

High concentration suspended sediment measurements using time domain reflectometry

Chih-Chung Chung^{a,*}, Chih-Ping Lin^b

^a Disaster Prevention and Water Environment Research Center, National Chiao Tung University, 1001 University Road, Hsinchu City, Taiwan

^b Department of Civil Engineering, National Chiao Tung University, 1001 University Road, Hsinchu City, Taiwan

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SUMMARY

The existing methods of suspended sediment concentration (SSC) monitoring provide a measurement accuracy significantly influenced by the particle size of suspended sediments, function only under limited measurement range and are not cost effective for field maintenance as well as wide spatial coverage. The paper introduces an innovative SSC monitoring methodology based upon time domain reflectometry (TDR), especially emphasizing on optimum TDR measurement accuracy investigated theoretically and experimentally. Pertinent probe design, probe calibration, as well as data reduction procedures were proposed. Ultimately, the approach can achieve the measurement accuracy to adapt the derived hardware resolution and beyond. In addition, the performance evaluation was carried out considering possible influence factors including water salinity, sediment types and particle sizes, and leading cable lengths. TDR SSC measurements indicate insensitive to sediment particle sizes. After proper calibration, the measurements are also insensitive to water electrical conductivity and not affected by leading cable resistances. There are further advantages of the TDR method including high measurement range from 2 to at least 300 g L⁻¹, easy calibration, robustness, maintainability, and cost-effective multiplexing.

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1. Introduction

The difficulty in quantifying sediment volumes transporting through natural streams has always impeded understandings of catchment hydrology and impacts on land management. Streams carry most of the total sediment transports during flood events, which often occur at night and are hard to predict. Although suspended sediment concentration (SSC) measurement by sediment sampling is the most direct approach, there is a considerable difficulty and expense for a full runoff event monitoring due to the large spatial and temporal variability associated with the suspended sediment transportation. Apparently, an automated surrogate measurement system is inevitable to estimate the discrete storm event loads. In general, the relation between instantaneous measurements of water discharge and suspended sediment concentration varies dramatically for such a purpose. Serious over- or under-estimating of loads using sediment rating curves have been observed particularly for short time-frames (Walling, 1977; Walling and Webb, 1981). Although bias-correction procedures can be applied, the substantial scatter evidenced by most rating relationships and complexities associated with hysteresis and exhaustion effects are considered to preclude any major

improvements under the reliability of rating curves (Walling and Webb, 1988). Methods are required to obtain more accurate load estimates for discrete storm events at reasonable costs.

Turbidity, although dependent on the sediment grain size and color (Sutherland et al., 2000), is a much better predictor than water discharge for estimating SSC. Continuous or near-continuous SSC data have been generated by recording turbidity meters (Walling, 1977; Lewis, 1996). Other surrogate techniques for SSC measurement have been reported, including acoustic, focused beam reflectance, laser diffraction, nuclear, optical transmission, and spectral reflectance (Wren et al., 2000; Campbell et al., 2005). However, these methods are subjected to the following limitations, at least one of them: (1) small measurement range; (2) strong particle-size dependency (Wren et al., 2000); (3) too expensive and delicate instruments in fluvial environment. Suspended sediment concentrations in runoff during large storms can be in excess of 10 g L⁻¹ or even 100 g L⁻¹, as increasingly encountered during Typhoon events in Taiwan since 2004. If SSC exceed the range of the continuous measurement device, information is lost during a critical sampling event. The continuous monitoring techniques most readily available as adequate commercial products are turbidity probes based on optical backscatter. However, most probes are suitable only for low SSC measurements (Campbell et al., 2005). Besides, optical and acoustic probes exhibit strong particle-size dependency. Site specific calibrations aimed to account for particle-size dependency can be extremely difficult

* Corresponding author. Tel.: +886 3 571 2121x55274; fax: +886 3 573 4116.

E-mail address: ccchung@mail.nctu.edu.tw (C.-C. Chung).

because the particle size of suspended sediments can vary drastically with water depth and flow velocity. Moreover, the main sensing components of existing instruments are packaged inside the probe for being submerged in water. These instruments are prone to damage during floods by speedy flows, rocks and debris entrapped. Furthermore, the instruments are often too expensive to deploy of wide spatial coverage.

Therefore, a continuous monitoring technique is yet to be developed that features high measurement range, easy calibration, robustness, good maintainability, as well as cost effectiveness for multiplexing. While searching for the potential technique, time domain reflectometry (TDR) stands out. TDR technique is based on transmitting an electromagnetic pulse through a coaxial cable connected to a sensing waveguide and watching for reflections of the transmission due to changes in characteristic impedance along the waveguide. Depending on the design of the waveguide and the analysis method, the reflected signal can be used to measure various engineering parameters, such as soil moisture content, electrical conductivity, water level, and displacement (Topp et al., 1980; O'Connor and Dowding, 1999; Robinson et al., 2003; Lin et al., 2007). Dissimilar to other techniques having a transducer with a built-in electronic sensor, TDR sensing waveguides are simple and durable mechanical device without any electronic components. When connected to a TDR pulser above water for measurement, the submerged TDR sensing waveguide is rugged and can be replaced economically if damaged. Multiple TDR sensing waveguides can be connected to a TDR pulser through a multiplexer and automated, hence increasing both temporal and spatial resolutions. In light of several advantages of TDR monitoring technique, this study was aimed to develop a TDR-based apparatus, including a data analysis method, for monitoring suspended sediment concentrations.

One of the major TDR applications is monitoring of volumetric water content of soils, which are generally three-phase materials. When saturated, soil is a two-phase material as is sediment suspension. Therefore, similar to measuring soil water content, TDR should be able to measure suspended sediment concentration in principle. However, the accuracy of TDR soil moisture measurement is about 1% volumetric water content, which is translated to 27 g L^{-1} (or 27,000 ppm) accuracy for sediment concentration measurement assuming specific gravity of sediment equal to 2.7. Better accuracy, at least an order higher, is required for typical SSC measurements. To adopt such a requirement, this paper introduces the methodology of SSC measurement based on TDR with special emphasis on optimizing measurement accuracy through theoretical and experimental investigations. The performance evaluation considering possible influence factors is also presented.

2. Theoretical background

2.1. Principles of TDR dielectric measurements

A TDR measurement installation is composed of a TDR device and a transmission line system. The TDR device generally consists of a pulse generator, a sampler, and an optional oscilloscope; the transmission line encompasses a leading coaxial cable and a sensing waveguide, as shown in Fig. 1. The pulse generator delivers an electromagnetic (EM) pulse along a transmission line, and the sampler is used to record returning reflections from the sensing waveguide. Reflections occur at impedance discontinuities along the transmission line; the reflected waveform depends on the impedance mismatches and electrical properties of materials in the transmission line system. TDR has been utilized since 1930s for cable fault locating. Over the last 20 years, TDR has evolved and become a valuable tool for measuring soil dielectric properties

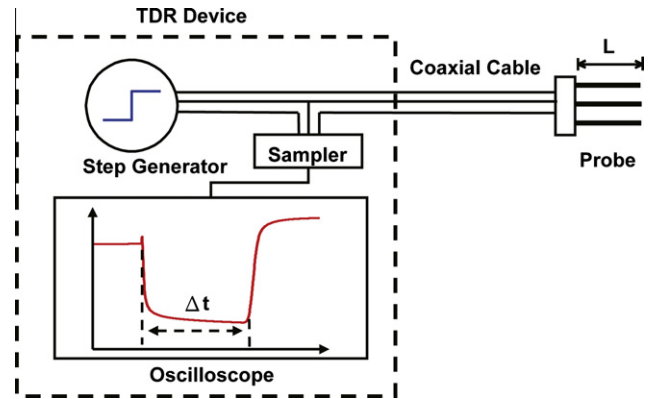


Fig. 1. Measurement configuration of time domain reflectometry (TDR).

and other materials as well (Topp et al., 1980; Feldman et al., 1996; Robinson et al., 2003).

