

High Precision and Range of Concentration Measurement for Sediment-Water Mixture based on Time Domain Reflectometry

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Abstract—Concentration measurement of sediment-laden flow is crucial in studying river morphology, impact of climate change on sediment yield from watershed, reservoir sedimentation management, and ecological impact. Suspended sediment concentration (SSC) in above applications ranges from sub 1g/L (1000 ppm) in natural streams to over 500 g/L (500,000 ppm) in dredging production. Particle size dependency is also an issue on top of the challenge to meet such a wide measurement range for any measurement technique. Dielectric-based method is recently developed to overcome these challenges using time domain reflectometry (TDR) technique. This study aimed to enhance the measurement precision and range through an advanced signal processing technique and a rigorous frequency-dependent dielectric mixing model. Probe and material factors were investigated to rationalize the necessary calibration. Experiments on both the lower SSC range and high SSC range verify the excellent performance of TDR method for SSC measurements.

Keywords--TDR, dielectric, sediment, suspended sediment concentration

I. INTRODUCTION

Knowledge of sediment transport in bodies of water is important from both a scientific and economic perspective. The ability to monitor sediment concentration in bodies of water is crucial in river morphology, impact of climate change on sediment yield from watershed, reservoir sedimentation management, and ecological impact of sediments. The most direct approach for determining suspended sediment concentration (SSC) is through performing composition analysis on the acquired samples in the laboratory. Nevertheless, the difficulty and expense in measurements during flood events, where the major sediment transports take place, have constantly lowered the degree of understanding on the hydrological conditions of watershed and the potential influences on land management. Surrogate techniques for measurement of suspended sediment concentration have been reported, including optical backscatter, optical transmission, acoustic,

vibrating tube, spectral reflectance, laser diffraction, focused beam reflectance, differential pressure, nuclear, and so on. [1-3]. Field tests in riverine settings have been mainly focusing on using more commercial instruments based on four approaches, namely the laser optic, bulk optic (turbidity), pressure difference, and acoustic backscatter [2]. These different methods demonstrated varying confidence levels as the alternative for conventional data collection methods. Nonetheless, at least one of the following drawbacks was encountered by the aforementioned methods: (a) significant particle size dependency ; (b) limited measurement range; (c) high deployment cost and fragile instruments exposed in torrent regimes. In addition to characterizing the sediment transport in rivers and reservoirs, monitoring slurry (mixture of solid and liquid) concentration is also crucial in dredging, mining, tunnelling, and well servicing industries.

Sediment concentration in above applications ranges from sub 1g/L (1000 ppm) in natural streams to over 500 g/L (500,000 ppm) in slurry. In theory, dielectric methods hold a great potential to cover such a wide range of suspended solid concentration (also abbreviated as SSC). To the extreme of SSC measurements, TDR (time-domain reflectometry) technique arises as a successful method for the determination of soil water content. TDR method works through generating an electromagnetic pulse and transmitting it via a coaxial cable connected to a sensing waveguide, where the reflections from the transmission path are observed. These reflections are caused by the variations in characteristic impedance along the transmitted waveguide. Sensing waveguides designated for TDR method are typically simple in mechanical structure and durable with the absence of electronic components. The submerged sensing waveguide is rugged and can be economically replaced if damaged, as the component is remotely connected to a TDR pulser. Hence, it is suitable for measurements in harsh environment. For fully saturated soils, it can be considered as a two-phase material, similar to the

sediment suspension. Analogous to soil water content measurements, TDR has high potential measuring suspended sediment concentration theoretically. However, the measurement accuracy of soil moisture using TDR is approximately 1% volumetric water content, implying an accuracy of 27 g/L (27,000 ppm) for sediment concentration measurement, where the specific gravity of sediment is assumed to be 2.7. Typical SSC measurements would require a better accuracy of at least an order higher. The earliest attempt to adapt TDR for SSC measurements is documented in Chung and Lin (2011) [4], in which their measurement methodology optimized the measurement accuracy of SSC through the inclusion of temperature compensation, modified travel time analysis and system calibration, and proper probe design. A measurement precision about ± 2 g/L can be achieved using a trifilar waveguide (with balanced conductor configuration) and their data reduction method. The system calibration was conducted in the range within 130 g/L. Measurements in the state of slurry have not been reported.

