LONG TERM PAVEMENT PERFORMANCE PROGRAM DIRECTIVE

For Technical Direction of the LTPP Program

Program Area:	Monitoring	Directive Number:	SM-28
Date:	August 7, 1998	Supersedes:	n/a
Subject:	Interpretation Manual TDR Traces		

1. Scope

1.1 Procedures are provided in this directive for interpretation of manually collected Time-Domain Reflectometry (TDR) traces from the LTPP Seasonal Monitoring Program.

2. Applicable Documents

2.1 **LTPP Seasonal Monitoring Program: Instrumentation Installation and Data Collection Guidelines**, FHWA-RD-94-110, Office of Engineering and Highway operations R&D, Federal Highway Administration, January 1995. (G. Rada, Elkins, G.E., Henderson, B., Van Sambeek, R.J., and Lopez, Jr., A.)

3. Definitions

(A) TDR — Time-Domain Reflectometry, a technique used to measure the travel time and properties of an electromagnetic wave induced into a waveguide; in this application a moisture probe. The travel time of the wave is proportional to the dielectric constant of the material surrounding the probe. For unbound soil, the dielectric constant is proportional to its moisture content.

(B) Moisture Probe — The FHWA TDR moisture probe used at the majority of LTPP SMP test sections, consists of three straight stainless steel metal tubes, .203-m long, held parallel to each other by a plastic spacer at one end and a printed circuit board at the other end. The printed circuit board contains a connection with the shielded coaxial metallic lead cable.

(C) Manual Traces — TDR waveform traces which have been recorded on strip chart paper.

(D) Apparent Length — Length between the begin and end points on the waveform which correspond to the beginning and end of the metal tube portion of the moisture probe.

(E) Begin Point — Location on the TDR trace which corresponds to the beginning of the metal tube portion of the moisture probe.

(F) Begin Point Zone — An area on the TDR trace which contains the probable location of the begin point.

(G) End Point — Location on the TDR trace which corresponds to the end of the metal tube portion of the moisture probe.

(H) End Point Zone — An area on the TDR trace which contains the probable location of the end point.

(I) RCOC Engineer — Professional engineer in the RCOC office with responsible charge for measurement and reporting of this data to a public agency.

(J) Cable Tester — The instrument which performs and records the TDR measurements.

4. Summary of Method

4.1 Interpretation of the TDR trace consists of classification of the trace into characteristic types and computation of the dielectric constant. The dielectric constant of the material surrounding the moisture probe is determined by measurement of the apparent length scaled off of the paper traces.

5. Significance and Use

5.1 The dielectric constant determined from interpretation of TDR apparent length can be used to estimate moisture content changes in the material surrounding the probe. Dielectric constant properties can also be used for other remote sensing applications which rely upon the electrical property of materials, such as ground penetrating radar.

5.2 The TDR trace type classification and bulk conductivity class can be used to identify changes in the vertical soil profile due to material variations, presence of frost, and moisture changes.

6. Equipment

6.1 Engineer's scale - (divisions in multiples of 10)

6.2 Straight edge and right triangle or two right triangles

6.3 Sharp pencil

6.4 Plain paper photocopier with enlargement capability and ability to handle 11" x 17" size paper.

7. Interpreter

7.1 One interpreter in each Regional Coordination Office is preferred, however, up to three interpreters may be used for production purposes. Each interpreter must be acquainted with the TDR equipment, its operational characteristics, TDR fundamentals and the trace interpretation procedures contained in this directive. The RCOC Engineer must verify that each interpreter can correctly scale lengths off of the paper traces.

8. TDR Trace Interpretation and Classification

8.1 Assemble all manual TDR trace originals collected from a single site on the same measurement day within a continuous measurement time period. The TDR traces collected from the same site on each measurement day are processed as a batch.

8.2 Group the traces in order of sensor number and photocopy enlarge each group onto 11" x 17" paper. The traces should be copied in portrait mode. The percent enlargement should be selected so that the resulting horizontal divisions on the copy match one of the intervals on the scale being used.

8.3 Classify each trace into the categories described in Appendix A.

8.4 Following the guidelines contained in appendix A, locate the extremes of the begin point zone (A_{min} and A_{max}),the begin point (A), the extremes of the end point zone

(B_{min} and B_{max}), and the end point (B). (Note that some traces do not require location of all defined A and B points.)

8.5 Draw vertical lines through the points located in 8.4. The vertical lines should be drawn parallel to the y-axis on the graph, using the sharp pencil and triangles or triangle+straight edge.

8.6 Scale the length between appropriate pairs of the vertical lines to determine the quantities for analysis apparent length - $L_{analysis}$, minimum apparent length - L_{min} , and maximum apparent length - L_{max}.

8.7 Interpret each trace for bulk conductivity of the soil surrounding the probe following the procedures presented in Appendix A.

9. Calculations

9.1 Calculate the dielectric constant, ε, as follows:

Install Equation Editor and double-click here to view equation.

where ε = dielectric constant (between 1.0 to 80).
L_a = apparent length scaled from trace, m.
L = physical length of the metal tube portion of the moisture probe, m; 0.203 m (8 in) for FHWA probes.
V_p = phase velocity setting on TDR cable tester (usually 0.99).

10. Report

Record the following on Data Sheets SMP-D11.1 and D11.2.

10.1 Identification information including: state code, sharp ID, measurement date (SMP Date), and measurement time (SMP time).

10.2 TDR sensor number (TDR No.)

10.3 Probe length in meters to three decimal places.

10.4 Cable tester settings recorded on the paper trace:

10.4.1 Distance per division setting to two decimal places.

10.4.2 Units for the distance per division setting, m - meters, ft - feet.

10.4.3 Propagation velocity setting, V_p, to two decimal places.

10.5 Interpretation and classification results:

10.5.1 Trace type classification, 1 - Classic , 2 - Shorted, 3 - Open, 4 - Rounded, 5 - Irregular, or 6 - Uninterpretable.

10.5.2 Conductivity level, Low or High.

10.5.3 Analysis, minimum and maximum apparent lengths, m, to two decimal places.

10.5.4 Analysis, minimum, and maximum dielectric constants computed from the corresponding apparent length, to the nearest whole number.

10.6 Interpreter's name, employer and interpretation date.

10.7 Interpretation comments.

11. Storage

11.1 Original and copy of TDR trace used in interpretation shall be archived in RCOC office. Data Sheets SMP-D11.1 and SMP-D11.2 shall also be archived in RCOC office once data have been entered into the IMS.

12. Problem Reporting

12.1 If there are any problems implementing this directive, please submit a SMP problem report (SMPPR) form in accordance with LTPP Monitoring Directive SM-6.

Prepared for: Aramis Lopez, Jr. Approved by:

Monte Symons
Team Leader, LTPP Operations

LTPP SMP Manual TDR Trace Interpretation Data Sheet SMP-D11.1 Trace Classification, Apparent Length and Dielectric Constant	STATE_CODE [___ ___] SHRP_ID [___ ___ ___ ___]

SMP Date (dd/mmm/yyyy): [___ ___ / ___ ___ ___ / ___ ___ ___ ___] TDR Time (hhmm): [___ ___ ___ ___]

TDR No.	Probe Length, PL (m)	Distance/Division		Propagation Velocity Setting, V_p	Trace Type	Conductivity (Low/High)	Apparent Length L_a (m) (0.2 - 1.85m)			Dielectric Constant $\varepsilon = [L_a / (V_p * PL)]^2$		
		Setting	Units				Analysis	Min	Max	Analysis	Min	Max

Trace Type: 1-Classic; 2-Shorted; 3-Open; 4-Rounded; 5-Irregular; 6-Uninterpretable

Were interpretation comments entered on Data Sheet SMP-D 11.2? ☐ YES ☐ NO

Interpreter: ______________________________ Date (dd/mmm/yyyy): ___ ___ / ___ ___ ___ / ___ ___ ___ ___

Employer: ______________________________

LTPP SMP Manual TDR Trace Interpretation Data Sheet SMP-D11.2 Interpretation Comments	STATE_CODE [___ ___] SHRP_ID [___ ___ ___ ___]

SMP Date (dd/mmm/yyyy): [___ ___ / ___ ___ ___ / ___ ___ ___ ___]   TDR Time (hhmm): [___ ___ ___ ___]

TDR No.	Comments

Interpreter: ________________________________   Date (dd/mmm/yyyy): ___ ___ / ___ ___ ___ / ___ ___ ___ ___

Employer: ________________________________

Appendix A
TDR Classification and Interpretation

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TDR Trace Classification and Interpretation

TDR Fundamentals

The time domain reflectometry cable tester was designed to detect faults in coaxial cables by sending ultra fast rise time voltage pulses down the cable and recording the reflected signals. The pulses propagate as an electromagnetic wave through the cable. Changes in impedance and other faults in the cable cause partial reflection of energy back to the source where it is sampled and recorded. The TDR moisture probe acts as an extension of the coaxial cable; the center wire in the coaxial cable is connected to the center steel tube in the probe. The mesh shielding in the coaxial cable is connected to the outer steel tubes. Due to the construction of the moisture probe, the impedance transitions at the beginning and end of the metal tubes create changes in the reflected waveform which can be identified. When the probe is inserted in soil, the distance between the points on the waveform corresponding to the begin and end of the tubes depends on the moisture content; as the moisture content increases the distance between the tube end points increases.

