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AN INVESTIGATION INTO THE USE OF TIME DOMAIN REFLECTOMETRY TO DETERMINE THE UNFROZEN WATER CONTENT OF FREEZING SOILS

M.W. Smith and D. Patterson
Geotechnical Science Laboratories
Carleton University, March 1979

37 pages

Price: $13.50

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ABSTRACT

This report provides an introduction to the use of electromagnetic methods (Time Domain Reflectometry) for measuring the unfrozen water content (θ_{uf}) of freezing soils. The limitation of the presently used methods are introduced along with the reasons why Time Domain Reflectometry is a viable alternative. Background information on Reflectometry principles are presented as are considerations for designing a system for measurement of the unfrozen water content in the lab or field.

RESUME

L'emploi des méthodes électromagnétiques pour mesurer la teneur en eau non gelée des sols gelés est introduit dans ce rapport. Les limites des méthodes utilisées présentement sont discutées ainsi que les raisons pour lesquelles la méthode de la Réflectométrie par intervalles de temps réprésente une alternative viable. Des renseignements de base sur la principe de la réflectométrie sont présentés ainsi que des considérations pour le dessein d'un système pour mesurer la teneur en eau non gelée dans le laboratoire et sur le terrain.

Dr. Judge:

This report represents the background and experimental work carried out by myself from January to the end of March 1979.

I wish to say that Dr. J. L. Davis (EMR) was most helpful in assuming the role of Scientific Advisor during Dr. Smith's sabbatical. His comments during the project, and review of the final draft were greatly appreciated.

It is hoped that this report will spark a continued interest in the project since the potential of this technique, for measuring the unfrozen water content of frozen soils, warrants further investigation.

Sincerely,

Danny Patterson

Danny Patterson

FINAL REPORT

AN INVESTIGATION INTO THE USE OF TIME DOMAIN REFLECTOMETRY TO DETERMINE THE UNFROZEN WATER CONTENT OF FREEZING SOILS

for the

Department of Energy, Mines and Resources

Earth Physics Branch

by

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March 31, 1979

PREFACE

The purpose of this paper is to introduce the reader to the use of electromagnetic methods (Time Domain Reflectometry) for measuring the unfrozen water content (θ_{uf}) of freezing soils. A brief introduction to the limitations of presently used methods is given and why Time Domain Reflectometry is a viable alternative. Background information on Reflectometry principles is presented as are considerations for designing a system for θ_{uf} measurement in the lab or field.

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*Reproduced, with permission, from Tektronix 1502 TDR Instruction Manual.

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*Reproduced, with permission, from Tektronix 1502 TDR Instruct . Manual.

SECTION 1

DETERMINING THE UNFROZEN WATER CONTENT OF FREEZING SOILS

1.1 Background

When planning for operations of any size in areas of frozen ground it is necessary (economically and aesthetically) to minimize the disturbance of the soil; hence, one must have a sound understanding of the thermal and moisture properties of frozen ground.

In freezing soils, the transfer processes are influenced by the unfrozen water content; this in turn, is controlled by the soil's physical and thermal state.

There are many methods available for determining the unfrozen water content (θ_{uf}) of a freezing soil, for example:

1. adiabatic calorimetry
2. dilatometry
3. pulsed nuclear magnetic resonance
4. calculating the freezing characteristic curve from suction-moisture data.

These techniques are limited to laboratory use (some nuclear methods do have potential for field use but generally require elaborate equipment and/or calibration, i.e., Tice, Burrous and Anderson, 1978). Other limitations are equally important. For instance, dilatometry cannot be used on 'natural' soils, since the soil must be slurried and completely de-aired. One must be cautious when using data obtained from slurried soils (i.e., θ_{uf} - T^oC) since it may not be representative of the same soil in the field. Hotzel (1974), for example, found that samsample treatment influenced the apparent moisture retention properties of a soil.

Producing a freezing characteristic curve from suction moisture data is one of the more commonly used approaches for estimating the θ_{uf} - T^oC relationship. This technique is time-consuming; there are many sources of potential error (see Hotzel, 1974) and it does not include the influence of salts. At temperatures between 0^oC and -0.5^oC, the osmotic potential can account for the presence of up to 50 per cent of the θ_{uf} in a soil (see El Khoraibi, 1975).

Davis, Topp and Annan (1977) discuss a technique for measuring the volumetric water content (θ_v) of soils which shows great promise for determining θ_{uf}. This method makes use of the principles of Time Domain Reflectometry to relate the dielectric properties of a soil to θ_v. The approach is attractive since it can be used in the field or laboratory and sensitivity to soil bulk density, temperature or salt concentration is minimal (these sensitivities can exist in nuclear methods).

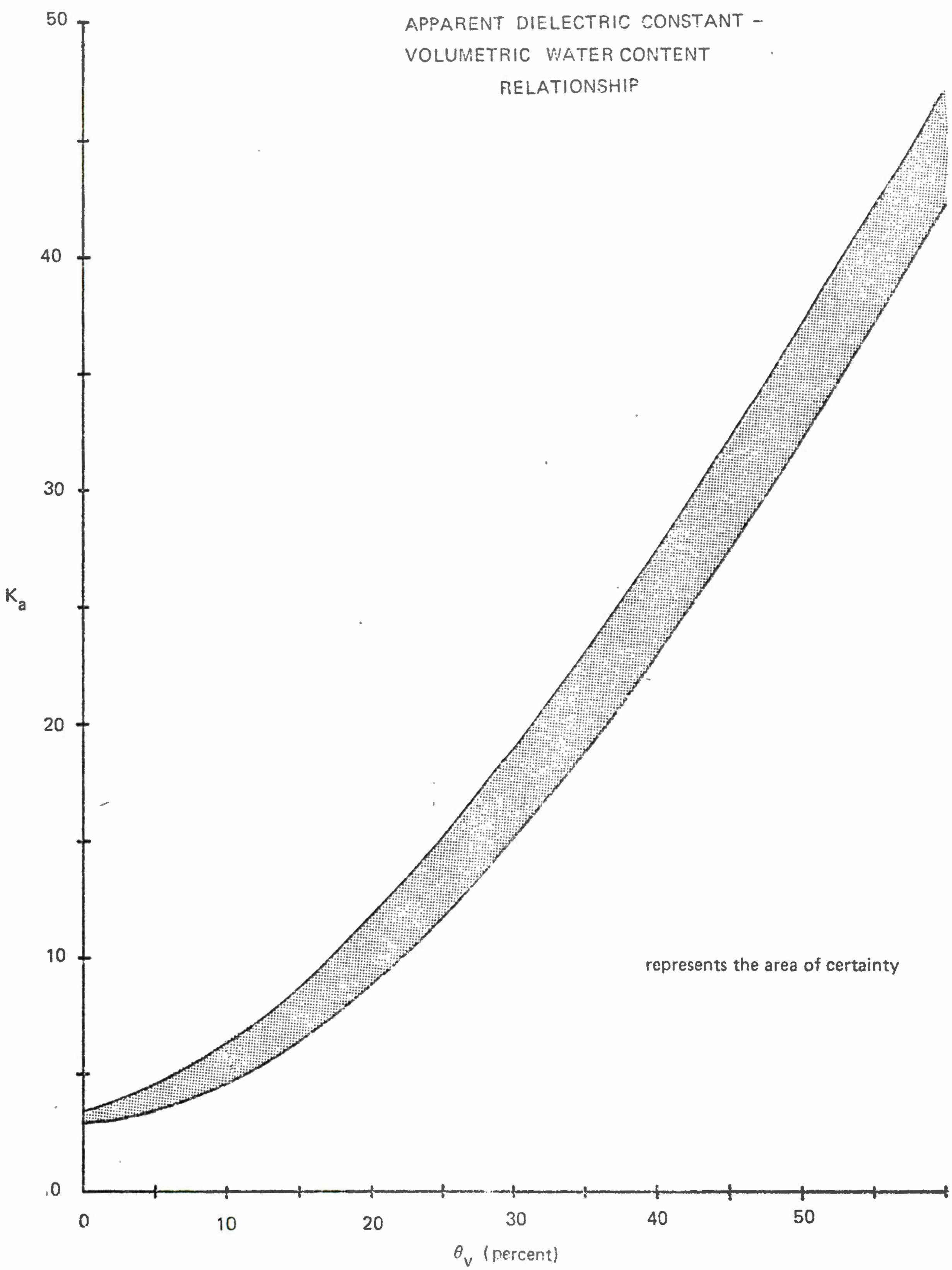
The quantity being related to θ_v is the apparent dielectric constant, K_a (see Appendix 1). The dielectric constant of a material, K' (or relative permittivity), is a measure of its ability to store electrical potential energy under the influence of an electric field relative to that of air. By definition, the relative permittivity of air is unity, while K' for most soil minerals range from 2-4; K' for ice is about 3.2, and for water: 87.7 at 0°C to 80.1 at 20°C. As such, a relatively small amount of water will have a large influence on the permittivity of a soil-water-ice system.

