

TDR 2006

Purdue University

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Ref.: Yu, Xianbu and Yu, Xiong, "Measurement of Simulated Scour by Time Domain Reflectometry", Proc. TDR 2006, Purdue University, West Lafayette, USA, Sept. 2006, Paper ID 5, 17 p., <https://engineering.purdue.edu/TDR/Papers>

Measurement of Simulated Scour by Time Domain Reflectometry

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Abstract

Scour contributes to most failures of highway bridges constructed over waterways in the United States. Sediments are washed away by floods and bridge piers are left inadequately supported. Field monitoring of bridge scour process is necessary to study the scour mechanism, to improve the bridge piers and abutments design, to plan an effective remediation measure, and to develop emergency warning systems. The current tools for bridge scour monitoring are generally not satisfactory for these purposes. This study introduces the development of an automatic scour monitoring system using Time Domain Reflectometry (TDR). The theoretical bases of TDR for scour detection are presented. A framework for TDR information analyses is developed. Tests were performed to simulate scour and sedimentation process. The acquired data were analyzed using the developed theory. From TDR measured apparent dielectric constant and electrical conductivity, the depth of scour and the properties of the sediments, such as the porosity and density, can be determined. The TDR instrument and analyses framework can be potentially refined into a very useful tool for bridge scour surveillance.

Key words Bridge scour, Time Domain Reflectometry, sediments, dielectric mixing formula

Introduction

The catastrophic collapse of the Schoharie Creek Bridge on the New York State Thruway in April 1987 during a near record flood, in which 10 people died, focused national attention on the bridge scour problem in the United States^[1]. Bridge scour or bridge sediments scour is the lowering of streambed around bridge piers or abutments. Bridge scour is the biggest cause of collapse of many bridges at service and a major factor contributing to high construction and maintain costs of bridges in United States.

Proper scour prediction is essential for an economical and safe design of bridge piers and abutments. The current design relies on the empirical scour prediction equations generated from laboratory data, which generally does not adequately predict the scour under field conditions. Collecting scour data from the field is important to improve the current scour prediction theory.

The data can also assist the implementation of remediation design and deployment of real time surveillance systems.

The current methods for field scour evaluation include yardstick, Ground Penetration Radar, Ultrasonic method, and fisher bulb etc. There are certain limitations of the existing methods for scour measurement. These include: “1) Most of these instruments are not sufficiently rugged for field applications. 2) Do not provide real time monitoring. 3) Systems are not automated and human involvements are needed.” (Yu and Zabilansky, 2006^[2])

Instruments based on TDR principle have been developed to monitor bridge scour to overcome these disadvantages. Dowding and Pierce (1994)^[3] developed a TDR scour detection system which can measure scour and footing displacement. However it is not reusable due to the sacrificial characteristics of the designed TDR probe. A TDR sensor made up of steel pipe was developed by Yankielun and Zabilansky (1999)^[4]. Field evaluation of the probe showed that this probe was sufficiently rugged to work under server conditions including flooding and icing. As the two steel pipes were electrically shorted at the ends, the information of electrical conductivity is lost, which could otherwise be utilized to obtain more information on the river conditions.

This paper presents the theoretical framework for analyzing the TDR signal to determine the scour condition and sediments status. Tests were preformed in this study to simulate the scour/sedimentation processes. TDR probe was installed in the simulation tank and signals acquired during the testing process. Preliminary data indicates that TDR accurately measures the scour depth, the density of sediment materials and the electrical conductivity of river water

Principles of Time Domain Reflectometry

TDR was originally used by electrical engineers to locate discontinuities in power and communication transmission lines (Ramo et al., 1965^[5]). Later on its application was extended to measure material dielectric and electrical properties. For Civil Engineering, the applications were extended to include soil water content measurement (Topp et al, 1980^[6]; Siddiqui et al., 1995^[7]; Siddiqui and Drnevich, 2000^[8], and Yu and Drnevich, 2004^[9]) and concrete strength evaluation (Yu and Drnevich et al. 2004^[10]). TDR is also utilized for various infrastructure applications including bridge scour monitoring (Dowding and Pierce, 1994^[3]; Yankielun and Zabilansky 1999^[4]) etc.

The configuration of a typical TDR system is shown in Figure 1. It generally includes a TDR device (pulse generator and sampler), a connection cable, and a measurement probe. The measurement probe is surrounded by materials whose properties are to be measured. TDR works by sending a fast rising step pulse or impulse to the measurement sensor and measuring the reflections due to the change of system geometry or material dielectric permittivity. The ability of TDR for scour monitoring lies in the large contrast between the dielectric constant of water (around 81) and that of the air (1) or sediment solids (the dielectric constant for dry solids is between 2-7; that of saturated solids varies depending on the degree of saturation). Because of the large contrast in the dielectric properties, reflections will take place at the interfaces between

material layers with different dielectric properties (including the air/water interface and the water/sediment interface).

