

TIME-DOMAIN REFLECTOMETRY

Time-domain reflectometry is used to determine the dielectric constant of the medium surrounding a transmission line by measuring the propagation velocity (V) of an electromagnetic wave transmitted along the transmission line for a known distance. For the complete range of soils studied by Topp et al. (1980) the electric loss was found to be small and did not affect the measured propagation velocity. They expressed the propagation velocity as:

$$V \approx c/(K_a)^{\frac{1}{2}} \qquad (1)$$

where c = velocity of light in a vacuum (30 cm/ns)

K_a = apparent dielectric constant of the medium.

The propagation velocity (V) along a

transmission line of known length (L) is given by:

$$V = \frac{L}{t} \qquad (2)$$

where t = time of travel

Combining equations 1 and 2 yields an expression for K_a in terms of the transmission line length (L) and the travel time (t):

$$K_a = \left(\frac{ct}{L}\right)^2 \qquad (3)$$

The travel times of electromagnetic waves transmitted along a transmission line are measured using a time-domain reflectometer (TDR). This instrument is widely used in the electronics industry to measure the reflection characteristics of transmission lines. A description of how the instrument operates in relation to the transmission line is presented in Baker et al. (1982). The TDR output consists of a waveform with a time base displayed on a cathode ray tube (CRT) and photographed or plotted on an x-y plotter. The shape and amplitude of the reflected wave, in relation to the outgoing wave, reveal the nature and magnitude of the impedance mismatches and discontinuities along the transmission line.

The amplitude of the reflected waveform is dependent upon the change in impedance along the transmission line. The impedance is dependent upon the line and the electrical properties of the geometrical shape of the transmission surrounding medium. For a balanced parallel wire transmission line, the characteristics impedance (Z_o) is given by:

$$Z_o = \frac{120}{(K)^{\frac{1}{2}}} \ \ell n \left(\frac{2S}{d}\right) \qquad (4)$$

where K = dielectric constant of the surrounding medium
S = spacing between the rods (cm)
d = diameter of the rods (cm).

In these experiments, the parallel wire transmission line is terminated in an open circuit. The impedance at an open circuit is infinite and the energy from impinging signals is totally reflected. Events on the TDR waveform can be used to calculate the dielectric constant of the medium, using equation 3, provided the physical distance between the discontinuities is known, or they can be used to locate the discontinuity provided the dielectric constant of the medium is known.

The difference in the dielectric constant of frozen and unfrozen soil with a high water content causes an impedance change at the freezing front producing a reflection on the TDR waveform. Using the time base on the waveform it is possible to measure the time for the wave to travel through the frozen zone (t_f) and unfrozen zone (t_u). In making the calculations these travel times are divided in half because reflected waves actually travel twice the distance along the transmission line. Prior measurement of the dielectric constant of the frozen and/or unfrozen material can be used to locate the freezing front relative to the frozen or unfrozen end of the transmission line using equation 3 written in the following form:

$$L = \frac{ct}{(K_a)^{\frac{1}{2}}} \qquad (5)$$

Being able to calculate the location of the freezing front, with respect to both ends of the transmission line, improves the accuracy of the technique (Baker et al., 1982). If the uniformity of the dielectric constant is better in one zone than the other, then it is better to locate the freezing front from one side only, as in the field measurements reported in Baker et al. (1982).

LABORATORY EXPERIMENTS

The soils used in this study were a graded standard quartz sand from Ottawa, Illinois (ASTM Spec. C-109), and a local marine silty clay. All samples were prepared from their dry state and compacted into waxed cardboard cylindrical moulds (15.2 cm in diameter and 28 cm in depth). Two steel rods (0.2 cm in diameter, 3 cm spacing) were inserted into drilled holes to a depth of 25 cm. A string of thermocouples was also inserted into the soil with sensors spaced at 2 cm intervals. Two other thermocouples were placed, one on the surface of the soil and one on the bottom of the mould. The cylindrical sample mould was seated on a battery heater, surrounded with 10 cm of vermiculite insulation and placed in a cold room at -5.5°C.