Since electrical impedance is a complex concept, the electrical resistance of the material between the inner wire or center probe rod, and shielding or outer probe rods, will be used to simplify the explanation the factors which cause the observed features of the TDR waveform in the moisture probe. In this context, the fundamental principles of the TDR waveform are:

- **As the resistance of the material between the center tube and outer tubes INCREASE, the amplitude of the waveform INCREASES (moves towards the top of the graph).**

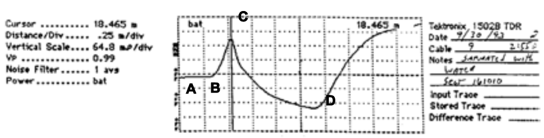
- **As the resistance of the material between the center tube and outer tubes DECREASE, the amplitude of the waveform DECREASES (moves toward the bottom of the graph).**

With these fundamental principles, the classic TDR waveform shown in figure A.1 from a probe inserted in soil can be explained as follows:

> The waveform between points A-B correspond to the coaxial cable. A straight line is obtained since there is no change in the resistance of the material separating the inner wire and the shield wire. On some traces, a slight slope near the probe can be observed.
>
> At point B the signal enters the connector and printed circuit board on the moisture probe. Since the resistance of the material between the inner wire and outer wire increases, the amplitude of the signal increases (moves toward the top of the graph).

At point C the signal enters the meal probe rod. Since the resistance of material between the inner tubes and the outer tubes are lower than that of the material in the printed circuit board, the amplitude of the waveform decreases (moves toward the bottom of the graph).

At point D the signal reaches the end of the metal rods. Since the resistance of the material at the ends of the tubes increases, the amplitude of the signal increases (moves toward the top of the graph.



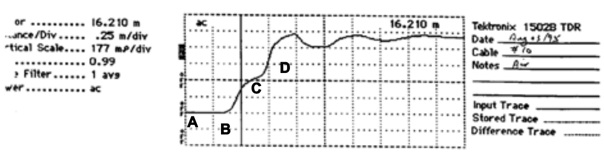
Although this explanation is simplified, it also satisfactorily explains the shape of a TDR trace from a probe held in air, as shown in figure A.2.

Between points A-B, the signal is inside the coaxial cable.

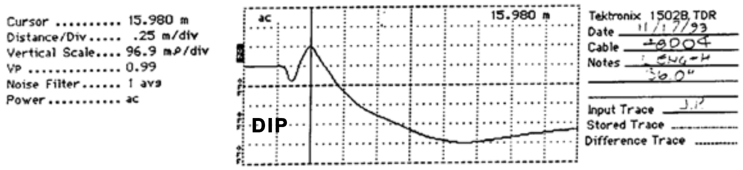
At point B the signal enters the connector and printed circuit board on the moisture probe. The increased resistance causes the amplitude of the signal to rise.

At point C, the signal enters the metal probe rods. Since the resistance of the air between the metal tubes are greater than the printed circuit board, the amplitude of the signal continues to increase, but at a decreased rate.

At point D, the signal reaches the end of the metal probe. Since the resistance at the ends of the tubes increases relative to the resistance between the metal rods, the slope and amplitude of the signal increase.



This model also helps to describe the “dip” in the waveform shown in figure A.3. During the standard preinstallation equipment checks performed in the SMP program, it was found that the “dip” at the start of traces were characteristic of probes in which the seal between the electrical connector and the printed circuit board was not water tight. When the water in this space was removed and the connection resealed, the “dip” disappeared. Under the electrical resistance model, the moisture in the connector creates a decrease in the resistance between the inner and shield wires which results in the characteristic “dip” prior to the point where the signal enters the printed circuit board. (Note, traces with this type of “dip” can still be interpreted.)



The TDR trace classification method is based, in part, on extension of the resistance model previously described to the extremes of an electrical "open" and "shorted" conditions. The trace of the TDR probe in air, figure A.2, represents the open condition, i.e. an open connection between the inner and outer rods. The shorted condition is created when the material between the inner and outer tubes has a very low electrical resistance. The trace in figure A.4 was created by shorting the inner and outer tubes with a piece of metal placed at the beginning of the rods, i.e. junction between metal probe tubes and printed circuit board. This type of shorted trace continues to drop at a decreasing rate and never reaches a minimum value where it flattens out.

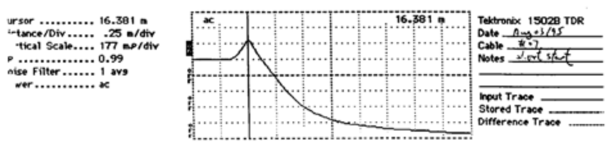
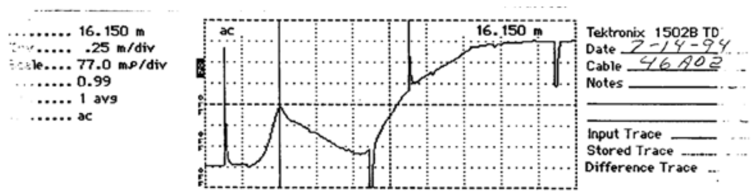


Table A.1 presents a general summary of factors affecting the shape of TDR traces, using the electrical resistance model explanation. These are general factors. Other factors influencing the shape of the TDR include mineralogical composition of the soil, chemical composition water, ratio of bound water to free pore water and to some extent, temperature.

Table A.1. General trends of factors influencing amplitude of TDR traces.

Factor	Resistance	Affect on trace amplitude
Low moisture content	High	Rise
Ice or frost	High	Rise
Rock or air void near probe	High	Rise
Broken probe connector	High	Rise
High moisture content	Low	Drop
Increased salinity or alkalinity	Low	Drop

Some traces contain blips and other types of short transient phenomena or noise. These "abnormalities" are thought to be due to electrical interference from outside sources. Some known causes include FWD tow vehicle parked across the coaxial TDR lead cables and poor quality AC inverter used to power the cable tester in the field. An example of this type of trace is shown in Figure A.5. These noisy traces tend to occur more frequently when the cable tester is powered by an AC source.



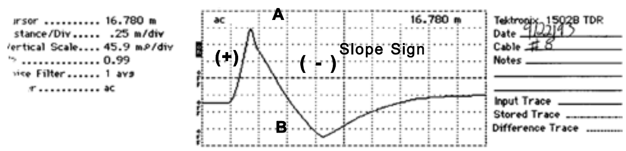
Although somewhat imprecise, the resistance model explanation is used here since it is easy to visualize a flow of electrons from the inner probe tube to the outer tubes being restricted by the soil between the rods. The higher the resistance between the rods, the higher the trace rises on the graph and vice versa. A more precise description of this phenomena is to use the term bulk electrical conductivity. Conductivity is best thought of as the inverse of resistivity. It is the presence of the free ions in the soil-water-air matrix that attenuate (reduce) the amplitude of the signal. Thus the change in the amplitude of the signal from the beginning points on the metal tube to the end points is proportional to the bulk soil conductivity. The quantitative estimate of this value requires a probe constant to be determined through a calibration process. Since the LTPP probes have not been calibrated to determine this constant, a qualitative classification will be used based on the amplitude of the signal at the end of the probe relative to the amplitude of the signal inside the coaxial cable.