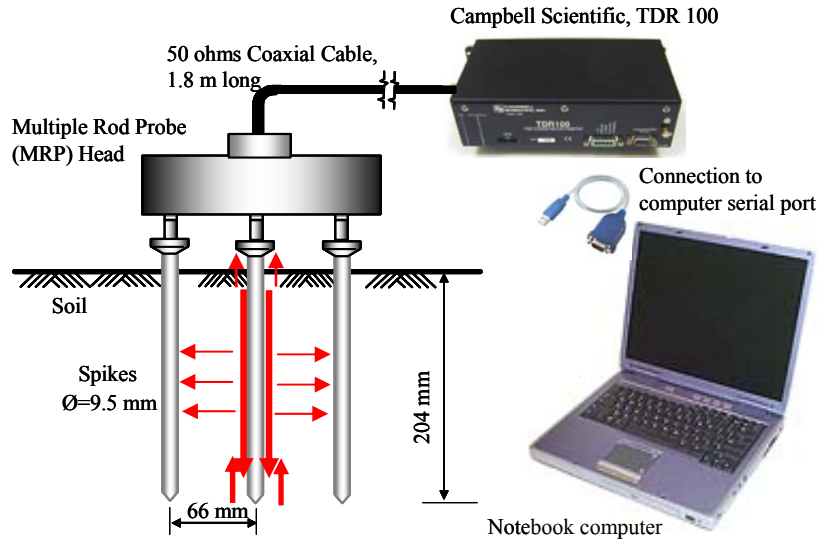


Figure 1. Schema of a typical TDR system

Figure 2. shows a typical measured TDR signal. By analyzing this signal, the material dielectric constant can be determined using equation (1); the electric conductivity can be determined from equation (2) (Yu and Drnevich, 2004^[9]).

$$K_a = \left(\frac{L_a}{L_p} \right)^2 \quad (1)$$

Where K_a is the measured dielectric constant; L_p is the physical length of probe in testing materials; L_a is the apparent length of probe in testing materials;

$$EC_b = \frac{1}{C} \left(\frac{V_s}{V_f} - 1 \right) \quad (2)$$

where EC_b is electrical conductivity, V_s is the source voltage which equals twice the step pulse; V_f is the long term voltage level; and C is a constant related to probe configuration, which can be obtained by calibration or from theoretical analyses. Schema of these parameters from a TDR signal is illustrated in Figure 2.

The TDR measured dielectric constant has been found to be strongly related to the water content of soils. Various empirical relationships have been established to describe the correlation, among these is Topp's Equation (equation 3, Topp et al., 1980^[6]). Equation 3 was developed in various types of cohesionless soils and is generally referred to as a "universal" equation. For study of saturated sediments, this relationship can be utilized to determine their physical properties.

$$\theta = 4.3 \times 10^{-6} K_a^3 - 5.5 \times 10^{-4} K_a^2 + 2.92 \times 10^{-2} K_a - 5.3 \times 10^{-2} \quad (3)$$

Where θ is volumetric water content defined as the ratio of the volume of water to the whole volume.

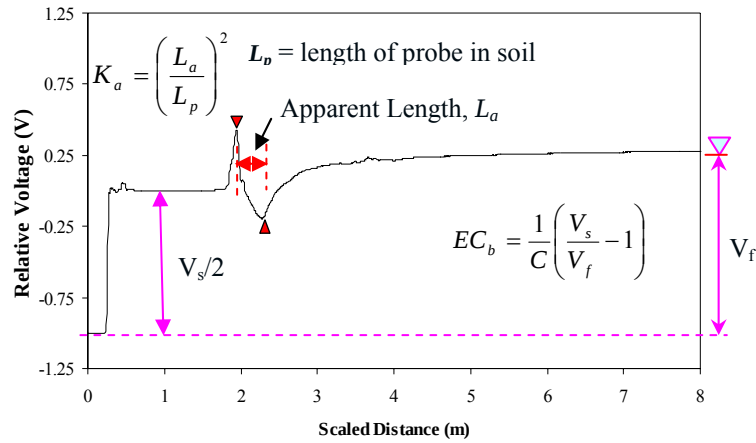


Figure 2. A typical TDR Output Signal

Laboratory Simulated Scour/Sedimentation Tests

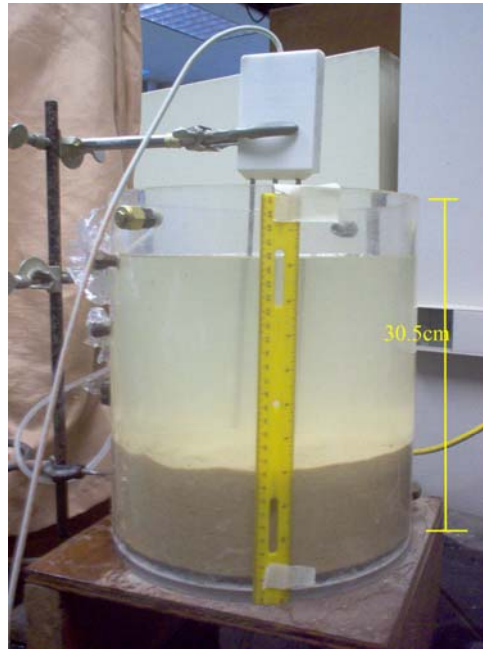


Figure 3. TDR probe and the experimental tank

The experiment setup for this study is shown in Figure 3. The simulated scour/sedimentation tests were conducted in a cylinder tank. TDR probe was installed with the aid of a fixture. The tank was first filled with water to a prescribed level. Dry sand was then gradually poured into the tank. In the meantime, the water level is maintained by draining appropriate amount of water through the base of the tank. At each specified sand layer thickness, the amount of sand placed for that layer was recorded from which the density of the sand layer can be calculated. In the meanwhile, TDR signals were acquired for each layer. This process proceeded until the sand

filled up to the surface of the water. Figure 4 shows the evolution of TDR signals during the experiment. The measured dielectric constant and electrical conductivity are shown in Figure 5. In order to simulate salty river water, tests were performed in water dissolved with 250ppm, 500ppm and 750ppm Sodium Chlorite (NaCl). A small cylinder container was used for these tests. The probe was completely submerged under water.