Figures 1 to 3 show information on the relationship between volumetric water content and the measured dielectric constant for the soils used in these experiments. Dielectric constant measurements were made on the unfrozen soils as soon as the transmission lines were in place. When the transmission lines had become completely frozen in and the temperature had stabilized, the frozen dielectric constant was measured.

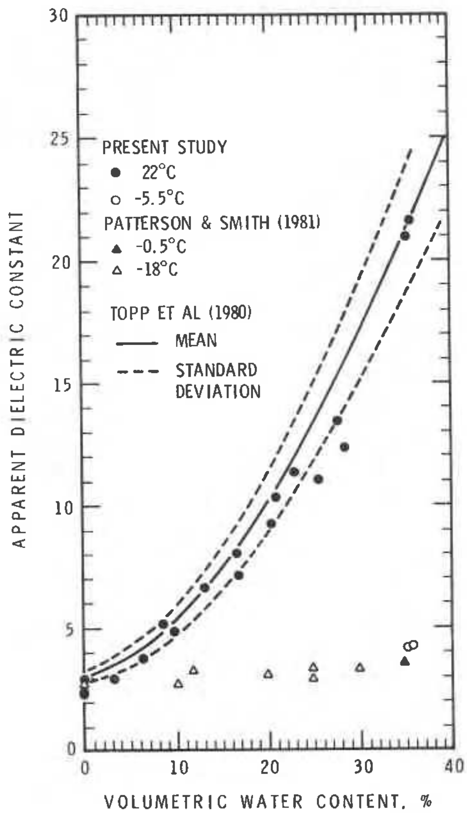

Figure 1. Volumetric water content versus apparent dielectric constant for Ottawa sand at various ambient temperatures

X-RAY MEASUREMENTS

In the silty clay experiments, it was felt necessary to have a means of observing the formation of ice in the sample during freezing. The radiographic equipment used by Penner and Goodrich (1980) had proven useful in locating segregated ice in their laboratory frost heaving experiments. The X-ray photographs were taken through the cylindrical sample on a 20 x 25 cm film placed behind the sample mould. The exposure time was about 7 to 8 minutes at a distance of 1.5 m and a setting of 200

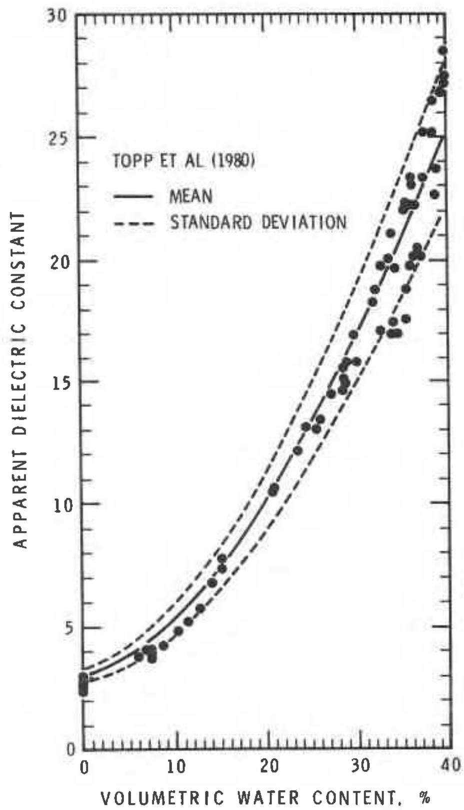

Figure 2. Volumetric water content versus apparent dielectric constant for silty clay at 22°C