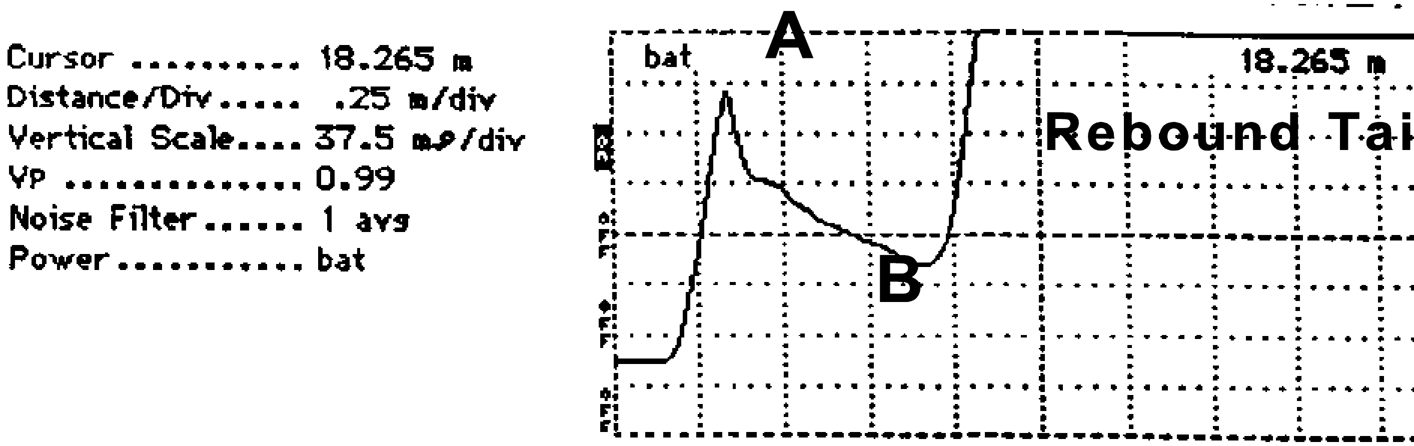
TDR Trace Classification

The shape and general characteristics of the TDR trace provides information on the nature of the material surrounding the probe. The classification information can also be used as a handy sort key for specific types of investigations. The interpretation method and uncertainty in determination of the apparent length also varies depending on the trace type. The following trace type categories will be used to classify manual TDR traces:

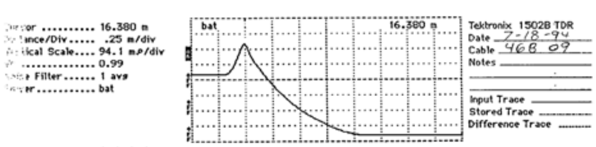
1. **Classic Trace**. The classic TDR trace contains a relatively sharp peak at the begin point and sharp dip at the end point of the metal tubes on the moisture probe. As shown in figure A.6, starting from the left side, the trace rises from the nearly flat portion of the curve representing the signal in the coaxial cable to a peak at point A, or local maxima point, where the slope of the curve reverses signs from positive to negative. From this point the curve drops to a minimum at point B and then rebounds upward, i.e. the slope of the curve reverses signs from negative to positive. On many classic traces, the rebound portion of the

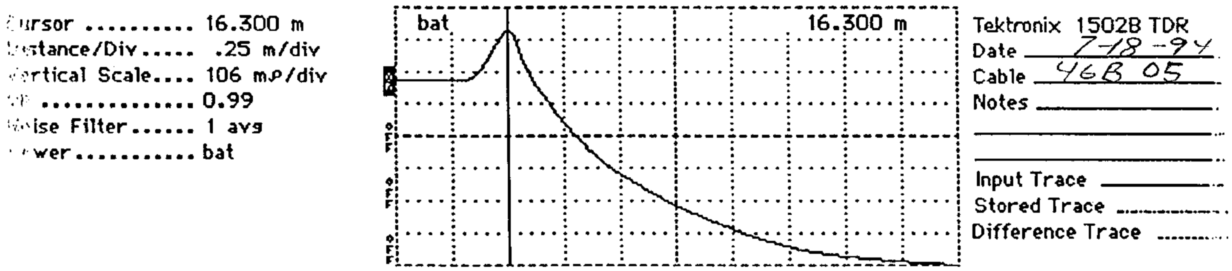
trace occurring after point B is concave downward (a decreasing change in the slope of the curve), as shown in figure A.6. However, some classic traces contain a concave upward rebound tail that creates uncertainty in the actual location of the end point, as shown in figure A.7. The classification rule for classic traces are that the slope of the curve reverses signs at point A from positive to negative and from negative to positive at point B. A curve that meets this criteria is classified as classical, unless it satisfies the criteria for rounded or irregular trace categories.



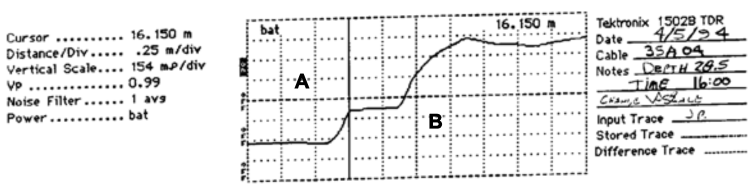


2. **Shorted Trace**. A trace that, after the first peak, drops to a minimum level and does not rebound to create a second, defined, inflection point. The tail portion of shorted traces either continue to drop in magnitude or fattens out and becomes parallel with the abscissa. These traces are characteristic of probes placed in highly conductive materials, such as soil with high alkalinity, which shorts the electrical signal between the probe rods; i.e. all of the electrical signal is returned. The apparent length determined from shorted traces typically has a high variability, and in some cases, can not be determined. Figure A.8 is an example of a shorted traces with a flat tail which pose some complications in determining the location of the final inflection point. Figure A.9 is a shorted trace whose tail position steadily decreases and never flattens out or rebounds.

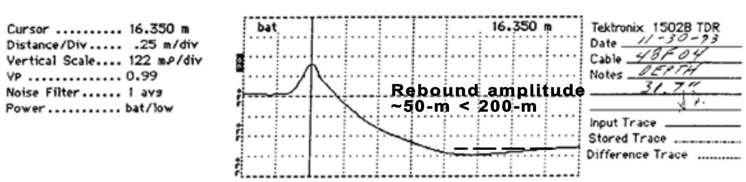




3. **Open Trace**. All of the line segments on the open trace have positive slopes; the traces continues to rise with very little drop as shown in Figure A.10. This is characteristic of a probe in a very highly non-conductive material, such as occurs in frost zones. Very little of the electrical signal is returned, in essence there is an electrical open between the rods. The classification rule for open traces is that the slope of the curve must be positive between points A and B.