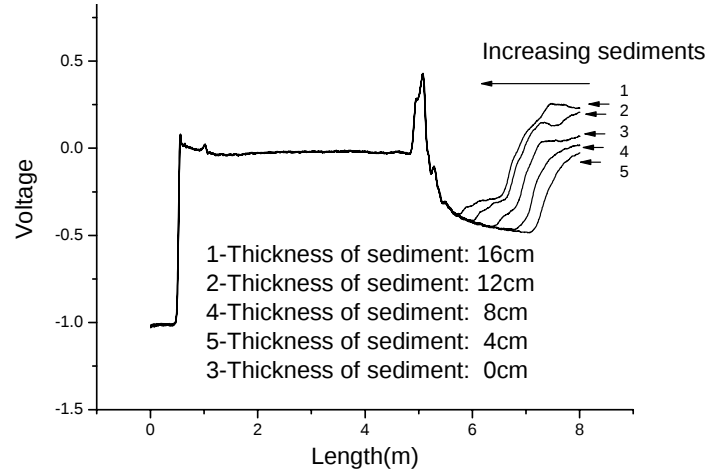


Figure 4. Example TDR signals variation with scour/sedimentation

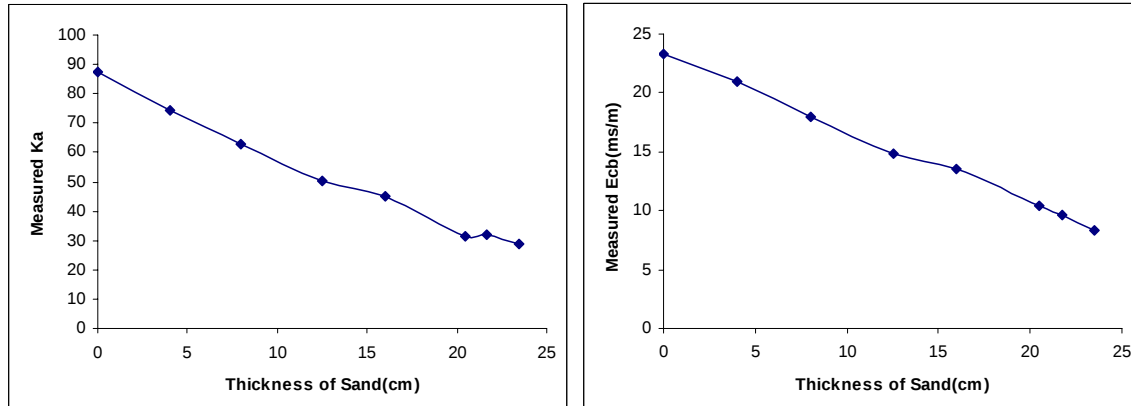


Figure 5. a) Measured K_a versus the thickness of sand deposit; b) Measured EC_b versus the thickness of sand deposit

Mixing Formula for the Dielectric Constant

Soil is a multiphase system composed of soil solids, water and air. Birchak et al. (1974^[11]) presented a semi-empirical volumetric mixing model (equation 4) to relate the bulk dielectric constant of a mixture to its components.

$$(K_m)^\alpha = \sum_{i=1}^n v_i (K_i)^\alpha \quad (4)$$

Where v_i and K_i are the volumetric fraction and permittivity (dielectric constant) of each component. The exponent α is an empirical constant that summarizes the geometry of the

medium with respect to the applied electric field. The value of $\alpha=0.5$ is suggested for homogenous and isotropic soils (Birchak et al., 1974^[11]; Ledieu et al., 1986^[12]).

Apply the mixing formula (equation 4) to layer consists of water and sediment, there is

$$L_1\sqrt{K_{a,w}} + L_2\sqrt{K_{a,bs}} = L\sqrt{K_{a,m}} \quad (5)$$

where $K_{a,w}$ is the dielectric constant of water; $K_{a,bs}$ is the dielectric constant of bulk sand(sand with water mixture); $K_{a,m}$ is the measured bulk dielectric constant; L_1 , L_2 and L are the thickness of water layer, sand layer and total thickness respectively (Figure 6).

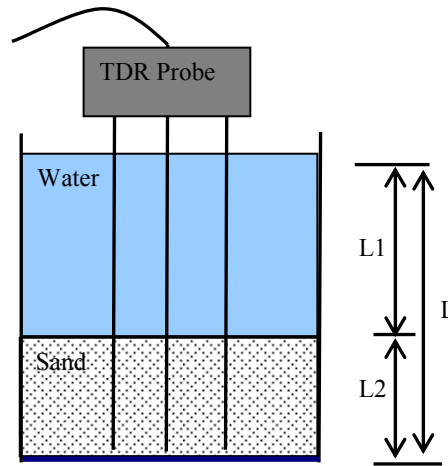


Figure 6. Schema of the simulated scour/sedimentation test setup

Let the thickness of sediment L_2 to be x , then the thickness of water layer L_1 is $L-x$. Substitute L_1 to equation (5) and normalize both sides of equation (5) by $\sqrt{K_{a,w}}$, the following equation (equation 6) can be obtained:

$$\frac{\sqrt{K_{a,m}}}{\sqrt{K_{a,w}}} = \frac{x}{L} \left(\frac{\sqrt{K_{a,bs}}}{\sqrt{K_{a,w}}} - 1 \right) + 1 \quad (6)$$

The equation indicates that square root of the measured bulk dielectric constant is linearly related to sediment thickness. The process of normalization also helps to reduce the potential effects of the measurements system. Figure 7 plots the $\sqrt{K_{a,m}} / \sqrt{K_{a,w}}$ versus sediment thickness from the measured data. Also shown in the plot is the data from theoretical predictions. For the predicted curve, the $\sqrt{K_{a,bs}}$ was estimated from Topp's equation and the density of sand layers from experimental records. The comparison shows that the mixing formula (equation 4) is valid for studying the layeriness during scour/sedimentation process.

