DETECTION OF DIESEL FUEL LEAKAGE FROM UNDERGROUND STORAGE TANK USING TIME DOMAIN REFLECTOMETRY

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ABSTRACT

The Environmental Protection Agency (EPA) has established regulations concerning the construction and maintenance of an underground storage tank (UST) system. These regulations also define the means and methods required to detect potential leaks. Leak detection methods defined as “other methods” can be used if specific requirements are achieved. We find in our study time domain reflectometry (TDR) can be used to detect leaks from an UST. The magnitudes of reflections measured by the TDR technique are used to calculate electrical properties of the soil. We find the introduction of diesel fuel, a light non-aqueous phase liquid (LNAPL), into the soil alters the physical and chemical properties of the soil and subsequently the electrical properties. We demonstrate the measured variance of electrical properties can be correlated to the changes of diesel fuel concentration. We find diesel fuel can be detected and changes of concentration can be measured using TDR.

APPROVAL PAGE

The persons listed below, appointed by the Dean of the College of Arts and Sciences, have examined a thesis titled, "Detection of Diesel Leakage from Underground Storage Tank Using Time Domain Reflectometry", presented by Daniel A. Barnett, candidate for the Master of Science degree, and certify that in their opinion it is worthy of acceptance.

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CHAPTER 1

INTRODUCTION

The Environmental Protection Agency has established regulations regarding operation and maintenance of an underground storage tank (UST) system in the United States of America. These regulations include UST system design, construction, installation, operating requirements, and release detection methods (U.S. Code of Federal Regulations, 2005). The present required release detection methods include inventory control, manual tank gauging, tank tightness testing, automatic tank gauging, vapor monitoring, groundwater monitoring, interstitial monitoring, and other indicators (U.S. Code of Federal Regulations, 2005). The present release detection methods are meant to provide redundancy so release of product from an UST is ultimately detected.

Release detection methods defined by U.S. Code of Federal Regulations (2005) as “other methods” include any method which can detect a 0.2 gallon per hour release rate or a release of 150 gallons of product within a month. The “other” release detecting method would be approved by the EPA if the UST owner/operator can demonstrate the method detects a release as effectively as the previously listed release detection methods. If one of the present release detection methods indicates that a release has possibly occurred, the UST owner/operator must conduct a site check (U.S. Code of Federal Regulations, 2005). The services of an environmental consulting firm are typically procured by the owner/operator when a release is detected. The environmental consulting firm will select the sample types, sample locations, and measurement methods. Mobilization of soil/groundwater sampling machinery is typically required to collect subsurface samples adjacent to the UST. The samples collected by the environmental consulting firm are sent to an analytical laboratory capable of conducting tests required to determine the presence and concentration of contaminant within the sample. The costs associated with such an investigation are relatively high. The present release detection methods require extensive documentation by the owner.

If a mistake in the established documentation procedure occurs or the documentation procedure is flawed, a release could be falsely detected. As a result, an unnecessary site check would be conducted resulting in a substantial monetary expenditure by the owner/operator.

A remote sensing instrument which can be installed at the time of UST construction would be another release detection method capable of providing additional redundancy in the established release detection procedures. The motivation of the present study is that the time domain reflectometer can be a potential remote sensing system that could be installed at points adjacent to the UST to determine if a release of product from an UST occurs.

Time Domain Reflectometry

Time domain reflectometry (TDR) was initially developed to locate cable faults by the power and telecommunications industries and later was applied to geo-materials (O'Connor and Dowding, 1995). TDR is conceptually similar to radar. In radar, a radio frequency transmitter emits a radio (electromagnetic) pulse in a specific direction. The radio pulse is reflected by objects located within the path of the pulse. An antenna receives the reflected pulses, and by measuring the time between pulse propagation and receipt of the reflected pulse by the antenna, and using the speed of light, the distance to the incident object can be calculated.

The TDR system includes a voltage pulse generator/receiver, data logger, multiplexer, transmission line, and monitoring probe. The data logger and multiplexer attach via a serial cable to the pulse generator. A monitoring probe, consisting of three electrodes in parallel arrangement, is connected to the end of the transmission line. The three electrodes can be considered an elongation of the coaxial transmission line, where the center electrode represents the inner conductor of the coaxial cable and the two outside electrodes represent the outer conductor of the coaxial cable. Programming the data logger allows collection of waveforms using the pulse generator. The multiplexer allows utilization of many sampling probes at once.

The pulse generator launches a fast rise time voltage pulse through the transmission line with a TDR monitoring probe attached at the end. The launched pulse encounters an impedance change at the surface of soil and part of pulse is reflected. The rest of the pulse travels the length of the TDR monitoring probe and reflects at the end of the TDR monitoring probe. The receiver measures the magnitudes of these reflections which are used to determine electrical properties of the soil sample. Many individual pulses propagate through the transmission line and monitoring probe until a stable waveform is captured. A typical TDR waveform is illustrated in Figure 1-1 (O'Connor and Dowding, 1995).

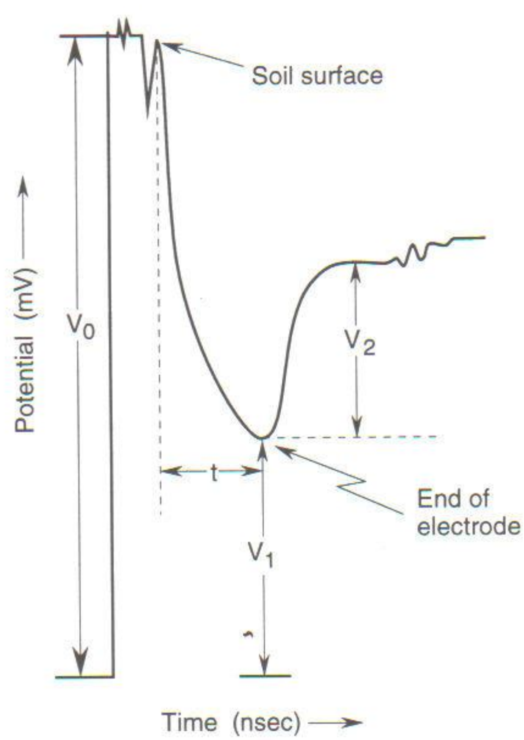

Figure 1-1. Typical TDR waveform (O'Connor and Dowding, 1995).

TDR is especially sensitive to changes in the dielectric constant of materials between the three conductors of the TDR monitoring probe. A dielectric material is a material resistant to electrical current (Crowell, 2012). It is not considered an electrical insulator, which is a substance with a very low conductivity, because once the electrical charges reach a specific magnitude, the dielectric substance will conduct the electrical charge (Crowell, 2012). Hence, a dielectric material can be placed between the plates of a capacitor to increase capacitance. The increase of capacitance is dependent upon the dielectric properties of the material placed between the plates of the capacitor. The dielectric constant (K) is represented by the following equation:

$$K = \epsilon/\epsilon_o$$

where ϵ is the absolute permittivity of the material under test and ϵ_o is the permittivity of air under vacuum. Table 1-1 (Crowell, 2012) indicates some sample values of the dielectric constant of a few substances.

Table 1-1. Dielectric constant of selected substances (Crowell, 2012)

Substance	Dielectric constant (K)
vacuum	1
air	1.00054
water	80
barium titanate	1250

The parameters obtained from the TDR waveform allow calculation of the apparent dielectric constant (K_a) of the soil sample and is given by:

$$K_a \approx [(ct)/(2l_p)]^2$$

where c is the speed of light, t is the time pulse takes to travel along probe and return, and l_p is the length of probe. The apparent dielectric constant is critical to the calculation of soil volumetric water content. However, to use the apparent dielectric constant for soil volumetric water content calculations, we must assume the soil is nonconductive and the apparent dielectric constant is due only to polarization of the soil materials (Mohammad, 2003). Conductive soils cause TDR signal attenuation and dispersion and would result in measurement error. The minimum allowable conductivity threshold reported by others is 3.7 dS/m (Sun et al, 2000). The conductivity of the soil used in the present study is << 3.7 dS/m, so signal error due to the soil conductivity is not expected.

A relationship between the dielectric constant and volumetric water content has been established by Topp et al (1980). However, the studies completed by Topp et al (1980) do not provide sufficiently accurate results for some fine-grained (clay) soils (Dasberg and Hopman, 1992), or volcanic soils (Fukumoto and Tanaka, 1995). As such, some researchers have developed calibration methods which are applied to TDR in order to more accurately determine the water content of fine-grained soils.

Introduction of light non-aqueous phase liquids (LNAPL) into the soil sample can create a measurable change of the soil material's dielectric constant. LNAPL is defined as any liquid which is not water soluble and has a lower unit weight (density) than water. Diesel fuel is defined as LNAPL and has a dielectric constant of approximately 2 (Bano et al, 2009). The change of the soil material's dielectric constant is dependent upon the amount of LNAPL present as pore fluid within the soil material.

CHAPTER 2

LITERATURE REVIEW

The electrical properties of contaminated and uncontaminated soils have been measured by Darayan et al (1998) using two independent techniques. Based on the results of the tests, the electrical properties of soils are directly related to the liquid occupying the pore space within the sample (Darayan et al, 1998). The two techniques employed by Darayan et al (1998) to measure the dielectric constant of soils are the guarded-electrode method and the parallel-plate capacitor method. Two different soil types were collected in the study completed by Darayan et al (1998) including coarse-grained (sandy) soils and fine-grained (clay) soils. Through the analysis of these two soil types using the guarded-electrode method and the parallel-plate capacitor method, it is found that the dielectric constant increases with the addition of diesel oil. This is attributed to the fact that diesel oil replaces air contained within the pore spaces of the soil samples and changes the path of electric current conduction (Darayan et al, 1998). The increase of dielectric constant is also claimed to be due to the fact the dielectric constant of diesel oil is about twice that of air (Darayan et al, 1998). A similar increase of the dielectric constant due to replacement of air contained within the pore spaces of the soil with diesel fuel is found in the present study.