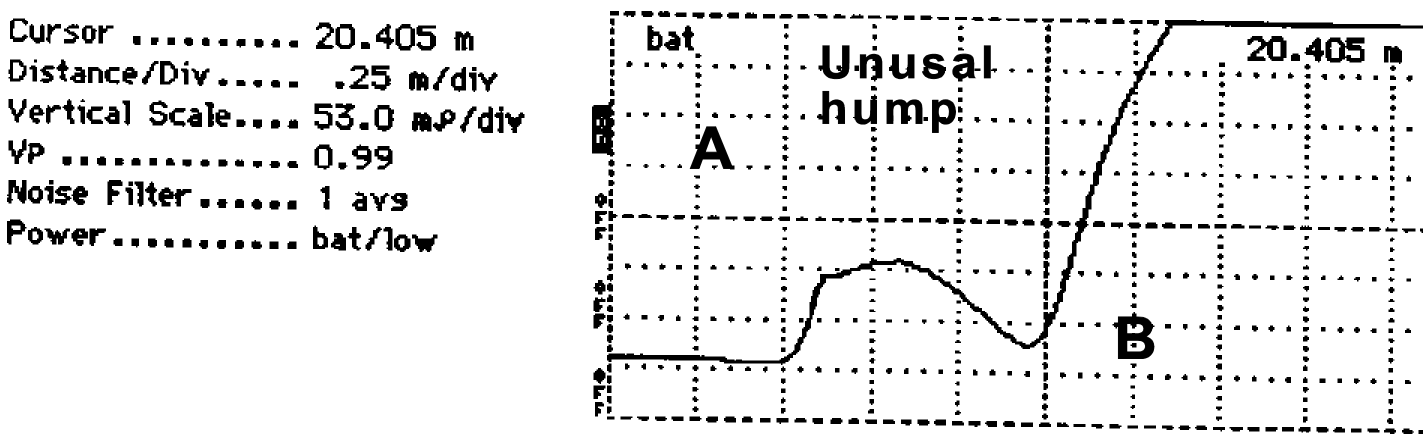


4. **Rounded Trace**. On rounded traces, the end point zone has a relatively large diameter curvature, is “rounded” instead of a sharp dip and has a low rebound height. The rebound height is the scaled distance from the local minima that occurs at the end point and maximum point on the trace to the right of the end point. The criteria for classification as a rounded trace is that the rebound height must be greater than zero and less than or equal to 200-mρ (milli rho). Figure A.11 shows a typical rounded trace with a rebound height of approximately 50-mρ. (Note that the vertical scale is set to 122-mρ per division.) This criteria must be exercised with some judgement in cases where the tail portion of the trace was cut-off. Aberrations in the vertical scale for manual traces from the pilot study sites where the horizontal distance scale was set to units of feet/div have been observed. If a TDR trace meets the rounded criteria, it is always classified as rounded, even if it meets the criteria for other trace categories.

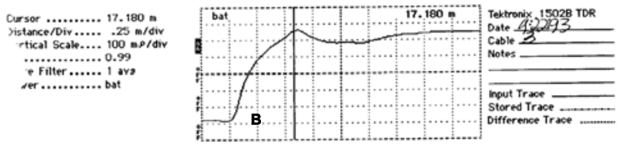


From an analysis of more than 100 manual TDR traces from a variety of SMP sites, it was found that the average height of the initial peak at the begin point was slightly more than 200 mρ. The initial peak height is the scaled vertical distance between the peak at the begin point and the flat portion of the trace to the left of the peak (the vertical distance between points B and C shown in figure A.1). Although there is some variation in this height, it can be used as a quick screening tool to distinguish rounded traces.

5. **Irregular Traces**. Irregular traces are those which deviate from the other trace categories. Figure A.12 shows an irregular trace in which a local maxima point occurs after the probable location of the A point at the beginning of the metal tube. The irregular trace classification should be used sparingly; traces which are thought to qualify as irregular shall be submitted to the LTPP Technical Support Services Contractor for approval prior to classification as an irregular trace. Traces which contain electrical noise, or other types of short length abnormalities should **not** be classified as irregular.



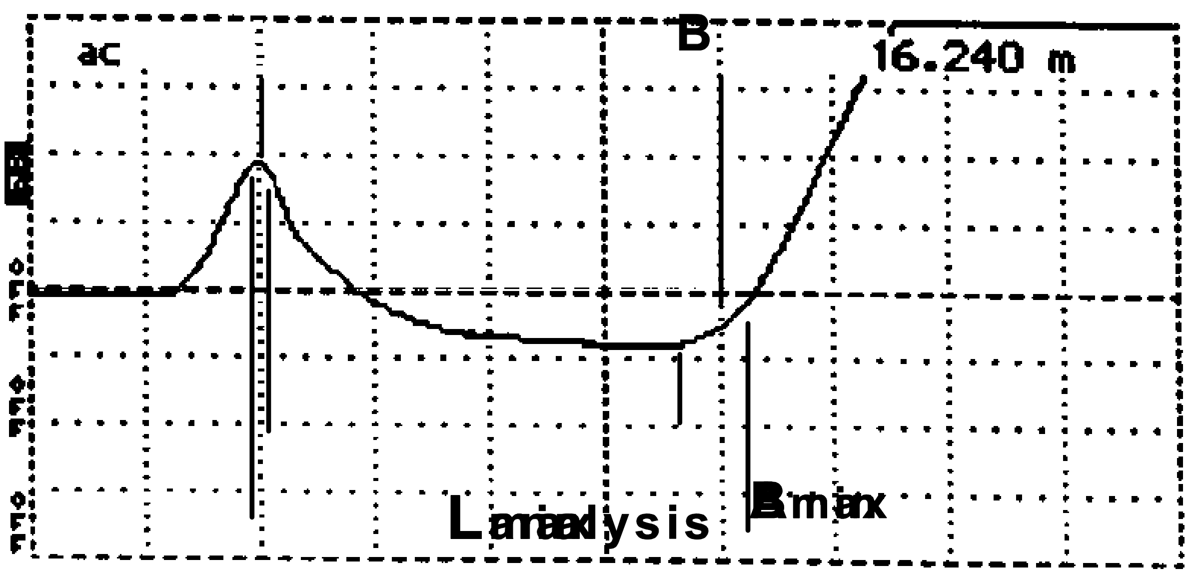
6. **Uninterpretable traces**. The general class of uninterpretable traces are those in which the location of either end points of the moisture probe are not captured on the print out. This is most often caused by an incorrect Cursor setting. Figure A.13 illustrates a trace in which the begin point of the probe is not captured. The visual clues to this type of error present in figure A.13 are the very steep positive slope immediately to the right of the point labeled as B and the change in slope from positive to negative at the local maxima point near the location of the cursor (the solid vertical line). Traces from other TDR measurements at this site, which are not shown, also reinforce the observation that probe begin point as not captured through comparison of TDR trace shape and distance to cursor settings. Other types of uninterpretable traces include end point not captured and some types of shorted traces (as explained under trace interpretation).



Trace Interpretation - Apparent Length

The trace interpretation process for apparent length consists of identification of locations of begin point zone, begin point, end point zone, end point, and scaling the distance between these features to produce estimates of analysis apparent length, minimum apparent length and maximum apparent length.

The graph shown in figure A.14 illustrates the points on the TDR trace used in the apparent length interpretation process and nomenclature.



General Rules for Apparent Length Interpretation

The general interpretation process is as follows:

1. Begin point zone. The begin point is the location on the TDR trace which corresponds to the beginning of the metal tube portion of the moisture probe. The begin point is shown as the A line in figure A.14. On some traces the exact location of the begin point may not be

apparent due to the absence of sharp changes. In these instances, a begin point zone is established by locating the minimum and maximum locations on the trace where the begin point could potentially be located. These locations are shown as A_{min} and A_{max} in Figure A.14. Many traces have a very distinct peaks at the begin point with very little to no measurable difference between A_{min} and A_{max}. In these instances, it is not necessary to establish a begin point zone, only the single begin point A is needed.

2. Begin point. The begin point is the most probable location of the point on the TDR trace which corresponds to the beginning of the metal tube portion of the moisture probe. If a begin point zone was established in step 1, the begin point will fall somewhere between A_{min} to A_{max}. In some cases it is possible for the begin point to fall on either the A_{min} or A_{max} points. On traces with sharp peaks, the begin point should be located at the point where the trace starts to descend; just to the right of the maximum point on the peak. The location of the begin point on other types of traces will be discussed in the next section of this document.

3. End point zone. The end point is the location on the TDR trace which corresponds to the end of the metal tube portion of the moisture probe. The end point is shown as the B line in figure A.14. On some traces the exact location of the end point may not be apparent due to the absence of sharp changes. In these instances, a end point zone is established by locating the minimum and maximum locations on the trace where the begin point could potentially be located. These locations are shown as B_{min} and B_{max} in Figure A.14. Some traces have a very sharp-distinct dip at the end point with very little to no measurable difference between B_{min} and B_{max}. In these instances, it is not necessary to establish an end point zone, only the single end point is needed. In general, there is more variation in the location of the end point than begin point and hence it is expected that this variation will constitute the major portion of the variation in the apparent length.

4. End point. The end point is the most probable location of the point on the TDR trace which corresponds to the end of the metal tube portion of the moisture probe. If a end point zone was established in step 4, the end point will fall somewhere between B_{min} and B_{max}. In some cases it is possible for the end point to occur at either the B_{min} or B_{max} points. On traces with sharp-distinct dips, the end point should be located at the point where the trace starts to rise, to the immediate right of the minimum point of the dip. The location of the end point on other types of traces will be discussed in the next section of this document.

5. Measure apparent lengths. Three apparent lengths are determined by measuring the scaled distance between the various A and B lines shown in figure A.14.

