TIME DOMAIN REFLECTOMETRY (TDR) IN MEASURING WATER CONTENTS AND HYDRATE SATURATIONS IN MARINE SEDIMENTS

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ABSTRACT

Time Domain Reflectometry (TDR) has been widely used in water system investigation in Agriculture, Geosciences, etc. In our experiments, we found that the conventional TDR probes are not able to measure water contents of a sample when the salinity of pore fluid is higher than about 0.5%wt. A coated TDR probe was then developed to solve water content measurement problem in high salty sediments. Observations of TDR measurements were made on sediments containing 0%, 0.5%, 2%, and 3.5% salinity NaCl solutions with the improved probe. Subsequently, the empirical relations between water content and dielectric constants of the salty sediments were given. The results have significance in introducing TDR technology in measuring water content and hydrate saturation of marine sediments.

Keywords: Time Domain Reflectometry (TDR); water content; high salinity; marine sediments; coated probe

NOMENCLATURE

- c: velocity of electromagnetic wave in free space [m/s]
- C₀: capacitance of air-filled parallel plate capacitor [F]
- C: capacitance of parallel plate capacitor filled with insulating material [F]
- I₁: loss current [A]
- Iₑ: charging current [A]
- Iₑ: total current [A]
- Kₑ: dielectric constant [F/m]
- l: length of TDR probe [m]
- Q: electric charge [coulomb]
- t: travel time in sample [s]
- V₀: applied voltage [V]
- V: applied voltage [V]
- ε₀: dielectric constant of the air [F/m]
- ε: relative dielectric constant [no unit]
- ε’: dielectric constant of the material [F/m]
- ε*: complex dielectric constant [F/m]
- ω: angular frequency [Hz]
- θv: water content [%]

INTRODUCTION

Hydrate pore saturation (Sh) of a sample is mainly determined by the porosity and water contents of the sample. Various methods, such as gravimetric method, neutron scattering method [1], Ground Penetrating Radar (GPR) [2] and Time Domain Reflectometry (TDR) [3], have been used to measure water contents of a sample. Among these methods, TDR is more suitable to measure a small-scale water distribution because it is nondestructive and more flexible [4-8].

TDR was initially used for detecting the position of breaks in transmission line cables. The technique was introduced in measuring water contents of soil samples in 1980s, and then it developed rapidly [3, 9]. Topp et al. [3] was probably the first one who measured water contents of soil samples with TDR technique. They found a practical relation between dielectric constants and water contents of the soil samples based on various types of experimental results. With regard to some particular substance, special
calibration is needed before measurements. For example, Regalado et al. [10] proposed a empirical equation for calculating water contents of volcanic soils; Wright et al. [11] found the relationship between dielectric constants and water contents of hydrate-bearing sediments. Thereafter, TDR was effectively used to measure hydrate pore saturations of the hydrated sediments [12-14]. Ye et al. [12] tested the affect of temperature and pressure on measuring water contents of the hydrated sediments using TDR. After that, they combined TDR and ultrasonic methods to research the relation between gas hydrate saturations and acoustic properties of the hydrate-bearing sediments [13, 14]. However, it can be found in this study that traditional TDR is not valid when the salinity of the sediments is higher than 0.5%wt. Thus, it focuses on the water contents measurement of high salty sediments using TDR in this work.

THEORETICAL BACKGROUND

The physical principles relating to the dielectric constant has been given by Dalton and Genuchten [9]. For an ideal, air-filled parallel plate capacitor with capacitance $C_0$, the electric charge $Q$ stored on the capacitor is:

$$Q = C_0V$$

(1)

where $V$ is an instantaneous voltage applied on the capacitor. If an insulating material is placed between the parallel plates, the capacitance is given as:

$$C = C_0\varepsilon/\varepsilon_0 = C_0\varepsilon'$$

(2)

where $\varepsilon'$ and $\varepsilon_0$ are the dielectric constant of the material and the air, respectively, and $\varepsilon$ is the relative dielectric constant. When the applied voltage is sinusoidal in time, that is,

$$V = V_0e^{i\omega t}$$

(3)