This study focused on further enhancing the measurement precision and range of TDR method for SSC. To improve measurement precision and accuracy, a new coaxial probe and data reduction scheme are introduced. The performance in extremely high SSC conditions is also investigated under the new approach.

II. PROBE DESIGN AND DATA ANALYSIS

Deploying a multiple-rod waveguide in natural environment for SSC measurement would often encounter interference from foreign substances and trapped by the sensing rods, for example submerged woods, leaves, and plants in water. Even for measurement in a container, the positioning of the sensing waveguide need special attention to make sure no unwanted objects are within the sensing range. To mitigate the unwanted interference from foreign objects, a coaxial waveguide is proposed. Confining most of the electromagnetic field within a tubular outer conductor can also enhance the signal to noise ratio in the measured TDR waveforms. As depicted in Fig. 1, the innovative TDR waveguide is a coaxial type probe of 25 cm length. The inner rod and outer cylinder composed the necessary conductors for the sensing waveguide. The outer cylinder prevented the interfering objects while the perforated openings allowed flowing water to enter the sensing range at the central conductor. For a coaxial probe, a temperature sensor could be attached at the outer conductor at the center level of the sensing section. This enables getting more representative temperature reading for temperature compensation without interfering the TDR measurement.

Typical TDR step pulse input and its derivative are illustrated in Fig. 2. Two distinct reflections were yielded by impedance mismatches, which occurred at the beginning of the sensing section while the other from the end. In order to determine the precise and accurate round-trip travel time of the electromagnetic wave within the sensing section, this demands an accurate and consistent approach for pinpointing the reflection locations. Some even introduce an electrical marker near the probe head and calibrate the time offset (the difference

between real travel time and measured travel time starting from the electrical marker) and probe length altogether. This is done by measuring two mediums with known dielectric constants (such as air and water). Even if this is done carefully, dielectric permittivity is a variable depending on frequency. Stronger frequency dependency is caused by electrical conductivity and interfacial polarization at different frequency range. Although not so obvious, the dielectric permittivity of water is also frequency dependent within TDR bandwidth. In order to quantify SSC more precisely, a frequency domain approach is proposed here.

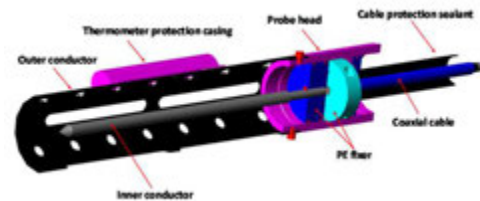


Fig. 1. Schematics of the innovative coaxial TDR SSC probe.

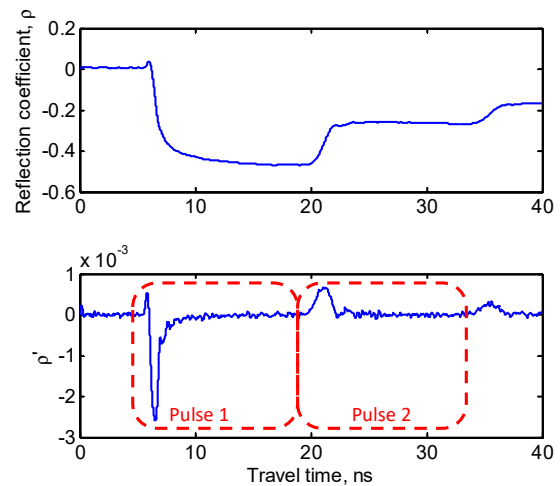


Fig. 2. Typical step-pulse waveform in a TDR SSC measurement, (b) the resulting derivative of the signal.

