Field Monitoring of Scour Critical Bridges: A Pilot Study of Time Domain Reflectometry Real Time Automatic Bridge Scour Monitoring System

Xiong (Bill) Yu and Xinbao Yu

for the Ohio Department of Transportation Office of Research and Development

and the Federal Highway Administration

State Job Number (134374)

8/6/2010
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Unclassified
Draft Final Report

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Project No. 134374

Prepared in Cooperation with the
Ohio Department of Transportation and the
U.S. Department of Transportation
Federal Highway Administration
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Acknowledgements

The project team would like to acknowledge the contributions, guidance and assistance of the following ODOT engineers during the course of this project.

Bill Krouse, Office of Structure Engineering
Brandon Collett, Structure Engineer, ODOT District 8

The guidance and assistance of industry collaborators are also highly appreciated:

Frank Rausche, GRL Engineers Inc.
Garland Likins, Pile Dynamics Inc.
Lance Cole and John Xu, J&L Laboratories Inc.
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CHAPTER ONE

INTRODUCTION

1.1 Motivation for Work: Bridge Scour Monitoring

In April 1987, the Schoharie Creek Bridge on the New York State Thruway collapsed during a near record flood and 10 people died as a result. This catastrophic collapse focused national attention on the bridge scour problem in the United States. Failure of the State Thruway Authority to maintain adequate supporting soils around the bridge piers was determined as the major cause by the National Transportation Safety Board (NTSB). The cumulative effect of local scour led to severe loss of glacial till beneath the spread footings (Figure 1.1). This significantly affected the stability of bridge and led to its collapse (NTSB 1988, cited in Lagasse 2001). Besides this infamous bridge failure, a number of other bridges have failed due to structure instability caused by scour. As reported by Lagasse (2001),

Two years later after the collapse of the Schoharie Creek Bridge, the collapse of a U.S. 51 Bridge over the Hatchie River in Tennessee, in which eight people died, broadened the concern to stream stability problems as well. The NTSB determined that the probable cause of the collapse of the northbound spans was the northward migration of the main river channel, which the Tennessee DOT did not evaluate or mitigate. As with the Schoharie Creek Bridge collapse, the lack of structural redundancy in the design of the bridge spans contributed to the severity of the accident. On March 10, 1995, at about 9 p.m., the southbound and northbound bridges on Interstate 5 over Arroyo Pasajero (Los Gatos Creek) in California collapsed during a large flood. Four vehicles plunged into the creek, resulting in seven deaths. The two bridges were built in 1967, and their deck spans were
supported by cast-in-place pile bents. Forensic analysis by the California Department of Transportation in cooperation with the FHWA and the U.S. Geological Survey indicated that stream channel degradation combined with local scour undermined the stability of the pile bents (Lagasse 2001).

In the United States, 604,279 bridges, including federal highway, state, county, and city bridges, are currently listed in the National Bridge Inventory (NBI) (Richardson et al. 2003). Approximately 84% (503,000) of these bridges exist over waterways. Among them, over 20,000 (26,000 as of 2002) are classified as “scour critical”, i.e., one bridge out of every twenty five is vulnerable to scour. A total of 1000 bridges collapsed in the United Sates between the years of 1961 and 1991 and had associated deaths. Scour was responsible for 60% of these failures (Shirole et al. 1991; Geo-institute 2009).

Figure 1.1 Pier scour holes at Schoharie Creek Bridge, 1987 (Lagasse 2001).
Bridge failures cost millions of dollars each year, including the direct cost of replacing and restoring the bridges and also the indirect cost related to the disruption of transportation facilities. Using the Schoharie Creek Bridge as an example, the Federal Highway Administration (FHWA) estimated that the indirect cost suffered by the general public, businesses, and industry, because of long detours and lost production time, were five times greater than the direct cost of the bridge repair (Lagasse 2001).

In response to the Schoharie Creek Bridge failure, the FHWA established a national bridge scour inspection program as an integral part of the National Bridge Inspection Program. In 1988, the National Bridge Inspection Standards (NBIS) were revised to include underwater bridge inspections every two years. Additionally, inspections by divers, of the scour and the structural integrity of bridges with members under deep water were required by the NBIS.

