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Technical Note

Time Domain Reflectometry (TDR) – Measuring Dielectric Constant of Polluted Soil to Estimate Diesel Oil Content

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Abstract

The paper presents results of experimental study on the possibility of calculating the content of diesel oil in soils from measurements of dielectric permittivity with the TDR technique in a soil-water-air-diesel oil system. Results of calculation were compared with the actual content of diesel oil measured in laboratory conditions. The comparison shows that the content of diesel oil in soils may be precisely determined pn the basid of measurements of dielectric permittivity in contaminated soils.

Key words: contaminated soils, dielectric permittivity, TDR, oil diesel content

1. Introduction

Studies on the effects of human impact on water-soil medium are now particularly important to maintain and protect high natural quality standards and to select effective and efficient restoration methods (Olchawa, Kumor 2007). From among many methods of estimating the pollution of soil-water medium, laboratory chemical analyses are in common use. They are precise though relatively time-consuming. Therefore, they can not be used in any circumstances where one urgently wants to obtain data on the dynamics of pollution. In the case of fuel spills, especially diesel oil spills, it is difficult to monitor spreading of pollutant loads using laboratory methods.

In situ measurement of contamination of saturated soil-water medium by oil pollutants could be an alternative to laboratory chemical analyses. Measurement of dielectric permittivity of soil-water-air-diesel oil system gives a possibility of relatively rapid and simple determination of soil pollution by diesel oil. The Time Domain Reflectometry (TDR) method may be used to measure dielectric permittivity (Ansoult et al 1985, Mojid, Cho 2004).

This paper presents results of empirical studies on the contamination of soil-water medium and shows a possibility of estimating diesel oil content in typical non-cohesive mineral soils and silt with the use of the TDR technique to measure dielectric permittivity.

2. Materials and Methods

The principles of TDR (Time Domain Reflectometry) are described in many papers concerning its application for soil water content measurements (Malicki, Skierucha 1989, Malicki 1999).

TDR, as applied to dielectric measurements, is based on a relationship between the velocity of electromagnetic wave propagation and the dielectric constant of the medium the wave propagates in.

For non-magnetic materials having low dielectric loss, this relation can be simplified to:

$$v = \frac{c}{\sqrt{\varepsilon}}, \tag{1}$$

where:

- v – electromagnetic wave propagation velocity,
- c – velocity of electromagnetic wave (light) propagation in free space,
- ε – relative apparent dielectric constant of the medium the wave propagates in.

The principles of reflectometric measurement of soil dielectric constant are sketchet in Fig. 1.

The time interval $t = t_2 - t_1$ can be measured and $\sqrt{\varepsilon}$ can be calculated according to Eq. (1) as:

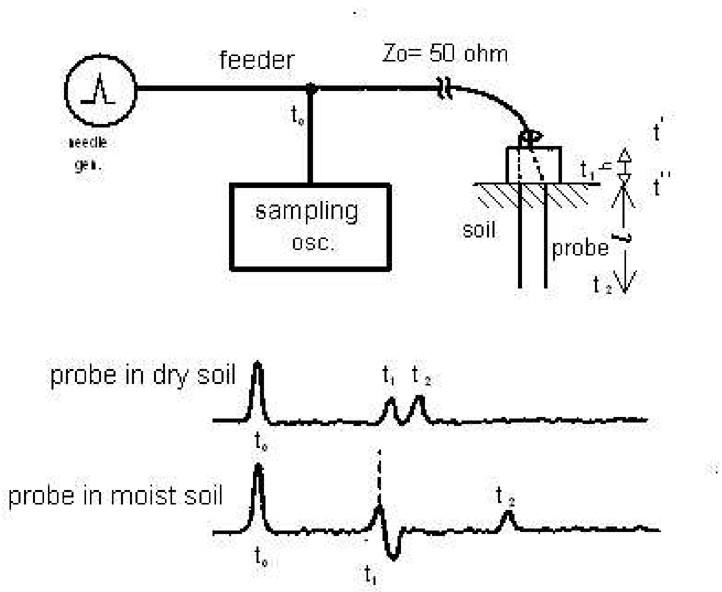
$$\sqrt{\varepsilon} = \frac{c}{2L \cdot t}, \tag{2}$$

where L is the TDR probe length.