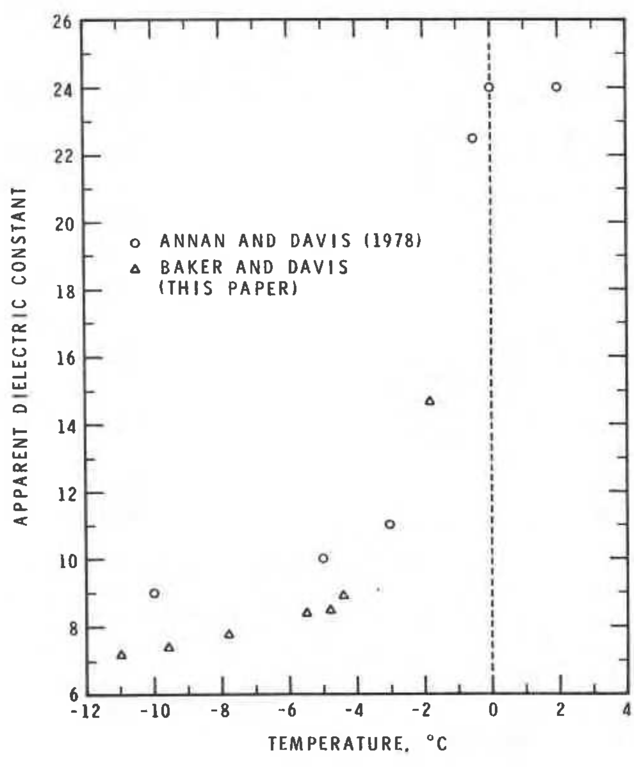

Figure 3. Temperature effect on apparent dielectric constant of silty clay

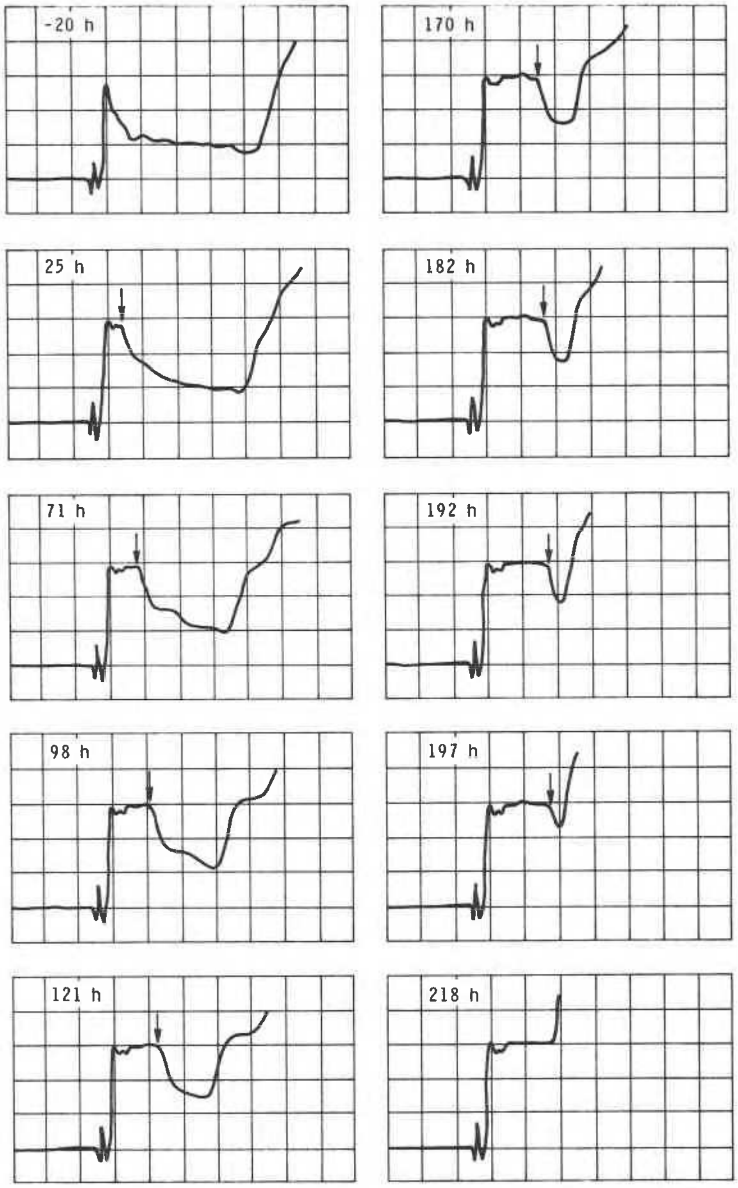

Figure 4. TDR waveforms for the sand experiment scale: vertical 200 mp/div; horizontal 2 ns/div

kV and 5 ma. A 1 cm^2 lead target was placed on the front of the mould to act as location indicator on the radiograph and to provide information on the maximum distortion.