1.2 Fundamentals of Bridge Scour

Bridge scour is defined by Richardson and Davis (2001) as, “the result of the erosive action of flowing water, excavating and carrying away material from the bed and banks of streams and from around the piers and abutments of bridges.” Under the same flow and bridge site conditions, the maximum scour in both cohesive and noncohesive soils is
the same assuming the soils are both susceptible to scour. However, the rate of scour is different and is dependent on the type of soil. Under the same flow conditions, scour will reach maximum depth in cohesionless soils, such as sand and gravel, in a matter of hours; while limestone, for example, will take years to reach maximum depth (Richardson and Davis 2001).

Scour is a dynamic process. When the amount of sediment leaving an area is greater than the amount of sediment entering the area, scour occurs. When the amount of sediment leaving an area is equal to the amount of sediment entering the area, scour is considered to be stable. When the amount of sediment leaving an area is less than the amount of sediment entering the area, deposition occurs. Sediment load is an important factor which affects scour development. It exists in two different forms. In the first form, sediment moves near the river bed, usually with a thickness equal to two particle diameters. In this form sediment load is termed “bed load”. When sediment is suspended in the water and moves the water flow, it is termed the “suspended load”. The water flow exerts both lifting and dragging forces on the sediment particles. When the resulting shear force is greater than the critical shear stress of the sediment, the sediment particles begin to move and scour is initiated. When flow velocity is reduced, due to geometry changes and/or bed resistance, the bed load settles and deposition is initiated. The critical shear stress of the sediment depends on the soil. For example, sand has a very low threshold shear stress,
while limestone has a much higher value (Sheppard and Renna 2005).

For engineering applications, bridge scour is normally divided into four categories: 1) general scour, 2) long term aggradation and degradation, 3) contraction scour, and 4) local scour (pier scour and abutment scour). At a bridge site, the total scour is the summation of these four types of scour (Figure 1.2).

![Figure 1.2](image)

**Figure 1.2** Different types of scour in a typical bridge cross section (Wang 2004).

1.2.1 General Scour

General scour refers to the bed elevation changes resulting from lateral instability of the waterway. For example, in a “riverine” environment, meanders in rivers are caused by the
shift of the channels. In a “tidal” environment, the inlet instability is caused by tidal waves (Richardson and Davis 2001).

1.2.2 Aggradation and Degradation

Aggradation and degradation refer to the overall elevation changes of the stream bed. These elevation changes occur over the entire span of water. Examples of these changes include the erection of a dam, changes in upland drainage basin characteristics (e.g., land use changes), upstream mining in the channel, etc. Similar processes exist in tidal waters (Richardson and Davis 2001).

1.2.3 Contraction Scour

Contraction scour is caused by cross-section changes in a river or waterway due to manmade or natural features. Some examples include: the long causeways, bridge piers and abutments, and headlands (as shown in Figures 1.3 and 1.4). In the Hydraulic Engineering Circular (HEC)-18, general scour and contraction scour are both considered to be general scour at bridge sties.
1.2.4 Local Scour

Local scour occurs near bridge piers, abutments, spurs, and embankments. Due to

*Figure 1.3* Two manmade features that create a contracted section in a channel (Sheppard and Renna 2005).

*Figure 1.4* An example of manmade causeway islands that create a channel contraction (Sheppard and Renna 2005).
obstruction of these structures, flow is accelerated and vortices are created. Thus, the resulting shear stress on sediment particles is increased. When the shear stress is larger than the critical shear stress of the sediments, a scour hole develops. The developed scour hole changes the flow field which reduces the resulting shear stress on the sediments. This process continues until a state of equilibrium is reached. Depending on the availability of sediment loads, the local scour can exist as either clear-water or live-bed scour.

![Figure 1.5 Complex flows around a bridge pier (Hamill 1999).](image)

Turbulent flow around a bridge pier (Figure 1.5) is complex due to its three dimensional nature and the existence of multiple vortices. The dynamic scouring process makes
turbulent flow even more complex. This flow initiates the scouring process, which in turn changes the flow field until a balance is reached. The mechanisms behind sediment movement as well as the interactions among flow, structure, and bedform need further understanding. This is essential for accurate scour prediction around piers.