From among many physical models of dielectric permittivity that describe the ground as a mixture of ground skeleton, water and air, the α model is used (Ansoult et al 1985, Mojid, Cho 2004). The simplest form of the α model can be derived based on the analysis of propagation of electromagnetic impulse along rods of the TDR probe placed in a medium composed of four layers, i.e. ground skeleton, air, water and diesel oil (Skierucha 2005) (Fig. 2).

The time during which an electromagnetic impulse travels the length L of the TDR probe rods is the sum of propagation times through particular phases of contaminated medium, i.e.

$$t = t_s + t_a + t_w + t_{ON}, \tag{3}$$



$$t = t_2 - t_1 = \frac{2 \cdot l}{c}\sqrt{\varepsilon}$$

Fig. 1. Principle of TDR–based measurement of soil dielectric constant (after Malicki, Skierucha 1989)

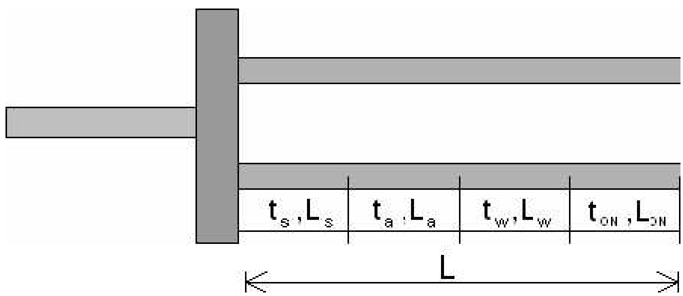


Fig. 2. Interpretation of 4-phase dielectric mixing α model of soil using reflectometric technique of wave propagation in the soil

where: s, a, w, ON denote particular phases of contaminated medium (ground skeleton, air, water, diesel oil, respectively).

Using Eq. (2), t might be expressed as:

$$t = t_s + t_a + t_w + t_{ON} = \frac{2L\sqrt{\varepsilon}}{c} = \frac{2L_s\sqrt{\varepsilon_s}}{c} + \frac{2L_a\sqrt{\varepsilon_a}}{c} + \frac{2L_w\sqrt{\varepsilon_w}}{c} + \frac{2L_{ON}\sqrt{\varepsilon_{ON}}}{c}, \quad (4)$$

where:

L – idealised parts of the TDR probe placed in component phases of contaminated ground (Fig. 2).

Considering geometric properties of the probe/soil skeleton/water/diesel oil/air system, we obtain a 4-phase dielectric model α that expresses the dielectric permittivity of the phase mixture with elementary components:

$$\varepsilon^{\beta} = \varepsilon_s^{\alpha} \cdot V_s + \varepsilon_a^{\alpha} \cdot V_a + \varepsilon_w^{\alpha} \cdot V_w + \varepsilon_{ON}^{\alpha} \cdot V_{ON}, \quad (5)$$

where:

V_s, V_a, V_w, V_{ON} – volume of soil skeleton, air, water and diesel oil, respectively, in unit soil volume,
ε – dielectric permittivity of the soil/water/air/diesel oil system,
$\varepsilon_s, \varepsilon_a, \varepsilon_w, \varepsilon_{ON}$ – dielectric permittivity of soil skeleton, air, water, diesel oil, respectively.

The value of exponent α in Eq. (5) varies between −1 and 1, depending on the shape of particles and their orientation relative to the direction of the applied electric field. For the soil water mixture, α was reported to be 0.5 (Malicki 1999, Mojid, Cho 2004).

Based on Eq. (5), and on main physical soil properties, the oil volume in unit volume of the soil is:

$$V_{ON} = \frac{\varepsilon^{\alpha} + \frac{M_s}{\rho_s}(1 - \varepsilon_s^{\alpha}) - M_m(\varepsilon_w^{\alpha} - 1) - 1}{\varepsilon_{ON}^{\alpha} - \rho_{ON}(\varepsilon_w^{\alpha} - 1) - 1}, \quad (6)$$

where:

M_s – mass of soil skeleton,
M_m – mass of porous medium in unit volume of contaminated soil,
ρ_{ON} – diesel oil density,
ρ_s – soil skeleton density.

From Eq. (6) it appears that determination of the mass of soil skeleton and of porous medium in unit soil volume is necessary to calculate the content of diesel oil. Both masses can be determined with the gravimetric method in any soil science laboratory.