The dielectric properties of a sandy soil contaminated with NAPL has been investigated by Francisco and Montoro (2012). The purpose of their study was to correlate the volumetric content of NAPL and dielectric permittivity of sandy soils (Francisco and Montoro, 2012). The dielectric permittivity of the soil in their study is measured using a Coaxial Impedance Dielectric Reflectometry (CIDR) sensor. The CIDR sensor has three metal rods, or tines, which have lengths of 6 cm. Three of the tines define a cylindrical measurement volume of 2.5 cm in diameter. A fourth tine is located in the center of the sensing volume. The CIDR generates a 50 MHz electromagnetic wave which propagates to the tines and reflects from the sensing volume creating a standing wave as in a coaxial transmission line (Francisco and Montoro, 2012). The dielectric permittivity is calculated based on three measured voltages. Two different tests were performed in the study completed by Francisco and Montoro (2012). The purpose of the tests was to characterize the dielectric properties of the soil and to verify the displacement of organic liquids inside the soil pores (Francisco and Montoro, 2012). The first group of tests were conducted in sandy soils with known volumetric content of either water or paraffin oil (kerosene). The saturation ratio of the soil samples in the first group of tests is maintained at 1.0 (Francisco and Montoro, 2012). The second group of tests were conducted in sandy soils initially saturated with paraffin oil and are flushed with colored water. Results of the Francisco and Montoro (2012) study indicate that as the volumetric NAPL content of the samples increase, the dielectric permittivity of the samples also increase. The measured increase is greater in the case of water in comparison to paraffin oil due to the significant difference between dielectric properties of water and paraffin oil. The study by Francisco and Montoro (2012) concludes by stating dielectric measurements can be used for the monitoring of NAPL displacement in porous media (Francisco and Montoro, 2012). The immiscible displacement of NAPL observed in the second group of tests, where paraffin oil was flushed with colored water, allowed for evaluation of the NAPL saturation ratio during remediation processes (Francisco and Montoro, 2012). The dielectric permittivity of the soil sample is dependent upon soil porosity, volumetric content of water and NAPL, and the saturation ratio. In order to compute the volume of the NAPL contained within the sample, the authors state baseline testing would be required on fully cleaned or fully contaminated samples, and the porosity of the material-under-test must be previously known (Francisco and Montoro, 2012). A similar increase of the dielectric permittivity of the soil samples due to addition of diesel fuel is found in the present study. In the present study, baseline testing of the materials proposed for use as UST excavation zone backfill is also recommended.

The use of multiple length TDR probes for soil water content evaluation has been conducted by Miyamoto et al (2001). The purpose of the study was monitoring of soil water distributions under different agricultural tillage systems (Miyamoto et al, 2001). The sites in the studies had been tilled in preparation for planting of crops. The sites were tilled in straight rows with varying widths and depths. The TDR probes were placed orthogonal to the direction of tillage at points of 0, 0.35, and 0.15 m away from the center of each row. The lengths of the TDR monitoring probes were 0.10, 0.20, 0.30, and 0.45 m (Miyamoto et al, 2001). The results of the study by Miyamoto et al (2001) indicate the distribution of soil water content can be measured using TDR probes of differing lengths, and differing tillage conditions, at each study site. No significant difference was found when a comparison between the gravimetric water content and the TDR-determined water content was completed (Miyamoto et al, 2001). In the present study, and attempt to calculate the dielectric constant by use of a partial length of the 30 cm long TDR monitoring probe is made. The calculation of the dielectric constant for a partial length of the TDR monitoring probe in the present study indicates some measurement error occurs with use of partial lengths of TDR monitoring probes.

The detection of organic contaminants consisting of NAPL using TDR and other geophysical methods has been conducted by others (Mohammad and Said, 2004; Darayan et al, 1998; Francisco and Montoro, 2012). However, there are few attempts to detect inorganic contaminants using TDR (Kim et al, 2010). An attempt to measure different concentrations of the inorganic chemicals sodium nitrate ($NaNO_3$) and zinc sulfate ($ZnSO_4$) within a sandy soil was conducted by Kim et al (2010). Concentrations of each inorganic chemical ranging from 0 to 40 g/L is injected into the soil samples, then TDR probes of 10, 15, and 25 cm are used to measure the resistance of the soil samples. The effect of probe length, concentration, and saturation ratio was discussed by Kim et al (2010). They find the use of 10 cm TDR monitoring probes shows higher resistance for a given concentration. The overestimation of resistance measured using short (10 cm) probes is explained by two reasons (Kim et al, 2010). The first reason is the higher ratio of rod spacing to diameter (Kim et al, 2010). The second reason is because the reflected voltage decays exponentially in proportion to the length of the TDR monitoring probe (Kim et al, 2010). The effect of solute concentration within the soil samples indicate, with the use of a 15 and 25 cm TDR monitoring probe, resistance values less than 1 kΩ are obtained at all solute concentration levels (Kim et al, 2010). However, the measured resistances are greater than 1 kΩ when the 10 cm TDR monitoring probe is utilized for concentrations of 5, 10, 50, and 100 mg/L. This indicates using a relatively short TDR monitoring probe to detect resistance of inorganic contaminant concentrations of less than 500 mg/L is inaccurate (Kim et al, 2010). The present study investigates organic contaminants and does not consider inorganic contaminants. The present study also measures the dielectric constant of the soil samples with partial lengths of a 30 cm long TDR monitoring probe and does not consider changes of sample resistivity.

The use of TDR for monitoring soil volumetric water content, detection of NAPL in soil, and detection of inorganic chemicals within soil, have been discussed in preceding paragraphs. Another potential application of TDR is to monitor liquid levels in industrial applications (Cataldo et al, 2006). This type of monitoring often requires monitoring more than one liquid level interface (Cataldo et al, 2006). The measurement of the dielectric properties of each individual liquid is also important (Cataldo et al, 2006). In the study by Cataldo et al (2006), TDR monitoring probes of varying length are individually placed within diesel oil and acetone. The TDR monitoring probes are also placed within these fluids combined with water. Due to the immiscibility of water and these fluids, a layered interface between water and the fluids is created. The authors then demonstrate the TDR monitoring probe can accurately distinguish the spatial localization of the interface between these liquids through analysis of the resulting TDR waveforms based on apparent distance and reflection coefficient (Cataldo et al, 2006). The analyses include consideration of the reflection coefficient derivative plot versus apparent distance (Cataldo et al, 2006). The use of this analytical technique results in the applicability of TDR for use as an instrument capable of measuring levels of fluids in tanks, localization of multiple interfaces in layered media, as well as measurement of physical properties such as dielectric permittivity (Cataldo et al, 2006). In the present study a similar analysis technique is employed. However, the reflection coefficient derivative plot versus the time of signal propagation is considered. The use of this analytical technique allows localization of the change of signal amplitude due to the saturation ratio of diesel fuel.

CHAPTER 3

METHODOLOGY

TDR System

A Campbell Scientific TDR100 is the voltage pulse generator/receiver to launch fast rise-time voltage pulses into the 30 meter long transmission line of coaxial cable. A monitoring probe consisting of three electrodes in parallel arrangement with lengths of 0.3 meter attaches to the end of the coaxial transmission line. Photographs of the TDR instrument are shown in Figures 3-1 and 3-2.

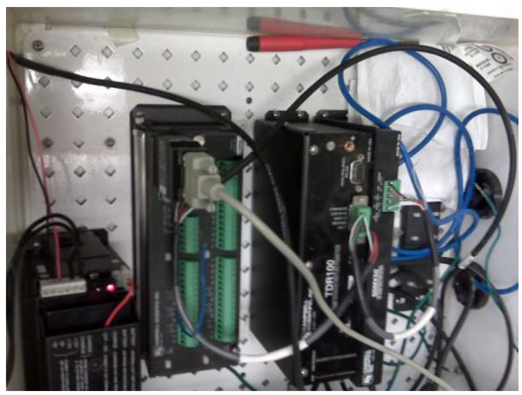

Figure 3-1. TDR pulse generator and multiplexer

Figure 3-2. TDR monitoring probe

The computer software PC-TDR, programmed by Campbell Scientific, Inc., is used to collect and save TDR waveforms. The waveforms collected via PC-TDR consist of waveform with time (ns) along the x-axis, and the reflection coefficient (ρ) along the y-axis. A sample TDR waveform collected using PC-TDR is illustrated in Figure 3-3.