When an incoming flow encounters a bridge pier, a complex flow field is created around the pier due to the flow, structure, and streambed interactions. The complex flow pattern within scour holes has been described in detail by several researchers including Breusers & Raudkivi (1991), Dargahi (1987), and Herbich (1984). Complex flow generally includes: surface rollers (bow wave) at the surface water on the upstream side of the bridge pier, downflow at the upper stream side of the pier in the vertical plane, a horseshoe vortex as a result of the interaction of downflow and bedform; and a wake vortex on the downstream side of the pier. The horseshoe vortex, rolling near the bedform, is the primary contributor to the scour occurring on the upper stream side of the bridge pier. However, the upper surface rollers can counteract the horseshoe vortex and weaken it in shallow flow depth. The wake vortex occurs on the downstream side of the bridge pier due to flow separation but, decreases rapidly as it moves further downstream. The axis of a wake vortex is nearly vertical and tends to act like a vacuum sucking the sediments into the flow. The suspended sediments then deposit as the wake vortex diminishes (Wang 2004, Lee 2006).
The FHWA published three Hydraulic Engineering Circulars (HEC) providing guidelines for bridge scour, stream stability, and for scour countermeasures. These HECs include: HEC-18, *Evaluating Scour at Bridges* (Richardson and Davis 2001), which provides guidance for the design, evaluation, and inspection of bridges for scour; HEC-20, *Stream Stability at Highway Bridges* (Lagasse et al. 2001a), which provides instruction on the identification of stream instability problems at highway stream crossings; and HEC-23, *Bridge Scour and Stream Instability Countermeasures-Experience, Selection, and Design Guidance* (Lagasse et al. 2001b), which provides guidelines for the various types of scour countermeasures. For conducting new or rehabilitation designs for bridges, both HEC-18 and HEC-20 are used. Countermeasure solutions may be developed when there are concerns with regard to scour or stream stability (Hunt 2005).

1.3 Bridge Scour Research

Research on bridge scour, including: scour prediction (pier scour, abutment scour, and contraction scour), scour countermeasures, and scour monitoring, has been a strong area of study for many years. Generally speaking, there are four various methods for conducting scour research: 1) analytical methods, 2) physical modeling, 3) numerical modeling, and 4) field observations.
1.3.1 Analytical Methods

Analytical methods aim to predict scour development based on the study of the relationship between the vortex system around a bridge pier and the pier-scour depth (Lee 2006). This approach is usually based on observations from small-scale laboratory experiments. Thus, it is a semi-empirical method. For example, Carstens (1966) assumed a scour hole to be in the shape of an inverted frustum of a right circular cone with a base diameter equal to the pier diameter. Using the proposed sediment transport equation, the proposed scour prediction equation is able to predict scour depth development with known approaching velocity, sediment size, specific gravity, angle of sediment repose, and pier diameter. Muzzammil and Gangadhariah (2003) found that the equilibrium scour depth is related to the size of the horseshoe vortex, tangential velocity, and vortex strength in the scour hole. They proposed that the mean size of the horseshoe vortex is about 20% of the pier diameter, and the tangential velocity of the vortex is approximately 50% of the mean approach velocity for $10^4 \leq \text{Re}_b \leq 1.4 \times 10^5$ at fixed bed conditions. Based on these findings, a maximum scour prediction equation was proposed. More analytical scour prediction equations can be found in the literature (Lee 2006). These analytical methods involve assumptions of the scour shape, determination of the critical shear stress or critical velocity, and assumptions of the continuity equations (sediment transport equation). Most of these methods are too complex to realistically use and not
applicable under certain conditions.