The $K_a - \theta_v$ relationship derived by Topp, Davis, Annan and Brulé (in preparation) is expressed in the third-degree polynomial:

$$K_a = 3.01 + 10.1\theta_v + 143.4\theta_v^2 - 75.0\theta_v^3 \quad (1)$$

θ_v can be determined to better than $\pm$ 2.5 per cent from (1). It is worth noting that this equation was based upon the $K_a - \theta_v$ data for four soils which represent a wide range of soil textures (see Figure 1). This author has found no discrepancy (within the range of certainty) for various grades of Ottawa sand, Oneida silty-clay or Castor silty loam.

FIGURE 1



Source: Topp, Davis, Annan and Brulé (in preparation).

SECTION 2

TIME DOMAIN REFLECTOMETRY

2.1 Background

Time Domain Reflectometry is a form of pulse-reflection measurement which makes use of a special pulse called a step-voltage (Blake, 1969). The pulse generator of a time domain reflectometer (TDR) is essentially a tunnel diode, a device that is used to amplify or control electrical impulses. The pulse generator circuitry provides a small step-voltage output connector of the TDR. When a coaxial cable (or other transmission line) is connected to the output, a pulse travels down the line and is reflected back at every impedance mismatch. The time it takes to travel the length of line can be determined from:

$$tt = \frac{L}{v_p} \qquad (2)$$

where tt is travel time in the line; L is line length and v_p is the velocity of propagation of the pulse.[1]

After the first pulse is initiated, a sampling circuit begins to sample the incident and reflected pulses over a short time and compares them. The signal is then displayed on the crt (cathode-ray tube) as a

[1]This equation should take the form of $tt = 2L/v_p$; however, the TDR used corrects to one-way travel time.

continuous trace (although it is really a series of dots) with the vertical axis being the ratio of the incident to reflected voltage and the horizontal axis representing 'distance' along the line.

2.2 Important Concepts

The voltage pulse produced by a TDR should theoretically change from zero volts ($V = 0$), to its maximum ($V = V_m$), instantaneously; in reality it takes a finite time to reach V_m; this is referred to as the rise time (t_r) of the unit (see Figure 2). The energy pulse produced will contain frequencies from d.c. to a maximum (f_{max}) which is a function of the rise time:

$$f_{max} = \frac{0.35}{t_r} \text{ in GHz} \tag{3}$$

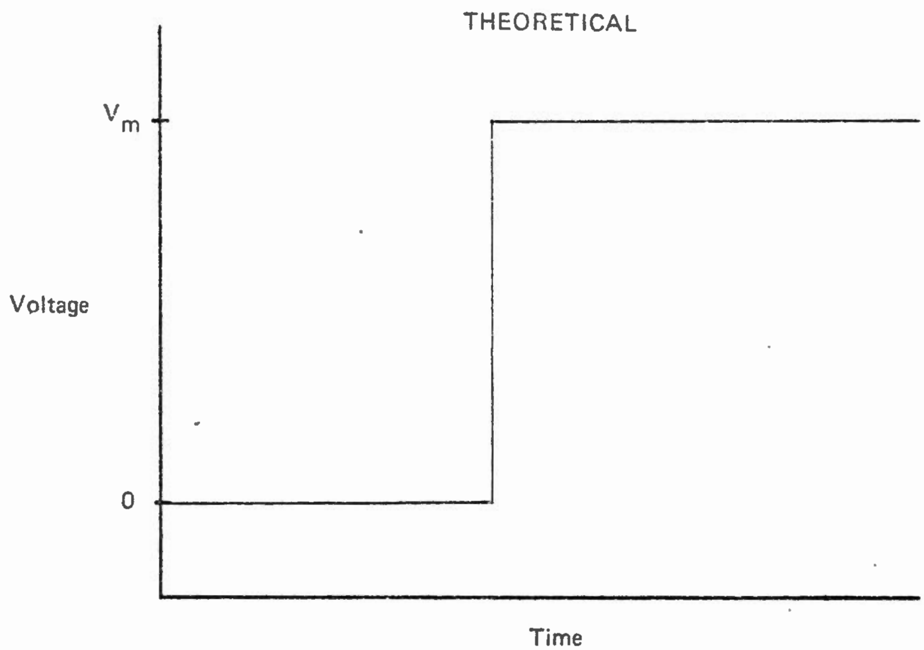
where t_r is in nanoseconds (ns = 10^{-9} sec).

The magnitude of V_m is determined by the characteristic impedance of the transmission line (Z_o), and the internal impedance of the pulse generator.

In Figure 3 a stylized TDR trace is presented for a cable which also shows the effects of line termination (R_L) on the display of the reflected pulse. To simplify matters, the vertical axis represents voltage and the horizontal axis is time (more will be said about axes in Section 2.3).

If no impedance mismatches exist in the line, the reflected wave will have an amplitude equal to that of the incident voltage and it will add or subtract from V_m depending upon polarity.

Figure 2 PULSE SHAPE AND RISE TIME



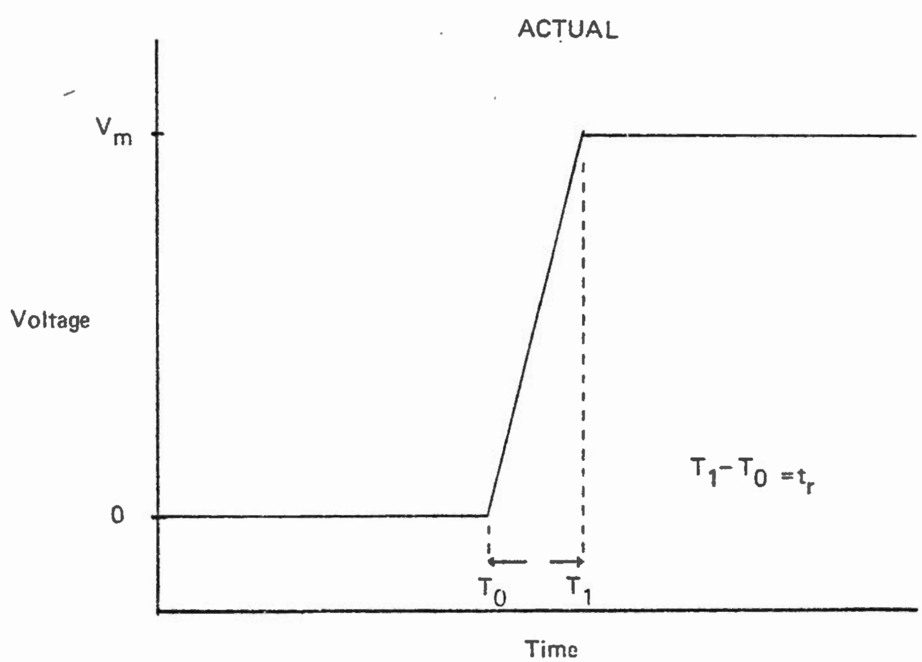
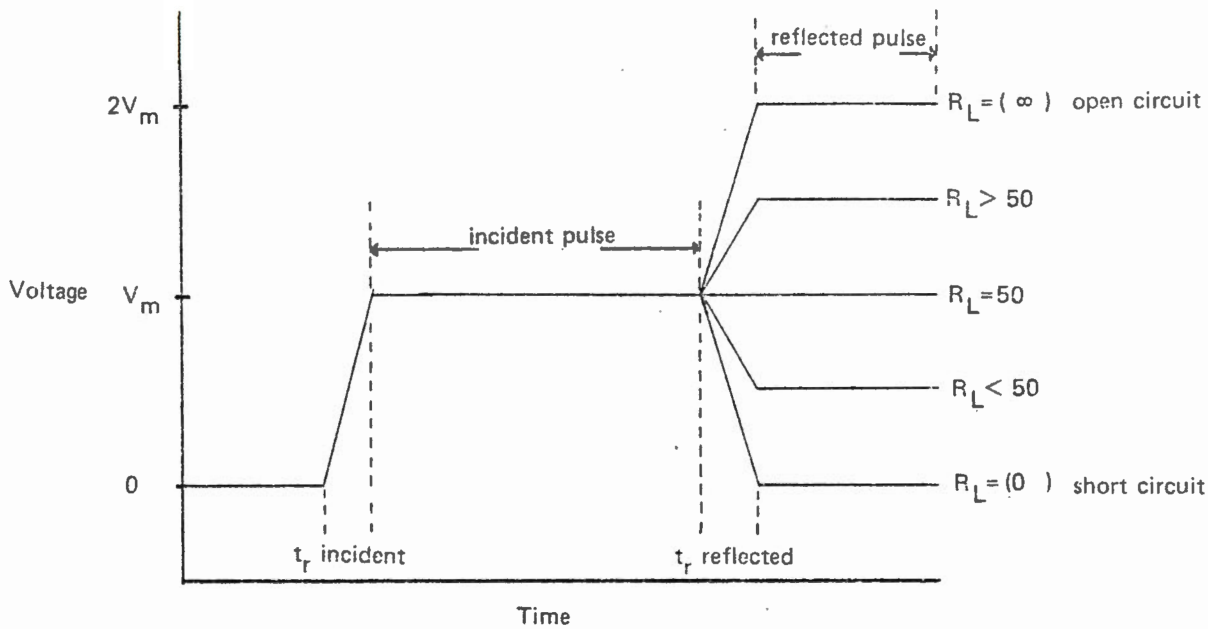


Figure 3 TDR TRACE



The time required to travel the length of the line can be determined from (2) as indicated in the previous section. It should be noted that v_p can also be expressed as (for low loss materials):

$$v_p = \frac{c}{(K')^{\frac{1}{2}}} \quad (4)$$

where c is the free space (air ≃ vacuum) velocity (3×10^8 m sec^{-1}). In practice, most coaxial cables do not have air as the dielectric but perhaps polyethelene (v_p = 0.66 c) or teflon (v_p = 0.70 c).