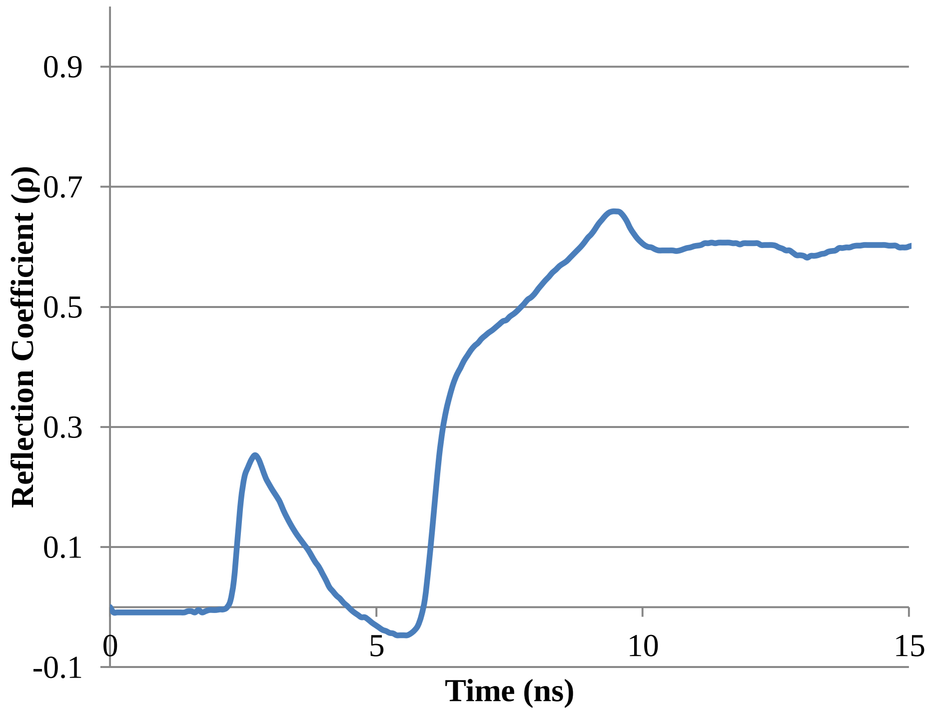

Figure 3-3. Sample TDR waveform from PC-TDR software.

Soil Sample Materials

The soil samples consist of commercially available sands. Some physical index properties of the sand are determined based upon the methods described by American Society for Testing and Materials (ASTM). Using ASTM D422, the grain size distribution curve for the commercial sand is established. The grain size distribution curve for the sand in this study is shown in Figure 3-4.

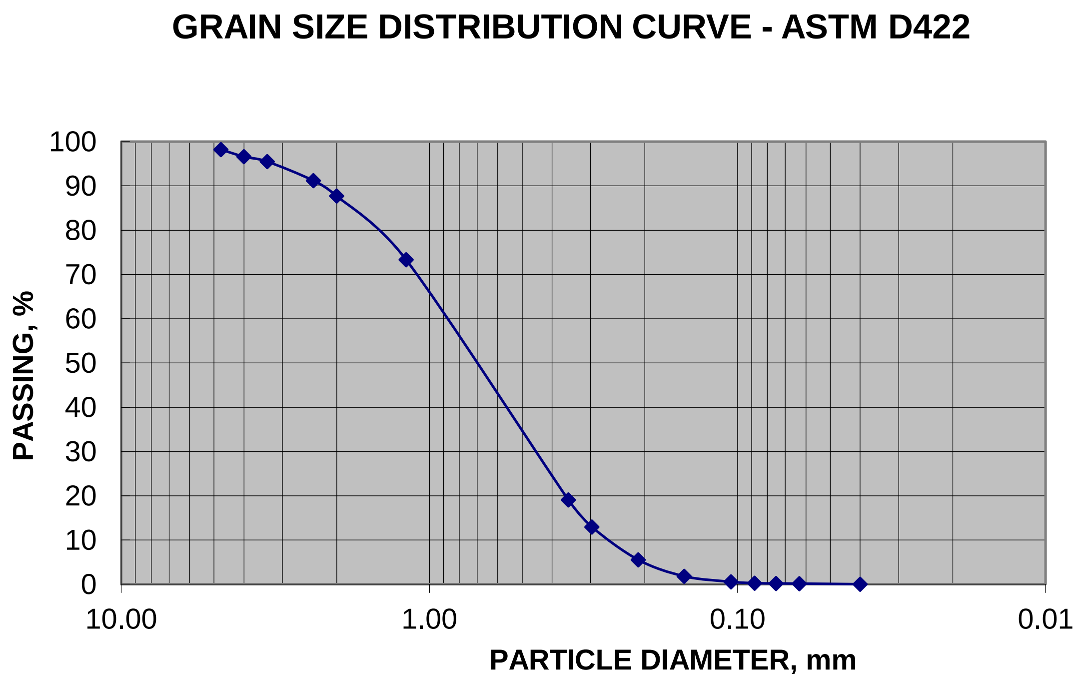

Figure 3-4. Grain size distribution curve for tested samples.

Based upon the grain size distribution curve and other definitions in ASTM D2487, the Unified Soil Classification System (USCS) symbol for a soil is determined. Using the curve in Figure 3-4, the percentage of mass of the total sample smaller than specific grain sizes is determined. For example, D_{30} is a size such that 30% of the grains of soil are smaller than this size. Using this convention, the tested sand exhibits a D_{60} of 0.9, a D_{30} of 0.45, and a D_{10} of 0.25. The D_{10} value is also known as the effective grain size. These values allow calculation of the coefficient of uniformity (C_u) and the coefficient of curvature (C_c). The C_u and C_c of the tested sands are 3.6 and 0.9, respectively. Using these values and the flowchart provided in ASTM D2487, the USCS symbol for the tested soil is SP, which stands for Poorly-graded sand. Poorly graded sand, by definition, has a greater void ratio than well graded sands resulting in relatively higher hydraulic conductivity. The higher level of hydraulic conductivity makes SP suitable for use as free-draining backfill placed in an UST excavation zone.

Modeled Conditions for Potential Diesel Contamination

The USCS symbol of the soil samples is SP and would be suitable for use as a drainable backfill placed within the limits of the UST excavation zone. We model three possible conditions of the UST excavation zone backfill materials, a Wet Condition, a Dry Condition, and for comparison, a Native Condition. The Wet and Dry conditions consider subsurface materials located outside the UST excavation zone are existing fine-grained (clay) soils with very low hydraulic conductivity. Thus, any release from an UST will be confined within the coarse-grained excavation zone backfill for a relatively extensive period of time.

The Wet Condition considers the elevation of groundwater is at a level above the base of the UST excavation zone. Due to the lower specific gravity of diesel fuel and its immiscibility in water, the diesel fuel release will immediately overlie the ground-water elevation within the UST excavation zone backfill. Therefore, the saturation ratio of the UST excavation zone backfill materials will be one, and the liquid portion of the soil sample will consist of water and diesel fuel. Depending upon the actual elevation of the TDR monitoring probe, the elevation of groundwater, and the volume of the diesel fuel release, the TDR probe will either be fully or partially submerged within diesel fuel or water. Figure 3-5 is an illustration of the Wet Condition.

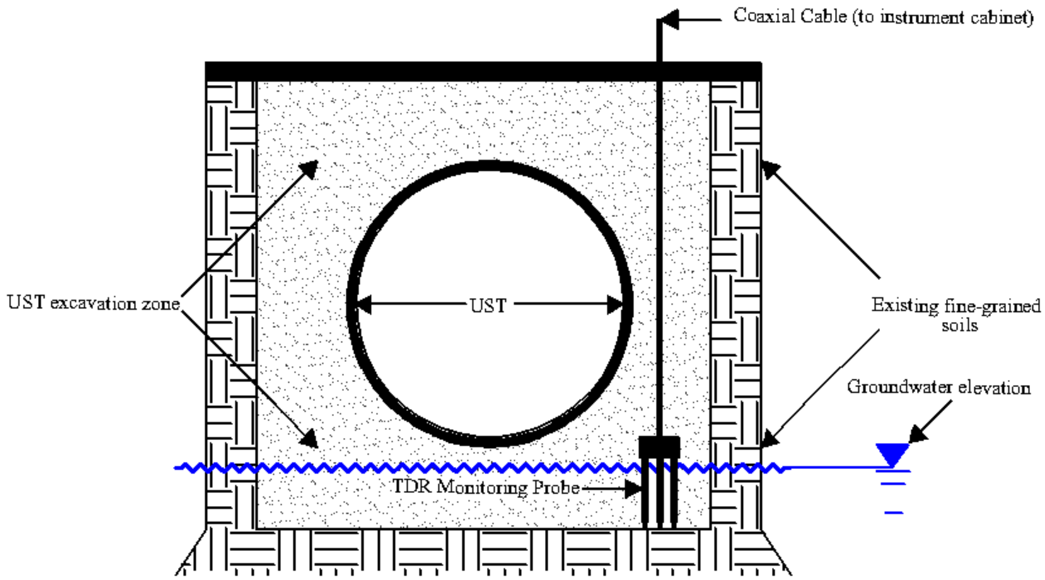

Figure 3-5. Wet Condition (not to scale).

The Dry Condition considers the elevation of ground-water is at a level below the base of the UST excavation zone. Due to the low hydraulic conductivity of the fine-grained soils outside of the UST excavation zone, the diesel fuel release would be the only liquid contained within the coarse-grained UST excavation zone backfill. To satisfy the requirements in U.S. Code of Federal Regulations (2005), the elevation of at least one TDR monitoring probe must be at the base of the UST excavation zone. Specifically, at least one TDR monitoring probe must be situated at the interface between UST excavation zone backfill and existing fine-grained (clay) soils. Figure 3-6 is an illustration of the Dry Condition.