The mixing formula equation (4) can also be applied to the saturated sediment:

$$n\sqrt{K_{a,w}} + (1-n)\sqrt{K_{a,s}} = \sqrt{K_{a,bs}} \quad (7)$$

Where $K_{a,bs}$ is the dielectric constant of the saturated sand layer; $EC_{b,w}$ is the water conductivity of the water layer; n is porosity and $K_{a,s}$ is dielectric constant of soil solid, typically in the range of 2-7 for soil solids (a value of 4 is used for $K_{a,s}$ in this study). From Equation (6), $K_{a,bs}$ can be solved as follows:

$$K_{a,bs} = \left(\frac{L}{x} \sqrt{K_{a,m}} - \frac{L-x}{x} \sqrt{K_{a,w}} \right)^2 \quad (8)$$

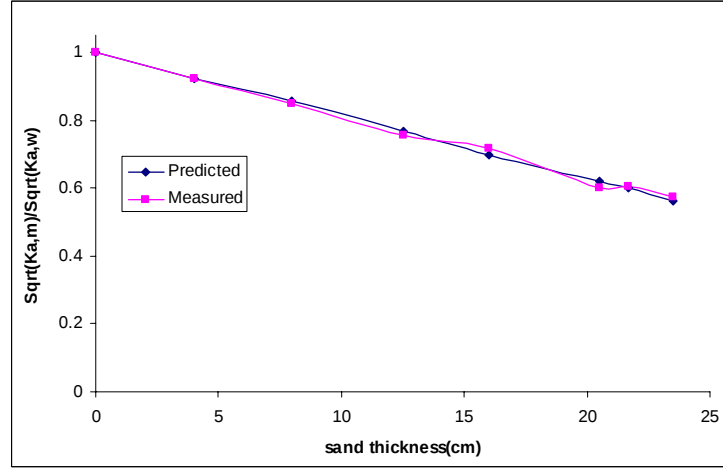


Figure 7. Measured and predicted relationship between $\sqrt{K_{a,m}} / \sqrt{K_{a,w}}$ and sediment thickness

By substituting the measured values from tests (L -total water and sediment thickness, x -sediment thickness, $K_{a,w}$ -measured dielectric constant of the water and $K_{a,m}$ -measured overall dielectric constant) and $K_{a,s}$, $K_{a,bs}$ can be obtained. $K_{a,bs}$ obtained from equations (7) and (8) are compared with values determined from Topp's equation (Figure 8).

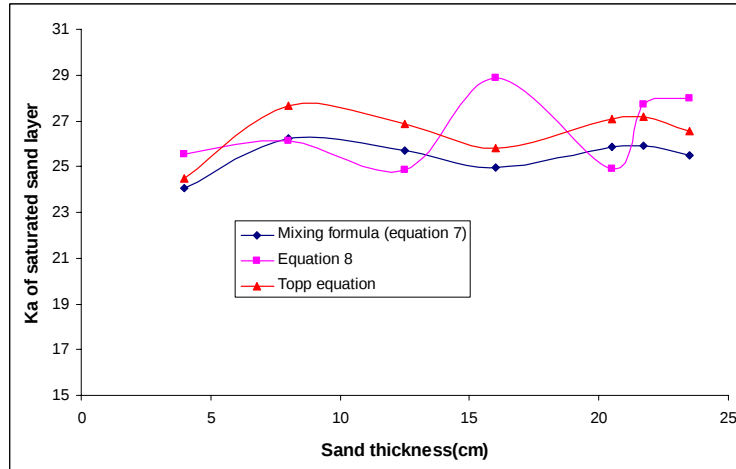


Figure 8. Estimation of K_a of saturated sediments from TDR measurements

From Figure 8, it can be seen that the dielectric constants of saturated sand obtained from equation (7) are closely related to that from Topp equation with an approximately same error at different points. Values determined from equation (8) are off the other two results at one point.

This might be caused by the inaccurate measurement of sediment thickness due to the uneven sediment surface. In general these three equations can be applied satisfactorily to obtain the dielectric constant of sediments. However, in most cases the porosity (volumetric water content) of sediment is unknown; it is convenient to use equation (8).

Mixing Formula for the Electrical Conductivity

The resistance of a hollow cylinder made of homogeneous material is related to the electrical conductivity of its material and its geometry by equation (9) (Ramo and Whinney, 1965^[13]):

$$R = \frac{1}{2\pi L \sigma} \ln\left(\frac{b}{a}\right) \quad (9)$$

Where a and b are the inner diameter and outer diameter of the cylinder respectively, L is the length of the cylinder, σ is the electrical conductivity of the material.