**1.3.2 Physical Modeling**

Physical modeling is also widely used in the study of bridge scour. Most of the currently used scour prediction equations were developed based on data obtained from these laboratory experiments. Small scale prototype bridge scour tests can be performed in a flume as shown in Figure 1.6. The flume bridge scour test has great advantages in that flow conditions and bridge geometry can easily be controlled. Therefore, the effects of these factors on scour development can be studied in detail. Numerous investigations have been performed to study pier scour, contraction scour, and abutment scour. The effects of soil including sand and clay, on the maximum scour depth and scour rate have been investigated. Other studies have included live or clear bed scour, flow field studies, and scour studies at complex pier groups.
Various scour prediction equations have been proposed based on laboratory observations (Breusers et al. 1977; Briaud et al. 1999; Laursen and Toch 1956; Melville and Chiew 1999; Richardson and Davis 2001; Shen et al. 1969; Sheppard et al. 2004). The parameters affecting bridge pier scour are summarized by Breusers et al. (1977) as follows:

- Parameters related to fluid properties
  - \( g \): acceleration due to gravity
  - \( \rho \): density of the fluid
  - \( \nu \): kinematic viscosity of the fluid
- Parameters related to flow properties
  - \( y_1 \): approach flow depth
  - \( V_1 \): approach mean flow velocity
- Parameters related to sediment properties
  - \( \rho \): density of the sediment
- $d_{50}$: median sediment size
- $\sigma_g$: geometric standard deviation of sediment size distribution
- cohesion of sediment

- **Parameters related to the bridge pier**
  - shape of the bridge pier
  - width of the bridge pier
  - alignment of the bridge pier

The result of the dimensional analysis concerning the problem of local scour around a bridge pier is given as (Sturm 2001):

$$\frac{d_s}{b} = f\left(K_s, K_\theta, \frac{y_1}{b}, \frac{V_1}{\sqrt{g y_1}}, \frac{\rho V_c b}{\mu}, \frac{V_1}{V_c}, \frac{b}{d_{50}}, \sigma_g\right) \quad (1.1)$$

where $d_s$ is the equilibrium scour depth; $b$ is the width of bridge pier; $K_s$ is the shape factor; $K_\theta$ is the pier alignment factor; $g$ is the acceleration due to gravity; $d_{50}$ is the median sediment size; $\sigma_g$ is the geometric standard deviation of sediment size distribution; $\mu$ is the fluid dynamic viscosity; $\rho$ is fluid density; $V_c$ is the critical velocity for initiation of sediment motion in the approach flow; and $y_1$ and $V_1$ are approach depth and velocity, respectively. Most pier scour prediction equations proposed from laboratory experiments can be written in the form of Equation 1.1, but only some of the dimensionless ratios on the right hand side of the euqation, not necessarily the same ones, are utilized in all of the equations (Ettema et al. 1998).
When applying the laboratory developed scour prediction equations to field conditions, scaling effects have to carefully be considered. Due to the difficulty encountered in producing a scour test that meets all hydraulic and hydrodynamic similitude requirements, these prediction equations tend to overestimate scour developed in the field.

1.3.3 Numerical Simulation

As computers have become widely used in every aspect of engineering design, the method of performing hydraulic analyses has also changed dramatically. Hydraulic modelers have become increasingly dependent on “user friendly” modeling programs. As a result, modelers have become more well-trained with respect to the computer programs, and are less well-trained in the theory behind the programs (Walton 1997). For bridge scour analysis there are several existing modeling systems for 1D simulation, such as HEC-RAS and WSPRO, for 2D simulation, such as Flo2dh and SED2D, and for 3D simulations such as Flow3D, FLUENT, and CCH3E3D. As such, modelers are faced with the difficult task of choosing the appropriate tools for the given application.

One of the most widely used computer programs for bridge scour analysis is HEC-RAS, a one-dimensional hydraulic analysis program with scour estimation modules. It predicts the scour at bridge crossings reasonably well for simple regular channels. However, it
was found to either significantly overpredict or underpredict scour compared to the actual field observations. For river channels with complex geometries or where lateral distribution of the flow is of concern, such as nearing bridge openings, a two dimensional model is preferred. 1D and 2D computer programs can solve simplified surface flow. With the obtained flow field, the maximum scour depth can be determined using the available scour prediction equations. 1D and 2D hydraulic models remain the most frequently used. However, the three-dimensional model provides the most realistic simulation of the flow field under turbulence conditions adjacent to bridge piers and abutments. The modeling process, however, can be complex; besides which, solving a 3D model requires a significant amount of computational time.