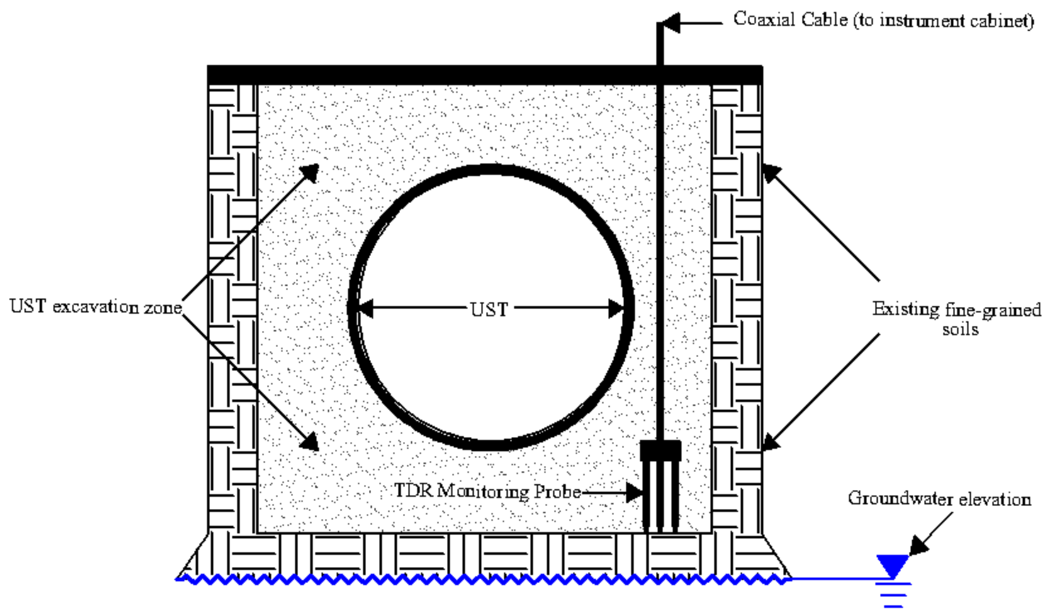

Figure 3-6. Dry Condition (not to scale).

The average void ratio (e) of the sample soils is measured using gravimetric techniques. The void ratio is the ratio of volume of voids (V_v) and volume of solids (V_s), expressed as an equation is ($e = \frac{V_v}{V_s}$). The average void ratio of the sample soils in this study is 1.59.

A sample container consisting of a glass cylinder is utilized to contain the soil samples for TDR interrogation. The diameter of the glass cylinder is 9 cm and the height of the glass cylinder is 40 cm, which results in a total glass cylinder volume of 2,548.5 cm^3. The distance between the two outside electrodes of the three-pronged TDR monitoring probe is 5 cm and the length of each electrode is 30 cm.

The glass cylinder is filled with oven-dried sample soil in approximately 10 cm lifts and each lift is compacted using a consistent vibratory technique, therefore assuring uniform compaction is achieved. The average void ratio is used to determine the volume of liquid required for a specific saturation ratio in subsequent tests.

The samples under TDR interrogation are prepared by first mixing the sample with selected volumes of liquids outside of the sample container. The soil/liquid mixture is placed and compacted within the sample container in a manner similar to that which is used for preparation of the samples for average void ratio determination. The TDR monitoring probe is manually inserted into the sample so the entire length of the TDR monitoring probe is below the soil surface. Careful insertion of the TDR monitoring probe must be achieved to reduce the likelihood of creating air pockets adjacent to the electrodes, which will introduce measurement error.

The Wet Condition considers the elevation of groundwater is at a level above the base of the UST excavation zone. For this condition we consider the saturation ratio of the sample is 1.0, and the liquid within the sample consists of water and diesel fuel. Table 3-1 indicates the sample mixing parameters used to satisfy the requirements of the Wet Condition.

Table 3-1. Ratio of full saturation between water and diesel.

Sample No.	Water	Diesel Fuel
W-1	0.0	1.0
W-2	0.2	0.8
W-3	0.4	0.6
W-4	0.6	0.4
W-5	0.8	0.2
W-6	1.0	0.0

The Dry Condition considers the elevation of ground-water is at a level below the base of the UST excavation zone. For this condition, we consider the TDR monitoring probe would be in contact with variable amounts of diesel fuel, dependent upon the actual volume of the diesel fuel release from the UST, and the extent of the UST excavation zone. Table 3-2 indicates the sample mixing parameters used to satisfy the requirements for the Dry Condition.

Table 3-2. Ratio of diesel saturation.

Sample No.	Water	Diesel Fuel
D-1	0.0	0.0
D-2	0.0	0.2
D-3	0.0	0.4
D-4	0.0	0.6
D-5	0.0	0.8
D-6	0.0	1.0

To aid in evaluating the TDR response to the Wet Condition and Dry Condition, the mixing parameters indicated in Table 3-3 are developed. These Native Condition parameters consider the samples would either be impacted by water due to a fluctuating groundwater elevation, impacted by water through capillary action of the soils within the UST excavation zone, or dry due to a groundwater elevation present well below the base of the UST excavation zone.

Table 3-3. Ratio of water saturation for Native Condition

Sample No.	Saturation Ratio Water
N-1	0.0
N-2	0.5
N-3	1.0

The samples are left undisturbed for a period of time so the sample's constituents can reach a stage of equilibrium. The TDR monitoring probe is manually inserted into each of the samples. The computer program PC-TDR is used to collect waveforms. The program is manually triggered and multiple measurements are collected for each individual sample. Waveform collection ceases once many waveforms appear geometrically similar.

The graphical data is utilized for calculation of the dielectric constant of each sample. The dielectric constant calculation requires manual selection of the time required for the launched pulse to travel down along the TDR monitoring probe and return. This procedure is illustrated in Figure 3-7.

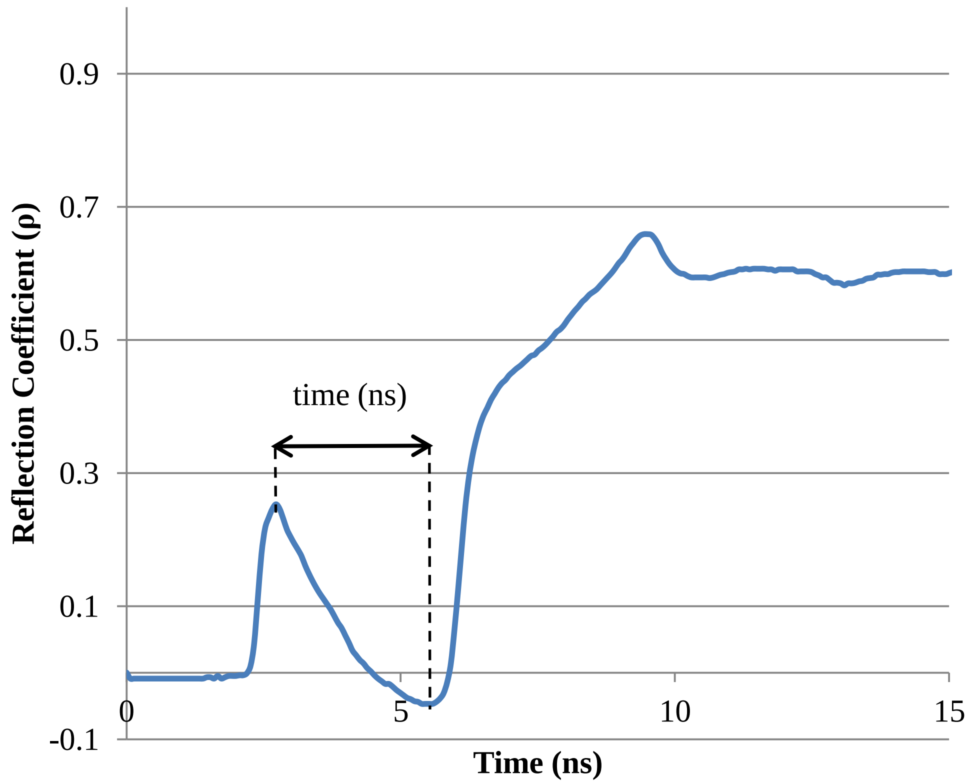

Figure 3-7. Procedure for determination of “time” for dielectric constant calculation.

CHAPTER 4

RESULTS AND DISCUSSION

The Wet Condition considers the elevation of groundwater is at a level above the base of the UST excavation zone. Therefore, the sample saturation ratio will be 1.0. Figure 4-1 shows the TDR waveforms collected from each sample in the Wet Condition, and Table 4-1 indicates the dielectric constant based upon the waveforms in Figure 4-1 and the sample mixing parameters.