For a cylinder made of n different layers, each layer can be treated as a resistor. These resistors are connected in parallel. The total resistance can be calculated using the electrical circuit principle:

$$\frac{1}{R} = \sum_{i=1}^n \frac{1}{R_i} \quad (10)$$

Substitute equation (9) into equation (10), there is

$$\frac{2\pi L \sigma}{\ln\left(\frac{b}{a}\right)} = \sum_{i=1}^n \frac{2\pi L_i \sigma_i}{\ln\left(\frac{b}{a}\right)} \quad (11)$$

The bulk electrical conductivity is thus related to the electrical conductivity of each layer by equation (11), which can be regarded as a mixing formula for the electrical conductivity.

$$\sigma = \frac{1}{L} \sum_{i=1}^n L_i \sigma_i \quad (12)$$

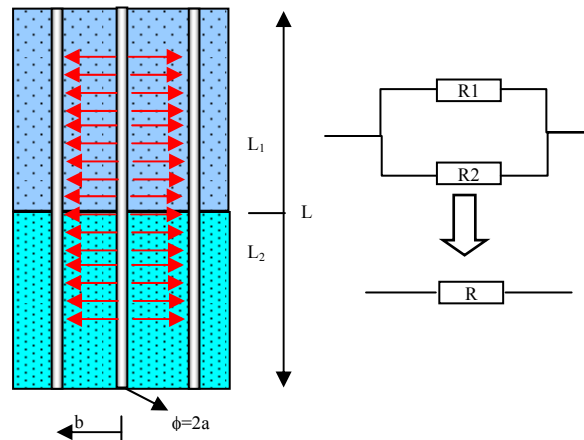


Figure 9. Schema of TDR electric field distribution for deducing the mixing formula for electrical conductivity

For a two-layered system made of water and saturated sediment, the mixing formula for electrical conductivity can be written as:

$$EC_{b,w}L_1 + EC_{b,bs}L_2 = EC_{b,m}L \quad (13)$$

where $EC_{b,w}$ is the electrical conductivity of water; $EC_{b,bs}$ is the electrical conductivity of sand layer (sediment); $EC_{b,m}$ is the measured overall electrical conductivity; L_1 is the thickness of water and L_2 is the thickness of sediment; L is the total water and sediment thickness. Equation 13 can be normalized by dividing both sides by $\sqrt{EC_{b,w}}$, i.e.:

$$\frac{EC_{b,m}}{EC_{b,w}} = \left(\frac{EC_{b,bs}}{EC_{b,w}} - 1 \right) \frac{x}{L} + 1 \quad (14)$$

Archie (1942^[14]) introduced the concept of formation factor F as the ratio between the conductivity of pore fluid σ_1 and the measured soil conductivity σ_m in a direct current (DC) or low frequency alternating current (AC) field.

$$F = \frac{\sigma_1}{\sigma_m} \quad (15)$$

Formation factor F can be related to the porosity, n , of the material by the equation presented by Arulandan and Sybico (1992)^[14].

$$F = n^{-f} \quad (16)$$

where f is form factor, a value of 1.2 for f was recommended for Nevada sand. From equation (15) and (16), there is:

$$\frac{EC_{b,bs}}{EC_{b,w}} = \frac{1}{F} = n^f \quad (17)$$

Substitute (17) to Equation (14)

$$\frac{EC_{b,m}}{EC_{b,w}} = (n^f - 1) \frac{x}{L} + 1 \quad (18)$$

Equation (18) shows the measured electric conductivity normalized by the electric conductivity of water is approximately linearly related to the sediment thickness. Figure 10 is a plot that validates this observation. Also show in the plot is the theoretically predicted relationship directly from equation (18). The porosity n of sand was obtained from experimental data. A f value of 1.2 was used. The comparison indicates that the mixing formula for the electrical conductivity of sediment system is valid.

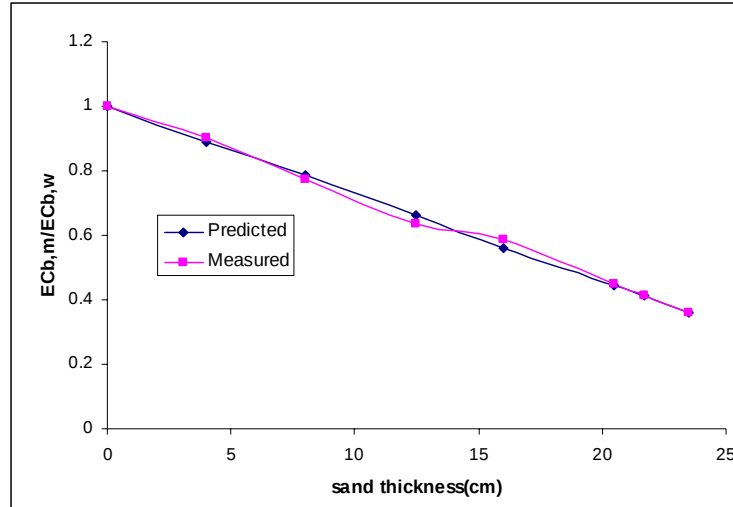


Figure 10. Measured and predicted relationship between $EC_{b,m}/EC_{b,w}$ and sediment thickness

Estimation of the Electrical Conductivity of Water

The electrical conductivity of water $EC_{b,w}$ can be obtained from Equation (18)

$$EC_{b,w} = \frac{EC_{b,m}}{n^f \frac{x}{L} + \frac{L-x}{L}} \quad (19)$$

Porosity n , sediment thickness x and total water and sediment thickness can be calculated from measurements or directly from measurements. Substituting these parameters to equation 19, the electrical conductivity of water can be determined. Results of calculation are compared with actual measurement as shown in Figure 11. It shows that the estimation of the electrical conductivity of water is reasonably accurate.