2.3 Measurements on a TDR

Before proceeding too far into this section one should become familiar with Figure 4 and Table 1.

The Tektronix 1502 TDR is used by the author since it is reasonably priced and field portable. The 1502 TDR provides the CABLE connector with a 200 mV step-voltage which has an incident rise time of ≤ 110 ps (reflected rise time ≤ 140 ps). The rise time of the incident pulse corresponds to a maximum output frequency of about 3.5 GHz.* The 1502's crt is calibrated in units of mρ/DIV vertically and M/DIV horizontally. The vertical scale represents the ratio of the incident to reflected voltage; the unit ρ is called the voltage reflection coefficient. If a cable is open (i.e., infinite impedance: $R_L = \infty$) the reflected step amplitude is +1ρ; for a short (zero impedance: $R_L = 0$), ρ = -1. When a cable is terminated with its characteristic impedance there is no reflection and ρ = 0. One can convert the reflected pulse amplitude to impedance since ρ is dependent upon the characteristic impedance, Z_o, of the line under test and the load on the cable, R_L, (or the impedance of a discontinuity):

---

* (from (3)).

Figure 4 Tektronix 1502 TDR

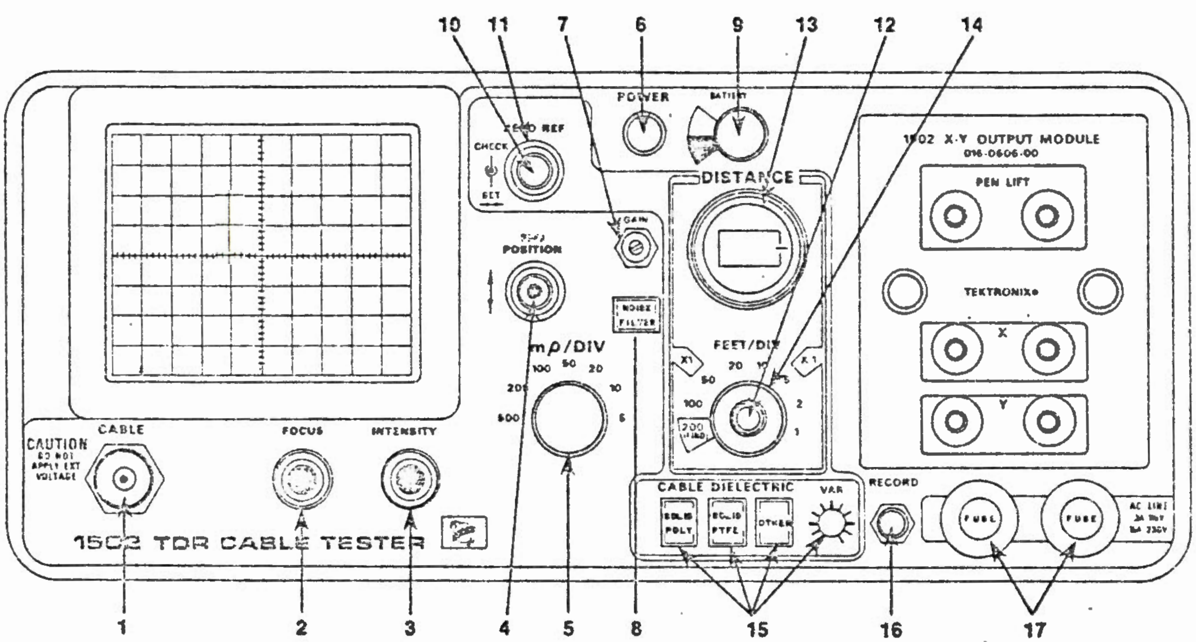


TABLE 1

CONTROLS FOR TEKTRONIX 1502 TDR

1.	CABLE	BNC connector, delivers 110 ps rise time pulse and receives reflected pulse
2.	FOCUS	visual controls for crt
3.	INTENSITY	
4.	POSITION/FINE	vertical position control of the crt
5.	mρ/DIV	vertical scaling control 5 mρ/DIV to 500 mρ/DIV
6.	POWER	ON-OFF
7.	GAIN	for adjusting gain of vertical amplifier
8.	NOISE FILTER	reduces noise
9.	BATTERY	battery level indicator
10.	ZERO REF CHECK	
11.	ZERO REF SET	horizontal position control
12.	MULTIPLIER	scaling of METRES/DIV control; X1 + X·1
13.	DISTANCE	
14.	METRES/DIV	X1 25 cm - 50 M/DIV X·1 2.5 cm - 5 M/DIV
15.	CABLE DIELECTRIC	permits selection of v_p
16.	RECORD	activates X - Y or Y - T recorder
17.	AC LINE FUSES	

For more detail consult the TEKTRONIX 1502 TIME DOMAIN REFLECTOMETER Instruction Manual.

$$\rho = \frac{R_L - Z_o}{R_L + Z_o} \qquad (5)$$

As stated, the horizontal axis on the 1502 is calibrated in M/DIV. This axis, though, can easily be converted to a time axis by dividing the horizontal scale by the velocity of propagation:

$$\frac{\text{TIME}}{\text{DIV}} = \frac{\frac{\text{M}}{\text{DIV}}}{v_p} \qquad (6)$$

For example, for a scale setting of 1 M/DIV and the CABLE DIELECTRIC set for a PTFE (teflon) coaxial cable ($v_p = 0.70 \cdot c = 2.1 \times 10^8$ m/sec), this represents 4.762 ns/DIV.

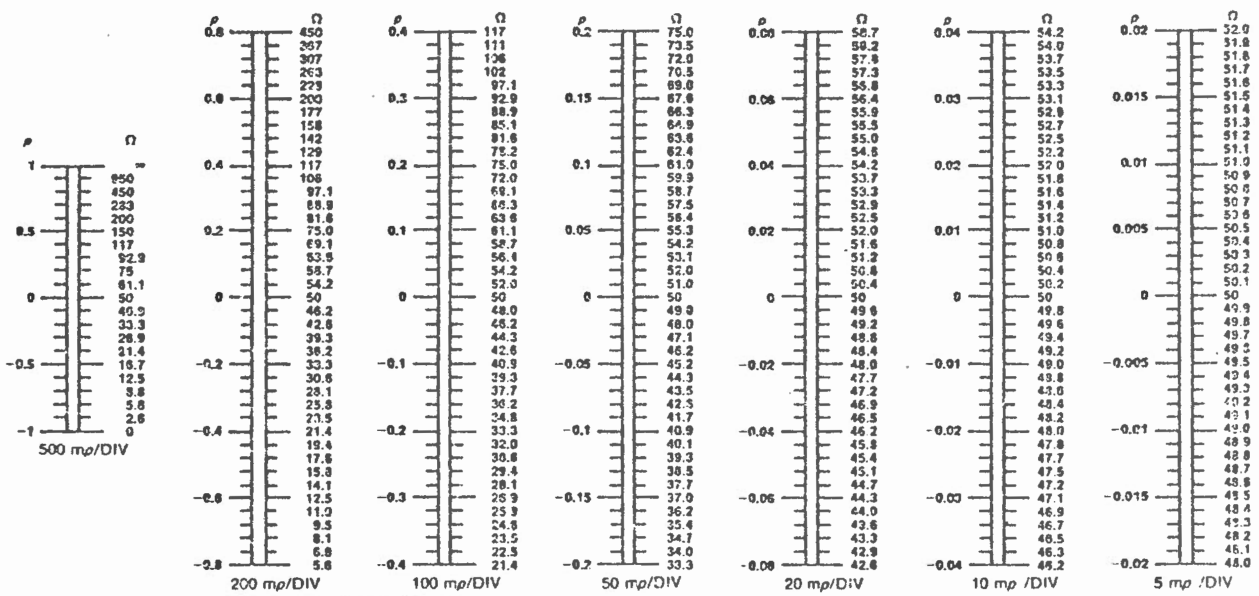
There are several pieces of information which can be determined from the display on the TDR's crt. First, the impedance of a transmission line can be obtained (or an impedance mismatch within a line) from (5) where Z_o is the impedance of a 'known' cable (the 1502 is balanced for 50Ω and a 50Ω precision cable is supplied) and R_L is the impedance of the 'unknown' cable (or impedance mismatch in a line). If the vertical scale setting is known the impedance of the R_L can be found from Table 2 (reference 50Ω cable to centre line). The length of the cable can also be determined directly off the crt display if the CABLE DIELECTRIC is set for the type of cable being tested (see Figure 5).