$L_{analysis}$ = B - A : most probable apparent length for analysis.

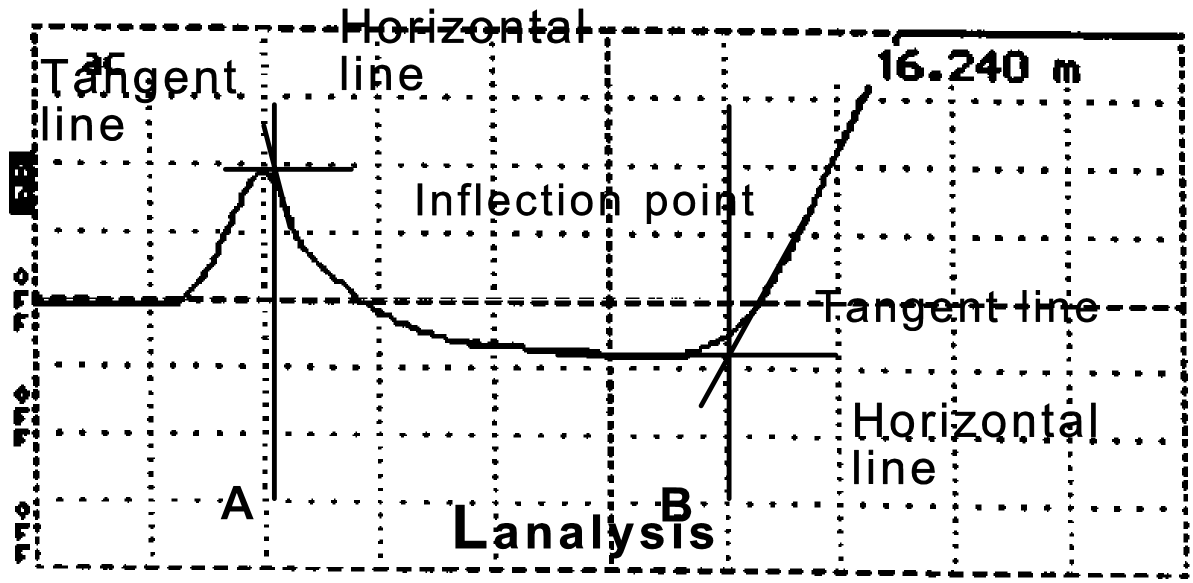
L_{min} = B_{min} - A_{max} : minimum apparent length

L_{max} = B_{max} - A_{min} : maximum apparent length

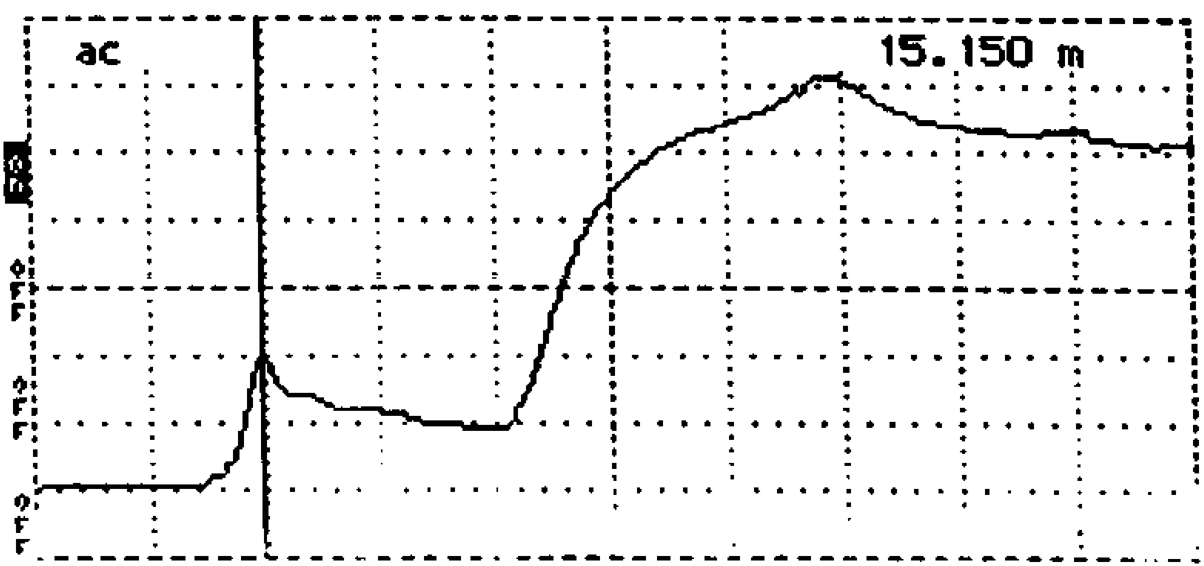
If a begin zone was not established, then A_{min}= A and A_{max} = A in the above equations. If an end zone was not established, then B_{min} = B and B_{max} = B in the above equations. If a begin and end zones where not established, then it is only necessary to compute $L_{analysis}$.

Apparent Length - Classic Traces

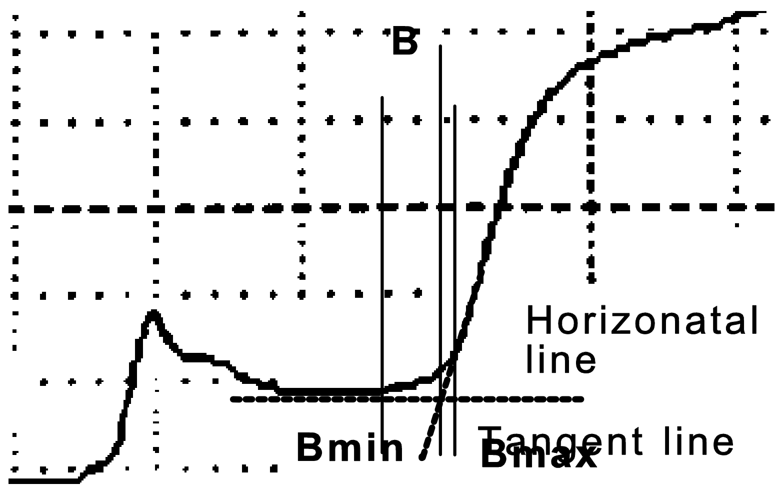
The most widely accepted apparent length interpretation method for classic TDR trace types is the method of tangents. The method of tangents, as illustrated in figure A.15, is based upon drawing a horizontal lines through the maxima at the begin point and minima at the end point. Tangent lines are then constructed through a portion of the trace to the right of the begin and end points. The intersections of the horizontal and tangent lines define the begin and end points (A and B lines). The biggest variable with the method of tangents technique is location of the tangent lines. One practice is to use an inflection point, if it exists, at a point on the trace to the right of the peak or dip. An inflection point is the location where the curve changes from concave upward to concave downward, or vice versa. It also generally occurs at the point in which the slope is the steepest, i.e. has the largest absolute value. (The more precise definition of the inflection point on a curve is where the second derivative equals zero, however this can not readily be determined through a visual analysis.) In instances where the inflection point is not apparent, the practice is to construct the tangent line through a portion of the curve, to the right of the local maxima or minima, that is relatively straight. As illustrate in figure A.15, this method tends to offset the begin and end points to the right of the point where the trace starts to fall or rise as stated in the general guidelines above.



Fortunately, for many classic TDR traces, the method of tangents and general location rule stated above produce identical begin and end points since the tangent line intersects the horizontal line at the point where the trace starts to fall and rise. This type of trace is shown in Figure A.16. These type of traces do not require estimation of zones about the begin or end points.

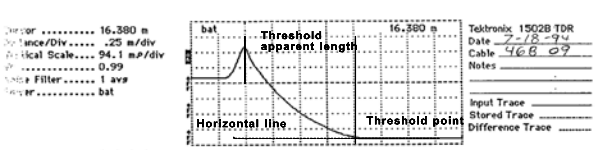


On traces in which there is some curvature associated with either the begin or end point locations, there is some uncertainty in exact location of these points. In this instance, the method of tangents and the general begin/end point location rule produce different results which can be significant. The begin/end points zones are used to capture and quantify this uncertainty. Figure A.17 is taken from a portion of a trace to illustrate the convention for determination of the end point and end point zone. The B_{min} point is located where the curve starts to rise from its minima which occurs at the point of divergence between the horizontal line and the trace. The end point, B, is located at the intersection of the horizonal and tangent line, constructed using the method of tangents. The B_{max} point is located at the point of divergence between the tangent line and the trace. The example shown in figure A.17 is for the end point. A similar construct can also be applied to the begin point, however rounding of the begin point is rarer than the end point. (This method equally applies to the rounded trace class.)