As illustrated in Fig. 1, the step pulse is reflected at beginning and at end of a sensing waveguide. The travel time analysis of the two reflections can determine the apparent round-trip travel time (Δt [s]) of the EM pulse in the sensing waveguide of length (L [m]). Propagation velocity of the EM pulse depends on dielectric permittivity of the material surrounding the conductors. The dielectric permittivity is generally a function of frequency, but in the time domain the apparent dielectric constant (ϵ_a [–]) can be defined as (Topp et al., 1980)

$$\epsilon_a = \left(\frac{c}{V_a} \right)^2 = \left(\frac{c\Delta t}{2L} \right)^2 \quad (1)$$

where c is the velocity of light ($2.998 \times 10^8 \text{ [m s}^{-1}\text{]}$) and $V_a \text{ [m s}^{-1}\text{]}$ is the apparent velocity determined by the travel time analysis. The apparent dielectric constants of common materials are listed in Table 1. TDR can also be used to measure electrical conductivity (EC) from the long time steady-state voltage (Robinson et al., 2003). But besides sediment concentration, the EC of sediment suspension is highly dependent on water salinity. Therefore, the dielectric-based method is adopted in this study.

2.2. TDR travel time analyses

To precisely determine the apparent dielectric constant in Eq. (1), it requires a consistent, accurate approach for locating the reflection points. However, the precise location of the first reflection off the sensing section can be obscured by preceding reflections due to mismatches in the probe head. Heimovaara (1993) defined a selected characteristic point and denoted the round-trip travel time from the selected point to the end reflection as $\Delta\tau$ [s].

Table 1

The apparent dielectric constants of common materials (modified after Cheng, 1989).

Material	Apparent dielectric constant
Air	1
Water	78.54 ^a
Soil solid	3–9 ^b
Dry wood	1–2 ^c
Glass	4–10
Oil	2.3
Polyethylene	2.3
Rubber	2.3–4.0

^a Water temperature is 25 °C (Pepin et al., 1995).

^b Depending on its mineral composition (Robinson, 2004).

^c From Sahin and Ay (2004).

The time difference between the selected point and the actual start reflection point as t_0 [s], indicated in Fig. 2. An electrical marker can be used to generate a clear characteristic point, are also displayed in Fig. 2. The relationship between the measured travel time $\Delta\tau$ [s] and the actual travel time Δt [s] in the sensing waveguide can be written as

$$\Delta\tau = t_0 + \Delta t = t_0 + \frac{2L}{c}\sqrt{\epsilon_a} \quad (2)$$

in which the time offset t_0 and the probe length (or electrical length of the probe, to be precisely) L can be calibrated by taking measurements in air and water with known values of permittivity, as suggested by Heimovaara (1993). In this study, both the dual tangent line method (Fig. 2a) and the apex of the derivative method (Fig. 2b) were applied to compare and locate the end reflection in the travel time analysis. It should be addressed that, generally, in dispersive media, different values of system parameters (t_0 and L) can be obtained when different methods of travel time analyses are selected; the measured ϵ_a depends on electrical conductivities and cable lengths. Fortunately, the dielectric permittivity of water with sediment suspension is practically non-dispersive under the TDR frequency range (unpublished results of dielectric spectroscopy on sediment suspension from 1 MHz to 1 GHz). In this case, the measured ϵ_a was found not affected by EC, and the effects of cable lengths on ϵ_a can be accountable by adjusting the probe parameters (i.e. t_0 and L) using air–water calibration for each cable length (Chung and Lin, 2009).

2.3. Dielectric mixing model for TDR SSC measurements

A sediment suspension is mainly composed of water and soil solid. The apparent dielectric constant soil solid ϵ_s [–] is temperature independent and narrowly ranges from 3 to 9, depending on its mineral composition (Robinson, 2004). On the contrary, dielectric constant of water ϵ_w [–] is much higher and temperature dependent as indicated in (Pepin et al., 1995)

$$\begin{aligned} \epsilon_w(T) = & 78.54 \cdot (1 - 4.58 \times 10^{-3}(T - 25)) \\ & + 1.19 \times 10^{-5}(T - 25)^2 - 2.8 \times 10^{-8}(T - 25)^3 \end{aligned} \quad (3)$$

where T is the measured temperature in degree Celsius [°C]. It has been well documented that the dielectric constant is also a function of water salinity (Klein and Swift, 1977). But it is neglected in Eq. (3) because the effect of salinity on the dielectric constant of water is insignificant in our targeted fresh water environment where EC of water is lower than $1000 \mu\text{s cm}^{-1}$.

The bulk dielectric permittivity of suspended sediment can be expressed as a function of SSC by the volumetric mixing model (Dobson et al., 1985) as:

$$\sqrt{\epsilon_a} = (1 - SS)\sqrt{\epsilon_w(T)} + SS\sqrt{\epsilon_{ss}} \quad (4)$$

where ϵ_a is the bulk apparent dielectric constant of the sediment suspension; SS [–] is the SSC in terms of volume fraction, which ranges from zero to 1, and ϵ_{ss} [–] is the apparent dielectric constant of the suspended sediment solid. The assumption of two-phase medium is made in Eq. (4) and throughout the following derivation. Other liquid or solid mixtures and entrapped air are considered as sources of uncontrollable error. Once the $\epsilon_w(T)$ and ϵ_{ss} are known, the volume fraction SS can be determined from the measured apparent dielectric constant ϵ_a in the sediment suspension as

$$SS = \frac{\sqrt{\epsilon_a} - \sqrt{\epsilon_w(T)}}{\sqrt{\epsilon_{ss}} - \sqrt{\epsilon_w(T)}} \quad (5)$$

The volume fraction SS can be converted into ppm (or milligram per liter [mg L^{-1}]) unit, commonly used in hydraulic engineering, as:

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

in which the G_s [–] is the specific gravity of suspended sediment, typically ranges from 2.6 to 2.8.