The lead target and steel rods showed up very clearly on the radiographs. Ice stringers or veins could be seen in the frozen zone and formed the characteristic reticulate pattern of frozen clay. The lowest ice stringer or lens occurring between the steel rods and/or within one rod spacing around the rods was used to indicate the depth of ice in the sample. This is referred to in this paper as the X-ray measurement.

SAND EXPERIMENT

Some TDR traces from the sand experiment are shown in Figure 4. These traces were made from photographs of the TDR scan on the CRT. The time in hours is indicated in the upper left corner of each trace and is relative to the time of the first indication of the freezing front on the TDR traces. The first trace at −20 hours shows the sample to be completely unfrozen. The sample was allowed to freeze from the top down and the location of the freezing front as

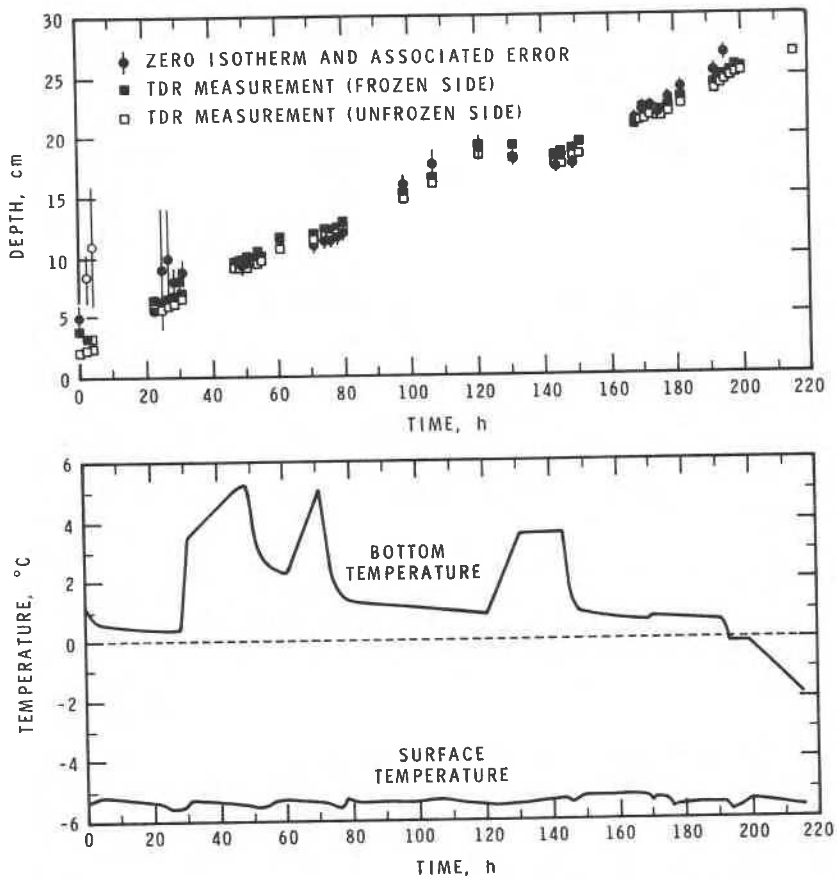

Figure 5. Data from the sand experiment

time progressed is indicated in Figure 4 by an arrow. At 218 hours, the sample was completely frozen and had reached an isothermal temperature of about −5.6°C. The dielectric constant of the frozen sand was used to locate the freezing front from the frozen side.

Figure 5 shows TDR measurements in comparison with the location of the zero degree isotherm interpolated from the temperature measurements. Vertical lines on the location of the zero degree isotherm indicate errors associated with shallow thermal gradients in the vicinity of 0°C. In the early stages of the experiment, there was almost an isothermal condition with depth as the sample approached 0°C. This condition remained for the first 30 hours before the bottom temperature was increased. In Figure 4, the TDR trace at 25 hours showed a distinct reflection which the authors attributed to the freezing front even though the temperature data indicated an isothermal condition as described above. As time progressed and the thermal gradient increased, the TDR measurements and the thermal measurements agreed more closely. Between 120 and 150 hours a slight thaw-back of the frozen layer was indicated by both the TDR and temperature measurements.