Sandy gravel (*saGr*), medium sand (*MSa*) and silt (*Si*) were selected for experimental studies. Physical properties of selected soils are given in Table 1.

Table 1. Physical properties of the soils used in experiment

Sample	Fraction content, %				Specific gravity of soil particles	Hygroscopic water content*
	Cl	*Si*	*Sa*	*Gr*	[−]	%
Sandy gravel (*saGr*)	1	12.5	33.5	53	2.65	0.008
Medium sand (*MSa*)	2	10	88	0	2.65	0.012
Silt (*Si*)	2	96	2	0	2.67	0.061

*measured at relative humidity $p/p_0 = 0.95$

Soils selected for experimental studies contain a small amount of hygroscopic water, whose dielectric constant is ca. 3.5–4 (Saarenketo 1998), and can therefore be neglected in further calculations.

Soils were wetted with tap water. Moisture of samples ranged between 0.17 and 65.20%. Six samples, varying in initial moisture were taken from each soil type. Each soil type was represented by a sample of initial moisture equal to air dry moisture. Polyethylene vessels of a volume of 158 cm^3 were filled with soil samples prepared in this way. Then the vessels were tightly closed to equilibrate soil moisture. Next, diesel oil was added to samples. The volume of diesel oil in the unit volume of soil samples of variable initial water content was: 2, 4, 8, 14 and 16%. Measurements of dielectric permittivity in contaminated soil samples were made at the Institute of Agrophysics, Polish Academy of Sciences, in Lublin.

Before measurements were made, the TDR probe was calibrated at room temperature (30.3°C on the day of measurements). Standard liquids, i.e. acetone, benzene and tap water, with dielectric constants of 20.08, 2.28 and 76.5, respectively, were used for calibration.

Dielectric constant ε_s of the soil skeleton (dried at 105°C) was calculated from measured dielectric constant and the simplified equation (5):

$$\varepsilon_s = \left[\frac{\sqrt{\varepsilon} - \left(1 - \frac{M_s}{\rho_s}\right)}{V_s} \right]^2, \tag{7}$$

symbols as in Eq. (6).

The dielectric permittivity of diesel oil was adopted as $\varepsilon_{ON} = 2.1$.

One TDR sensor was vertically inserted in each receptacle and the average dielectric constant of the contaminated soil was measured by 5 or 6 repeated measurements with the sensor. After all measurements had been made, all samples were dried at 105°C for 24 h to determine the mass of porous medium M_m and of the soil skeleton M_s.

3. Discussion

Volumetric content of diesel oil, added in laboratory conditions $V_{ON(lab.)}$, was compared with the content $V_{ON(TDR)}$ calculated from equation (6). The relationship between the two volumes is presented in Fig. 3. Linear correlation between actual and calculated diesel oil content has a general form $V_{(ON)lab} = A \cdot V_{ON(TDR)} + B$. Constants A and B, estimated with the least squares method (Nowak 2002), were 0.91 and 0.08, respectively at $R^2 = 0.94$, and Fischer-Snedecor coefficient was $F = 344 > F_{kr} = F_{(1,13,0,95)} = 4.67$ (Draper, Smith 1973). Based on the statistically established relationship $V_{(ON)lab} = 0.91 \cdot V_{ON(TDR)} + 0.08$, one may determine practically the content of diesel oil in soils.

The analysis of the correlation between $V_{(ON)lab}$ and $V_{ON(TDR)}$ indicates that the oil content calculated from Eq. 6 is higher than that determined in the laboratory studies. Obtained differences are, however, small and may arise from experimental errors and from the adopted value of $\alpha = 0.5$.