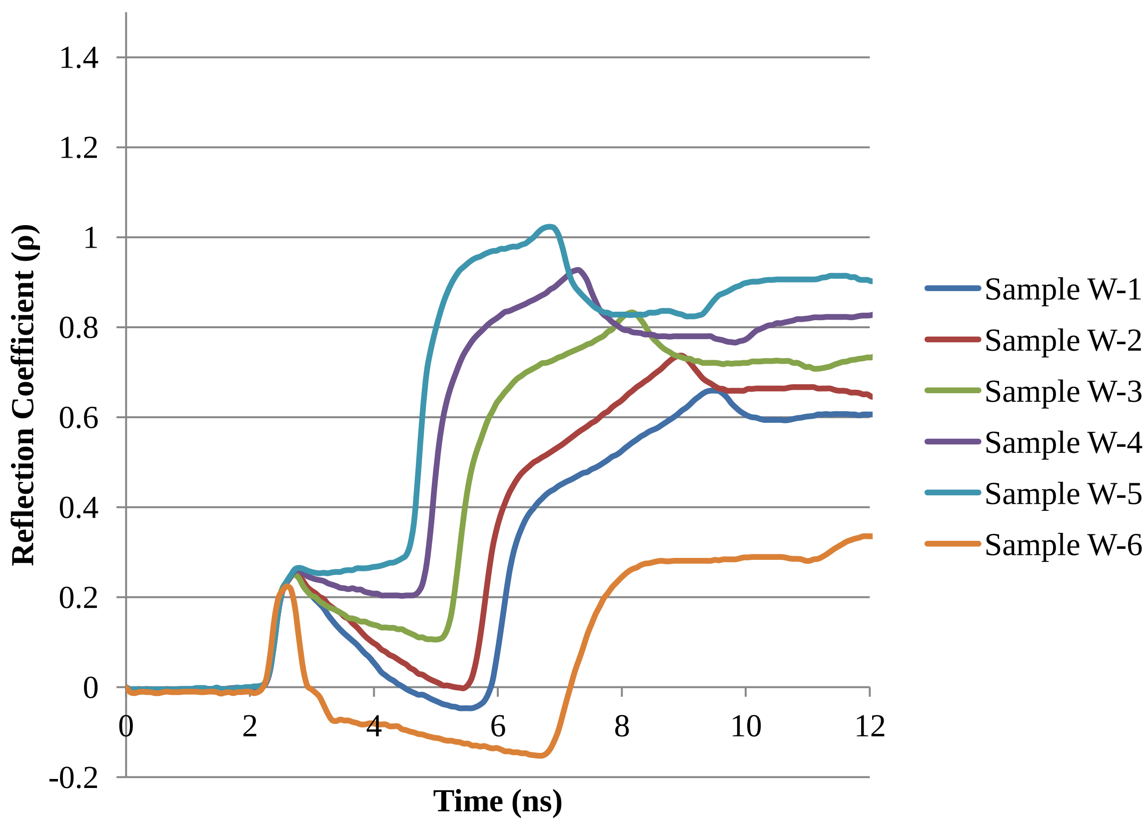

Figure 4-1. TDR waveforms for Wet Condition.

Table 4-1. Dielectric constant and ratio of full saturation between water and diesel.

Sample No.	Water	Diesel	Dielectric Constant
W-1	0.0	1.0	1.19
W-2	0.2	0.8	0.68
W-3	0.4	0.6	1.27
W-4	0.6	0.4	1.86
W-5	0.8	0.2	2.04
W-6	1.0	0.0	4.23

The Dry Condition considers the elevation of ground-water is at a level below the base of the UST excavation zone. For this condition, we consider the TDR monitoring probe is in contact with variable amounts of diesel fuel, dependent upon the actual volume of the diesel fuel release from the UST and the extent of the UST excavation. Figure 4-2 shows the TDR waveforms collected from each sample in the Dry Condition and Table 4-2 indicates the dielectric constant based upon the waveforms in Figure 4-2 and the sample mixing parameters.

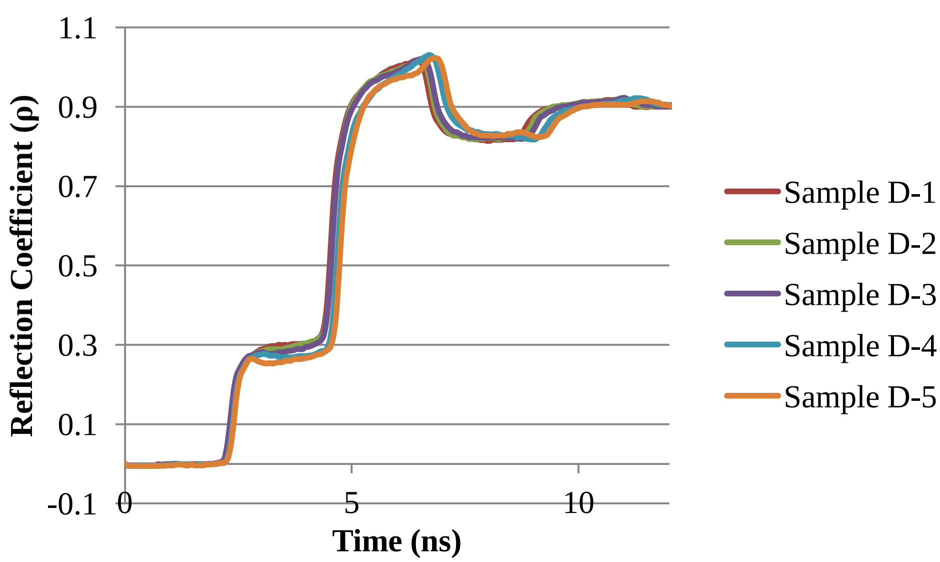

Figure 4-2. TDR waveforms for the Dry Condition

Table 4-2. Dielectric constant and ratio of diesel saturation.

Sample No.	Diesel	Dielectric Constant
D-1	0.0	1.88
D-2	0.2	1.84
D-3	0.4	2.75
D-4	0.6	2.75
D-5	0.8	2.86
D-6	1.0	3.21

To aid in evaluation of the TDR response to the Wet Condition and Dry Condition, samples are prepared in a Native Condition to model impact exclusively from water or to model a completely dry condition. Figure 4-3 indicates the TDR waveforms collected from each sample in the Native Condition and Table 4-3 shows the dielectric constant based upon the waveforms in Figure 4-3 and the sample mixing parameters.

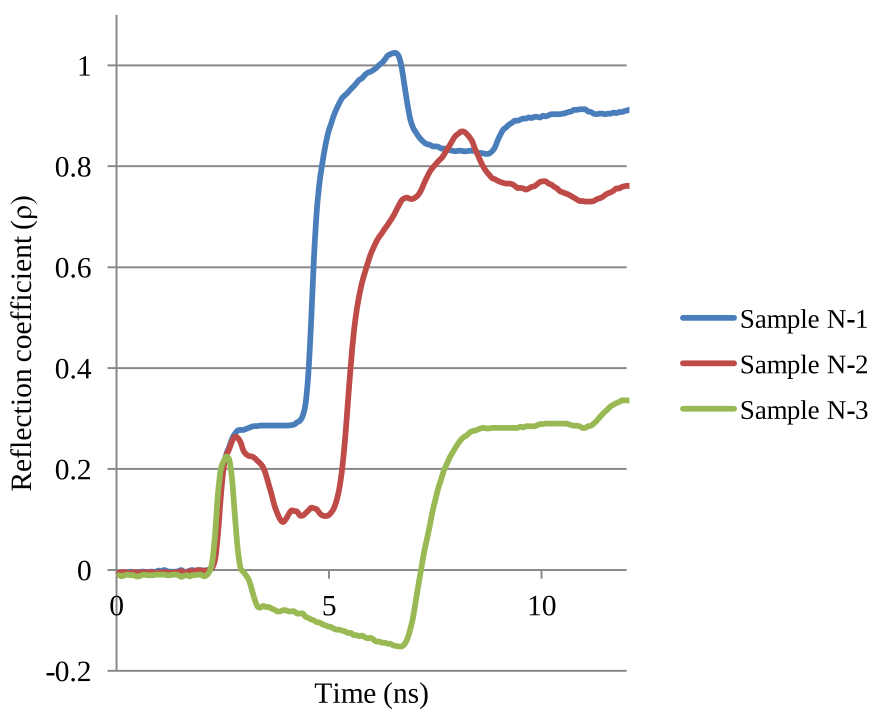

Figure 4-3. TDR waveforms for Native Condition.

Table 4-3. Calculated dielectric constant and ratio of water saturation.

Sample No.	Saturation Ratio Water	Dielectric Constant
N-1	0.0	1.13
N-2	0.5	0.53
N-3	1.0	4.23

TDR measurement of the samples for the Wet Condition, where the sample has a saturation ratio of 1.0, indicates as the diesel fuel saturation ratio increases, the apparent dielectric constant value decreases. TDR measurement of the samples for the Dry Condition, where diesel fuel is the only liquid within the pore spaces of the sample, indicates as the diesel fuel saturation ratio increases, the apparent dielectric constant increases. Figure 4-4 is a graph illustrating the dielectric constants for the Wet Condition and Dry Condition versus the saturation ratio of diesel fuel.

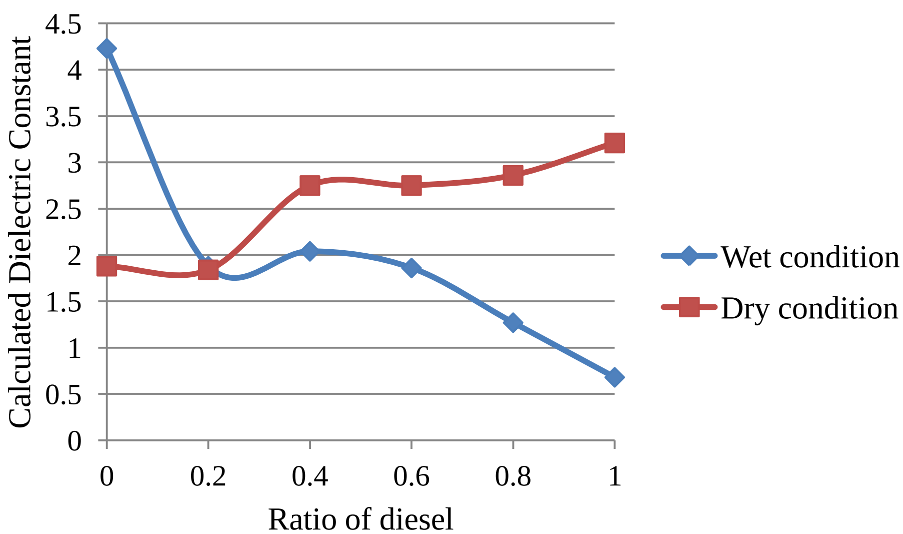

Figure 4-4. Saturation ratio versus dielectric constant for the Wet Condition and Dry Condition

For the Wet Condition, a saturation ratio of 1.0 is established. Depending upon the length of the TDR monitoring probe, the extent of the UST excavation zone, and the volume of UST leakage, the TDR monitoring probe will either be fully or partially submerged within diesel or water. In previous tests, we consider the apparent dielectric constant based upon the time required for the pulse to travel down the entire length of the TDR monitoring probe and return. We now consider the dielectric constant based on the time required for the pulse to travel along the partial length of the probe submerged within either water or diesel. This analysis technique is an attempt to model analysis techniques completed by Sun et al (2000) and Kim et al (2010). In lieu of using TDR monitoring probes of differing physical lengths, the present study utilizes a TDR monitoring probe with a consistent physical length of 30 cm. The time required for the pulse to travel partial distances along the TDR monitoring probe is multiplied by two to simulate pulse propagation along a shorter length of the TDR monitoring probe and return.