Lin (2003) [5] showed that the dipolar polarization of water is minimal below 2 GHz, while the electrical conductivity effect and interfacial polarization are negligible above 200 MHz. Within this optimal frequency range, the soil dielectric constant depends primarily on water content and it is also practically independent of particle size distribution or soil type. The dielectric permittivity will be determined explicitly within this frequency range using the newly-proposed phase velocity analysis (PVA) method [6]. Transforming the two extracted reflection pulses (as shown in Fig. 2b) into the frequency domain, the aforementioned PVA method determines the phase shift between the extracted pulses, while the apparent dielectric spectrum of the tested material is calculated from the phase velocity. This approach does not measure the complex dielectric permittivity (i.e., the real and imaginary parts of dielectric permittivity, $\epsilon^* = \epsilon' + j\epsilon''$), it yields the frequency-dependent

apparent dielectric permittivity, $\varepsilon_a(f)$, a combined effect of the real and imaginary parts at frequency f . It is determined by the phase shift between the two pulses as:

$$\sqrt{\varepsilon_a(f)} = \frac{c\Delta\varphi(f)}{4\pi fL} \quad (1)$$

where $\Delta\varphi(f)$ is the phase shift between the two pulses at frequency f , L is the length of probe, while c is the speed of light. A more rigorous dielectric mixing model will be derived to invert for the SSC value from the measured $\varepsilon_a(f)$.

Using the two-phase volumetric mixing model [7], the bulk dielectric permittivity of any sediment suspension is expressed as a function of SS by:

$$\sqrt{\varepsilon(f)} = (1 - SS)\sqrt{\varepsilon_w(f, T, EC_w)} + SS\sqrt{\varepsilon_{SS}} \quad (2)$$

where ε is the effective dielectric permittivity of the sediment suspension, SS is the SSC in terms of volumetric fraction that spans from 0 to 1, ε_w is the dielectric permittivity of water (a function of water temperature T and electrical conductivity EC_w), and ε_{SS} is the dielectric constant of the suspended sediment solid. ε_{SS} is reasonably assumed to be independent of temperature and frequencies. The dielectric constant of soil solid ranges narrowly from 3 ~ 9, subject to the mineral composition [8]. Rearranging Eq. (2), the desired SS can be written as:

$$SS = \frac{\sqrt{\varepsilon(f)} - \sqrt{\varepsilon_w(f, T, EC_w)}}{\sqrt{\varepsilon_{SS}} - \sqrt{\varepsilon_w(f, T, EC_w)}} \quad (3)$$

Alternatively SSC is often expressed as $ppm(mg/L)$,

$$ppm(mg/L) = \frac{SS \cdot G_s}{1 - SS} 10^6 \quad (4)$$

where G_s is the specific gravity of sediment and ranges from 2.6 ~ 2.8 generally. In Eq. (3), the SS can be determined if the water term ε_w is known. Dielectric property of water has been well studied. It can be described by the Cole-Cole function as [9]:

$$\varepsilon_w(f) = \varepsilon_{w\infty} + \frac{(\varepsilon_{w0} - \varepsilon_{w\infty})}{1 + j2\pi f\tau_{wr}} - j \frac{EC_w}{2\pi f\varepsilon_0} \quad (5)$$

where ε_{w0} and $\varepsilon_{w\infty}$ are dielectric permittivity at $f = 0$ and ∞ , respectively; ε_0 is the absolute dielectric permittivity of free space; τ_{wr} is the relaxation time. The $\varepsilon_{w\infty}$ is basically independent of temperature and salinity, for computational purpose it can be considered as a constant $\varepsilon_{w\infty} = 4.9$ [9]. ε_{w0} , τ_{wr} , and EC_w are generally functions of temperature and salinity. Only the fresh water environment was considered in this study. In this case, the effect of salinity on ε_{w0} and τ_{wr} are considered negligible. From the literature [10], the temperature-dependent ε_{w0} and τ_{wr} can be written as:

$$\varepsilon_{w0}(T) = 88.045 - 0.4147T + 6.295 \times 10^{-4}T^2 + 1.0710 \times 10^{-5}T^3 \quad (6)$$

$$2\pi\tau_{wr}(T) = 1.1109 \times 10^{-10} - 3.824 \times 10^{-12}T + 6.938 \times 10^{-14}T^2 - 5.096 \times 10^{-16}T^3 \quad (7)$$