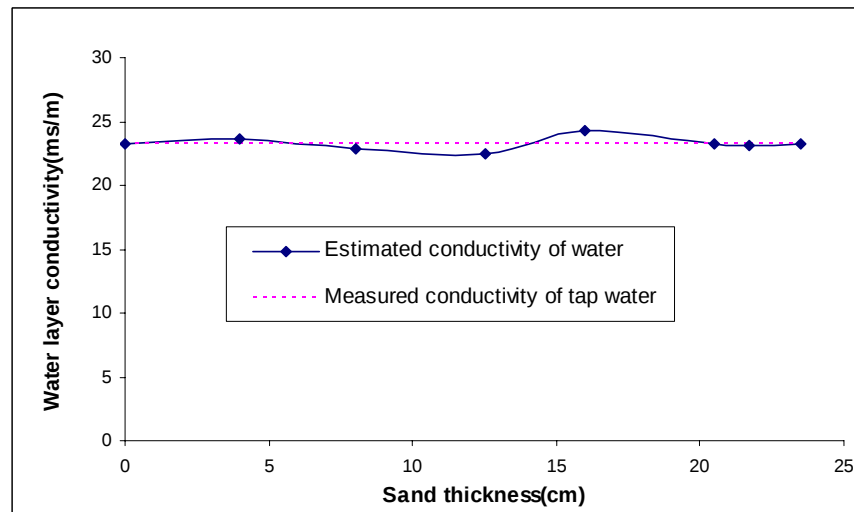


Figure 11. TDR estimated electrical conductivity of water versus the actual values

Simulated Experiments Considering the Variation of Electrical Conductivity of Water

Under the field situations, the electrical conductivity of water in the rivers might vary over time. This may be caused by the chemical pollution or other dissolved minerals. Experiments were conducted to investigate the potential influence of river water variation on TDR scour monitoring. Simulated scour tests were performed with water dissolved with Sodium Chlorite at concentrations of 250ppm, 500ppm and 750ppm.

The dielectric constant of water was found not significantly influenced by its electrical conductivity as shown in Figure 12.

The test results for dielectric constant and electrical conductivity are summarized in Figure 13 and 14 respectively. The plots show that most measurement data falls on similar trend after being normalized. Since the dielectric constant is not strongly influenced by the electrical conductivity of river water, it can be used as reference to estimate the scour thickness. Subsequently, the electrical conductivity of river water can be estimated. The idea is summarized to generate the design plot and application procedures as will be discussed below.

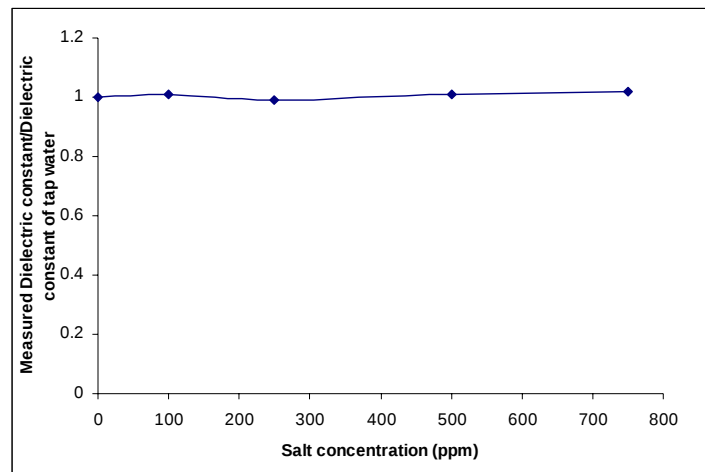


Figure 12. Dielectric constant of water at different salt concentrations normalized by tap water

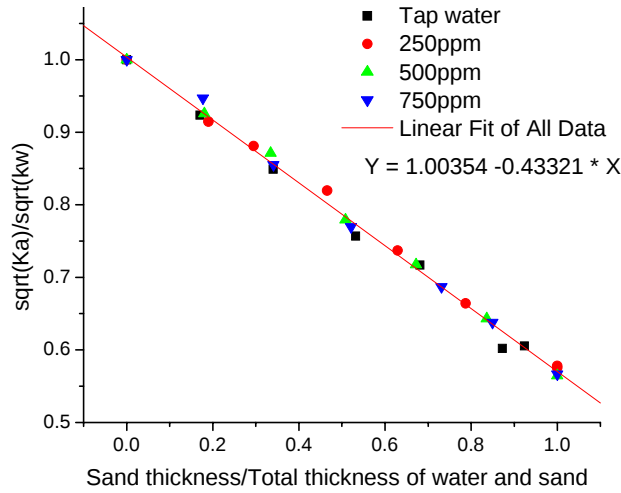


Figure 13. Measured $\sqrt{K_a}$ of sediment system normalized by that of water versus the normalized sediment thickness

Design Plot and Procedures for Application in Bridge Scour Monitoring

Two general linear equations were obtained by fitting the experimental data as shown in Figure 13 and 14, i.e.,

$$\frac{\sqrt{K_{a,m}}}{\sqrt{K_{a,w}}} = -0.43x_r + 1 \quad (20)$$

$$\frac{EC_{b,m}}{EC_{b,w}} = -0.67x_r + 1 \quad (21)$$

where x_r is the ratio of sand thickness to the total thickness of water and sand. The other symbols are the same as mentioned above.