3. Material and methods

3.1. Sensitivity-resolution analysis

SSC measurements require much higher resolution and accuracy than those of soil water content measurements. Sensitivity is first defined for resolution analysis to theoretically examine effects of acquisition and probe parameters as well as the limitation of TDR SSC measurements. The estimation of SSC by the TDR method relies on the measurement of the EM wave travel time in the TDR probe. Thus, the measurement sensitivity can be defined as the change of travel time due to a unit change of volumetric sediment content SS

$$\text{Measurement sensitivity} = \frac{\partial \Delta t}{\partial SS} = \frac{2L}{c} (\sqrt{\epsilon_{ss}} - \sqrt{\epsilon_w(T)}) \quad (7)$$

The measurement sensitivity of SSC is a function of apparent dielectric constants of water and suspended sediment, and more importantly the probe length L . It increases linearly with probe lengths. The resolution of TDR SSC measurement can then be defined as the relative SS change in response to a unit travel time change (i.e. sampling interval dt [s]). From Eq. (7), the resolution of TDR SSC measurement can be written as:

$$\text{Resolution} = \frac{dt}{\frac{2L}{c} (\sqrt{\epsilon_w(T)} - \sqrt{\epsilon_{ss}})} \quad (8)$$

The unit of the TDR SSC measurement resolution in Eq. (8) is volume fraction SS . It can be transferred into milligram per liter or ppm by Eq. (6). The measurement resolution is proportional to the sampling interval dt and inversely proportional to the probe

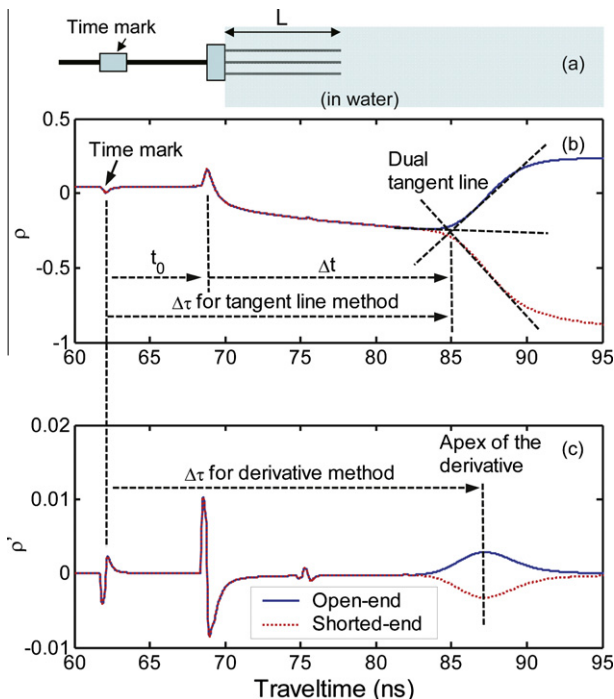


Fig. 2. (a) Schematic of TDR probe in water and definitions of travel time parameters for the dual tangent line method (b) and the derivative method (c).

length L . The sampling interval is limited by the TDR device and the length of probe that can be used is restrained by signal attenuation due to EC. To improve the resolution of SSC measurement, the sampling interval ought to be minimized and the probe length should be maximized.

In a TDR measurement, the recording time window is Ndt , where N is the number of recorded data points. All desired reflections of the TDR waveform should be contained in this recorded time window. For the purpose of TDR SSC measurement, the recording time window should be greater than the travel time of the probe in water. Take Campbell Scientific TDR100 device as an example, the required recorded travel time Ndt is defined as

$$Ndt \geq \text{constant} + \frac{2L}{c} \left(\sqrt{\varepsilon_w(T)} \right) \quad (9)$$

where the constant term represents time required before the start reflection and after the end reflection. The maximal N is 2048 and the shortest sampling time interval dt is 12.2 ps for the TDR100 device (Campbell Scientific, 2004). However, the shortest time interval that can be actually set increases as the probe length increases. Since the resolution is proportional to dt and inversely proportional L , the optimal resolution can be obtained from Eqs. (8) and (9). But, it should be noticed that the probe length can be limited by the signal attenuation due to EC of the suspension under measurement.

3.2. TDR probe design for SSC measurement

Since SSC measurement requires the highest possible accuracy than that of water content measurement in soil, special attention was introduced while designing the TDR SSC probes. A metallic shielding head was utilized to prevent leakage of electromagnetic waves. In addition, both balanced and unbalanced configurations of the conductors were tested to determine the best configuration for the TDR SSC probe. An electrical marker, as illustrated in Fig. 2, was constructed by connecting a splice connector whose impedance is apparently less than the cable impedance. The optimal

probe length and sampling interval can be determined by optimizing the resolution in Eq. (8) subjected to the data acquisition constraint in Eq. (9). Assuming $\varepsilon_w = 78.54$ (at 25 °C), $\varepsilon_{ss} = 4$, and the time constant equivalent to the travel time of 1 m cable in Eqs. (8) and (9), Fig. 3 presents the SSC measurement resolution as a function of the probe length L and sampling interval dt . The double shaded area in the upper left of the diagram illustrates the area satisfying the data acquisition constraint. The optimal SSC resolution lies in the lower boundary of the constraint. This optimal curve (the interface between the two shaded areas in Fig. 3) monotonically decreases with combined increments of L and dt . Thus, the longer the probe the better the measurement resolution, as long as the end reflection is strong enough to be detected.

3.3. Methodology: calibration, temperature correction, and measurements

To measure SSC, the dielectric constant of the sediment in Eq. (5) needs to be calibrated. In addition, temperature dependency of water dielectric constant should be considered for SSC measurement, since water is the major component in a sediment suspension. From Eqs. (2) and (5), the TDR travel time in a sediment suspension at certain temperatures can be rewritten as

$$\Delta\tau(T) = t_0 + \Delta t = t_0 + \left(\frac{2L}{c} \right) \left[\sqrt{\varepsilon_w(T)}(1 - SS) + \sqrt{\varepsilon_{ss}}(SS) \right] \quad (10)$$

The temperature-corrected method for TDR SSC measurement takes the following steps:

1. To calibrate the system parameters L and t_0 of the TDR sensing waveguide: Water and air are accessible and have known values of dielectric constants. The dielectric constant of air ε_a is 1; the dielectric constant of water ε_w can be expressed as Eq. (3). Hence, TDR travel time in air $\Delta\tau_a$ and TDR travel time in water $\Delta\tau_w$ can be expressed, respectively, as:

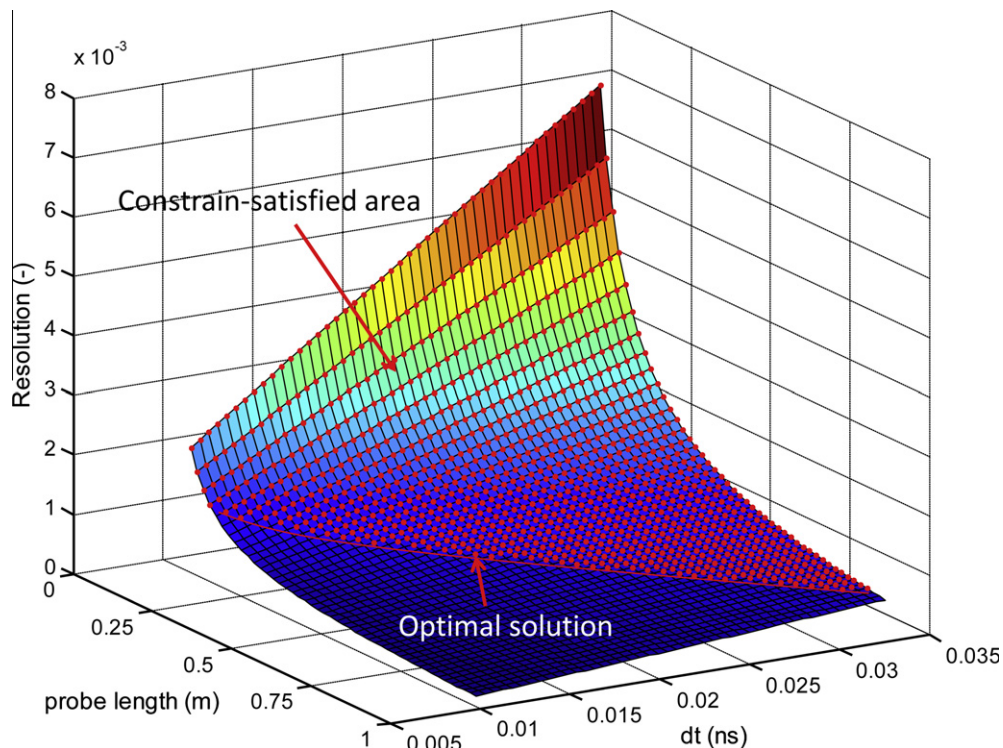


Fig. 3. Theoretical resolution of TDR SSC measurement as a function of sampling interval dt and probe length L , in which double shaded area are the area satisfying the data acquisition constraint.

$$\begin{cases} \Delta\tau_a = t_0 + \frac{2L}{c} \sqrt{\epsilon_a} \\ \Delta\tau_w = t_0 + \frac{2L}{c} \sqrt{\epsilon_w(T)} \end{cases} \quad (11)$$

Afterwards, L and t_0 can be solved by measuring the TDR travel times in air and in water with the water temperature.

- To calibrate the dielectric permittivity of suspended sediment ϵ_{ss} : Several sediment suspension samples with different and known concentrations are prepared, and TDR travel times $\Delta\tau$ and corresponding temperatures are measured. ϵ_{ss} is then calibrated using Eq. (10) by the least square method.
- To determine SSC: Once the system parameters L and t_0 and the dielectric permittivity of the suspended solid ϵ_{ss} are obtained after calibration, the TDR sensing waveguide and a temperature sensor can then be used to measure the TDR travel time $\Delta\tau$ and the temperature of the sediment suspension under testing, respectively. The volumetric sediment content can be calculated from Eq. (10) as

$$SS_{estimated} = \frac{(\Delta\tau(T) - t_0) - \frac{2L}{c} \sqrt{\epsilon_w(T)}}{\frac{2L}{c} (\sqrt{\epsilon_{ss}} - \sqrt{\epsilon_w(T)})} \quad (12)$$

Since the TDR travel time $\Delta\tau$ is a function of suspension temperature T , the SSC error resulted from measurement error of temperature can be determined analytically. Let $\Delta\tau_1$ be the TDR travel time corresponding to the actual temperature T and $\Delta\tau_2$ assigns to the erroneous temperature $T + \Delta T$, the resulting error in SSC can be determined from Eqs. (8) and (10):

$$SS \text{ error} = \frac{\Delta\tau_2 - \Delta\tau_1}{\text{Sensitivity}} = \frac{(1 - SS)(\sqrt{\epsilon_w(T + \Delta T)} - \sqrt{\epsilon_w(T)})}{(\sqrt{\epsilon_{ss}} - \sqrt{\epsilon_w(T)})} \quad (13)$$

Note that the SSC error, resulted from temperature error, is independent of probe lengths. Although it depends on SS, but SS value is a small number for typical applications of SSC monitoring. Assuming some typical values ($SS \cong 0$, $T = 25^\circ\text{C}$, and $\epsilon_{ss} = 4$), the error per 0.1°C (typical accuracy of commercial temperature sensors) is about 0.03% volumetric sediment concentration ($\cong 800$ ppm).

3.4. Influence factors and performance evaluations

To evaluate the performance of TDR SSC measurements, various influence factors, such as water salinity, sediment type, and cable length, are systematically examined. A Campbell Scientific TDR100 device with a SDMX50 multiplexer was used for the experimental evaluation. Several trial TDR probes, as illustrated in Fig. 4, were connected via 25 m CommScope QR320 cables to the SDMX50 multiplexer. A submerged temperature sensor with $\pm 0.1^\circ\text{C}$ accuracy was used to obtain the suspension temperature along with TDR measurements. All the probes indicated in Fig. 4 were made of metallic shielded heads. The selected trial probes have been considered to cover the differences in probe configuration (balanced vs. unbalanced), boundary condition (open end vs. shorted end), and probe length. U-shape probes were also evaluated to reduce the probe size while maintaining the desired sensing lengths. In addition, the smallest possible sampling interval dt was chosen for each probe to achieve the best resolution. Ten waveforms were repeatedly recorded for each measurement to estimate the standard deviation of measurements. Probe parameters (t_0 and L) for each probe were calibrated by the procedure introduced in the previous section. The waveforms were analyzed by both the dual tangent and the derivative methods as depicted in Fig. 2 for further comparisons.

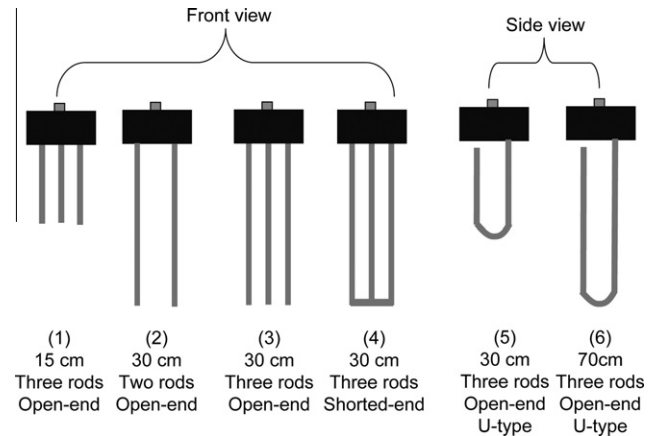


Fig. 4. Six types of the TDR probe for performance evaluation.

The first concern of the TDR method for SSC measurements is the effect of water salinity, which is the major problem of other electrical methods such as the resistivity method and capacitance method. The effect of water salinity on TDR SSC measurements is twofold, namely, the effect of water salinity on water dielectric constant and effect of electrical conductivity on apparent travel time. The former is neglected in Eq. (3) for fresh water environment and the latter depends on dielectric dispersion and method of travel time analysis. A feasible TDR probe and data reduction method should yield the same SSC regardless of the water salinity. The effect of water salinity was examined for each probe. Probes were immersed into clean water ($SS = 0$) with electrical conductivity varied from 5 to $650 \mu\text{S cm}^{-1}$. The SSC error and variation range, due to EC change, were examined for each probe. The probe with the lowest SSC error in clean water and least affected by EC was selected for further evaluations.