With the increasing capabilities of computer hardware and software and economic availability, computational fluid dynamics (CFD) has also been widely used for solving bridge scour problems. In this aspect, many companies and research groups have developed their own codes for general or specific CFD applications. The commercially available software includes, for example, FLUENT, Star-CD, CFX, and FLOW3D. Some of the more well known codes developed by research groups are CCHE (1D, 2D, and 3D) (Figure 1.7), and codes developed by Ge (2004) (Figure 1.8), Olsen (2003), Roulund (2005), and Tseng (2000).
**Figure 1.7** Simulated local scour hole around a bridge pier (NCCHE n.d.).

**Figure 1.8** Simulated complex turbulent flow around bridge piers (Ge 2004).
The flow field around a bridge pier is three dimensional. A 3D model of bridge scour is thus necessary to explore the details of the scour hole. Ushijima et al. (1992) implemented a two-equation turbulence model to calculate local scour caused by the unsteady convection and diffusion of warmed jets in both 2D and 3D. The scour prediction accounted for both the bed load and the suspended load. Ushijima (1996) later extended the model on the basis of the Lagrangian-Eulerian formulation and found a great improvement on scour prediction compared with the previous one.

Fukuoka et al. (1994) presented a 3D model to simulate bridge scour. The flow model was based on the empirical eddy viscosity equation assuming a hydrostatic water pressure. In their study a non-equilibrium sediment transport process was considered in the calculation of bed deformation. The simulation results were satisfactory. Later, this model was extended to curved channels by Watanabe et al. (2001).

Peng et al. (1998) treated the scouring process as a steady state problem by assuming a steady bed deformation within each calculation step. Combining a modified k-ε turbulence model with a modified Meyer-Peter and Muller formula for sediment transport, the equilibrium scour pattern around a bridge pier was successfully modeled. Yen et al. (2001) employed large eddy simulation incorporated with Smagorinsky’s sub-grid scale turbulence model to simulate the 3D flow field and bed shear field around bridge piers. The sediment continuity equation, in conjunction with Van Rijn’s bed load transport
formula, was used to simulate bed evolution for coarse bed materials. Great savings in computation time was achieved by using modified bed shear stress obtained from flat bed flow field. Compared with experimented results documented in the literature, the simulation of scour was found to be satisfactory. Nagata et al. (2002) introduced a non-linear k-ε model based on a moving boundary fitted coordinate system to simulate the flow field around a cylindrical pier. A stochastic model was adopted to simulate sediment transportation in addition to the momentum equation. Salaheldin et al. (2004) studied 3D separated turbulent flow around vertical piers using the commercially available software, FLUENT. Calculations were performed using a two phase Volume of Fluid (VOF) model. Two scour conditions, flat bed and scour hole, were considered in clear water scour simulation. Several available turbulence models were studied in the simulation. These included: the one-equation Spalart-Allmaras model, the two-equation k-ε model (the standard, the renormalization group, and the realizable model), and the Reynolds Stress Model (RSM). These models were evaluated by analyzing the velocity profile and bed shear stress and the simulation results were compared with available data from previous literature. The one-equation model was found to perform poorly. The k-ε model performed well in simulating the velocity field, but performed unsatisfactorily in simulating the bed shear stress. The RSM model produced good results for the velocity profile and the bed shear stress on a flat bed and scour hole as well as for velocity field on the flat bed. The flow field was obtained by Zhang et al. (2005) by solving the RANS
(Reynolds-averaged Navier-Stokes) equation with the k-ε model. The scouring process was modeled with the sediment continuity equation and the modified Ashida-Michiue formula. The finite Volume Method (FVM) was adopted to numerically solve these equations using a moving unstructured mesh with an arbitrary polyhedral mesh of up to six faces.

The most challenge numerical simulation for bridge scour is described as follows: (Zhang et al. 2005)

According to the previous researches, it is found that the bottleneck of the state-of-the-art of the local scour simulation lies in the accurate modeling of the sediment behavior and the interaction between the flow and bed variation.

