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Locating the frozen–unfrozen interface in soils using time-domain reflectometry

T. H. W. Baker
Division of Building Research, National Research Council of Canada, Ottawa, Ont., Canada K1A 0R6
J. L. Davis[1]
Geological Survey of Canada, Energy, Mines and Resources, Ottawa, Ont., Canada K1A 0E8
AND
H. N. Hayhoe and G. C. Topp
Land Resource Research Institute, Agriculture Canada, Ottawa, Ont., Canada K1A 0C6
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The time-domain reflectometry technique was compared with the temperature measurement method for locating the frozen–unfrozen interface in water and sandy soils. This technique depends on the high-frequency (1–1000 MHz) electrical properties of water that change significantly and abruptly between the liquid and solid phases. Parallel wire transmission lines were inserted into the soil to guide electromagnetic pulses produced by a time-domain reflectometer (TDR). The frozen–unfrozen interface produced reflections measured by the TDR which were in turn used to locate the interface as it moved along the transmission line. In the laboratory it was possible to locate the interface using the TDR to within ±0.5 cm and in the field to within ±2.4 cm. These errors were equal to those associated with the temperature measurements.

Keywords: soil freezing, temperature measurements, dielectric constant, time-domain reflectometry.

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[1]Present address: EarthTech Research Ltd., Baltimore, MD 21227, U.S.A.

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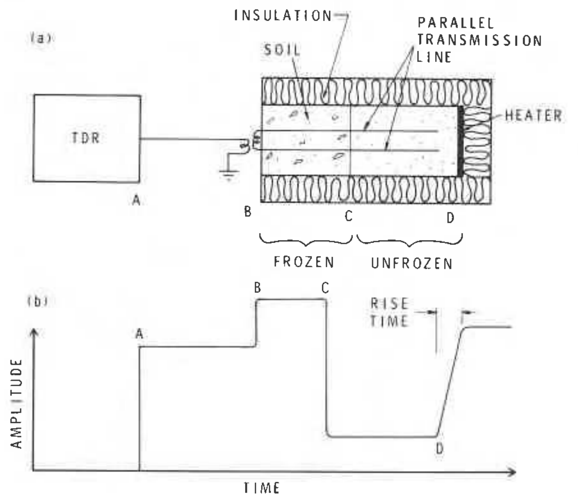

FIG. 2. Time-domain reflectometry: (*a*) schematic diagram of TDR and transmission line inserted in soil; (*b*) an idealized TDR response curve from the experimental arrangement shown in (*a*).

the reflected signal. Point D is easily located in Fig. 2*b* since the rise time of the reflected signal is relatively short. Topp *et al.* (1980), in their study of water content determination, found that this rise time increased with a decrease in soil grain size or an increase in the impurity content of the soil water.

If one knows the dielectric constant in either the frozen or unfrozen zones, the respective travel times and the length of the transmission line permit calculation of the distance of the frozen–unfrozen interface relative to point B on the frozen side or to point D on the unfrozen side. If the dielectric constants of both the frozen and unfrozen media are known then one measurement can be used to check the other and measurement precision can be improved. This technique can be used to locate the frozen–unfrozen interface as it moves along the length of the transmission line.

Laboratory measurements

Laboratory tests of frost penetration in a saturated Ottawa sand and the freezing of distilled water were undertaken to establish the feasibility and precision of using time-domain reflectometry to locate the frozen–unfrozen interface. These media were chosen to ensure little or no freezing point depression.

The transmission lines in the laboratory sand and distilled water experiments consisted of two parallel steel rods, 0.2 cm in diameter, spaced 3 cm apart and inserted into the unfrozen media to a depth of 25 cm. These transmission lines are of similar configuration to those used by Davis and Annan (1977). Uniaxial freezing of the media in the cold room was achieved by the use of insulation and a heater as shown in Fig. 2*a*.

Time-domain reflectometer measurements of the location of the frozen–unfrozen interface were compared with temperature measurements using copper–constantan thermocouples spaced at 2 cm intervals to a depth of 20 cm and one thermocouple placed next to the bottom heater. Precision of the temperature measurement was ±0.05°C as determined by a constant temperature bath accurate to ±0.001°C. Adjustments to the heater allowed changes in the thermal gradient to control the freezing rate. In the vicinity of the frozen–unfrozen interface the temperature gradient was maintained at about 0.1°C/cm. In the freezing water experiment the ice thickness was also measured using a hot-wire technique (Untersteiner 1961) and an ultrasonic pulse-echo technique (ASTM Standard E317).