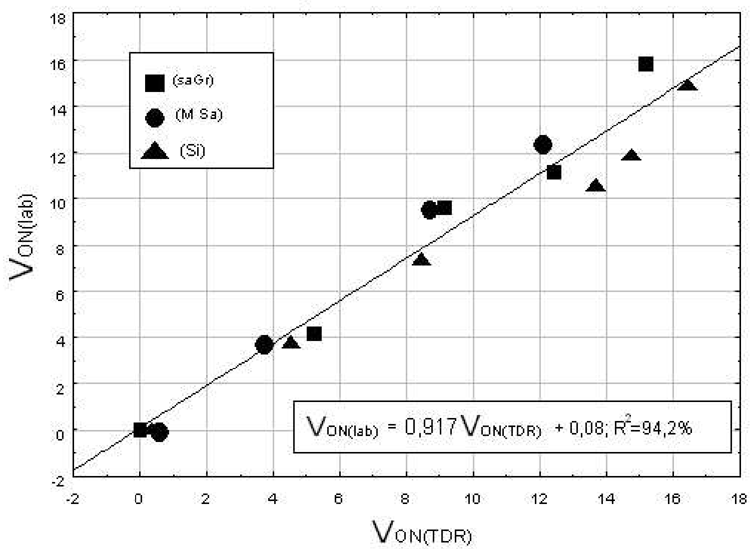


Fig. 3. Relationship between actual content of diesel oil and the content calculated from dielectric permittivity of contaminated soil

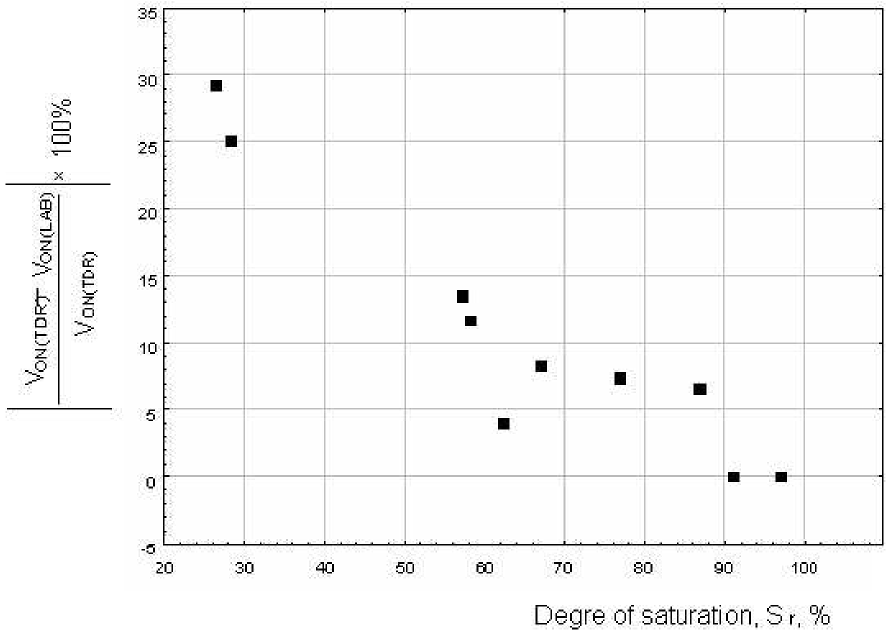


Fig. 4. The dependence of modulus of relative error on the degree of soil saturation with water

Figure 4 presents the relationship between the modulus of the relative error

$$\left|\frac{V_{ON(TDR)} - V_{ON(lab)}}{V_{ON(TDR)}}\right|$$

and the degree of soil saturation S_r. As seen, the relative error decreases with increasing degree of soil saturation. This phenomenon might be associated with a smaller volume of gas phase, whose dielectric permittivity is $\varepsilon_a = 1$, and is thus close to that of diesel oil, $\varepsilon_{ON} = 2.1$. The observed relationship may have practical meaning for the determination of diesel oil content with the TDR technique. Saturation of contaminated soil with water before measurement of dielectric permittivity will result in increased precision of the determination of diesel oil content.

The relatively high precision of the determination oof diesel oil content in soil by the TDR technique allows for the application of this technique in every soil laboratory. Low labour intensity and time consumption enables the performance of more analyses in comparison with routine chemical analyses.

The TDR technique might also be used to determine other substances like petrol or engine oil in soils. Dielectric permittivities of these substances are close to that of diesel oil (1.9–2.1 and 2.75, respectively) (Izdebska-Mucha 2005).

4. Conclusions

The results obtained allow us to formulate the following conclusions:

1. The content of diesel oil in soils may be precisely determined from measurements of dielectric permittivity with the TDR technique and a knowledge of the basic physical soil properties.
2. Precision of determination increases with soil moisture which, in practice, necessitates saturating the soil with water before measurements of its dielectric permittivity are conducted.
3. Low labour intensity and time consumption of the method based on the measurements of the dielectric constant might be an alternative to presently used chemical methods of estimating the soil contamination.
4. Measurements of dielectric permittivity might also be used to determine other substances, like petrol or engine oil in soils.

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