Apparent length - Shorted Traces

It is not possible to interpret some shorted traces because the signal either does not flatten out, or flattens out at a point too far from the begin point. For this research study, the interpretation of some shorted trace types will be attempted. The primary determinate between those traces which are potentially interpretable and those which are not, is the "threshold apparent length". The threshold apparent length is determined by drawing a horizontal line parallel to the x-axis passing through flat end portion of the shorted trace. The point where the trace diverges from the horizontal line is the reference threshold point. The threshold apparent length is determined as the scaled distance between the begin point and the reference threshold point. The threshold apparent length is illustrated in figure A.18.



The following criteria will be used to determine interpretable and uninterpretable shorted trace types:

Interpretable shorted traces: A shorted trace is considered interpretable if all of the following conditions are satisfied:

- The probable location of the first inflection peak can be identified.
- The tail portion of the traces becomes parallel with the x-axis.
- The threshold apparent length is less than 1.8-m (for the LTPP .203-m long probes and $V_p = 0.99$).

Uninterpretable shorted traces. A shorted trace is considered uninterpretable if any of the following conditions exist:

- The probable location of the first inflection peak can not be identified.
- The tail portion of the trace does not become parallel with the x-axis, but continues to fall.
- The threshold apparent length is greater than 1.8-m (for the LTPP .203-m long probes and $V_p = 0.99$).

For shorted traces which meet the interpretable criteria, only the threshold apparent length, as illustrated in figure A.18, should be determined. For reporting purposes, this value will correspond to the B_{min} point used in the other trace interpretation methods. Locations for B and B_{max}, as shown in figure A.14, should not normally be established.

Only a value for the minimum apparent length should be computed as follows:

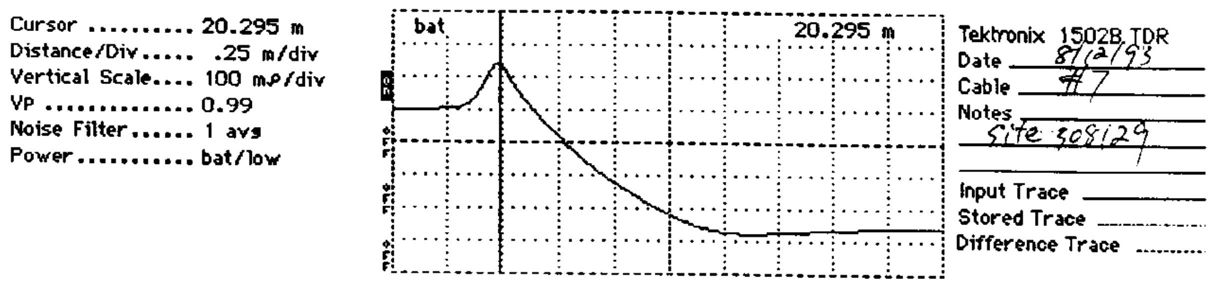
$L_{analysis}$ = null : do not report.

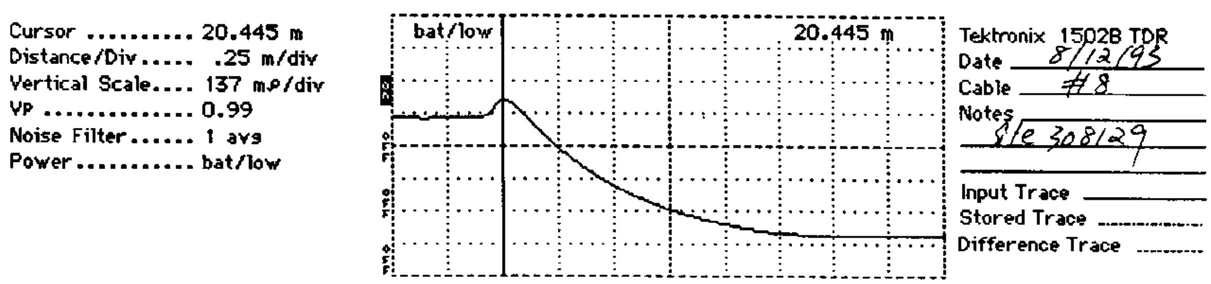
L_{min} = B_{min} - A : minimum apparent length.

L_{max} = null : do not report.

Only the begin point A, as shown in figure A.14 should be used in this computation. A begin point zone should not be established for shorted traces.

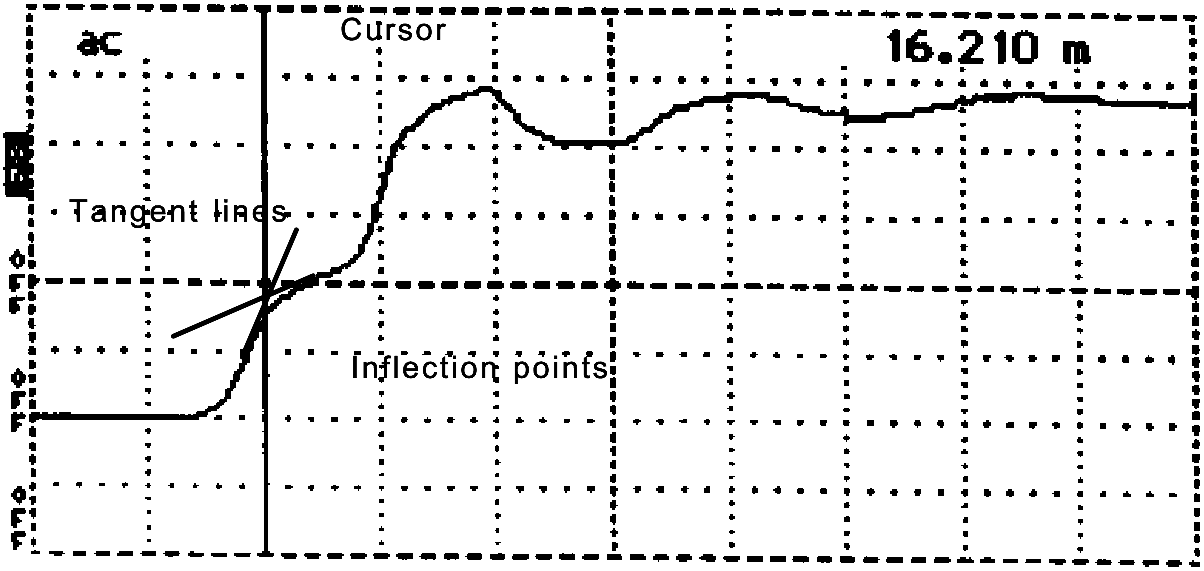
Figure A.19 illustrates the comparison of a shorted trace to traces from nearby TDR probes. In this example, the rebound height of the trace tail decreases with increasing depth. TDR # 8 has a shorted shape, while TDR #7 is rounded with very little rebound. The threshold apparent length for TDR #8 is approximately 1.3-m.