1.3.4 Field Observation

HEC-18 was presented by the FHWA as the guidelines for predicting local and contraction scour at planed and existing bridges. Although the methods presented in HEC-18 represent the state-of-the-art-knowledge at the time of publication, several potential limitations to these methods has been identified (Mueller and Wagner 2005). For example, Richardson and Davis (2001) state,

The current equations and methods for estimating scour at bridges are based primarily on laboratory research. Very little field data have been collected to verify the applicability and accuracy of the various design procedures for the range of soil conditions, streamflow conditions, and bridge designs encountered throughout the United States.
Field measurements of bridge scour are essential to validate the existing scour prediction equations and to better understand the scour process. The problem due to lack of and need for reliable and complete field data on bridge scour has been repeatedly raised by many researchers (Hjorth 1975; Lagasse 1991; Laursen and Toch 1956; Melville et al. 1989; Shen et al. 1969). Early field observations only collected pier scour data. There were no measurements of the major factors that affect scour, such as flow depth and velocity. For example, Froehlich (1988) was not able to consider the effect of sediment gradation in his model because of the lack of this information in the recorded data. For the same reason Johson (1995) had to assume uniform sediment gradation when he compared seven published pier scour equations with field data. Additionally, the number of documented observations of contraction and abutment scour are significantly fewer than those of local scour (Mueller and Wagner 2005).

The many cases of bridge failures which occurred in the late 1980s and early 1990s have raised the awareness of the public and the authorities to the importance of field measurements of scour. In 1987, the FHWA, State highway departments, and the U.S. Geological Survey (USGS) initiated a co-operative National Bridge Scour Project to collect bridge scour data during floods. A national bridge scour database was generated to provide the public with this information including a total number of 394 measurements of scour depth at 90 different bridge piers (Landers and Muller 1996). A second USGS
field-collection study, funded by the FHWA, was completed in 2005 by Muller and Wagner (2005). In this study, field data representing the bridge scour at 79 sites located in 17 states were collected and compiled into a report. This data was analyzed to isolate pier scour, contraction scour, and abutment scour. The national data base currently contains 493 local pier scour measurements, 18 contraction scour measurements, and 12 abutment scour measurements. The pier scour measurements were used to evaluate 26 various published pier scour equations (Muller and Wagner 2005).

However, the quality of field data still needs to improve. Muller and Wagner (2005) states in their report:

… a deficiency that is primarily a reflection of the difficulty in collecting the necessary data. Accurate and complete field measurements of scour are difficult to obtain because of complex hydraulic conditions at bridges during floods, inability to get skilled personnel to bridge sites during floods, and problems associated with existing measuring equipment.

This calls for the research needs of robust equipment for the field measurement of bridge scour. In Chapter 2, a more detailed literature review of scour measurement technologies will be presented.

1.4 Organization of the Dissertation

This dissertation presents the development of a new TDR sensor for fixed bridge scour monitoring. It is organized into six chapters as follows:
• Chapter one provides background information pertaining to this research. It contains research motivation, fundamentals of bridge scour, and various approaches to scour study.

• Chapter two reviews the literature discussing the historical and existing practice of field measurements of bridge scour. In particular, the literature review focuses on the available existing technologies for scour monitoring. It also offers detailed background information on Time Domain Reflectometry (TDR) and its development for scour monitoring.

• Chapter three presents the development and validation of various algorithms for scour estimation. Laboratory experiments of simulated scour are monitored with a TDR moisture probe in fine sand in saline water with varying salinity. Theoretical models to determine the dielectric constant and scour depth are presented. Three algorithms for analyzing TDR scour signals are presented and compared.

• Chapter four discusses the TDR monitoring of simulated scour tests under various conditions that are expected to be encountered at different bridge sites. The situations studied in this chapter include various sediments, water of high electric conductivity, turbulent flow conditions, and fluctuation of water level. Signal interpretation to determine scour depth for these situations is investigated.

• Chapter five presents the development of a new TDR scour sensor for field deployment. The performance of TDR sensors is analyzed using a finite element
analysis model. The analysis is first conducted on a coated commercial probe. And is then extended to the new scour sensor. Procedures for the determination of the effective measured dielectric constant are presented. A method for scour depth determination is established, which is able to provide accurate scour measurements.