The dielectric constant of a cable can also be determined if the length of transmission line (coaxial or parallel line) is known; the relationship can be expressed by combining (2) and (4):

$$K' = \left[\frac{v_p \times tt}{L}\right]^2 \qquad (7)$$

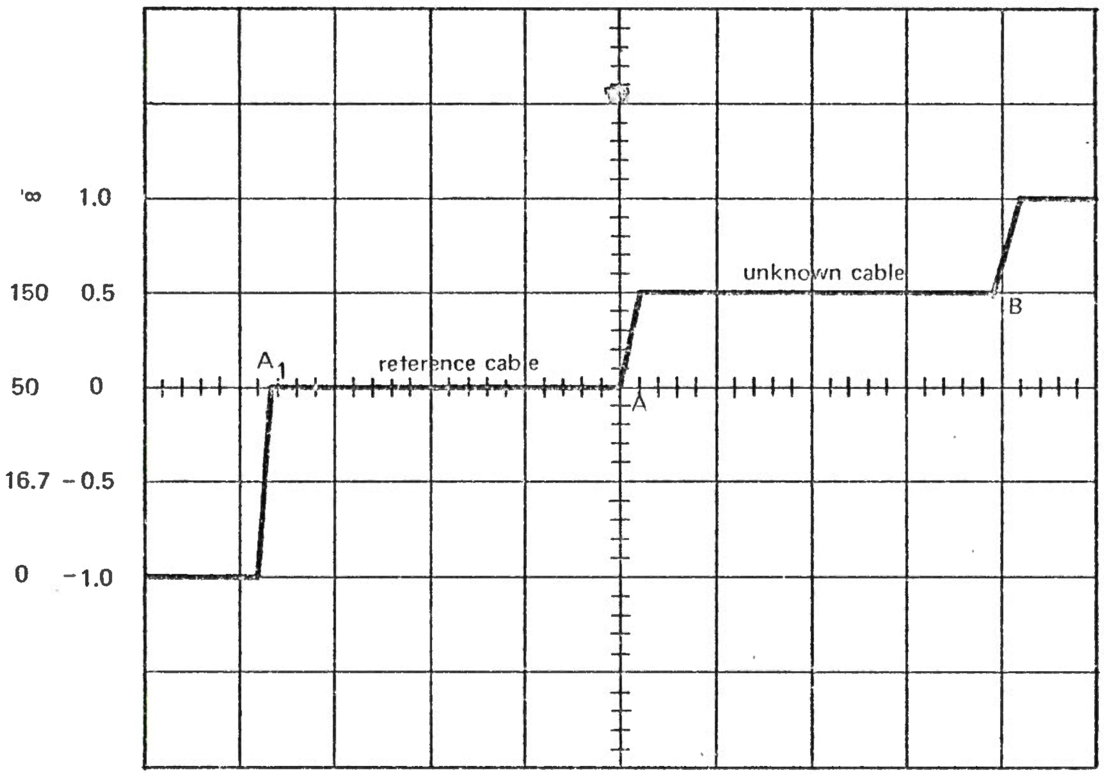
Table 2

IMPEDANCE CHART FOR TEKTRONIX 1502 TDR



DIRECTIONS FOR USE: LOCATE THE COLUMN OVER THE SETTING OF THE mρ/DIV SWITCH. FIND THE ρ VALUE ON THE LEFT SIDE OF THE COLUMN AND READ THE IMPEDANCE ON THE RIGHT SIDE CORRESPONDING TO THE ρ VALUE.

Figure 5 DETERMINING CABLE IMPEDANCE AND LENGTH



CABLE DIELECTRIC SOLID POLY
METRES / DIV 0.25
X1/X.1 X.1 = 25 cm/Div

A_1-A=3.66 DIV
A-B=3.66 DIV
cable length 91.44 cm.

It is (7) which is used to calculate K_a (from Appendix 1, $K_a \simeq K'$) for a soil-water-ice system simply by knowing the length of the tranmission lines in the soil (or containing the soil in the case of a coaxial system); letting $v_p = c$, and measuring the trace length on the crt (or photograph of crt or plot on x-y recorder). A sample calculation is presented in Figure 6, and θ_v (or θ_{uf}) is obtained from Figure 1.

2.4 Design Considerations

There are several factors which must be considered when designing a system for measuring the water content of soils (or θ_{uf}). The first consideration is the geometry of the transmission lines; this can be divided into two entities: length and cross-sectional geometry. The latter shall be discussed first.

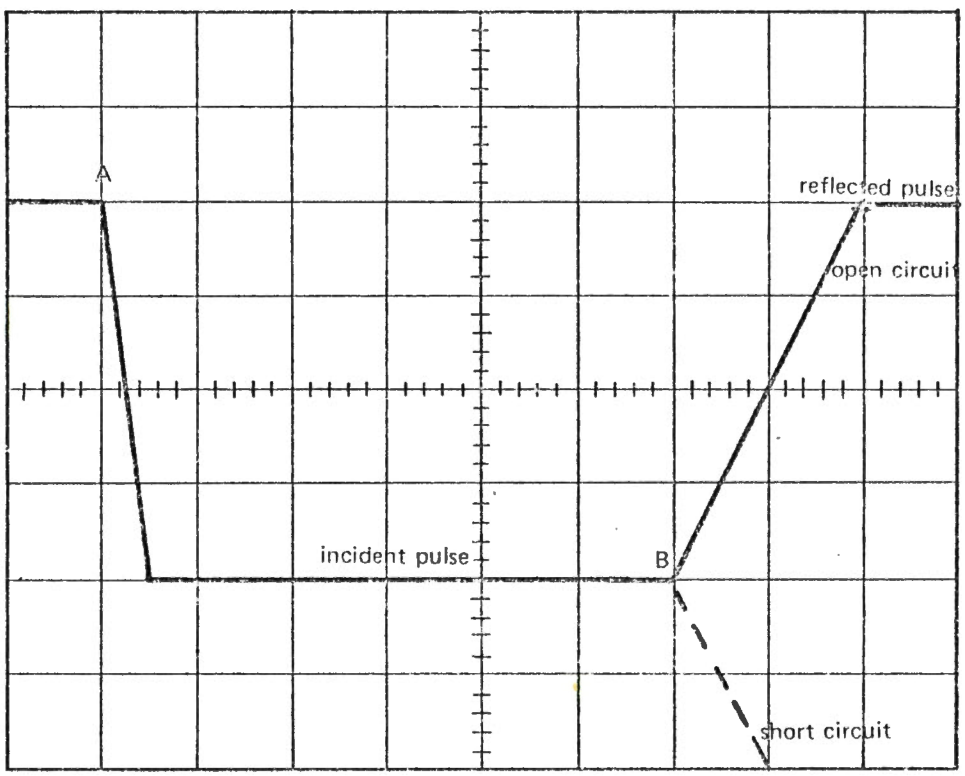
The impedance of a transmission line containing a given dielectric is a function of the spacing of the lines of transmission. For a parallel transmission line, (whether they are parallel wires or rods) the impedance, Z_o, can be determined from: (Chipman, 1968)

$$\begin{aligned} Z_o &= \frac{120}{K'} \cosh^{-1} \frac{S}{2a} \\ &= \frac{276}{K'} \log_{10} \left(\frac{S}{2a} + \sqrt{\left(\frac{S}{2a}\right)^2 - 1} \right) \end{aligned} \tag{8}$$

for S/2a < 10 where S is the spacing between conductors, and a is the radius of the conductors. For a coaxial line:

$$Z_o = \frac{138}{K'} \log_{10} \frac{b}{a} \tag{9}$$

Figure 6 CALCULATING K_a



CABLE DIELECTRIC air
X.1, METRES/ DIV 0.10 M/DIV
TIME/DIV 0.33333 ns/DIV

A– B dist= x DIV

travel time in soil = no. DIV X TIME/DIV

$$K_a = \left[\frac{30 \text{ cm/ns} \times \text{travel time}}{\text{line length (cm)}}\right]^2$$

where b is the inside radius of the outer conductor and a is the radius of the inner conductor. In both cases the velocity of propagation of a pulse, v_p, is determined by (4). Figure 7 shows the geometry for parallel and coaxial transmission lines.

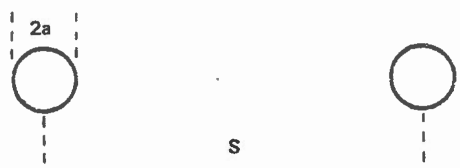
It is also apparent from (8) and (9) that as the dielectric constant of the material between conductors increases, the impedance decreases. Figure 8 shows the impedance--cross-sectional geometry relationship for several values of K'.

The spacing of the transmission lines will have a maximum value beyond which point unwanted electrical modes will be present (i.e., other than TEM). The higher order modes occur when the wavelength in the sample, λ_s, is (Davis and Chudobiak, 1975):

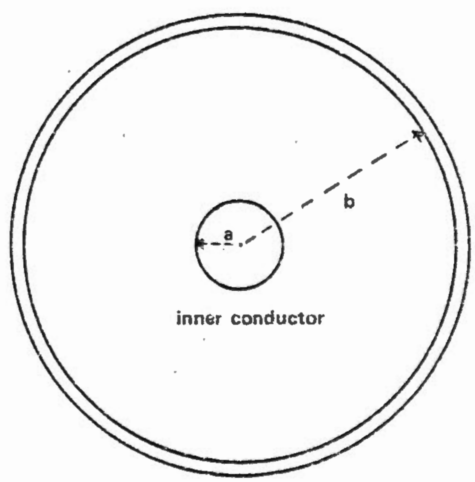
$$\begin{aligned} &\lambda_s \leq 2\ (b + a) && \text{coaxial lines} \\ &\lambda_s \leq 10\ S && \text{parallel transmission lines} \end{aligned} \qquad (10)$$

The second design consideration is line length (L) since the travel time in a medium is a function of K' and L (from (6)). The lower limit to line length will be determined by how accurately one can measure the trace length on the crt (photograph of crt, x-y recorder, y-t recorder). Practically, the length of a trace can be measured to $\pm$ 0.1 division on the Tektronix 1502 TDR, which means that with a trace length of one division the certainty in distance (and hence time) is $\pm$ 10 per cent; for a five division trace, $\pm$ 2 per cent. If the trace length is longer than five divisions the certainty does not improve, particularly if the length of the transmission lines is long. For trace lengths less than five divisions, it is necessary to change to the next lowest horizontal scale to maintain the $\pm$ 2 per cent certainty.