In the higher frequency end of the TDR bandwidth (i.e., for frequencies higher than 200 MHz and lower than 1 GHz), the imaginary part of the complex dielectric permittivity can be ignored. Therefore, $\varepsilon(f) \approx \varepsilon_a(f)$ and $\varepsilon_w(f) \approx \varepsilon'_w(f)$, the real part of $\varepsilon_w(f)$. As a result, Eq.(3) becomes

$$SS = \frac{\sqrt{\varepsilon_a(f)} - \sqrt{\varepsilon'_w(f, T)}}{\sqrt{\varepsilon_{SS}} - \sqrt{\varepsilon'_w(f, T)}} \quad (8)$$

In summary, SS can be explicitly determined by Eq. (8). This is typically done for some frequency range (e.g., 200 MHz~300MHz) and taking the average. A mean value of ε_{SS} can be assumed for typical sediments. Thus, only the effective sensing section length, L in Eq. (1) is remained to be calibrated, where this can be easily done by performing a single measurement in clear water where $SS = 0$. For better accuracy, ε_{SS} can be treated as an additional calibration constant. This can be done with a single sample of known SS in the high SSC range, as will be elaborated in the following discussion.

III. EXPERIMENTAL RESULTS AND DISCUSSION

This TDR SSC measurement system is ready once the zero calibration intended for effective probe length at zero SSC is completed. In clear water, repeatable measurements show a precision better than 0.5 g/L (500 ppm). The precision can be improved by taking more waveform averaging. During a TDR based SSC measurement, TDR waveform and the concurrent water temperature are acquired simultaneously. TDR signals were acquired using TDR3000 device (Sympuls Aachen, Germany) while the temperatures were measured with PT100 thermometers. The TDR signal is reduced to $\varepsilon_a(f)$ using Eq. (1), while the water temperature is used to determine the real part of dielectric permittivity of water, $\varepsilon'_w(f)$, using Eq.(5)-(7). For measurements with a long leading cable, frequencies beyond 300 MHz may be filtered out. The frequency range from 200 MHz to 300 MHz often works well in most scenarios.

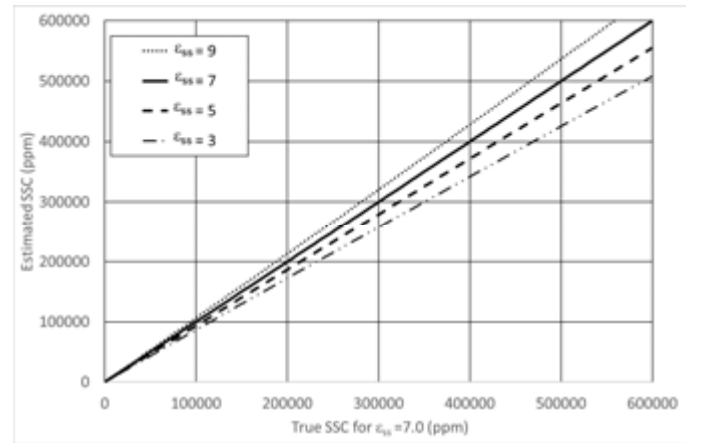


Fig. 3. The effect of ε_{SS} on the estimated SSC in ppm .