SILTY CLAY EXPERIMENT

Some TDR traces from the silty clay experiment are shown in Figure 6. The first trace at −25 hours shows the sample completely unfrozen at 22°C. The sample was allowed to freeze from the top down, similar to the sand experiment. The freezing front is indicated on each of the TDR traces in Figure 6 by an arrow. Reflections from the freezing front are not as distinct as those in the sand experiment (Fig. 4). All TDR traces were simultaneously produced on the x-y plotter where the larger scale made the reflections from the freezing front much more distinct than shown in Figure 6. Travel times in the unfrozen zone were used to locate the position of the freezing front from the unfrozen side. At 336 hours (Fig. 8), the sample had stabilized at an isothermal temperature of −5.7°C. For the times 240 hours and 336 hours, reflections are noted at a location similar to that previously attributed to the freezing front. The temperature data indicated that the sample had been completely lowered well below 0°C and that some ice should exist

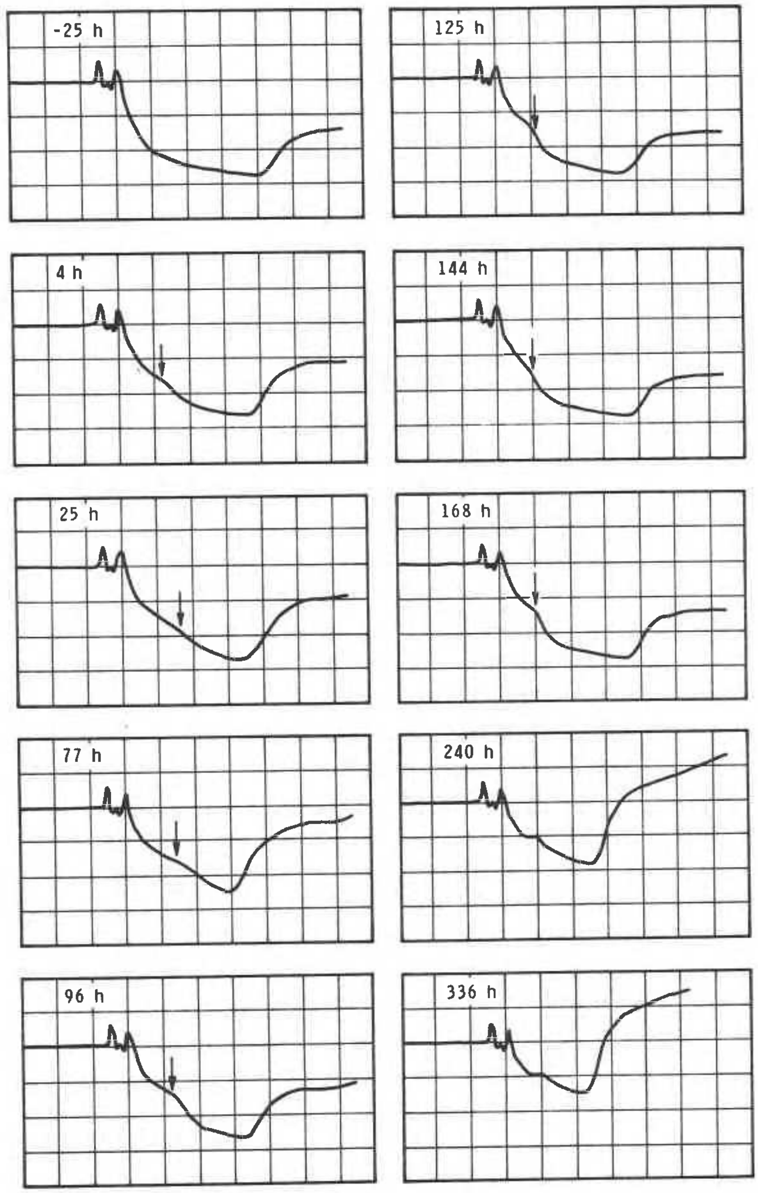

Figure 6. TDR waveforms for the silty clay experiment scale: vertical 200 mp/div; horizontal 2 ns/div

along the entire length of the sample.