Figure 7 TRANSMISSION LINE GEOMETRY



PARALLEL TRANSMISSION LINE



outer conductor

COAXIAL LINE

Figure 8 PARALLEL TRANSMISSION LINES

GEOMETRY - IMPEDANCE RELATIONSHIP

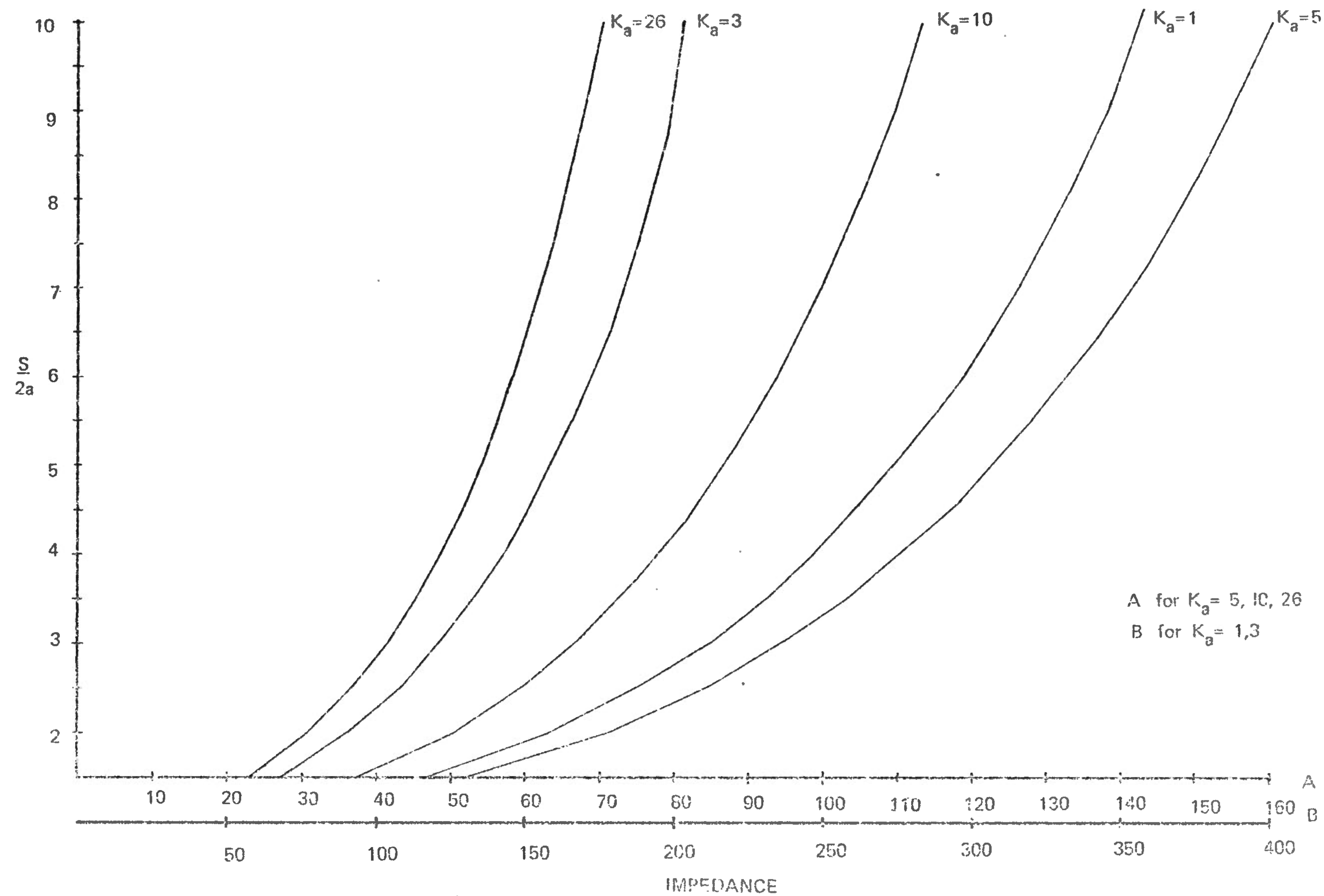
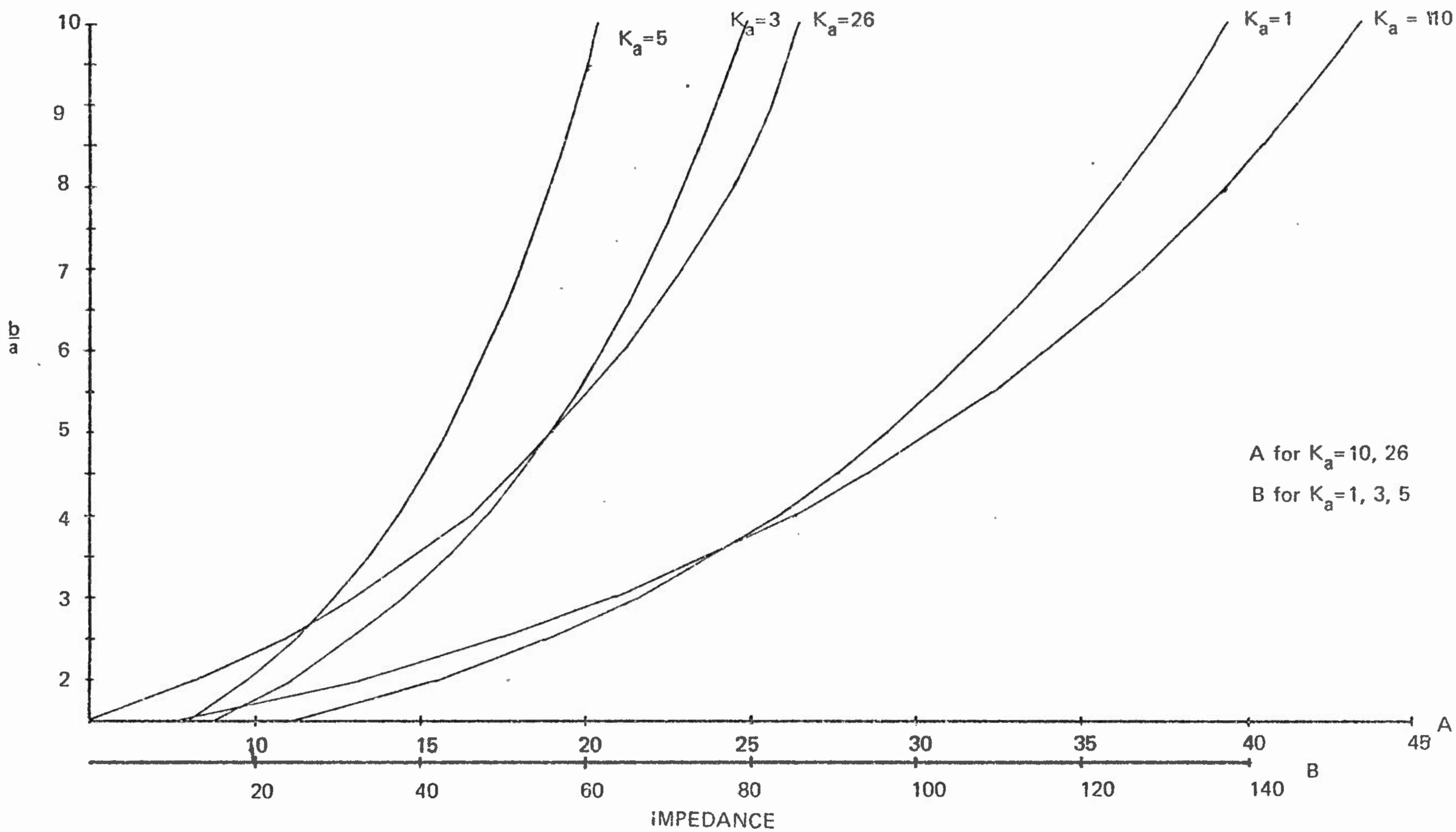


FIGURE 8 continued

COAXIAL LINES
GEOMETRY - IMPEDANCE RELATIONSHIP



The minimum line length at which K_a can be measured (using Tektronix 1502 TDR and $K_a = 3$ and 0.025 M/DIV to represent the minimum) with any certainty is $L \simeq 7$ cm (see Appendix 2).