For the Wet Condition, we consider the propagation velocity of the TDR pulse is dependent upon the type of pore fluid present in the soil sample. Due to the lower unit weight diesel exhibits, diesel always overlies water in the UST excavation zone. Based on this condition, we calculate apparent dielectric constant by using the time required for the pulse to travel along the partial length of the TDR monitoring probe submerged exclusively in either diesel or water. For example, the mixing parameters for Sample No. W-3 in Table 4-1 indicate the water ratio is 0.4 and the diesel ratio is 0.6. Based on the volume of the container and void ratio of the sample, we consider the top 24 cm of the TDR monitoring probe is in contact with diesel and the bottom 6 cm of the TDR monitoring probe is in contact with water. Based on propagation velocity of the pulse along the TDR monitoring probe in these zones, the dielectric constant for these particular zones within the soil sample is determined. Table 4-4 indicates the dielectric constants for each of these Wet Condition zones based upon the elevations of the specific pore fluid in the specific zone. Only four of the samples from the Wet Condition are used for this analysis because in Sample no. W-1 and Sample no. W-6, the only pore water fluid is diesel and water, respectively.

Table 4-4. Partial dielectric constants for Wet Condition.

Sample No.	**W-2**	**W-3**	**W-4**	**W-5**
Ratio of Diesel	0.8	0.6	0.4	0.2
Ratio of Water	0.2	0.4	0.6	0.8
Length TDR monitoring probe in diesel (cm)	30	24	16	8
Length TDR monitoring probe in water (cm)	0	6	14	22
Apparent dielectric constant for diesel	0.68	0.99	0.99	0.99
Apparent dielectric constant for water	N/A	0.98	2.91	0.99

For the Wet Condition, we can infer from the test results that as the volume of water decreases and the volume of diesel fuel increases, the partial dielectric constants remain relatively equal. On the contrary, we see a decrease of the bulk dielectric constant for the Wet Condition sample mixing parameters indicated in Table 4-1. Water has a dielectric constant of 80. We expect the dielectric constant of the samples to decrease with decreasing amounts of water, which the data indicate does not occur. Based on the test results in the present study, the limitations in the use of TDR monitoring probes with shorter lengths described by Kim et al (2010) appear to be valid when collecting dielectric constant measurements with short TDR monitoring probes.

For the Dry Condition, we consider the propagation velocity of the TDR pulse would be dependent upon the elevation of diesel pore fluid present in the soil samples. Based on this condition, the apparent dielectric constant is obtained based upon the time required for the pulse to travel along the shorter length of the TDR monitoring probe submerged exclusively in diesel. Table 4-5 indicates the dielectric constants for each of these Dry Condition zones based upon the elevation of the diesel pore fluid in the specific zone. Sample nos. D-2, D-3, D-4, and D-5 of the Dry Condition samples are used for this analysis because the diesel pore fluid in Sample No. D-1 is below the end of the TDR monitoring probe.

Table 4-5. Partial dielectric constants for Dry Condition.

Sample No.	**D-2**	**D-3**	**D-4**	**D-5**
Ratio of Diesel	0.4	0.6	0.8	1.0
Length TDR Sampling probe in diesel (cm)	6	14	22	30
Apparent dielectric constant for diesel	0.99	0.99	0.99	0.99

For the Dry Condition, we can infer from the test results that as the volume of diesel fuel increases and no water is present, the calculated partial dielectric is consistent. On the contrary, we see an increase of the bulk dielectric constants indicated in Table 3-2 with greater amounts of diesel.

In the study by Miyamoto et al (2001), no error was reported for water content measurements obtained through the use of short (< 10 cm) TDR monitoring probes. The results of the study completed by Sun et al (2000) indicate the use of shorter TDR monitoring probes results in resistivity measurement error. The measurement error is reportedly due to the higher ratio of rod spacing to the sensing volume diameter and exponential decay of reflected voltage propagation in proportion to the length of the TDR monitoring probe (Kim et al, 2010). The results of the present study indicate apparent error in dielectric constant measurement utilizing partial probe length. The apparent error is similar to errors reported by Kim et al (2010). The present study focuses on detection of diesel fuel leakage in lieu of soil water content, so the satisfactory results reported by Miyamoto et al (2001) do not apply to the present study.

Due to inconsistent results, we further analyze the test results of the Wet Condition and Native Condition through use of a method similar to that described by Cataldo et al (2006). The analysis in the Cataldo et al (2006) study consists of calculation of the derivative of the reflection coefficient values versus distance. The derivative is interpreted as the slope of the tangent to the measured signal at each point. Based upon the plots of the waveforms for the Wet Condition and the Native Condition, we can visually identify differences of the amplitude of the waveforms dependent upon the saturation ratio of diesel fuel and/or water contained within the pore spaces of the samples. For samples in the present study, the derivative of the reflection coefficient (ρ) versus time (ns) appears to localize the change of signal amplitude due to the presence of diesel fuel or water within the pore spaces of the sample. Figures 4-5, 4-6, 4-7, 4-8, and 4-9 indicate the derivative of the diesel-water reflection coefficients versus time for Samples W-2, W-3, W-4, and W-5, respectively. The annotations on the figures indicate the peak value representative of the change of signal amplitude due to the saturation ratio of diesel fuel and water.