Three types of sediments were used for further experiments, including a clayey sediment ($G_s = 2.73$) from the Shihmen reservoir in Northern Taiwan, a sandy silt ($G_s = 2.71$) from the ChiChi weir in central Taiwan, and a man-made ground quartz ($G_s = 2.67$) grinded from glass materials. The particle size distributions of these three sediments are presented in Fig. 5. The particle size of the ground quartz was chosen such that its average particle size is close to that of ChiChi silt. Their major difference is in their mineral compositions, in which the ground quartz is mainly composed of silica while the mineral composition of ChiChi silt is diverse. Calibration tests for the TDR travel time–SSC rating curve were conducted on sediment suspensions with SSC varied from 0 to 150,000 ppm. The dielectric constant of each sediment ϵ_{ss} was backcalculated by regression analysis. For one of the sediment (ground quartz), having different leading cable lengths (2 m, 15 m, and 25 m), were used to evaluate the effect of cable resistance. For each cable length, the probe constants are individually calibrated before assessing measurements in sediment suspensions.

4. Results and discussions

4.1. Effect of water salinity: Implications on optimal probe type and data reduction

For measurements in clean water ($SS = 0$) with different salinities, the measured TDR travel time was transferred to SSC values by assuming $\epsilon_{ss} = 4$ in Eq. (12) and $G_s = 2.75$ in Eq. (6) for ppm conversion. The sampling resolution from Eq. (8) and SSC variation range due to salinity change are listed in Table 2. Close examination of the experimental data indicated that the SSC variation in

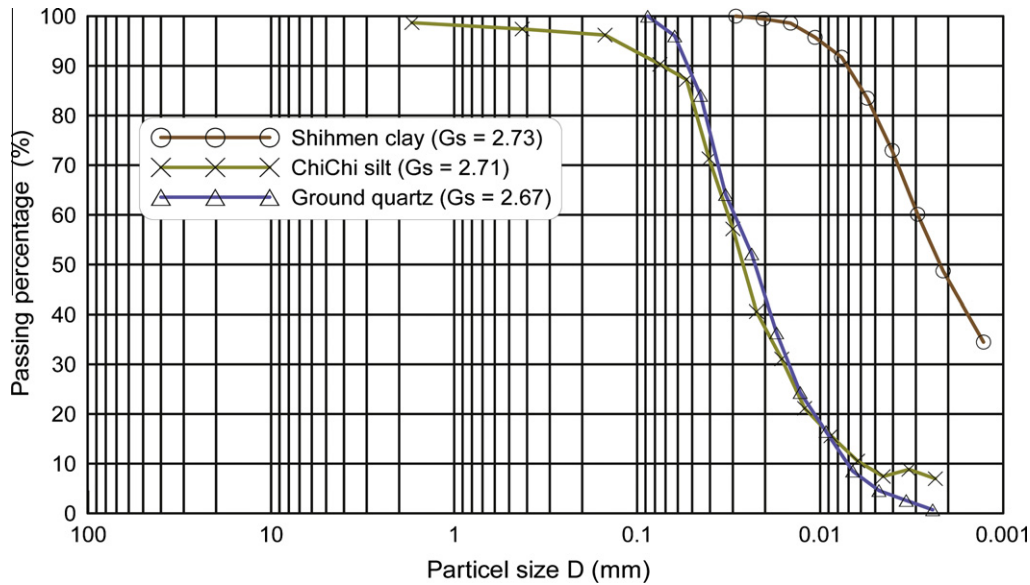


Fig. 5. Particle size distribution and specific gravity G_s of Shihmen clay, ChiChi silt, and ground quartz.

Table 2

Theoretical resolution and SSC derivation range in clean water of various salinities (Unit: ppm or mg L^{-1}).

Probe type (see Fig. 4)	(1) 15 cm three-rod open end	(2) 30 cm two-rod open end	(3) 30 cm three-rod open end	(4) 30 cm three-rod open end U-type	(5) 30 cm three-rod shorted end	(6) 70 cm three-rod open end U-type
Theoretical resolution	7000	3200	3200	3200	3200	2500
Deviation range by dual tangent method (deviation range/resolution)	29,700 (4.2)	27,000 (8.4)	12,000 (3.8)	22,000 (6.9)	11,000 (3.4)	7000 (2.8)
Deviation range by derivative method (deviation range/resolution)	14,700 (2.1)	16,800 (5.3)	5200 (1.6)	4600 (1.4)	7300 (2.3)	2100 (0.84)

Table 2 is mainly from repeatability error; there is no apparent trend between TDR measurements and the water salinity in all probe types and methods of the travel time analysis.

In terms of the data reduction method, the derivative method of travel time analysis performs significantly better than the dual tangent method. It has a better repeatability and smaller SSC variations from salinity changes than those of the dual tangent method. The derivative method is more advantageous over the dual tangent method because it has a clear mathematical definition and is easy to be automated. However, it is rarely used for TDR water content measurements because soils are dielectric dispersive in the TDR frequency range, and the effective frequency of the derivative method varies drastically with soil types. Chung and Lin (2009) demonstrated that the apparent dielectric constant (ϵ_a) of dispersive materials is affected by EC and cable lengths. However, in non-dispersive materials, ϵ_a becomes insensitive to EC, and the effects of cable length on ϵ_a can be accounted for by adjusting the probe parameters using air–water calibration for each cable length. According to measurements in sediment suspensions, the better performance can be attributed to the fact that the sediment suspension is not dispersive under TDR frequency ranges.

In the aspect of probe configuration, trifilar (three-rod) probes perform much better than bifilar (two-rod) ones. This has not been elaborated in the literature of TDR water content measurements, in which major comparisons between trifilar probes and bifilar probes were conducted regarding their spatial sampling ranges. Later experiments revealed that the performances of coaxial probes are equivalent to those of trifilar probes. This observation suggests the importance of balanced configuration for accurate

SSC measurements. The shorted-end probe does not clarify any improvement over the open-end one, implying that the probe boundary condition (or fringing effect) is not significant to affect the SSC measurements. However, the open-end probe is preferred when EC measurements are to be collected at the same time. The U-shape probe performs similarly as the straight one having the same sensing length. Hence, it can be used to shorten the probe length without reducing the sensing length.

For the same or similar theoretical resolution from Eq. (8), the accuracy seems to increase with probe lengths. After examining the measured waveforms, it revealed that the reflections from electrical marker or mismatch in the probe head may interfere with the end reflection for short probes, resulting in less satisfactory performance than the long probes. Hence, a pure and clear end reflection is essential and should be ensured by placing the electrical marker at an appropriate location relative to the probe lengths and minimizing reflections in the probe heads.

Among all the probes tested, the 70 cm U-shape probe with the derivative method of travel time analysis provides the most accurate measurements in clean water having various salinities. It was deployed for further investigations. Fig. 6 exhibits the mean values and error bars of the measured travel times (corrected to a common water temperature 25 °C) and corresponding SSC errors relative to the measurement in de-ionized water (with $\text{EC} = 5 \mu\text{S cm}^{-1}$). Although there seems to be a positive correlation with the water salinity, the mean error is less than 2100 ppm, better than the theoretical resolution due to interpolation in the travel time analysis. After repeated experiments, the results confirm that there is no obvious correlation between the measured SSC and water salinity for the EC range tested.