Where complex notation is used ($i^2 = -1$) and $\omega$ is the angular frequency, then the charging current $I_c$ represents the time rate of change of the stored charge:

$$I_c = \frac{dQ}{dt} = C_0dV/dt = i\omega C_0V$$

(4)

If the material between the capacitor plates is not an insulator, such as a saline soil, then there will be a conduction or loss current $I_c$ proportional to the material conductance $G$ and applied voltage $V$ such that $I_c = GV_0$. The parameters $I_1$ and $I_c$ are important factors for simultaneous measurement of dielectric constants and electrical conductivities. The ratio of the loss current to the conductance current is called the dissipation factor D or loss tangent, $\tan \delta$:

$$D = \tan \delta = I_c/I_1$$

(5)

The total current $I_t$ (charging current + loss current) becomes:

$$I_t = I_1 + I_c = (G + i\omega C)V$$

(6)

which shows that the total current can be viewed as a complex variable consisting of real and imaginary components. Since the loss current may be due to any energy consuming process and not just to conduction losses, it is convenient to introduce in analogy to equation 6 a complex dielectric constant:

$$\varepsilon^* = \varepsilon' - i\varepsilon''$$

(7)

Using equations 2 and 7, the total current (equation 6) can now be expanded into a form that does not specifically include the loss current:

$$I_t = i\omega C_0V/\varepsilon + (i\omega \varepsilon' + \omega \varepsilon'')C_0V/\varepsilon_0$$

(8)

The parameter $\varepsilon''$ is called the loss factor, where $\omega \varepsilon''$ is equivalent to the dielectric conductivity. In equation 8, the imaginary part represents the attenuation of dielectric constants, with which the frequency-dependent dielectric properties of a medium can be measured [9]. The real part represents the static component of the dielectric constant, which can be used to correlate with the water content of a sample [3].

TDR waveform of a soil or sediment sample is shown in Fig 1. The electromagnetic wave is generated by TDR instruments, and transmitted along the coaxial cable and the TDR probe. Because there is loss current during electromagnetic wave transmitting in the samples, the characteristics of the entry point and the end point are obviously. The velocity of electromagnetic wave transmitting in the samples can be calculated with:

$$V = l/t$$

(9)

Where $l$ is the length of the TDR probe, $t$ is the time-interval between entry point and end point (Fig 1). At the same time, the velocity of electromagnetic wave in the samples can be also related to dielectric constants:

$$V = c/Ka^{1/2}$$

(10)

Where $c$ is the velocity of propagation in free space (approximately $3 \times 10^8$ m/s). From equation 9 and 10 it solves:

$$Ka = (ct/l)^2$$

(11)

When the Ka is calculated, with the relationship between Ka and water contents we can obtain the water contents of the sample. For soils [3]:

$$\theta_v = -5.3 \times 10^2 + 2.92 \times 10^2 Ka - 5.5 \times 10^4 Ka^2 + 4.3 \times 10^6 Ka^3$$

(12)
For hydrate-bearing sediments, it’s effective to use Wright et al.’s empirical equation:

\[ \theta_v = -11.9677 + 4.506072566Ka - 0.14615Ka^2 + 0.0021399Ka^3 \]  \( (13) \)

As a result, the hydrate pore saturation of the hydrated sediments can be calculated with:

\[ Sh = (\phi - \theta_v) / \phi \times 100\% \]  \( (14) \)

Where \( \phi \) is the porosity of the sample.

**TDR in High Salty Sediments**

**Apparatus**

In order to measure water content of marine sediments, an apparatus has been developed (Fig 2) based on [13, 14]. In the experimental process, a constant flux pump is used to add pure or salty water into the sediments. In order to consider the affect of pressure on TDR measurement, the experiments were conducted in a high pressure vessel. Also, there are two platinum resistance thermometers using for temperature measurement of the surface and inner sample. All data, including TDR waveform, temperature, and pressure data, are recorded by the computer system.

**TDR Probe Improvement**

The sediments are 0.09-0.125mm sands. It is convenient to use TDR for water content measurement when the salinity of the injected water is low. However, we found that it’s hard to observe the end point from the TDR waveform so it’s unable to measure the water contents when the salinity of the sediments’ pore water is higher than about 0.5%wt (Fig. 3).