Figure 3 shows typical TDR scans in freezing sand. Figure 3*a* shows the response before freezing begins. The travel time, t_u, for the pulses moving along the full 25 cm of the transmission line in the unfrozen material was 8.20 ns. Using [2], the dielectric constant of the unfrozen soil (K_{au}) was calculated as 24.2. From the equation presented by Topp *et al.* (1980), this gives an average volumetric water content of 39 ± 1.3%. The sand had been placed and compacted at a volumetric water content of 40%.

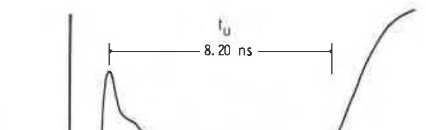

FIG. 3. Typical TDR scans in freezing sand: (*a*) completely unfrozen; (*b*) frozen layer overlying unfrozen layer; (*c*) completely frozen.

Figure 3*b* shows the sample partly frozen along the length of the transmission line. The location of the frozen–unfrozen interface can be determined, using the unfrozen dielectric constant (K_{au}) given above and the time for the pulses to move through the unfrozen soil, as $t_u = 4.39$ ns. Using [2], the distance from the bottom of the transmission line to the frozen–unfrozen interface is calculated to be 13.4 cm. The thickness of the frozen soil is therefore $25.0 - 13.4 = 11.6$ cm.

Figure 3*c* shows the sample completely frozen along the length of the transmission line. The travel time, t_f, for pulses moving along the full length (25 cm) of the transmission line in the frozen material was 3.40 ns. From [2], the dielectric constant of the frozen soil (K_{af}) is calculated to be 4.2 This value can now be used to calculate directly the thickness of the frozen layer of soil. In Fig. 3*b* the time for the pulses to move through the frozen soil is $t_f = 1.66$ ns. Using [2], the distance from the beginning of the transmission line to the frozen–unfrozen interface is calculated to be 12.2 cm. Using this technique the thickness of the frozen soil layer can be calculated from the unfrozen side using t_u and K_{au}, or from the frozen side using t_f and K_{af}.

In order to verify these measurements the foregoing values were compared with the thermocouple temperature measurements, as shown in Fig. 4. Note from Fig. 1 that the temperature gradient in the vicinity of the zero-degree isotherm (0.1°C/cm) induces an uncertainty of ±0.5 cm in accurately locating the zero degree isotherm.

Figure 5 shows a comparison of two methods for measuring depth to the frozen–unfrozen interface in a saturated sand during freezing along the length of the transmission line. Measurements are presented using data from both the frozen and unfrozen side. The

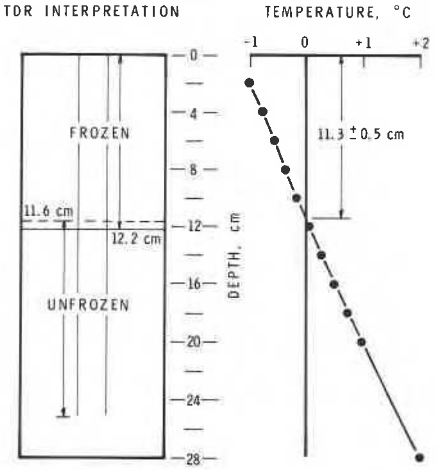

FIG. 4. Comparison of TDR and temperature measurements.

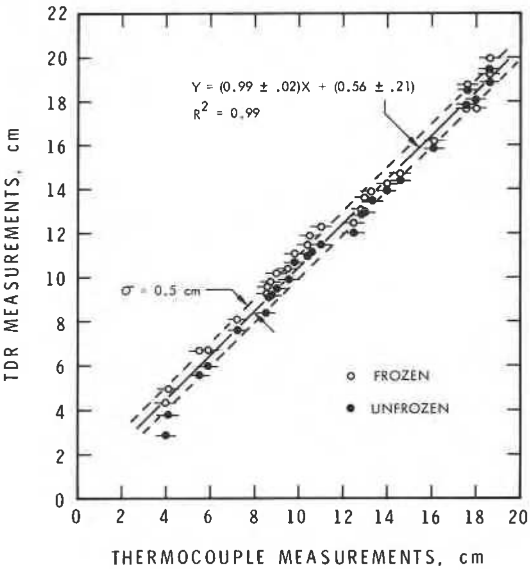

FIG. 5. Comparison of two methods for measuring depth to frozen–unfrozen interface during freezing of saturated sand.

regression line through the data points indicates an excellent correlation. The standard deviation was 0.5 cm. Note that this is equal to the uncertainty in accurately locating the zero-degree isotherm from the thermocouple measurements. Horizontal lines in the figure indicate the accuracy of the thermocouple measurements.