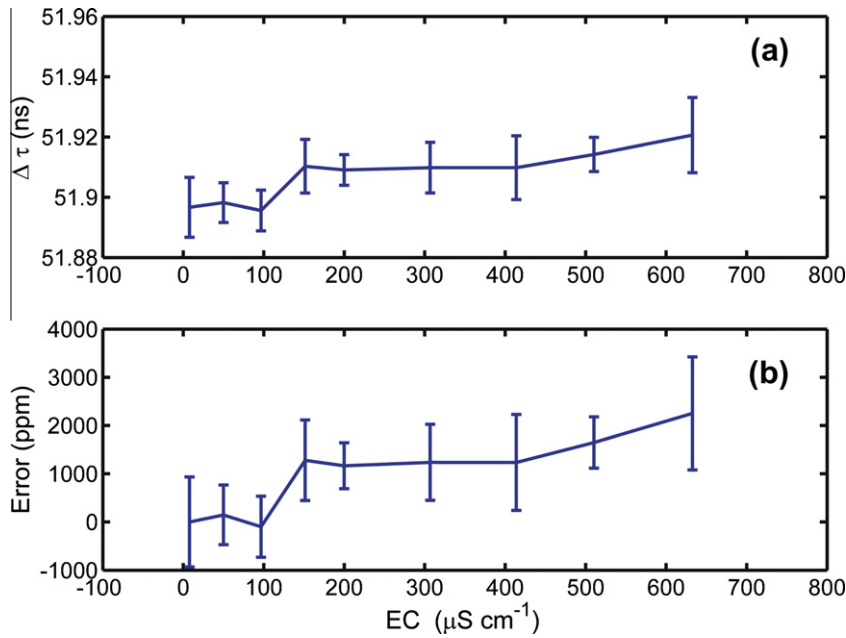


Fig. 6. (a) Mean values and error bars of the measured travel times (corrected to a common water temperature 25 °C) and (b) corresponding SSC errors relative to the measurement in de-ionized water (with EC = 5 μS cm⁻¹), using the 70 cm probe and the derivative method.

One Celsius degree change in water temperature was recorded during the experimental investigation. According to Eq. (13), this temperature difference could result in 8000 ppm error without temperature correction. The mean error in Fig. 6 is within 2000 ppm after temperature correction, validating the applicability of Eq. (10) for temperature correction. Moreover, it is noted that the maximum EC value in Fig. 6 is about 650 μS cm⁻¹. The reflected signal becomes too lossy when EC is much higher. In such a case, coating the conductor is recommended but is not investigated under the scope of this study. In addition, it is also worth noting that the effect of water salinity on water dielectric constant should be considered in Eq. (3) in highly saline condition (i.e. EC > 1000 μS cm⁻¹) or when significant variation of salinity (e.g. >500 μS cm⁻¹) may occur.

4.2. TDR travel time–SSC rating curve

The relationship for TDR travel time (Δτ) vs. SSC is theoretically derived as Eq. (12), and the relationship of Δτ vs. SSC (in SS unit) is linear and as a function of sediment dielectric constant at a constant temperature. Parameters not given or calibrated a priori in Eq. (12) include the dielectric constant of sediment (ε_{ss}) and temperature. To verify the relationship, Shihmen clayey sediments were first mixed in water with EC = 200 μS cm⁻¹ to make suspensions with SSC varying from 0 to 150,000 ppm for TDR measurements. To better visualize the relationship between Δτ and SSC shown in Fig. 7, the measured TDR travel times were temperature corrected to a common temperature T_{ref} = 25 °C by the following equation derived from Eq. (10).

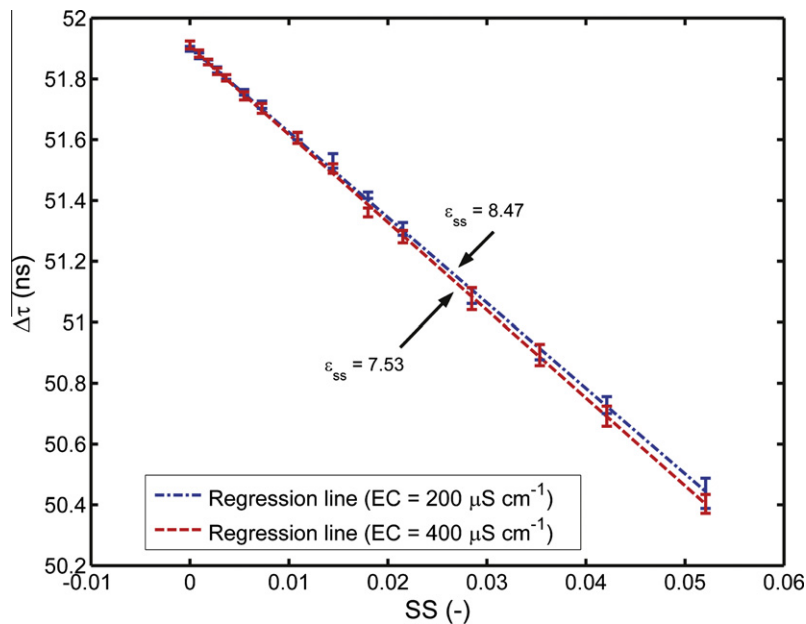


Fig. 7. Relationship between TDR travel time Δτ and SSC in volume fraction (Δτ–SSC rating curve) in background water of different salinities.

$$\Delta\tau(T_{ref}) = \Delta\tau(T) + \frac{2L}{c}(1 - SS) \left[\sqrt{\epsilon_w(T_{ref})} - \sqrt{\epsilon_w(T)} \right] \quad (14)$$

Fig. 7 clearly indicates a linear trend between $\Delta\tau(T_{ref})$ and SS in SS unit. According to Eq. (12), the slope of the $\Delta\tau$ -SSC rating curve is $\frac{2L}{c} [\sqrt{\epsilon_{SS}} - \sqrt{\epsilon_w(T_{ref})}]$. Linear regression yields sediment dielectric constant $\epsilon_{SS} = 8.47$, which is within the reasonable range of dielectric permittivity of clay minerals (Robinson, 2004). The TDR SSC measurement has been shown to be insensitive to water salinity in the case of clean water. To further verify whether water salinity affects the slope of the $\Delta\tau$ -SSC rating curve, the experiments were repeated for water salinity $EC = 400 \mu S cm^{-1}$. The results are also shown in Fig. 7. Two data sets are practically overlapped for

$SS \leq 1\%$, showing no significant effect of water salinity on the rating curve. For $SS > 1\%$, there seems to be a shift in the relationship, perhaps due to systematic error in sample preparation. Even using the full range data, the difference in the resulting slopes of the rating curves is less than 3%. Slightly different value of sediment dielectric constant ($\epsilon_{SS} = 7.53$) was obtained for water salinity $EC = 400 \mu S cm^{-1}$.