When the travel time of the step-voltage in the soil is long (due to high K_a and/or line length) the trace on the crt can appear 'lossy'. This 'lossy' nature is manifested as an increase in the rise time of the reflected pulse. Practically, this causes uncertainties in determining the 'B' point in Figure 6. (It should also be noted that clays are more 'lossy' than sands and lossiness increases with increasing temperature.) Davis, Topp and Annan (1977) have successfully used parallel transmission lines with conductor spacings of 5 cm (2a = 0.9525) which have an impedance $Z_o = 280.7\Omega$ in air and 162Ω for $K' = 3$ (dry soil). Coaxial lines with conductor spacings of 2.5 cm (a = 0.9525) ($Z_o = 99.4\Omega$ in air and 57.4Ω for $K' = 3$) have also been used. Line lengths of a metre have been used in both cases.

SECTION 3

MEASUREMENT OF θ_{uf} USING THE TDR

3.1 Freezing Characteristic Curves

When discussing the freezing characteristics of soils there are several important aspects which must be considered:

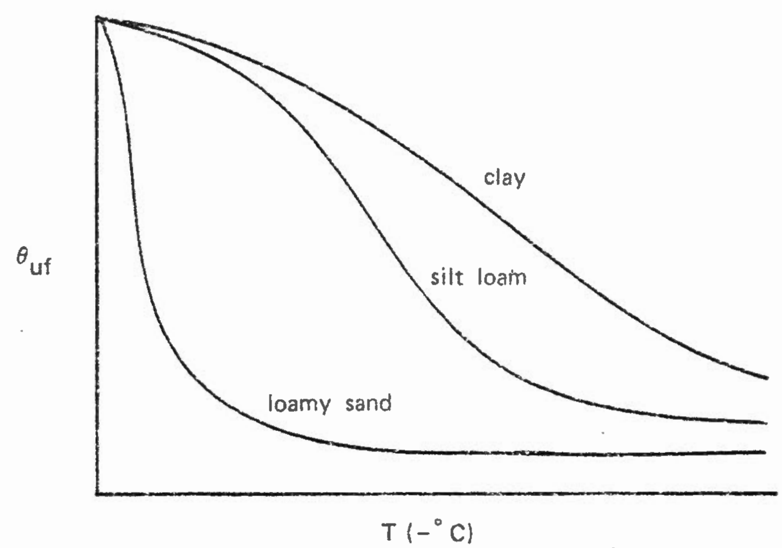
1. For a given soil, a decrease in temperature causes a decrease in θ_{uf}.
2. The rate of change in θ_{uf} (and its magnitude) for a change in temperature is a function of pore size and the range of pore sizes (i.e., texture and structure).
3. At a given temperature, θ_{uf} is greater the finer the soil texture.
4. The presence of soluble salts in the soil water further depresses the freezing point.

These relationships are represented in Figure 9. Several authors (eg., Williams, 1963) have noted a hysteresis phenomenon in θ_{uf} between freezing and thawing cycles (θ_{uf} freezing > θ_{uf} thawing at a given temperature).

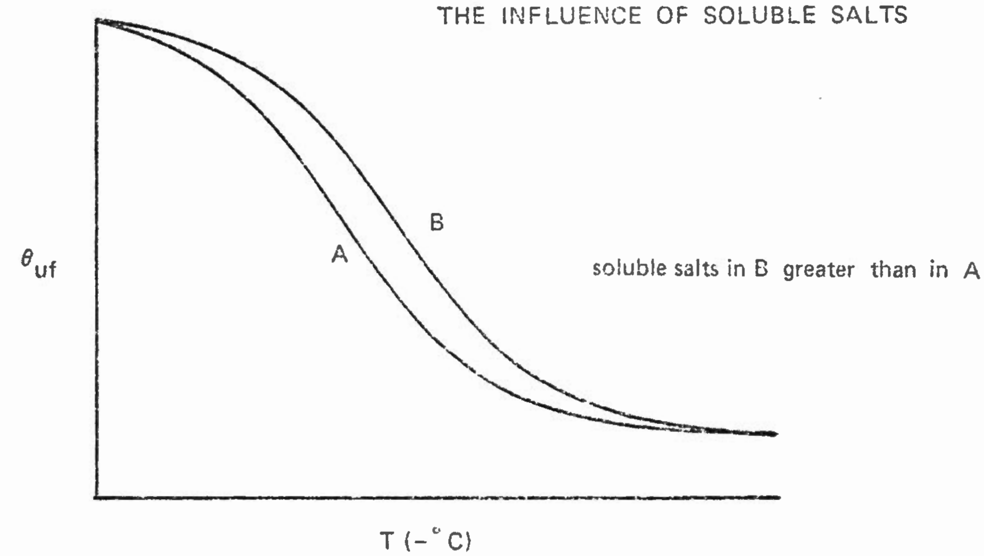
Considering the above, it is apparent that there is no unique freezing characteristic curve for a soil since a change in any of the physical properties of the soil can alter the relationship between θ_{uf} and negative temperature. These aspects make it difficult to assess the efficacy of any technique used to measure θ_{uf} since efficacy is generally determined by "how well does it compare to other methods".

FIGURE 9 THE EFFECT OF SOIL PROPERTIES ON THE FREEZING CHARACTERISTIC CURVE

THE INFLUENCE OF SOIL PARTICLE SIZE



THE INFLUENCE OF SOLUBLE SALTS



The only solution to this dilemma is to integrate two techniques into one system using the same soil sample. In most instances this is physically impossible and comparisons must be made by describing the shape of the freezing characteristic curve for similar soils.

3.2 The Freezing Cell

The basic problem in designing the system for determining the θ_{uf} - T^oC relationship in the lab is accommodating the electrical system yet maintaining a high degree of temperature control. In the first stages of the design, an attempt was made to use a coaxial system to measure θ_{uf}. The coaxial tube has an internal diameter of 5 cm and is 25 cm long (see Figure 10). After several freezing cell designs, two considerations caused abandonment of this system until a future date:

1. The soil could not be completely saturated since the expansion of ice could conceivably rupture the cylinder.
2. Temperature control could not be attained.

At this point, a parallel transmission line system was constructed. Essentially the 'freezing cell' consisted of a thin-walled PVC tube (4.5 cm I.D.) 20 cm long. The transmission lines were attached to a plexiblass cap which serves as the top of the freezing cell (see Figure 11). A perforated disc served as the bottom which would permit water intake by the soil during wetting. The cylinder is then placed in a tank of distilled water and allowed to wet. The water content would be close to a natural saturated field condition (≃ 38 per cent) since no attempt was made to attain complete saturation.

Figure 10 COAXIAL LINE SCHEMATIC

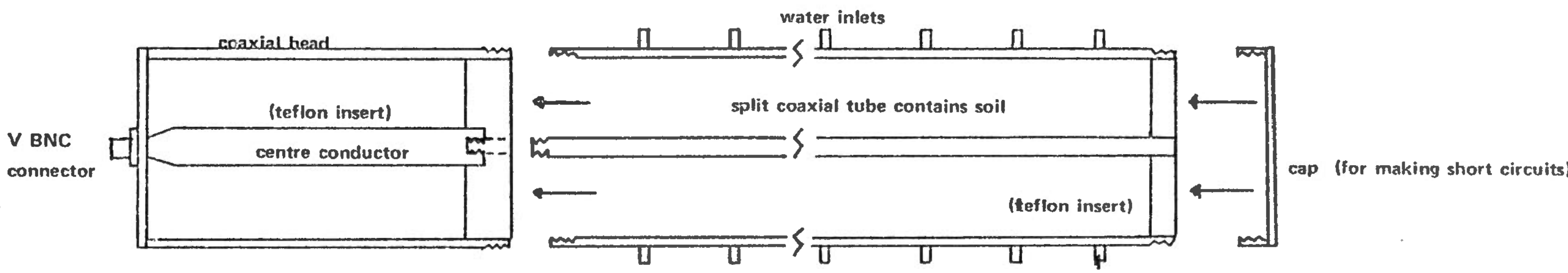
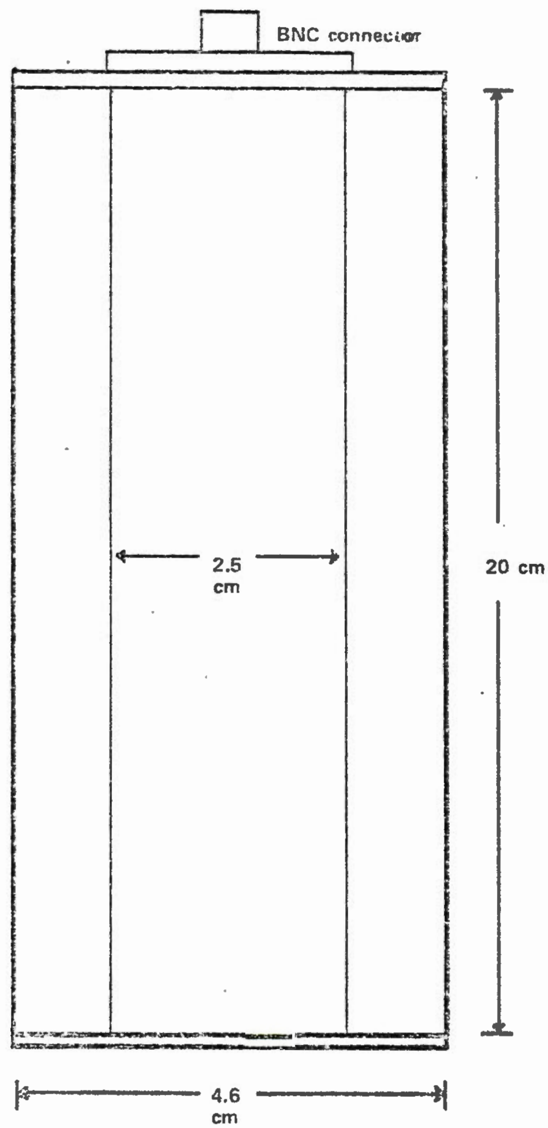