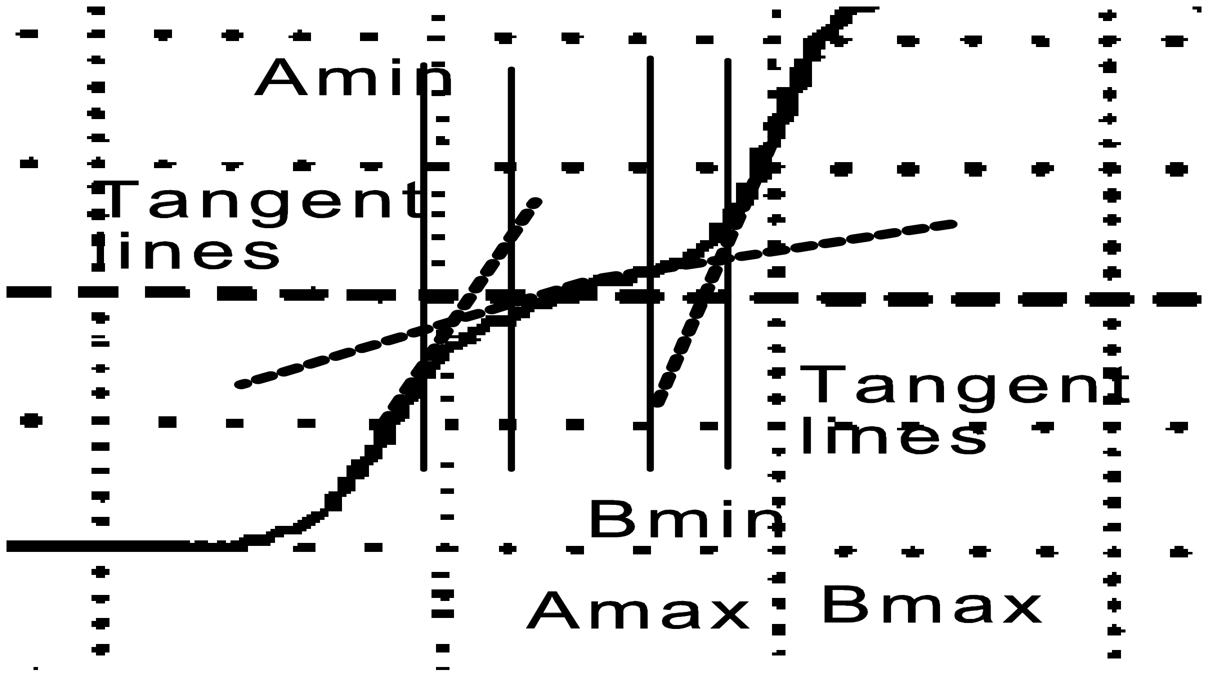


Apparent Length - Open Traces

Open trace types cannot be interpreted using the method of tangents or the general rules stated above since the trace merely bends at the begin and end points and does not change slope from positive to negative nor does it possess local maxima or minima. Figure A.20 is taken from a TDR probe check in air. (All LTPP probes were checked in this fashion.) Note that the location of the cursor, the solid vertical line, was placed at the peak of the curve created when the probe was shorted at the begin point with metal while being held in air. (Figure A.4 shows a probed shorted at the begin point while held in air.) The cursor provides a convenient reference for the location of the begin point.

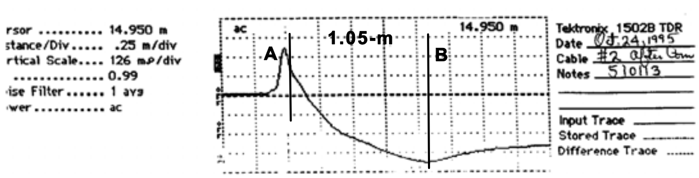


The convention for determination of the begin and end points for these types of traces is to construct two tangent lines, passing through the inflection point on each side of the begin/end point locations. As shown in figure A.20, the intersection of the tangent lines approximate the known location of the begin point. (The tangent lines for determination of the end point are not shown in figure A.20.) The locations corresponding to the divergence between the tangent lines and the trace should be used to determine the limits of the begin point and end point zones, A_{min}, A_{max}, B_{min}, and B_{max}, as illustrated in figure A.21.

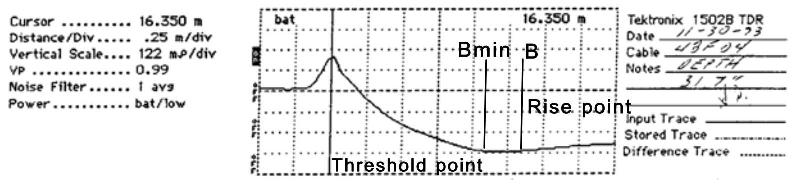


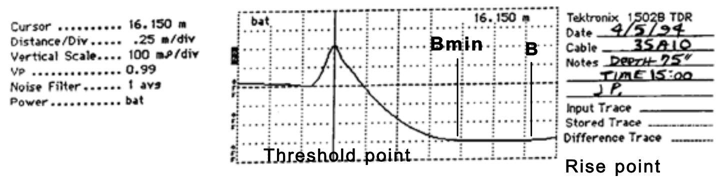
Apparent Length - Rounded Traces

The interpretation of rounded traces should be performed in accordance with the guidelines for interpretation of classic or open traces, depending on the trace characteristics. For some rounded traces, the end point is characterized as a short-sharp dip. For these type of traces, the general rule for location of the end point at the point where the curve begins to rise, will correspond to the point determined using the method of tangents. The rounded trace in figure A.22 illustrates a curve in which the tangent line does not deviate from the trace near the end point; i.e. no end point zone is needed.



Some rounded traces flatten out, become parallel with the x-axis, and then rebound as shown in figure A.23. On a portion of these traces, the flat portion of the trace at the end point is relatively long (greater than 0.25-m) and the rebound height is very small making it difficult to distinguish them from shorted traces, as illustrated in figure A.24. The convention for interpretation of rounded traces is to use the threshold point as the B_{min} point and the location of the rebound rise point as B and B_{max}. This convention is illustrated in figures A.23 and A.24.

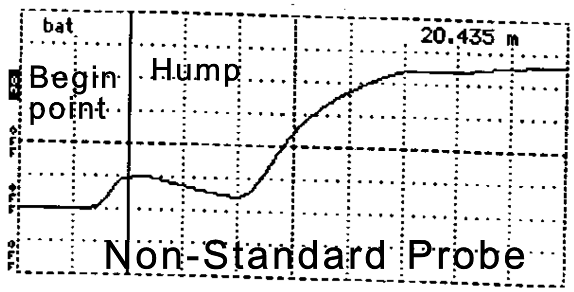




Apparent Length - Irregular Traces

The guidelines presented for the other trace types should be applied to irregular traces as appropriate. In some cases it is useful to compare the irregular TDR traces with those obtained from adjacent TDR's. The example of the irregular trace shown in figure A.12 comes from a non-standard LTPP probe installed at the pilot SMP site in Montana. Figure A.25 shows a comparison of the traces from the first five TDRs installed at this site. The traces from both sensors 1 and 4 are considered irregular since a local maxima point (hump) occurs after the location interpreted as the begin point. It is suspected that the begin point on these traces occurs at the slope change point and not at the top of the "hump" through a comparison with the traces from the adjacent probes. If the begin point on traces 1 and 4 where located in the traditional location to the left of the first local maxima, this would produce very short apparent lengths in relation to those from the nearby probes. Other non-standard LTPP probes may also have different behavior from that described here for the standard three tube LTPP moisture probe. For any TDR traces suspected of being classified as irregular, the Technical Support Service Contractor should be notified and an example copy of the trace submitted.

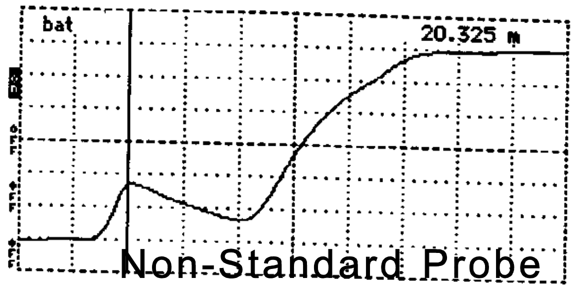
Cursor .... 20.435 m
Distance/Div ..... .25 m/div
Vertical Scale.... 115 mρ/div
VP 0.99
Noise Filter...... 1 avg
Power........... bat



Tektronix 1502B TDR
Date 8/12/93
Cable #1
Notes
Site 308129

Input Trace
Stored Trace
Difference Trace

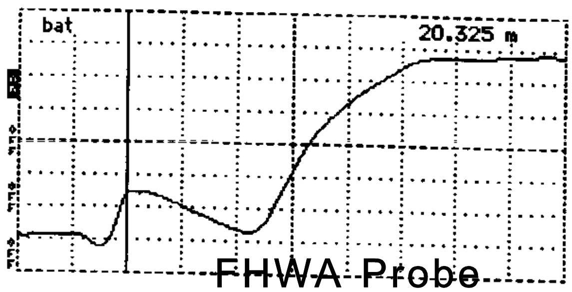
Cursor .... 20.325 m
Distance/Div ..... .25 m/div
Vertical Scale.... 96.9 mρ/div
VP 0.99
Noise Filter...... 1 avg
Power........... bat/low