Figure 6 shows a similar comparison for the depth to the frozen–unfrozen interface in distilled water. Measurements were made in a large tank. The position of the ice–water interface was determined using the TDR, thermocouple, hot-wire, and ultrasonic methods. A standard deviation of 0.2 cm was obtained for the comparisons between the thermocouple measurements

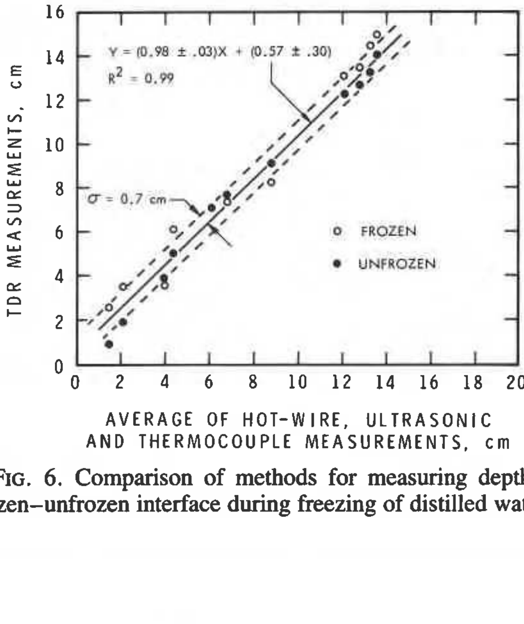

FIG. 6. Comparison of methods for measuring depth to frozen–unfrozen interface during freezing of distilled water.

and the hot-wire and ultrasonic measurements. The average of these three methods is compared with the TDR measurements in Fig. 6. Again the regression line through the data points indicates an excellent correlation. The standard deviation was 0.7 cm. The accuracy of the hot-wire and ultrasonic measurements was about 0.1 cm. Since these measurements were not taken at exactly the same location as the transmission lines the thermal effect of the steel rods could not be evaluated. From Fig. 1 the temperature gradient of 0.1°C/cm would indicate an uncertainty of ±0.5 cm in accurately locating the zero-degree isotherm. The standard deviation above could reflect the error in all of these measurements.

Field measurements

During the summer of 1980, TDR transmission lines were installed in a sandy loam soil at a field site in Ottawa, Ontario. The installation comprised three pairs of 50-cm long lines placed horizontally at depths of 7.5, 15, and 22.5 cm and three vertical lines 50, 80, and 120 cm long inserted from the surface. The 50-cm stainless steel rod lines were 0.3 cm in diameter and the balance were 0.6 cm in diameter. Each pair of rods was spaced 5 cm apart. Copper–constantan thermocouples were installed at 5-cm intervals down to 100 cm, and 10 cm apart to a depth of 140 cm. Precision of the temperature measurement system was ±0.3°C. The site was kept clear of snow during the 1980–1981 winter and periodic readings were taken of the ground temperature and the response of the TDR lines. From the temperature measurements the temperature gradients during this period were 0.13 ± 0.03°C/cm. From Fig. 1 an error of ±2.5 cm is associated with locating the zero-degree isotherm.

The location of the frozen–unfrozen interface was determined using [2], with the frozen dielectric constant determined from the horizontal transmission lines located within the frozen zone. In an open system, such as occurs in the field, it was possible for water contents and thus dielectric constants to change with depth and time. More than one transmission line was necessary to determine the value of the dielectric constant to be used for calculating the position of the frozen–unfrozen interface (freezing front). For example, when the interface had reached about 10 cm depth, the horizontal transmission line at 7.5 cm provided a measure of dielectric constant (K_{af}) for the frozen zone that was used to determine the location of the frozen–unfrozen interface along the 50, 80, and 120-cm vertical lines. As the other horizontal lines became frozen in, their readings could be used to obtain a better value of the average dielectric constant of the frozen zone.

Figure 7 shows the correlation between the TDR and thermocouple measurements at the field site; the standard deviation was 2.4 cm.