FIGURE 11 FREEZING CELL



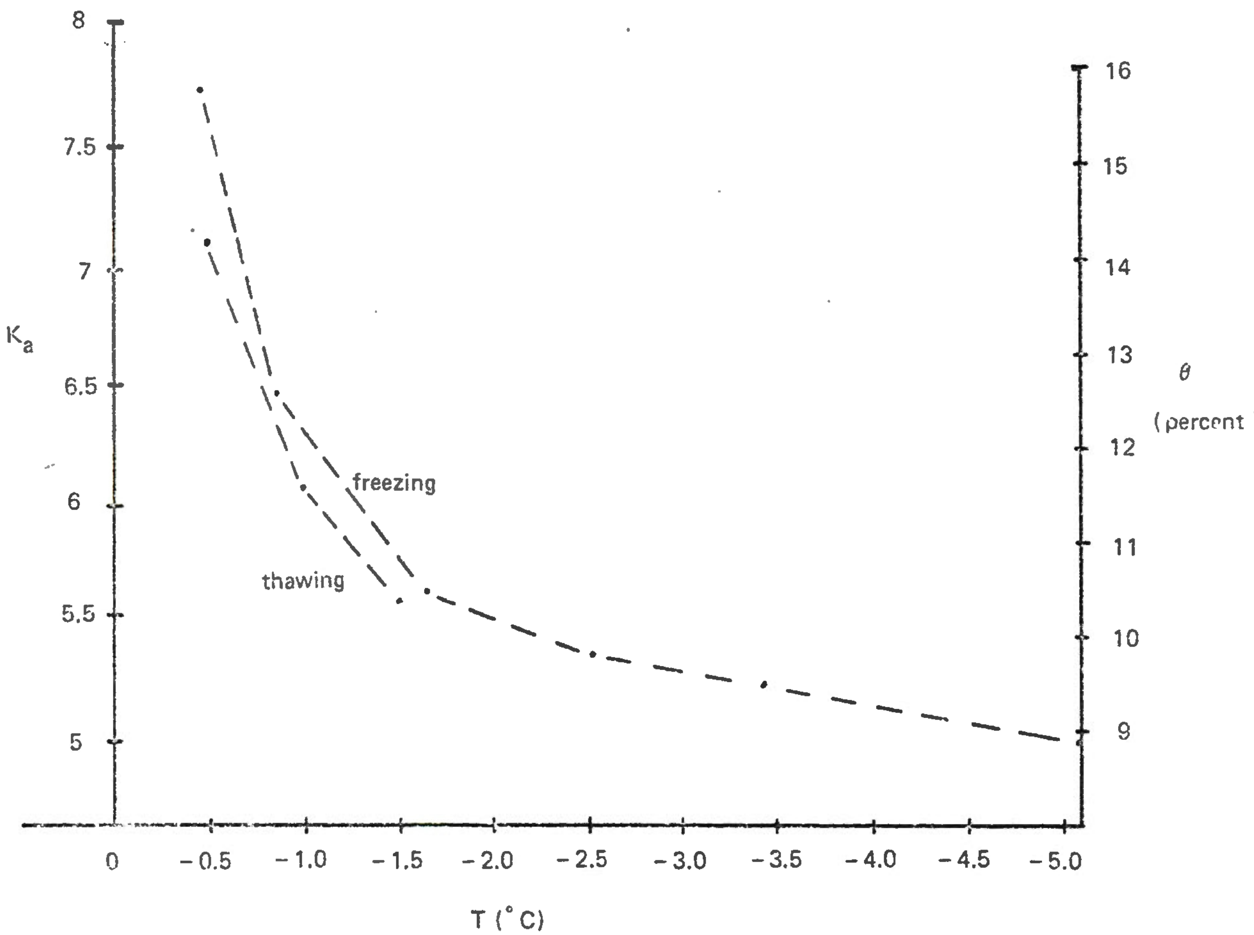
Once the soil is wetted, the bottom is sealed to prevent drainage or evaporation. The freezing cell is then covered with latex rubber sleeves and placed in a circulating methanol bath. The bath temperature is controlled to better than $\pm$ 0.01^{o}C. The soil temperature was within $\pm$0.05^{o}C from top to bottom. It is suspected that part of this variation was due to heat flow along the coaxial cable which connects the freezing cell to the TDR (this aspect can be rectified by using larger rubber sleeves and placing the freezing cell horizontally in the middle of the methanol bath). At least two hours were allowed to equalize sample temperature.

3.3 Results

The relationship between K_a and temperature for a Castor soil is presented in Figure 12 (see also Table 3). (Note: The θ axis on Figure 12 represents the volume of water indicated by K_a from (1)). The curve shows a rapid decrease in K_a over the temperature range 0^{o}C - 0.5^{o}C and a decrease in the rate of changes at colder temperatures. A difference between the freezing and thawing curves was also present. Since the difference is within measurement precision, it cannot be definitely stated that this is due to hysteresis (even though the consistency of the trend would suggest otherwise).

As indicated in Section 3.1, there is difficulty in assessing the efficacy of a technique for measuring θ_{uf}. It is of the utmost importance that technique comparison be performed on the exact same soil sample since changes (however minor) in the soil properties can influence the nature of the freezing characteristic curve. Time did not permit

FIGURE 12 K_a-TEMPERATURE RELATIONSHIP FOR A CASTOR SOIL



θ is determined from (1) for the values of K_a

TABLE 3

FREEZING CHARACTERISTIC CURVE

CASTOR SILTY LOAM

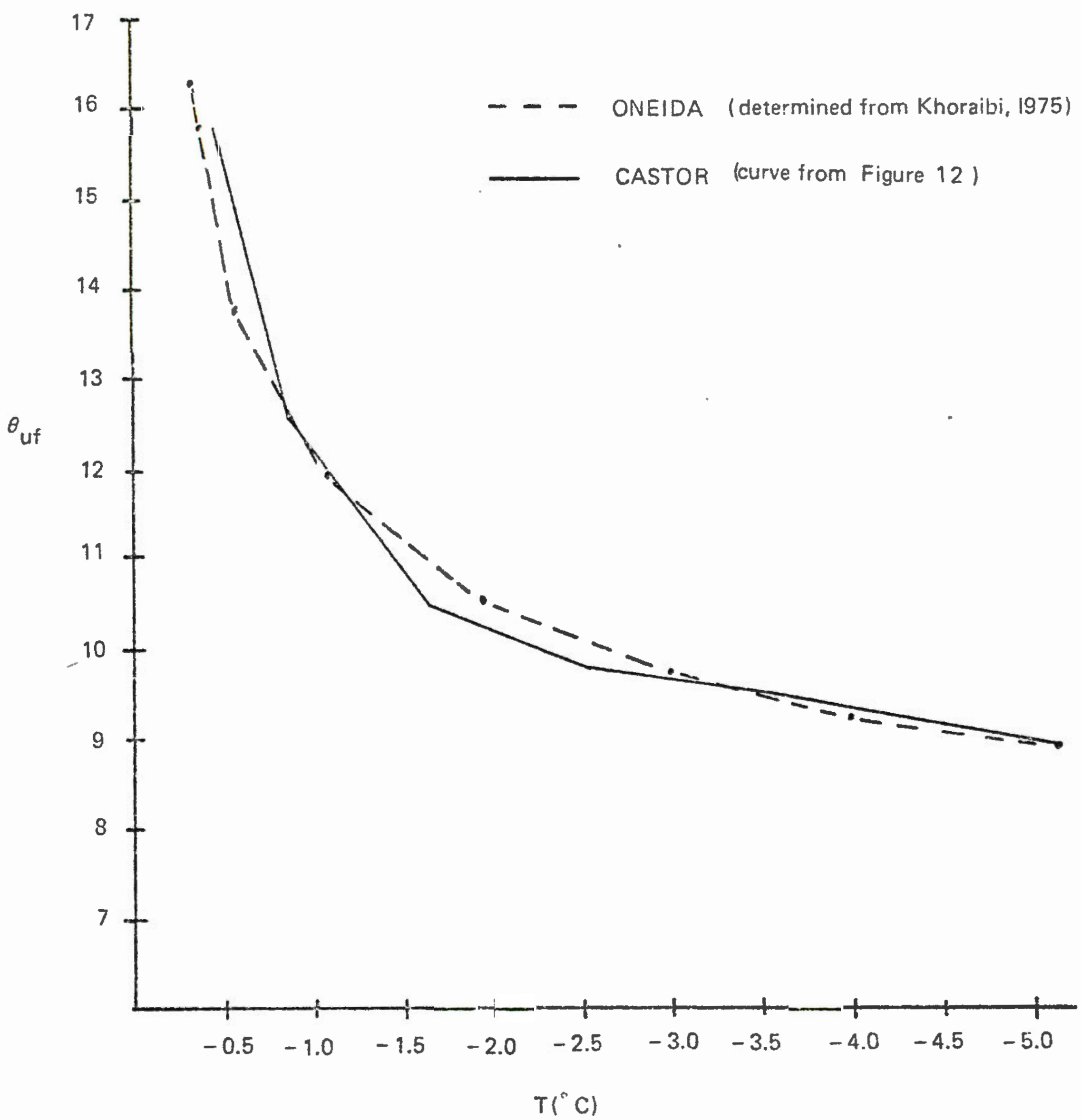
T (^{o}C)	K_a	θ_{uf}* (%)
+0.50 & 0	22.87	37.5
-0.46	7.84	15.8
-0.86	6.37	12.6
-1.65	5.55	10.5
-2.52	5.29	9.8
-3.42	5.23	9.5
-5.10	5.04	8.9
-1.50	5.68	10.4
-0.97	6.02	11.6
-0.50	7.08	14.2