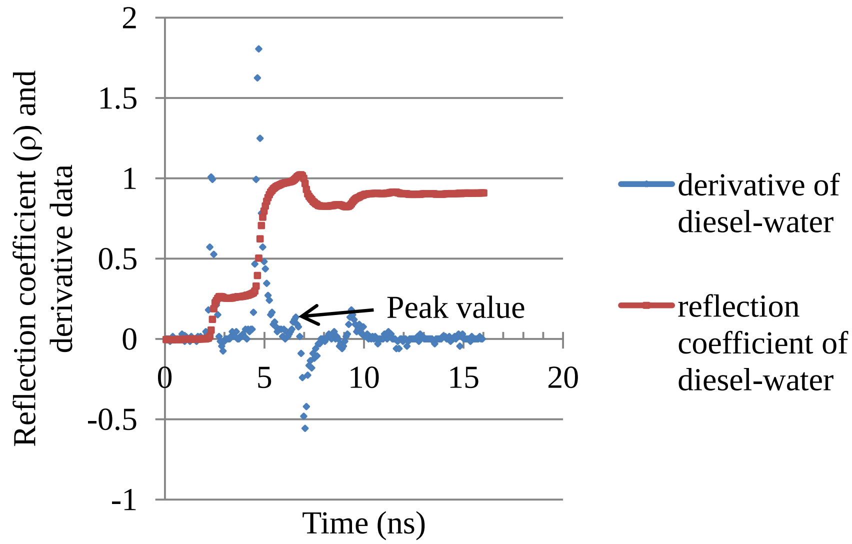

Figure 4-5. TDR waveform and derivative data for Sample no. W-1

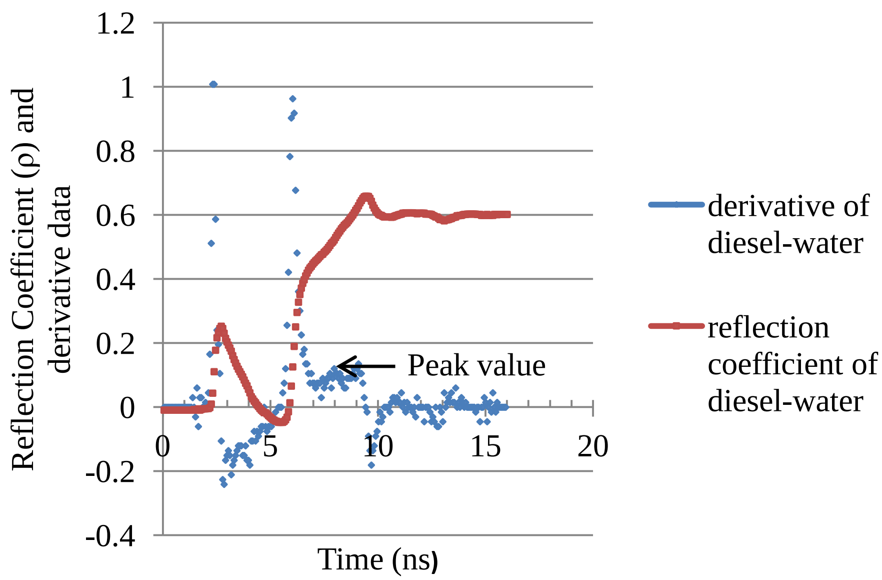

Figure 4-6. TDR waveform and derivative data for Sample no. W-2

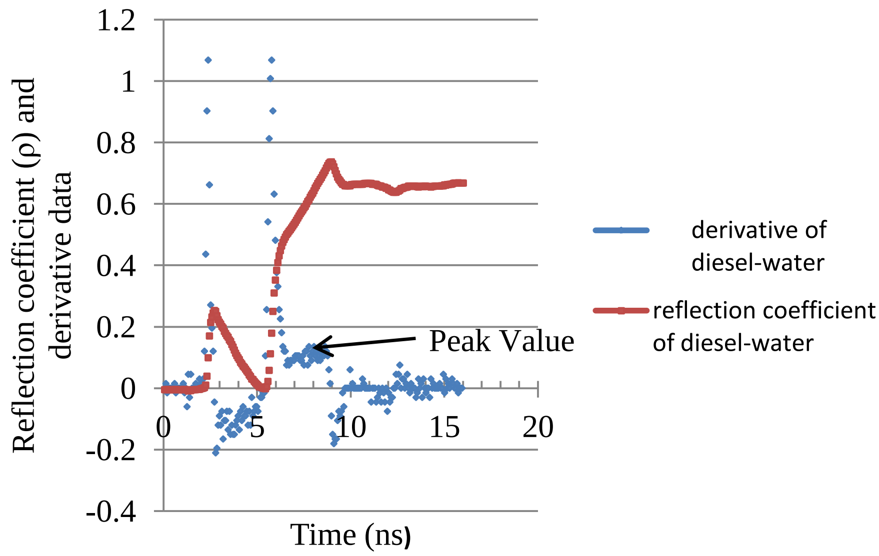

Figure 4-7. TDR waveform and derivative data for Sample no. W-3

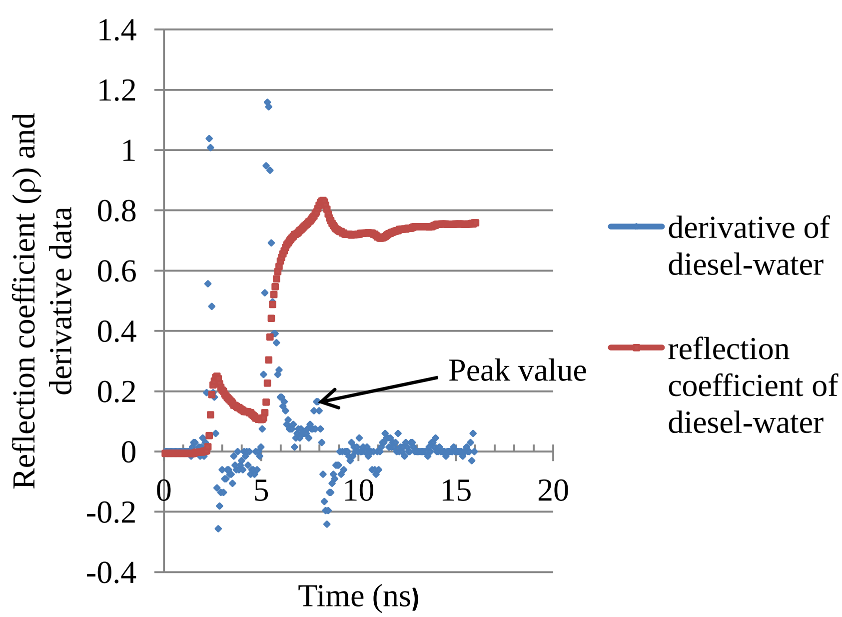

Figure 4-8. TDR waveform and derivative data for Sample no. W-4

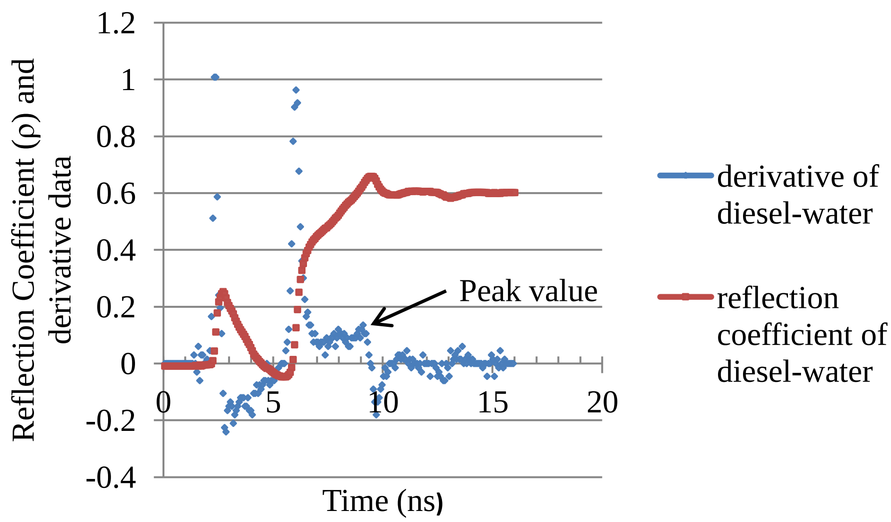

Figure 4-9. TDR waveform and derivative data for Sample no. W-5

Table 4-6 indicates the peak values selected from the derivative data in Figures 4-5, 4-6, 4-7, 4-8, and 4-9. The selected peak values are representative of the change of signal amplitude due to the saturation ratio of diesel fuel and water.

Table 4-6. Peak time and derivative data for Wet Condition

Sample No.	Time (ns)	Derivative reflection coefficient versus time
W-1	6.57	0.13
W-2	6.77	0.12
W-3	7.70	0.16
W-4	7.77	0.13
W-5	7.97	0.12

The analysis of the derivative of the reflection coefficient versus time is useful for determining if a leaking UST is continuing to leak or the leakage rate increases. In order to distinguish the changes of amplitude of the TDR waveform due to a leaking UST, and the changes of amplitude of the TDR waveform due to a non-leaking UST with fluctuations of the groundwater elevation within the UST excavation zone, further analyses are required.

The derivative of the reflection coefficient versus time is calculated for the Native Condition samples, which correspond to a fluctuating groundwater table. Based upon the sample mixing parameters in Table 3-3, the following figures illustrate selection of the same peak values selected in the previous analysis. These peak values are representative of the change in signal amplitude due to the saturation ratio of water.