Although Fig. 7 shows SSC up to 150,000 ppm, much higher SSC (300,000 ppm) has been tested without problem. The upper bound of the TDR measurement range is theoretically unlimited, as long as the sediment suspension is not too conductive and the reflected signal can be clearly observed. If the sediment suspension is too

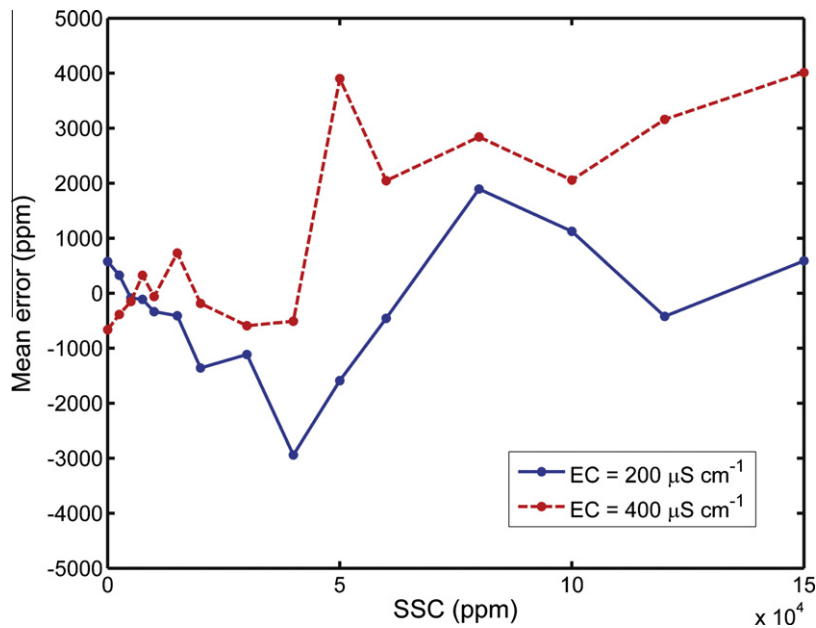


Fig. 8. Mean errors of TDR SSC measurements using the rating curve obtained from water salinity $EC = 200 \mu S cm^{-1}$.

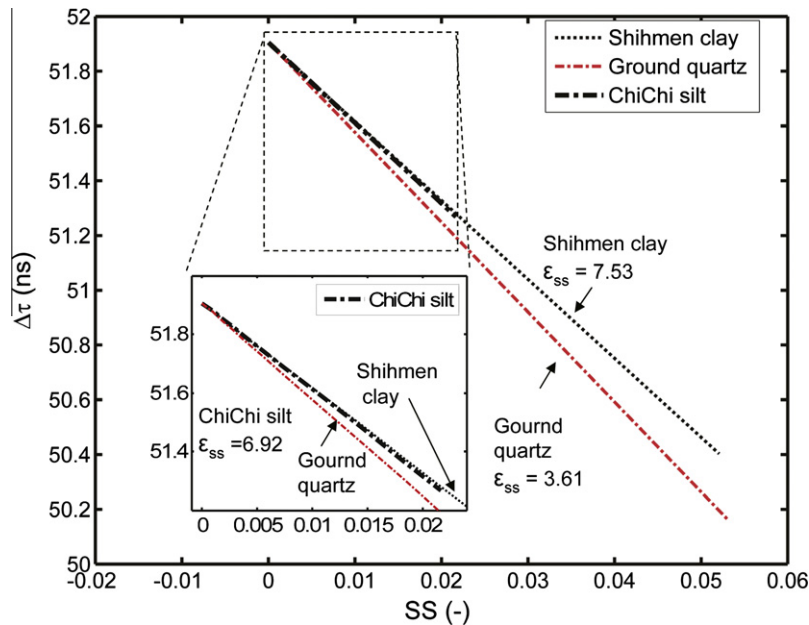


Fig. 9. The $\Delta\tau$ -SSC rating curves for Shihmen clay, ChiChi silt, and ground quartz.

conductive due to much higher concentration, coated conductors may be used to avoid signal loss and extend the measurement range. Using $\epsilon_{ss} = 8.47$ obtained in the first place, Fig. 8 shows the mean errors of TDR SSC measurements. For $SSC < 30,000$ ppm, the mean errors are within ± 2000 ppm, consistent with what was observed in Fig. 6. Except for larger errors at high SSC in the case of water salinity $EC = 400 \mu s cm^{-1}$, which were attributed to systematic errors in sample preparation, measurement accuracy is independent of measurement range. From the principle of TDR measurement, the accuracy is only limited by the timing resolution and accuracy of temperature compensation.

4.3. Effect of sediment type and particle size

Using water with $EC = 400 \mu s cm^{-1}$, the $\Delta\tau$ -SSC rating curves for the ground quartz and ChiChi silt were also performed to compare the obtained sediment dielectric constants. Due to limited samples, the highest SSC for ChiChi silt reached only 0.02 (50,000 ppm). Fig. 9 signifies the $\Delta\tau$ -SSC rating curves for the three types of sediments, whose grain size distributions are presented in Fig. 5. The rating curve of ChiChi silt nearly overlaps with that of Shihmen clay, showing no signs of particle size effect. However, the calibrated ϵ_{ss} of ground quartz is 3.61, apparently different

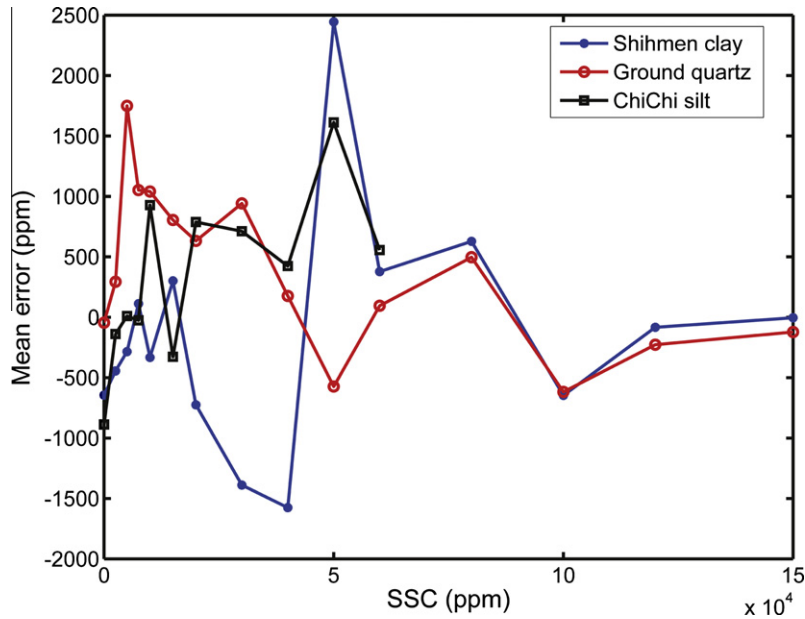


Fig. 10. Mean errors of TDR SSC measurements, in which ChiChi and Shihmen sediments use the same rating curve and that for ground quartz was individually calibrated.