In order to measure water content of marine sediments (with high salinity), a coated coaxial TDR probe is made, on which an insulating coat is added (Fig 4). In theory, the insulating coat of the improved TDR decreases the attenuation of electromagnetic wave, so that the end point can be observed. Using the improved TDR probe, we measure the water contents of sands containing salinity of 0%, 0.5%, and 2%. We also compared the results with that measured by the traditional TDR probe (Fig 5). From Fig 5a, it shows that it’s easy to find the end point when using the improved TDR probe although the end point is different from that measured by the traditional TDR probe. From Fig 5b and c, it can be found that the improved TDR probe is able to measure the end point even the salinity is very high. Because the end point is changed with the improved TDR probe, a calibration is needed to use this probe for water content measurements.

**Determine Water Contents of Marine Sediments**

With the improved TDR probe, observations of TDR measurements were made on sediments containing 0%, 0.5%, 2%, and 3.5% salinity NaCl solutions. For each measurement, the process was as follows (e.g. adding 3.5% NaCl solutions to dry sands): (1) install the TDR probe, filled the inner barrel with dry sands (0.09-0.125mm); (2) pump 3.5% NaCl solution into the dry sands at a speed of 5ml/min for 2min, then waiting for about 5min and record the TDR waveform; (3) repeat step 2 for about 20 times, as a result, about 21 TDR waveforms were recorded at different salinities; and (4) calculate dielectric constant from waveforms, corresponding with the known water contents. An example of TDR waveforms recorded during adding 3.5% NaCl solutions to dry sands are shown in Fig 6. It shows that the TDR waveforms measured by the improved TDR probe are valid to calculate the dielectric constant of marine sediments (average salinity 3.5%wt). On the basis of the experimental data, the relationship between dielectric constant and water content of the 0.09-0.125mm sands under different salinities has been established:

- Salinity 0%: \[ \theta_v = -4.7156 + 2.7675Ka - 5.7 \times 10^{-2}Ka^2 + 2.3 \times 10^{-3}Ka^3 \]  \( (15) \)
- Salinity 0.5%: \[ \theta_v = -4.6649 + 2.8137Ka - 9 \times 10^{-2}Ka^2 + 2.7 \times 10^{-3}Ka^3 \]  \( (16) \)
- Salinity 2%: \[ \theta_v = -1.4721 + 1.7103Ka - 0.0282Ka^2 + 0.0004Ka^3 \]  \( (17) \)
- Salinity 3.5%: \[ \theta_v = -2.314 + 1.9831Ka - 0.0661Ka^2 + 0.0012Ka^3 \]  \( (18) \)

**Discussion and Conclusions**

Although TDR has been used for measuring hydrate pore saturation of hydrate-bearing sediments for about ten years, it mainly focused on water content measurement of low salty sediments. When the samples become real oceanic sediments, the traditional TDR probe is not able to detect the dielectric constant of the sample effectively. Chen et al. [15-16] described an approach for determining the dielectric constants in highly conductive soils from surface reflections of TDR signals, however, the approach is only applicable where the salinity of sediments is less than about 122.3 mS/m (which is lower than salinity of marine sediments ). In this study, we used an insulated coat on the TDR probe, which decreases attenuation of TDR signal. With the coated TDR probe, we established empirical equations related dielectric constant to water content. However,
more efforts need to be made for measuring water content of hydrate-bearing sediments with high salinity.

References
Fig 1. TDR waveform of low-salty sediments with traditional TDR probe

Fig 2. Sketch map of apparatus for water content measurement of marine sediments

Fig 3. TDR waveform using traditional TDR probe under different salinity
Fig 4. (a) traditional TDR probe; (b) Coated TDR probe

Fig 5. Comparison of waveforms measured by the traditional probe and the improved (coated) probe under different salinities.

Fig 6. Changes of TDR waveform during adding 3.5% NaCl solution to dry sands using coated probe.
Fig 7. Dielectric constant versus water content in 0.09-0.125mm sands under different salinity