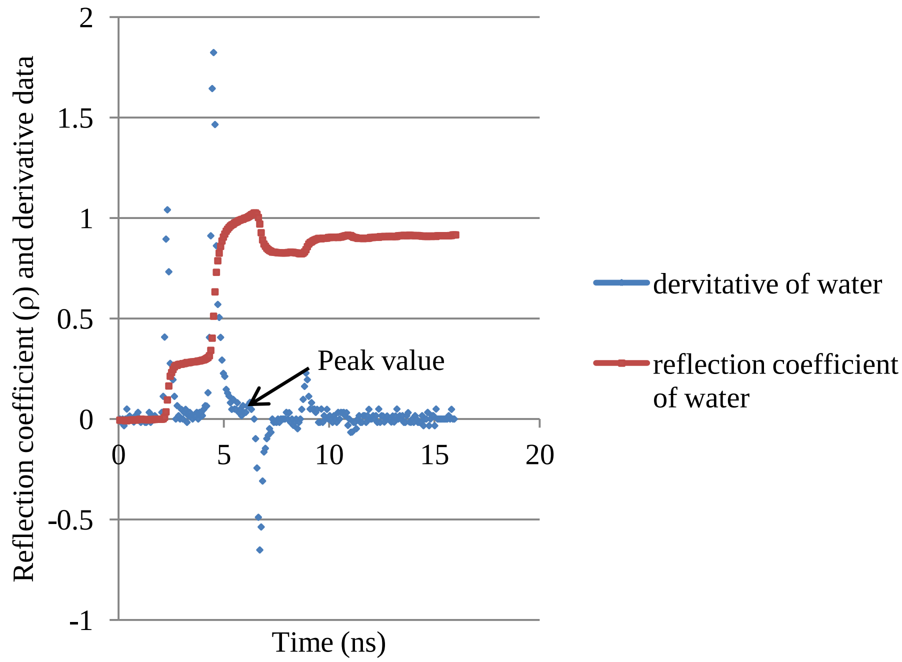

Figure 4-10. TDR waveform and derivative data for Sample no. N-1

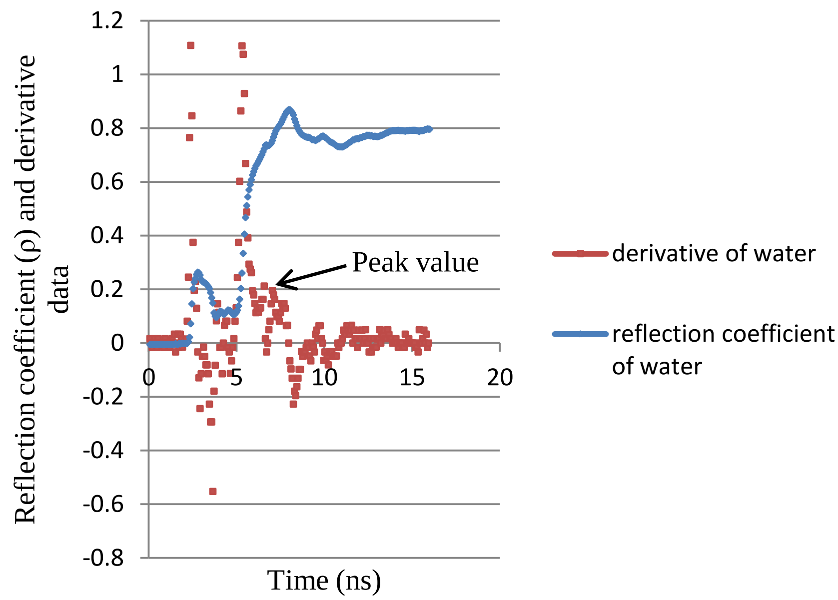

Figure 4-11. TDR waveform and derivative data for Sample no. N-2

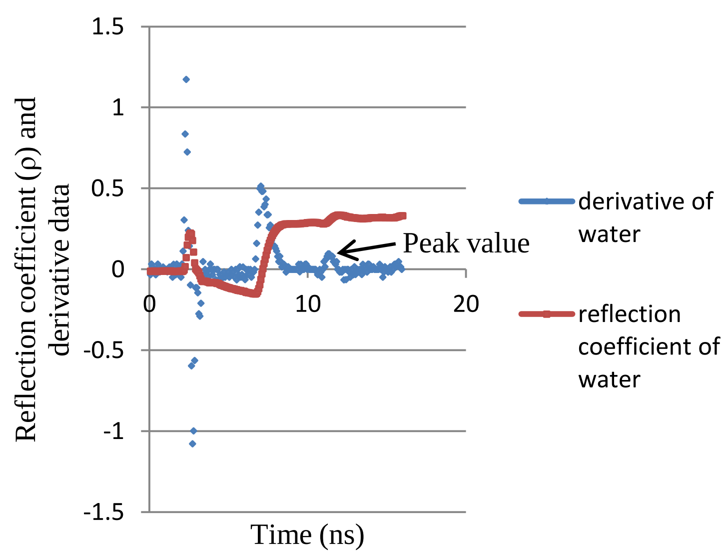

Figure 4-12. TDR waveform and derivative data for Sample no. N-3

Table 4-7 indicates the peak values selected from the derivative data in Figures 4-10, 4-11, and 4-12. The selected peak values are representative of the change of signal amplitude due to the saturation ratio of water.

Table 4-7. Peak time and derivative data

Sample No.	Time (ns)	Derivative reflection coefficient versus time
N-1	6.24	0.08
N-2	6.57	0.21
N-3	6.97	0.49

We compare the results indicated in Tables 4-6 and 4-7 for the Wet Condition and the Native Condition. The results are shown in Figure 4-13.

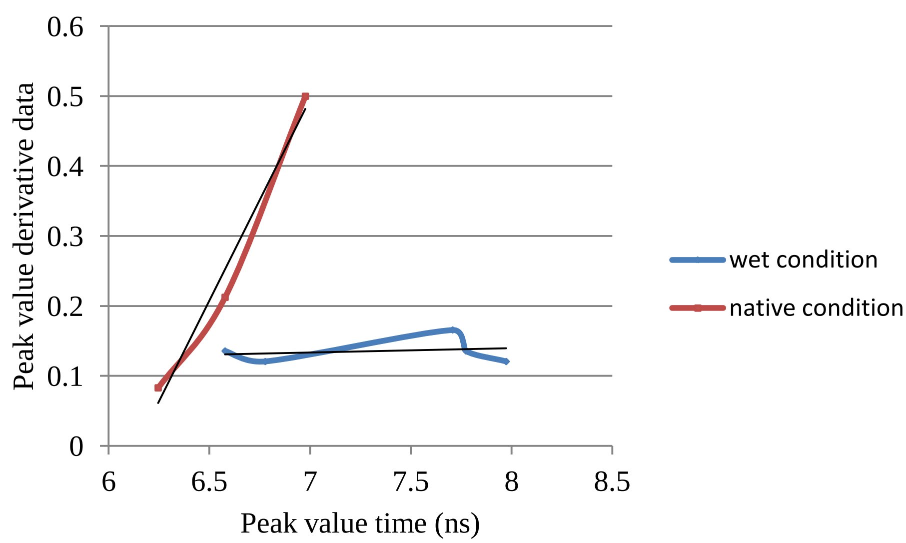

Figure 4-13. Peak value derivative data for Wet Condition and Native Condition

The data plotted in Figure 4-13 indicate a pronounced difference of the Wet Condition and Native Condition. By plotting the peak values from the derivative data versus time, we can see the slope of the line is significantly different for each condition. When diesel fuel occupies pore spaces within the sample, the slope of the resulting derivative data and time plot is minor. On the contrary, when air or water occupies the pore spaces within the sample, the slope of the resulting derivative data and time plot is relatively steep. Through this analysis, we are able to distinguish between UST excavation zone backfill impacted by diesel (Wet Condition) and UST excavation zone backfill impacted by water or air (Native Condition).

Baseline Testing

To predict how the soil will behave when either water or contaminants enter the soil medium, baseline testing of materials proposed for UST excavation zone backfill must be performed prior to UST installation. To perform baseline testing, a representative sample of the material proposed for use as UST excavation backfill must be obtained. The representative sample would then be compacted into a cylinder mold at 95% of the material's optimum dry unit weight as determined by a standard Proctor test. In geotechnical engineering, a typical recommendation for placement and compaction of coarse-grained (granular) soil as engineered fill is to place the soil at workable moisture contents. Once the soil has been compacted into a cylinder mold, the void ratio of the soil would be determined using gravimetric techniques. Upon determination of the void ratio, the addition of diesel fuel proposed for storage in the UST and water would both be completed, in two separate tests, to the compacted sample at varying saturation ratios. The dielectric constant is determined at each saturation ratio using TDR, and a graph of the derivative of the reflection coefficient and time is constructed. The resulting graphs are utilized when subsequent TDR measurements are obtained throughout the life of the UST structure to determine if leakage has begun.

Field Application

Field application of TDR would consist of measurements obtained remotely via a data-logger and continuous real-time monitoring of the UST integrity would be possible. Based on our test results, it is possible to detect minor to moderate UST leakage efficiently. The TDR method can be further enhanced through the development of software capable of interpreting acquired TDR data and alerting the user when a leak is detected. Upon receiving the alert, the user can verify the presence of a leak by using existing leak detection procedures.

CHAPTER 5

CONCLUSIONS

We have demonstrated TDR can be used to detect leakage of an UST through baseline testing of the material's proposed for backfill adjacent to the UST. The dielectric constant measurements and graphs of the derivative data and time, obtained through use of TDR, can adequately serve as a method to characterize the extent of leakage and serve as a method for back-checking existing leak detection procedures. Though the process of establishing a baseline is rigorous, the process is similar to existing procedures which have been developed to adequately engineer the structure and ensure positive performance throughout the lifespan of the structure.

Based upon the results of the present study, obtaining dielectric constant measurements should be completed by utilizing the entire physical length of the TDR monitoring probe. The TDR monitoring probe should also have a minimum length of 30 cm. Measurement error is likely when using partial lengths of TDR monitoring probes. Measurement error is also likely when using full lengths of shorter TDR monitoring probes (Kim et al, 2010).

To adequately instrument the UST excavation zone using TDR monitoring probes, the TDR monitoring probes must be situated so the full elevation of the UST excavation zone is instrumented. To efficiently accomplish this task, it may be necessary to develop TDR monitoring probes of a greater length than those used in this study. The physical length of the electrodes is included in the equation for dielectric constant calculation, so it is possible to accomplish baseline testing using longer TDR monitoring probes. The TDR monitoring probes used for baseline testing and proposed for installation at the project site must be of equal length. The use of shorter TDR probes should be avoided, because using a relatively short TDR probe provides inaccurate measurements (Kim et al, 2010).

There are many methods which can be used to install the equipment at the site. One necessity is the TDR monitoring probes must be in direct contact with the UST excavation zone backfill. The TDR monitoring probes can be placed as the UST excavation zone is backfilled, and coaxial cables can be strung to an equipment cabinet at the site. Once installation of the TDR monitoring probes into the soils is complete, backfilling of the excavation can continue normally. The use of manual compacting machinery (i.e. jumping jack or hand compaction) may be required immediately adjacent to TDR components to avoid potential damage to the equipment. Initial TDR measurements should be obtained immediately upon backfill completion.

To preclude error which can occur due to conductivity of the soil proposed for use as UST excavation backfill, the proposed backfill must consist of non-conductive materials. Conductivity testing of the proposed backfill materials must be performed prior to use as UST excavation zone backfill. The maximum allowable conductivity threshold is 3.7 dS/m (Sun et al, 2000). The backfill must also consist of coarse-grained (granular) materials, since electrical properties of fine-grained soils could greatly vary (Dasberg and Hopman, 1992; Fukumoto and Tanaka, 1995). It is also desirable to use free-draining materials as backfill to fulfill geotechnical properties.

The conditions of the models in this study are dependent upon the elevation of groundwater at the project site. As such, piezometers or monitoring wells must be installed at the site to monitor the presence and elevation of groundwater. The use of vibrating wire piezometers will automate this task, thus the TDR leak detection system can still be operated remotely.

Provided all the discussed design parameters are implemented, the TDR system can successfully be used as a leak detection method for USTs. To successfully implement the procedures and technology, an experienced geoscientist must be employed at the design stage. Full-scale tests should also be conducted to evaluate the performance of the technology outside of a laboratory setting.

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