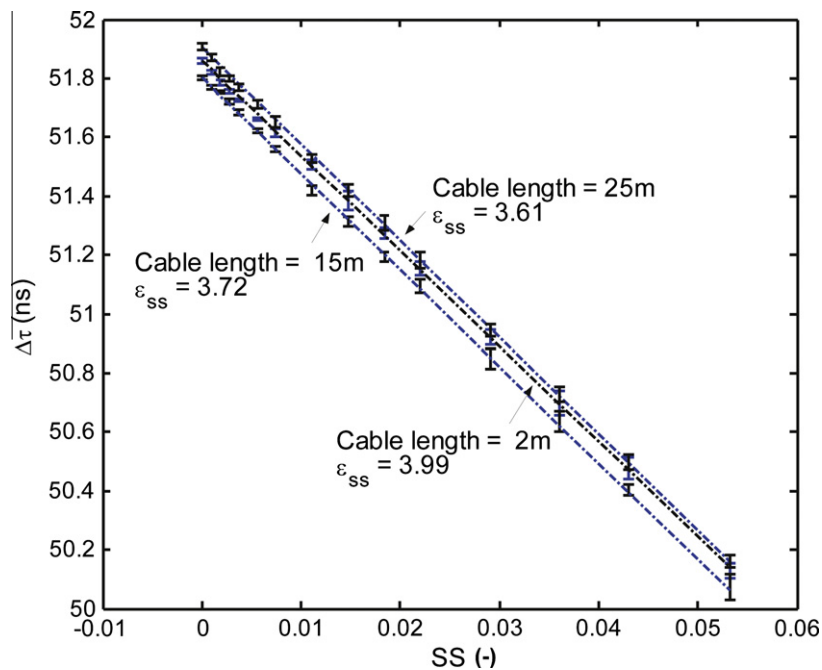


Fig. 11. The $\Delta\tau$ -SSC rating curves of ground quartz for three different lengths of leading cable.

from that of ChiChi silt and Shihmen clay, resulting in almost 14% difference in the slope of the $\Delta\tau$ -SSC rating curve. The obtained dielectric constant of ground quartz is quite close to that of quartz in the literature (Robinson, 2004). The different rating curve for ground quartz can be attributed to the apparently different mineralogy of silica from natural suspended sediments. Although this 14% discrepancy in the rating curve due to mineralogy may appear significant in Fig. 9, it is insignificant compared to the effect of particle size on optical and acoustic instruments, in which 100% and 800% difference was respectively observed for measurements between ChiChi silt and Shihmen Clay.

While sediment particle size can vary significantly during a run-off event, it is believed that the mineralogy of the natural sediments does not vary significantly with time. Therefore, the sediment dielectric constant can be easily calibrated with a few direct SSC measurements by sampling. Even if the mineralogy does vary, the dielectric constants of different minerals fall within a small range (from 3 to 9). The SSC error due to mineralogy will be bounded within 15%. A major advantage of TDR SSC method over optical and acoustic methods is its invariance to the particle size. Fig. 10 shows mean errors of TDR SSC measurements, in which ChiChi and Shihmen sediments use the same rating curve and that for ground quartz was individually calibrated. Once again, the mean errors are mostly within ± 2000 ppm.

In practice, other interferences, such as air bubble, algae, wood, and trash may exist in the flowing water. Other inclusions to the sediment suspension will result in overestimated SSC. To minimize the effect of these interferences, practical measures to avoid trapping debris on the measurement probe and periodic maintenance to remove fouling are recommended.

4.4. Effect of leading cable length

The $\Delta\tau$ -SSC rating curves for three different lengths of leading cable are shown in Fig. 11 for the ground quartz. Due to the effect of cable resistance, the travel times of the three cases at 0 ppm ($SS = 0$) are not the same. However, with individual calibration of the probe parameters (t_0 and L) under each case, slopes of the three $\Delta\tau$ -SSC rating curves are approximately parallel, and calibrated ϵ_{SS} remains similar ($\epsilon_{SS} = 3.61$ for 25 m cable, $\epsilon_{SS} = 3.72$ for 15 m cable, and $\epsilon_{SS} = 3.99$ for 2 m cable). These results illustrated that, although the cable length affects the TDR travel time $\Delta\tau$, the effect of cable resistance can be taken into account through calibration of system parameters (t_0 and L). Chung and Lin (2009) demonstrated that the TDR apparent dielectric constant of non-dispersive materials is not affected by EC and the effect of cable resistance can be accounted for by adjusting the probe parameters using air-water calibration for each cable length. The success of TDR method for SSC measurements independent of EC and cable length is attributed to the fact that the sediment suspension is not dispersive in the TDR frequency range, at least in the SSC range tested ($< 150,000$ ppm).

5. Conclusions

The existing techniques for suspended sediment concentration (SSC) monitoring, such as optical and acoustic methods, are sensitive to particle size or limited in measurement range. Furthermore, these techniques may not be cost effective for field monitoring due to the required maintenance and limited spatial coverage. To overcome these problems, an innovative SSC monitoring methodology based upon time domain reflectometry (TDR) has been proposed by taking advantages of TDR's unique features, e.g., wider measurement ranges; insensitive to particle size distribution; easy calibration; robustness; maintainability; as well as cost-effective

multiplexing. The major achievements of the study are summarized as follows:

1. Based upon the TDR water content measurement procedure, the TDR SSC methodology has been especially devised, enhanced to optimize the SSC measurement accuracy by including temperature compensation, pertinent probe design, and a different method of travel time analysis.
2. The theoretical resolution of TDR SSC measurements was determined as a function of probe length, sampling interval as well as the bounded number of data points via data acquisition of the TDR sampler. For TDR probe lengths between 30 cm and 70 cm and the TDR device often utilized for soil moisture measurements, the corresponding resolution of SSC measurement is approximately 3000 ppm.
3. The probe with the balanced configuration (e.g. trifilar or coaxial probes) was shown to perform exceedingly well over the unbalanced two-rod ones.
4. The derivative method of travel time analysis was found applicable in the case of sediment suspension. It possesses better repeatability compared with the dual tangent approach commonly used in soil measurements. As a result, it leads to better SSC accuracy being almost half of the theoretical resolution (± 2000 ppm) when the balanced probes are applied. The TDR method is good for high SSC measurement ranging from 2000 ppm to at least 300,000 ppm. The upper limit of TDR SSC measurements is theoretically unrestricted as long as the reflection signals can be clearly identified. Furthermore, measurement error is related to instrument resolution and does not increase with increasing SSC.
5. The water temperature affects TDR SSC measurements significantly. Every 0.1 °C change of water temperature induces 800 ppm differences in SSC measurements. The influence of temperature effect was formulated based on volumetric mixing model and validated experimentally.
6. The proposed TDR method for SSC measurements was shown to be insensitive to either electrical conductivity or sediment particle size compared with optical and acoustic methods. The effect of cable resistance on TDR measurements can be eliminated by calibrating the probe parameters accordingly. The calibration constant does depend on sediment mineralogy. However, the associated SSC errors are confined within 15% and can be further reduced by regional calibrations.

Field implementations including bank installation in waterways and floating station in reservoirs are underway to evaluate the field performance and investigate practical issues such as debris entrapment and fouling. The accuracy of TDR SSC measurements may also be further improved by upgrading the TDR sampling resolution as well as accuracy of temperature compensation in future studies.

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