*From Figure 1 or (1)

designing and constructing a system which integrates two techniques. The use of TDR techniques to measure θ_{uf} could be assessed (at this time) with regard to results obtained on similar soils. This approach was necessary since performing experiments using one or more of the techniques cited in Section 1 is time-consuming and does not guarantee any solid foundation to which the TDR technique can be compared.

El Khoraibi (1975) presents θ_{uf} - $T^{o}C$ data for an Oneida soil which has a similar particle size distribution to the Castor soil. As can be seen in Figure 13 the nature of the curves are similar.

FIGURE 13 FREEZING CHARACTERISTIC CURVES FOR TWO 'SIMILAR' SOILS



SECTION 4

CONCLUSIONS AND SUMMARY

The use of TDR techniques appears to have good potential for measuring the unfrozen water content of freezing soils. The efficacy will ultimately be determined by integrating the TDR technique with another method. At present work is being carried out in the Geotechnical Science Laboratories to design a system which will combine a modified dilatometry setup (to measure volume expansion of the soil) and the TDR technique. Other interests at present involve using the TDR technique to monitor the rates and magnitude of water movement toward the freezing front (using freezing soil columns) to provide data for numerical model testing.

If the TDR technique proves to be a viable method for measuring θ_{uf} it may be possible to measure θ_{uf} of core samples in the field and determine the freezing characteristic curve of core samples brought back to the laboratory.

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APPENDIX 1

DIELECTRIC NOTATION

When applying the theory of dielectrics to the measurement of the electrical properties of soils, Davis, Topp and Annan (1977) state that the notation used to calculate the complex dielectric constant, K^*, is:

$$K^* = K' + j(K'' + \frac{\sigma dc}{\omega \varepsilon_o})$$

where K' is the real part of the dielectric constant; K'' represents dielectric loss (the imaginary part of K^*); dc is the d.c. conductivity; ω is the angular frequency ($2\pi f$); ε_o is the free space permittivity and j equals $-1^{\frac{1}{2}}$. An electric loss term, $\tan\delta$, can also be defined (Davis and Annan, 1977):

$$\tan\delta = \frac{K'' + \frac{\sigma dc}{\omega \varepsilon_o}}{K'}$$

which, for the range 1 - 1000 MHz, is small for most soils; therefore, $K^* \simeq K'$. When using the TDR technique both the real and imaginary parts of the complex dielectric constant are measured; hence, the term 'apparent dielectric constant', K_a can be used. For low loss material K_a is essentially K' (Topp, Davis, Annan and Brule, in preparation).

APPENDIX 2

APPROXIMATE TRAVEL TIME IN SOIL VS LINE LENGTH FOR SEVERAL VALUES OF K_a

Travel Time (ns) for:

Line Length (cm)	$K_a = 3$ ($\theta \simeq 0\%$)*	$K_a = 5.4$ ($\theta \simeq 10\%$)	$K_a = 16.9$ ($\theta \simeq 30\%$)	$K_a = 34.4$ ($\theta \simeq 50\%$)
7.5	0.43	0.57	1.02	1.46
10.0	0.58	0.77	1.37	1.96
15.0	0.87	1.16	2.05	2.93
20.0	1.15	1.55	2.74	3.91
25.0	1.44	1.93	3.42	4.89
30.0	1.73	2.32	4.11	5.86
35.0	2.02	2.71	4.80	6.84
40.0	2.31	3.10	5.48	7.82
50.0	2.89	3.87	6.85	9.77
60.0	3.46	4.65	8.22	11.73
70.0	4.04	5.42	9.59	13.69
80.0	4.62	6.19	10.96	15.64
90.0	5.20	6.97	12.33	17.59
100.0	5.77	7.75	13.70	19.55

* $\theta = \theta_v$ or θ_{uf}

$$\rho = \frac{R_L - Z_o}{R_L + Z_o} \tag{5}$$

As stated, the horizontal axis on the 1502 is calibrated in M/DIV. This axis, though, can easily be converted to a time axis by dividing the horizontal scale by the velocity of propagation:

$$\frac{\text{TIME}}{\text{DIV}} = \frac{\frac{\text{M}}{\text{DIV}}}{v_p} \tag{6}$$

For example, for a scale setting of 1 M/DIV and the CABLE DIELECTRIC set for a PTFE (teflon) coaxial cable ($v_p = 0.70 \cdot c = 2.1 \times 10^8$ m/sec), this represents 4.762 ns/DIV.

There are several pieces of information which can be determined from the display on the TDR's crt. First, the impedance of a transmission line can be obtained (or an impedance mismatch within a line) from (5) where Z_o is the impedance of a 'known' cable (the 1502 is balanced for 50Ω and a 50Ω precision cable is supplied) and R_L is the impedance of the 'unknown' cable (or impedance mismatch in a line). If the vertical scale setting is known the impedance of the R_L can be found from Table 2 (reference 50Ω cable to centre line). The length of the cable can also be determined directly off the crt display if the CABLE DIELECTRIC is set for the type of cable being tested (see Figure 5).

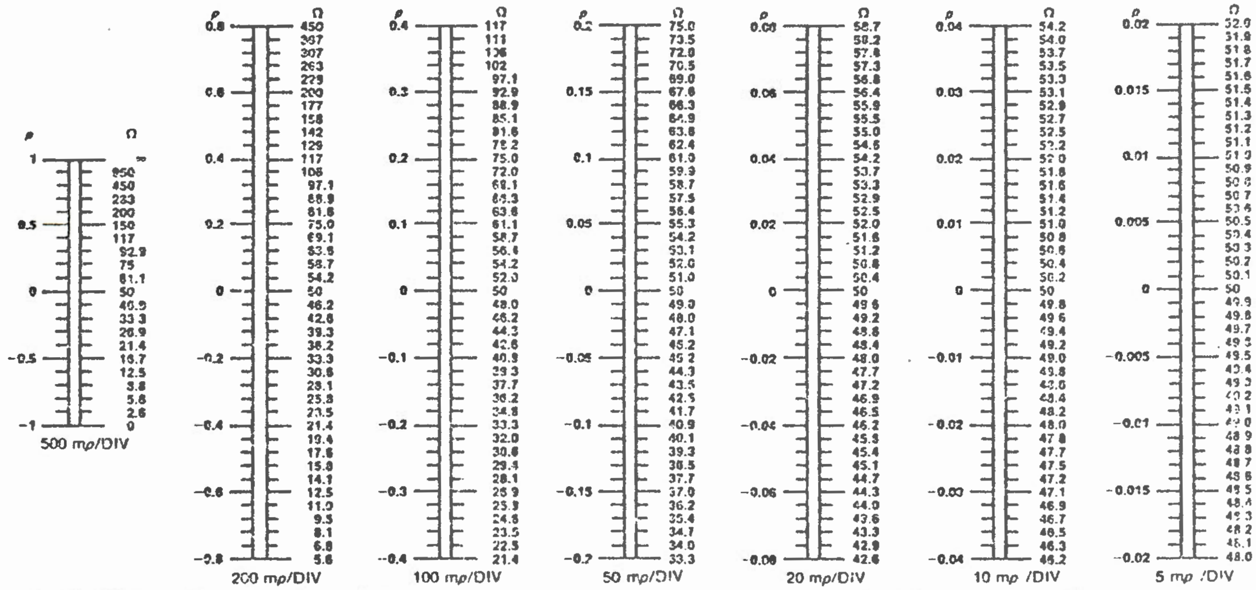
The dielectric constant of a cable can also be determined if the length of transmission line (coaxial or parallel line) is known; the relationship can be expressed by combining (2) and (4):

$$K' = \left[\frac{v_p \times tt}{L}\right]^2 \tag{7}$$

[redacted]

Table 2

IMPEDANCE CHART FOR TEKTRONIX 1502 TDR



DIRECTIONS FOR USE: LOCATE THE COLUMN OVER THE SETTING OF THE mρ/DIV SWITCH. FIND THE ρ VALUE ON THE LEFT SIDE OF THE COLUMN AND READ THE IMPEDANCE ON THE RIGHT SIDE CORRESPONDING TO THE ρ VALUE.

Figure 5 DETERMINING CABLE IMPEDANCE AND LENGTH