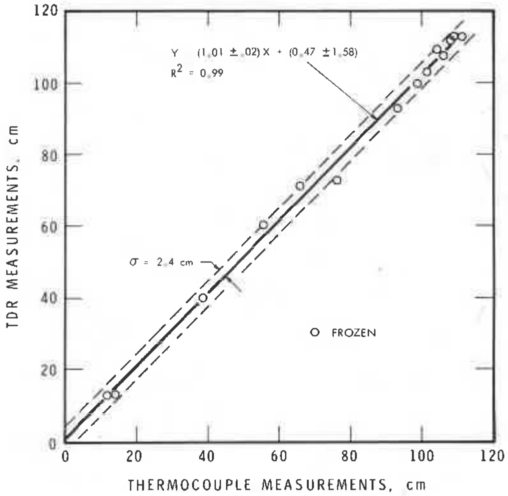

FIG. 7. Comparison of two methods for measuring depth to frozen–unfrozen interface in sandy loam soil *in situ*, November 1980 to January 1981.

Conclusions

Time-domain reflectometry has been used to locate the frozen–unfrozen interface in freezing soils where the freezing boundary is moving along the axis of the transmission line. Measurements of the dielectric constant of the frozen (K_{af}) and/or unfrozen (K_{au}) material were required to locate the interface relative to the ends of the transmission line.

The correlations between time-domain reflectometry and other techniques for locating the frozen–unfrozen interface were excellent as indicated by the slopes of the regression lines, which were close to 1.0.

In each of the experiments, the standard deviation for the TDR data correlated with the temperature data was about equal to the error associated with the temperature measurements as determined from Fig. 1. For this reason one can say only that the precision of the TDR technique is as good as the temperature technique for locating the frozen–unfrozen interface in soils.

Laboratory experiments were also undertaken using fine-grained clay soils where the frozen–unfrozen interface was not necessarily at the zero-degree isotherm (Baker and Davis 1982). The position of the interface determined by X-ray techniques (Penner and Goodrich 1980) was compared with that determined by time-domain reflectometry.

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Annan, A. P., and Davis, J. L. 1978. High frequency electrical methods for the detection of freeze–thaw interfaces. Proceedings, 3rd International Permafrost Conference, Edmonton, pp. 496–500.

Arcone, S. A. 1979. Review of electrical resistivity of frozen ground and some electromagnetic methods for its measurement. Materials Performance, **18**, pp. 32–37.

Baker, T. H. W., and Davis, J. L. 1982. Application of time-domain reflectometry to determine the thickness of the frozen zone in soils. Proceedings, 3rd International Symposium on Ground Freezing, Hanover, Vol. 2, 8 p.

Banner, J. A., and van Everdingen, R. O. 1979. Frost gauges and freezing gauges. National Hydrology Research Institute, Paper No. 3, Inland Waters Directorate, Bull. No. 110, Ottawa, 18 p.

Davis, J. L., and Annan, A. P. 1977. Electromagnetic detection of soil moisture: Progress Report 1. Canadian Journal of Remote Sensing, **3**, pp. 76–86.

Heinrich, D., Mueller, G., and Voort, H. 1979. Ground freezing monitoring techniques. Engineering Geology (Amsterdam), **13**(1–4), pp. 455–471.

Patterson, D. E., and Smith, M. W. 1980. The use of time-domain reflectometry for the measurement of unfrozen water content in frozen soils. Cold Regions Science and Technology, **3**, pp. 205–210.

——— 1981. The measurement of unfrozen water content by time-domain reflectometry: results from laboratory tests. Canadian Geotechnical Journal, **18**, pp. 131–144.

Penner, E., and Goodrich, L. E. 1980. Location of segregated ice in frost susceptible soil. Proceedings, 2nd International Symposium on Ground Freezing, Trondheim, pp. 626–639.

Pilon, J. A., Annan, A. P., Davis, J. L., and Gray, J. T. 1979. Comparison of thermal and radar active layer measurement techniques in the Leaf Bay Area, Nouveau-Québec. Géographie Physique et Quaternaire, Université de Montréal Press, **33**(3–4), pp. 317–326.

Topp, G. C., Davis, J. L., and Annan, A. P. 1980. Electromagnetic determination of soil water content: measurements in coaxial transmission lines. Water Resources Research, **16**, pp. 574–582.

Untersteiner, N. 1961. On the mass and heat budget of Arctic sea ice. Archiv für Meteorologie, Geophysik und Bioklimatologie, Ser. A, **12**(2), pp. 151–182.