Figure 7 presents data from the silty clay experiment. During the initial freezing stage, the TDR measurements remained at a shallower depth than the zero degree isotherm. In the second half of the experiment, the high bottom temperature produced a thaw-back of the frozen zone and the TDR measurements and zero degree isotherm are coincident. X-ray measurements were made during the experiment and they showed ice stringers occurring about 1.5 to 2 cm deeper than the TDR measurements. At 173 hours, the TDR measurements and the X-ray measurements coincide. Three radiographs taken at 7.5, 79 and 173 hours, respectively, are presented in Figure 8. At 7.5 hours, the reticulate ice structure indicates the extent of the frozen zone down to a depth of about 12 cm. By 79 hours, the frozen zone extends down to about the same depth as the lead target. The ice stringers appear to have grown in size from the previous photograph. At 173 hours, the frozen zone has thawed back to between 10 and 11 cm in depth and a segregation of ice (ice lens) is clearly visible. It is felt that the ice lens was formed during the cooling trend initiated by the lowering of the bottom temperature at 144 hours.

The growing ice lens would account for the reflections on the TDR traces in Figure 6 at 144 and 336 hours.

CONCLUSIONS

Time-domain reflectometry has been used to distinguish the freezing front in laboratory experiments involving the uniaxial freezing of Ottawa sand and a silty clay. Measurements of the apparent dielectric constants have been used to calculate the thickness of the frozen zone. These measurements have been compared with the standard temperature method of locating the position of the zero degree isotherm and showed excellent correlations in the sand experiment.

In the silty clay experiment, the three measurement techniques depended upon three different properties of water associated with freezing soils. The technique using time-domain reflectometry was dependent upon the change in electrical properties of water when it changed from a liquid to solid state. Location of the zero degree isotherm from temperature measurements was not a precise indicator of the change of state of water in fine-grained soils due to a freezing point depression. The X-ray technique provided a qualitative indication of the presence of segregated ice in the frozen soil. The uncertainty between the TDR and X-ray measurements was in the order of 2 cm. This difference may be attributed to the resolution of the TDR measurements or the dependence on the volume and thickness of ice required to produce reflections on the TDR trace.

The TDR measurements alone may not in themselves provide enough information to totally delineate the extent of the frozen zone, but should be used in conjunction with other methods now being applied.

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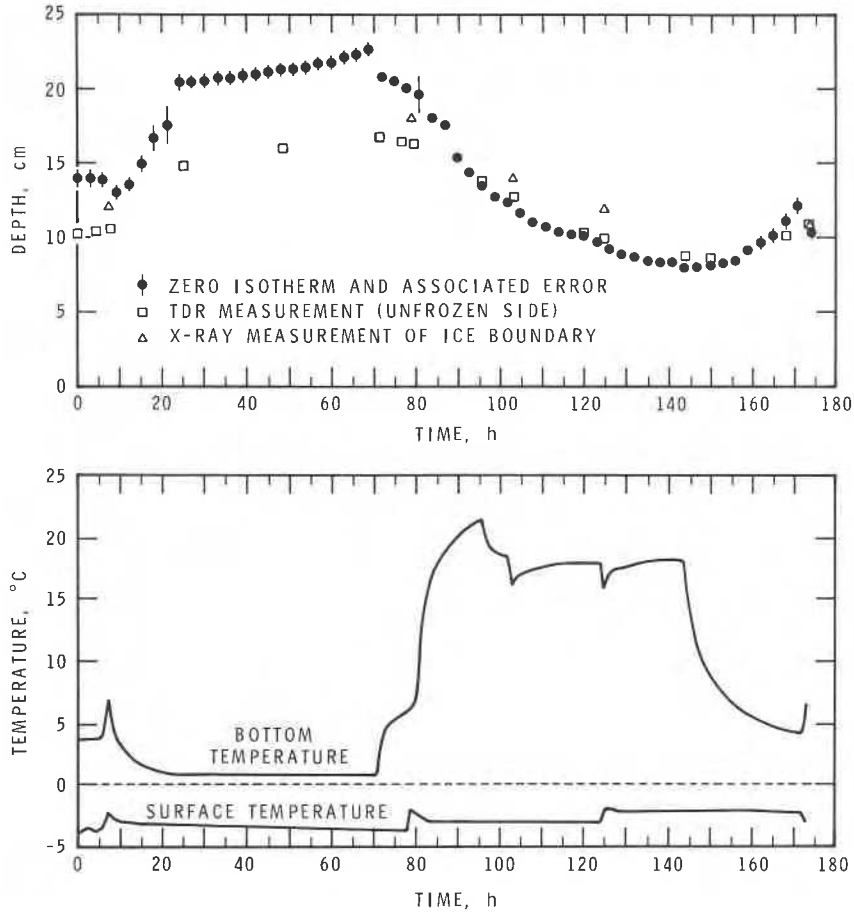