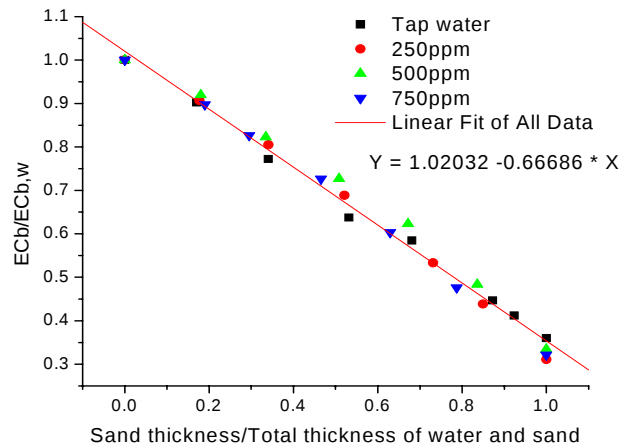


Figure 14. Measured EC_b of sediment system normalized by that of water versus the normalized sediment thickness

By using these equations and referring to the fact that the dielectric constant of water is approximately constant (81), the following procedures were designed to obtain the information on scour status:

- 1) Determine the scour depth, x , from measured bulk dielectric constant $K_{a,m}$ using (step a) ;
- 2) Determine the electrical conductivity of river water, $EC_{b,w}$, from the obtained scour depth and the measured bulk electrical conductivity (step b);
- 3) From the estimated scour depth, determine the dielectric constant of sediments by equation (8); from this determine water content of sediment and its density (step c).

A schematic plot of applying these two design equation is also shown in Figure 15. Figure 16 and 17 show the results of calculated sand layer thickness and electrical conductivity of river water using the reference curves and following the application procedures. All closely matches the values from the actual measurements. Both results are typically within around 5% error range. The dry density of sediments is determined from step c, which is shown in

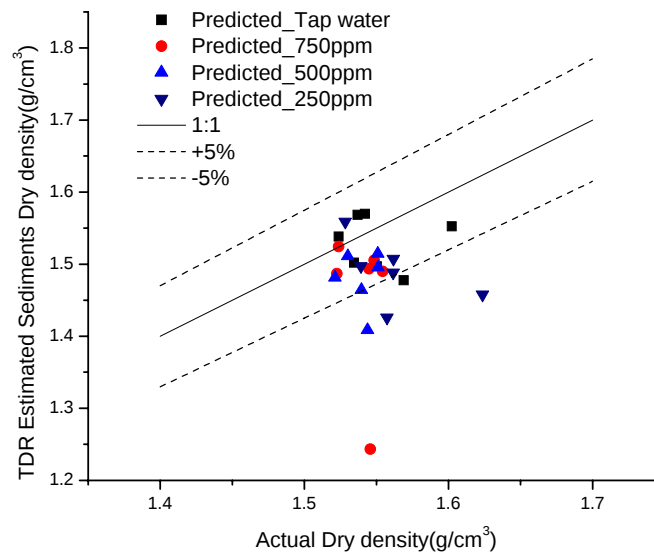


Figure 18. The results are typically satisfactory with the exception of a few points which correspond to the cases with very short probe embedment depth in the sediments.

The results indicate that TDR can accurately determine the scour condition and sediments status from the TDR measured apparent dielectric constant and electrical conductivity. Besides, this method normalizes the effects of the electrical conductivity of river water. Therefore, it can be applied to various river conditions. The estimated electrical conductivity of river water can also

be used as an environmental quality indicator for contaminant detection. Potential application in this aspect will be further explored.

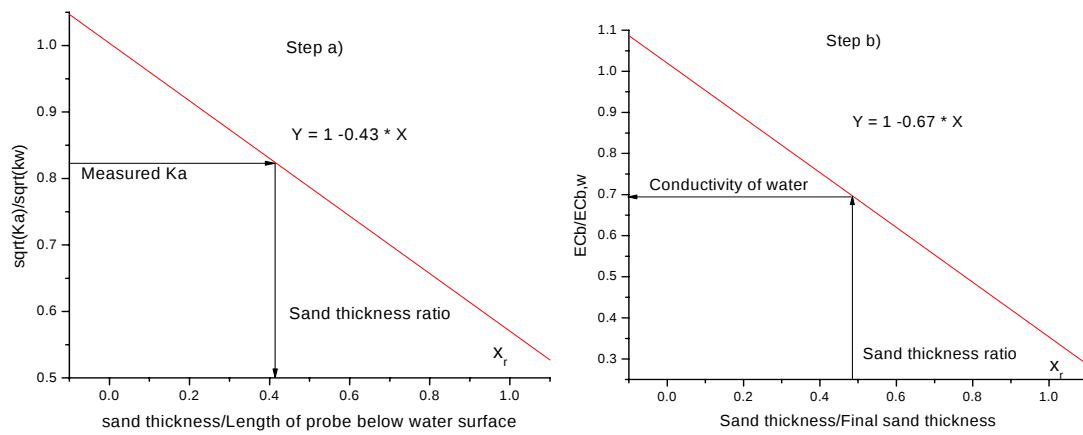


Figure 15. Design diagram for determining the sediment thickness and water conductivity