To finally calculate the SS value using Eq. (8), ε_{SS} needs to be assumed or calibrated. A simulation was performed to appraise the sensitivity of SS measurement to the ε_{SS} . For ε_{SS} taking the value from 3 to 9, the estimated ppm assuming a fixed value equal to 7.0 is shown in Fig. 3. If the actual ε_{SS} is the same as the assumed value for Eq. (8), the estimation in Fig. 3 will be on the 1:1 line. As the actual ε_{SS} deviates from the assumed value, the estimation deviates from the 1:1 line. In terms of SS , the deviation is perfectly linear as can be seen from Eq. (2). The deviation becomes slightly nonlinear after SS is transferred to

ppm through Eq. (4). The deviation grows faster as ppm increases. Nevertheless, the ϵ_{ss} can be practically and accurately calibrated using a single sample with known SSC in the medium to high SSC range (e.g., > 200,000 ppm).

TDR SSC measurements were performed on sediment suspensions for three sediments with known SSC, ranging from 0 to 150 g/L. The sediments were oven dried and weighted to determine the actual SSC values in ppm. Assuming a fixed value of ϵ_{ss} equal to 7.0, the estimated SSCs for the three types of sediments are shown in Fig. 4. One of the sediments is slightly off the 1:1 line, while the other two are basically on the 1:1 line. If the oven-dried SSC values were used to calibrate ϵ_{ss} for each sediment, $\epsilon_{ss} = 3.6, 6.9,$ and 7.5 were found for ground quartz, Chichi silt, and Shihmen clay, respectively. All of these values fall within the typical dielectric permittivity range for soil minerals. ϵ_{ss} of Shihmen clay and Chichi silt are both close to the assumed ϵ_{ss} , resulting in more accurate SSC estimation. The measured dielectric constant of ground quartz is quite close to the values reported in the literature [8], but significantly different from Chichi silt and Shihmen clay, due to the apparent mineralogy difference in silica compared to natural suspended sediments. This can clearly explain why the estimated SSC is slightly off the 1:1 line for ground quartz when the estimation is based on $\epsilon_{ss} = 7$.

The Chichi silt has similar ϵ_{ss} with the Shihmen clay, but shows significantly different particle size distribution. Nevertheless, the estimated SSCs are quite close regardless of the particle size distribution. The estimated SSC of ground quartz deviates from the 1:1 line by 14.0%, as its ϵ_{ss} is reduced by half ($\epsilon_{ss} = 3.6$ compared to 7.0). This 14.0% discrepancy from mineralogy may seem obvious in Fig. 4, however, this is rather insignificant considering the impact of particle size towards optical and acoustic instruments. While the particle size of sediments may vary considerably during a single runoff event, it is reasonably logical that the natural sediments would have insignificant temporal variation in their mineralogy within the same region. The dielectric constant of sediments could therefore be easily calibrated using a small number of direct SSC measurements with the oven-dried or pycnometer method. In the events of certain mineralogy variation over time, the dielectric constants of these minerals only spans over a narrow range from 3 ~ 9. The resulting error in SSC measurement attributable to mineralogy variation would still be limited within 15 %. This particle size invariance of TDR SSC measurement technique forms its major advantage over optical and acoustic methods.

Fig. 4 shows the possible SSC measurement range in rivers and reservoirs. We next turn our attention to the application in high SSC environment, such as in dredging production. We applied the proposed TDR method in two dredging projects, Zengwen reservoir and Nanhua reservoir. During the verification phase, a very high concentration samples from dredging was obtained and several TDR measurements were conducted by gradually diluting the samples with clear water. To benchmark the TDR measurements, the SSCs were also determined by weighting method using a pycnometer. Since SSC mixtures are essentially two-phase materials containing