Figure 7. Data from the silty clay experiment

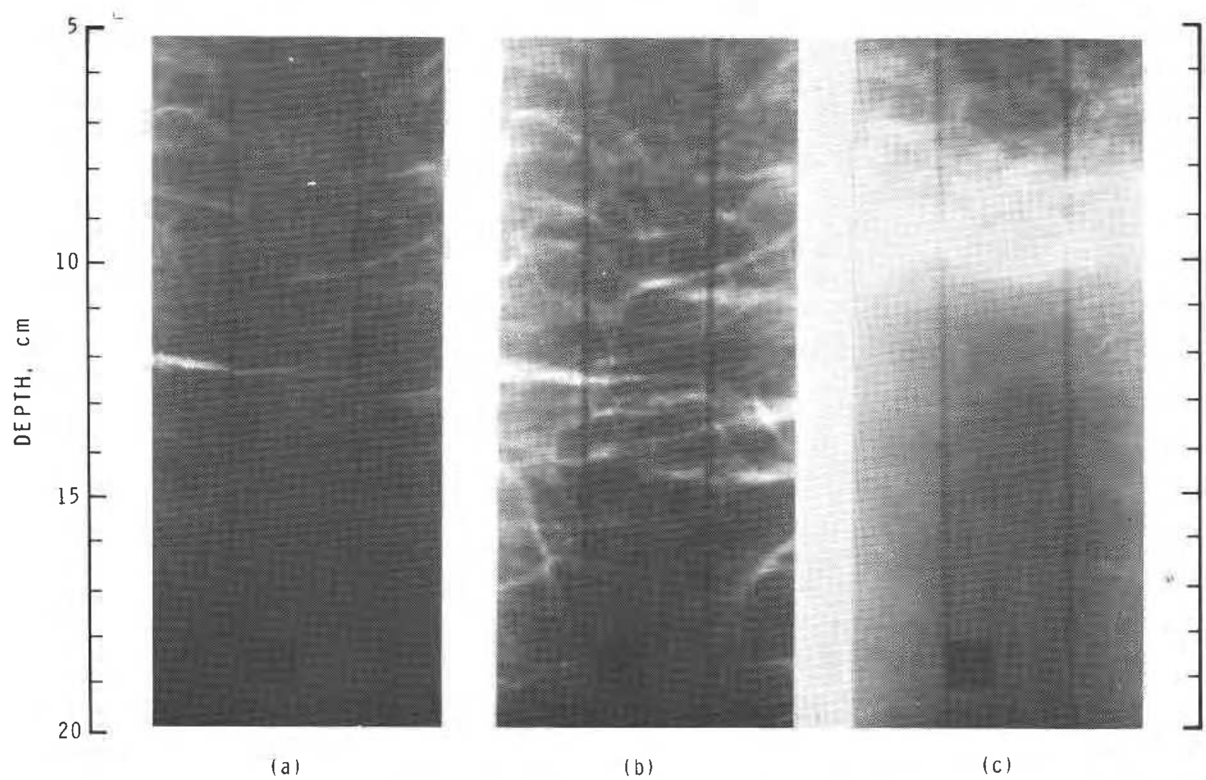

Figure 8. Radiographs from the silty clay experiment, (a) 7.5 hours (b) 79 hours (c) 173 hours

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