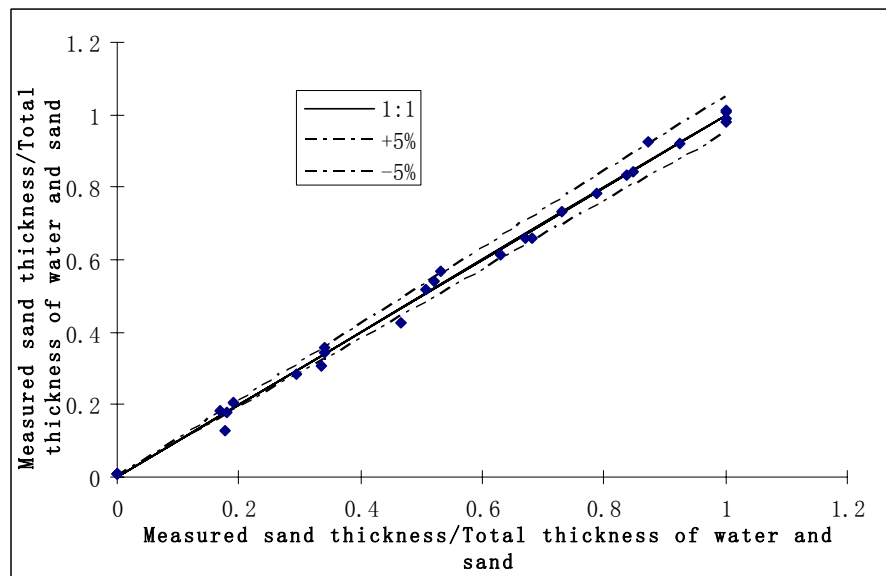


Figure 16. TDR estimated depth of sediment versus the actual sediments thickness

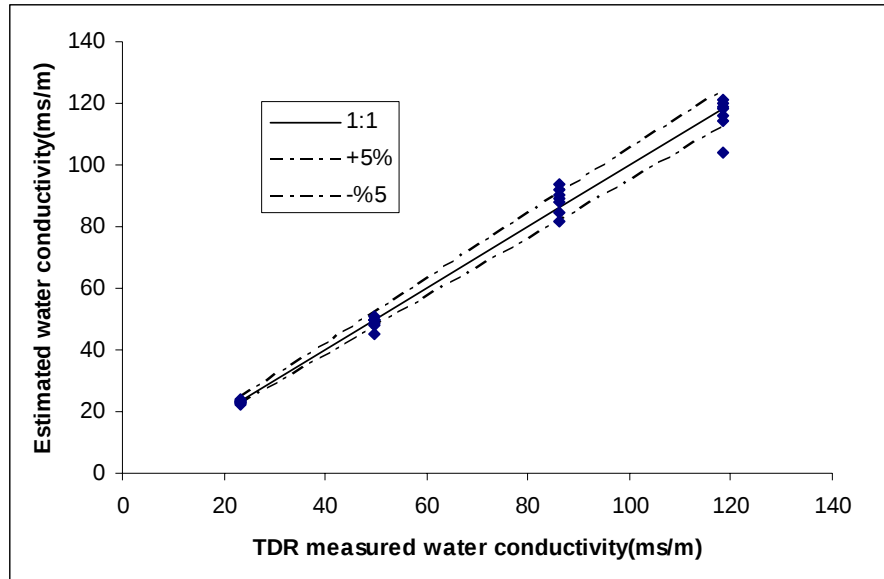


Figure 17. TDR estimated electrical conductivity of water versus the actual electrical conductivity

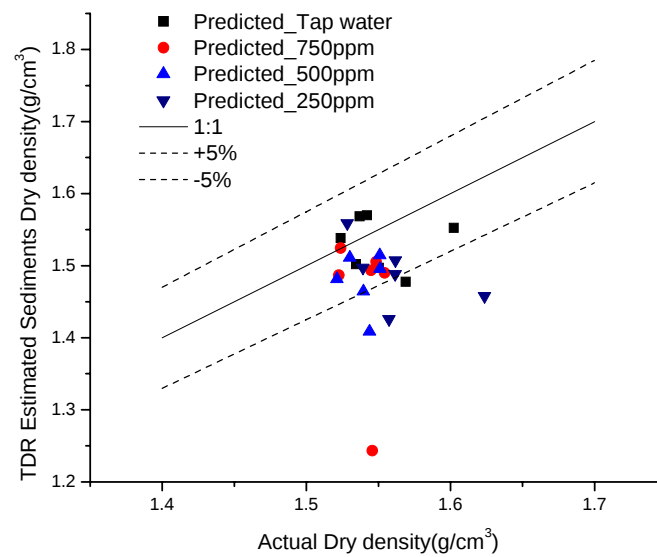


Figure 18. TDR estimated dry densities of sediments versus the actual dry densities

Conclusion

Simulated scour/sedimentation tests were performed in tap water and water with different salt concentrations. The theoretical bases and application schema have been developed to interpret the information from TDR signal to determine scour conditions. Application of these approaches results in satisfactory results of scour depth, sediment density, and river water electrical conductivity. Reference equations and application procedures were established for practical applications. Research will continue to further validate and refine this instrument.

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Xinbao Yu is from China and completed his B.S degree in civil engineering at Chang'an University, Xi'an, China in 2000. He completed his M.S degree in geotechnical engineering at Southeast University, Naging, China in 2003. In 2005, he completed his M.S. in civil engineering at Clarkson University, Potsdam, NY. He is currently working towards Ph.D. degree in geotechnical engineering at Case Western Reserve University, Cleveland, OH.

Xiong Yu obtained his B.S. and M.S. degree in civil engineering at Tsinghua University and his Ph.D degree from Purdue University. He also holds degrees in computer science and electrical and computer engineering. He is currently a faculty member at department of civil engineering, Case Western Reserve University. His research interests embrace applying interdisciplinary principles to solve broad spectra of Civil Engineering problems.