water and suspended particles, by calibrating for the specific gravity of target sediment mixtures, SSC measurements from TDR PVA approach may be cross-checked with SSC measurements using pycnometer method. Assuming $\epsilon_{ss} = 7.0$ and $G_s=2.7$, the TDR SSC measurements are compared with pycnometer measurements in Fig. 5. The results do not fall onto the 1:1 line. However, a consistent different slope can be observed, 0.8089 for Nanhua reservoir and 0.7635 for Zengwen reservoir. The different slope can be explained by different ϵ_{ss} . The effect from bound water, water salinity, and different G_s may also contribute to some deviation from the 1:1 line. Nevertheless, this can be easily calibrated with a few samples in the high SSC end. For such high SSC range shown in Fig. 4, the TDR measured SSCs are quite accurate, considering the uncertainty in achieving fairly homogeneous condition for TDR and pycnometer measurements in dredged muds.

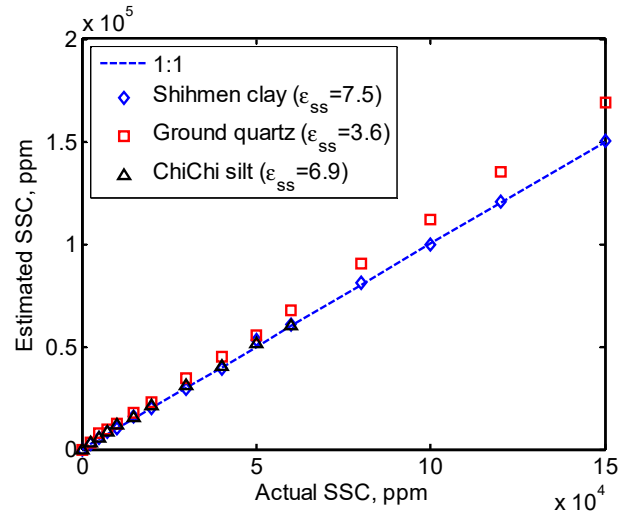


Fig. 4. Estimated SSC compared against actual SSC for ground quartz, Chichi silt, and Shihmen clay, assuming a fixed $\epsilon_{ss} = 7.0$ in Eq. (8).

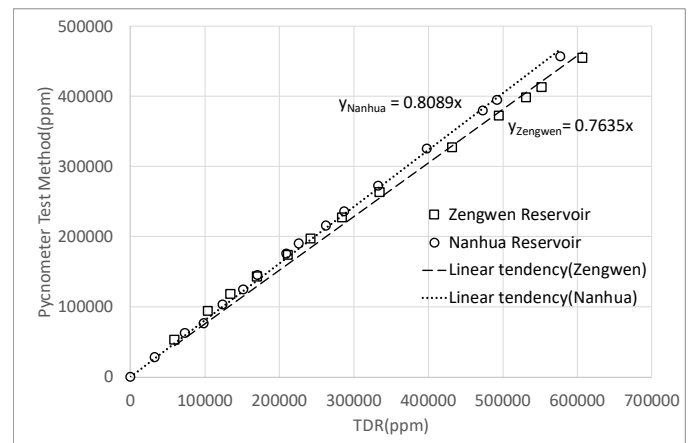


Fig. 5. The TDR measured SSCs in comparison with that measured by weighting using a pycnometer for samples from two dredging projects.

IV. CONCLUSIONS

Taking advantage of the phase velocity analysis (PVA)

method, the frequency-dependent dielectric permittivity can be explicitly and precisely measured. When combined with a rigorous frequency-dependent dielectric mixing model, the relationship between suspended sediment concentration and bulk dielectric permittivity can be established and the optimal frequency range can be utilized. The geometric factor (i.e., the probe length) can be easily and precisely calibrated in clear water and the material factor (i.e., the dielectric constant of sediment ϵ_{ss}) can be calibrated with a sample with known high SSC (e.g., >200,000 ppm). Experimental results show that the measurement resolution is better than 500 ppm and excellent accuracy can be achieved in the entire SSC range from 0 to 600,000 ppm. This study was conducted in fresh water environment. Further study is underway to adapt the proposed methodology for high conductivity environment.

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