Tektronix 1502B TDR
Date 8/12/93
Cable #2
Notes
Site 308129

Input Trace
Stored Trace
Difference Trace

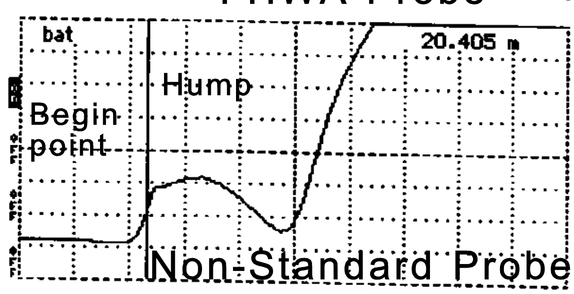
Cursor .... 20.325 m
Distance/Div ..... .25 m/div
Vertical Scale.... 86.4 mρ/div
VP 0.99
Noise Filter...... 1 avg
Power........... bat/low



Tektronix 1502B TDR
Date 8/12/93
Cable #3
Notes
Site 308129

Input Trace
Stored Trace
Difference Trace

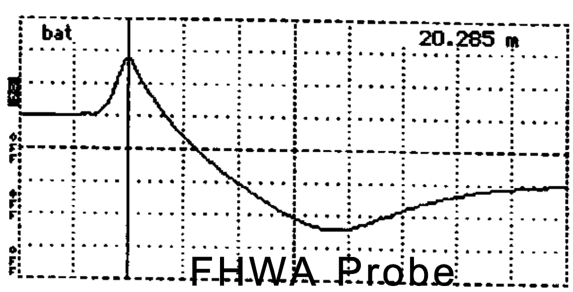
Cursor .... 20.405 m
Distance/Div ..... .25 m/div
Vertical Scale.... 53.0 mρ/div
VP 0.99
Noise Filter...... 1 avg
Power........... bat/low



Tektronix 1502B TDR
Date 8/12/93
Cable #4
Notes
Site 308129

Input Trace
Stored Trace
Difference Trace

Cursor .... 20.285 m
Distance/Div ..... .25 m/div
Vertical Scale.... 83.9 mρ/div
VP 0.99
Noise Filter...... 1 avg
Power........... bat/low

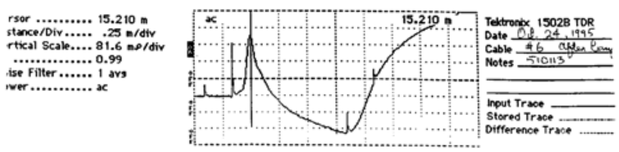


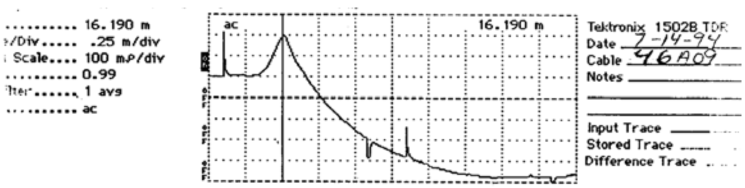
Tektronix 1502B TDR
Date 8/12/93
Cable #5
Notes
Site 308129

Input Trace
Stored Trace
Difference Trace

Apparent Length - Noisy Traces

To interpret noisy traces, those such as shown in figure A.5, the curves should be "smoothed" by drawing a line connecting the trace at the opposite sides of the blips. Some judgement must be used when a blip occurs near the begin or end points such as shown in figures A.26 and A.27.





Apparent Length - Summary

Table A.2 presents a summary of the special techniques, in addition to those under the general rules, which may be used for location of points on TDR traces in the apparent length interpretation process. The shaded cells indicate locations which must always be determined, while the unshaded cells are optional, depending on trace characteristics. Irregular traces are not shown in the table since their interpretation depends upon trace characteristics.

Table A.2 Summary of special techniques for location points used in apparent length interpretation process.

Trace Type	Special Technique	Begin Point Locations			End Point Locations		
		A	A_{min}	A_{max}	B	B_{min}	B_{max}
Classic	H-Horizontal & T -Tangent lines	H-T intersect	H line diverge	T line diverge	H-T intersect	H line diverge	T line diverge
Shorted	H-T lines @ A H line @ B	H-T intersect	not reported	not reported	not reported	threshold point	not reported
Open	T - Tangent	T-T	left T	right T	T-T	left T	right T

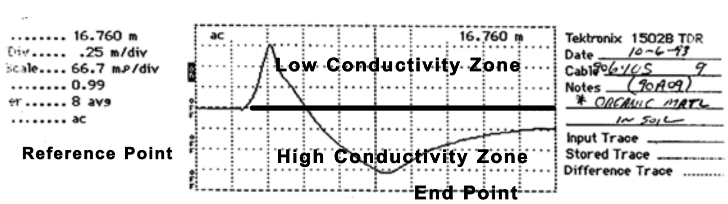
Trace Type	Special Technique	Begin Point Locations			End Point Locations		
		A	A_{min}	A_{max}	B	B_{min}	B_{max}
	& T-Tangent lines	intersect	line diverge	line diverge	intersect	line diverge	line diverge
Rounded	H-Horizontal & T -Tangent lines	H-T intersect	H line diverge	T line diverge	H-T intersect	threshold point	T line diverge

Notes:

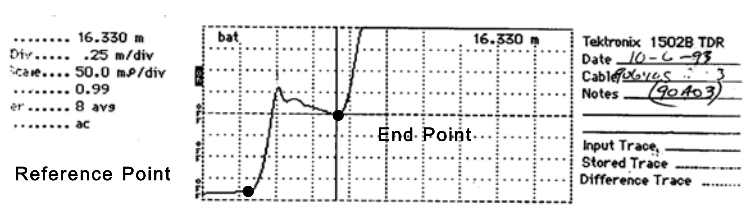
intersect - intersection of specified lines.
diverge - location where specified lines diverges from the trace.
left T line - tangent line to left of A or B point.
right T line - tangent line to right of A or B point.
threshold point - location where horizontal line through end point diverges from trace.

TDR Trace Interpretation - Conductivity

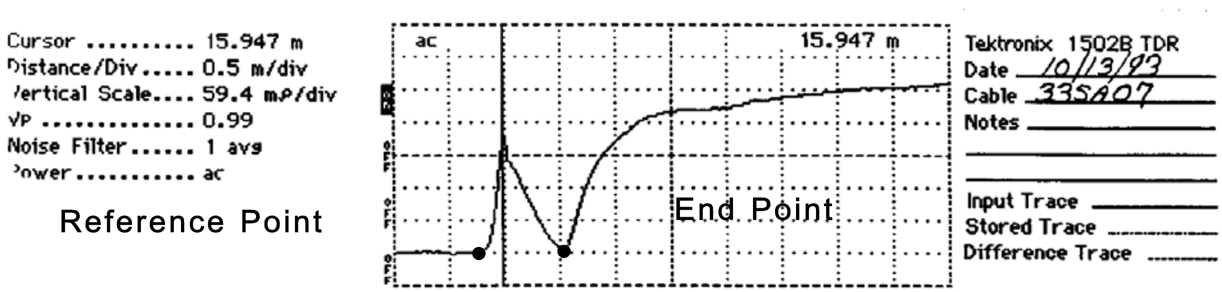
The bulk conductivity of the material surrounding the TDR moisture probe is proportional to the amplitude of the drop in the signal from the begin to end point. The bulk conductivity of this material will be classified into either low or high categories. The vertical location of the end point relative to the reference point on the portion of the trace corresponding to the signal in the coaxial lead cable is used to discriminate between low and high conductivity. The conductivity classification rule is shown in figure A.28.



An example of a trace classified as with low conductivity is shown in figure A.29.



If the end point is approximately the same magnitude as the reference point, the trace should be classified as low conductivity as shown in figure A.30.



For traces with a dip immediately to the left of the begin point peak, the reference point for conductivity classification should be located at the local minima point in the dip, as shown in figure A.31. In many cases, the location of the reference point at the bottom of the dip or at the left most portion of the trace will not affect the classification of the trace with respect to conductivity.