- Chapter six summarizes the dissertation. Conclusions and recommendations of future study are presented.
CHAPTER TWO

LITERATURE REVIEW: SCOUR MONITORING PRACTICE AND TECHNOLOGY

There are many bridges on scour susceptible foundations, such as spread footings and shallow piles, and a large number of bridges with unknown foundations. These bridges cannot be replaced or repaired immediately due to the limitation of funds available. Therefore, they must be monitored and inspected following high floods. Scour monitoring includes “activities used to facilitate early identification of potential scour problems” (Lagasse 2001b). Monitoring also serves as “a continuous survey of the scour progress around the bridge foundations” (Lagasse 2001b). According to HEC-23 (Lagasse 2001b), bridge scour can be monitored/measured by various types of instrumentation or by visual inspection, i.e.:

Fixed instruments and portable instruments
• Fixed instrumentation describes monitoring devices which are attached to the bridge structure to detect scour at a particular location. Typically, fixed monitors are located at piers and abutments. The number and location of piers to be instrumented should be defined, as it may be impractical to place a fixed instrument at every pier and abutment on a bridge. Instruments such as sonar monitors can be used to provide a timeline of scour, whereas instruments such as magnetic sliding collars can only be used to monitor the maximum scour depth. Data from fixed instruments can be downloaded manually at the site or it can be telemetered to another location.

• Portable instrumentation describes monitoring devices that can be manually carried and used along a bridge and transported from one bridge to another. Portable instruments are more cost effective in monitoring an entire bridge than fixed instruments; however, they do not offer a continuous watch over the structure. The allowable level of risk will affect the frequency of data collection using portable instruments.
Visual inspection
• Visual inspection describes standard monitoring practices of inspecting the bridge on a regular interval and increasing monitoring efforts during high flow events (flood watch). Typically, bridges are inspected on a biennial schedule where channel bed elevations at each pier location are taken. The channel bed elevations should be compared with historical cross sections to identify changes due to scour. Channel elevations should also be taken during and after high flow events. If measurements cannot be safely collected during a high flow event, the bridge owner should determine if the bridge is at risk and if closure is necessary. Underwater inspections of the foundations could be used as part of the visual inspection after a flood.

2.1 Motivation for Scour Instrumentation

Hunt (2005) conducted a survey among State Departments of Transportation (DOTs) on the reasons for or benefits of using a scour monitoring system. The results of this survey are summarized in the following paragraphs. Most DOTs mentioned safety for the traveling public as the main benefit of scour monitoring systems. Additional benefits include a reduced number of underwater and/or regularly scheduled inspections, early identification of problems prior to diving inspections, and insight into site-specific scour processes. Scour monitoring is a component of the comprehensive program to implement a plan of action for emergency conditions and underwater inspections. The scour monitoring system serves as an initial warning system for a potential problem at the bridge site. However, it is the responsibility of bridge engineers to determine the urgency of response.
The scour monitoring system can also provide data that can be used to verify scour prediction equations. The Hawaii DOT funded a research project which used sonar devices to obtain field bridge scour data to validate some of the HEC-18 scour equations. During the monitoring period, a storm was recorded and the experimental scour data was compared with the predicted scour obtained from the existing equations. Results showed that the predicted depth could be four times larger than the recorded scour depth in the field (Hunt 2005).

Good instrumentation is essential for making proper decisions, such as scheduling countermeasures or even closing bridges. Poor instrumentation leads to poor decisions which often result in economic waste and inconvenience to the public with respect to transportation. For example, during the 1994 flood in Georgia, more than 2,100 bridges were monitored and inspected during the flood, 1,000 of which were closed. Georgia was commended for the prompt action, and no lives were lost as a result of bridge failures. Yet, although the decision to close 1,000 bridges probably saved lives, it also crippled the transportation system in the flooded area (Jones et al. 1995, cited in Schall and Price 2004). Due to the limitations of the portable scour monitoring equipment, some of the closures might not have been necessary, while others, perhaps, ultimately should have been closed to reduce the risk to the traveling public and/or to minimize structural damage to the bridge (Schall and Price 2004).
Field conditions at bridge sites are generally very complex which can make it difficult for the scour monitoring device to be properly implemented. Common problematic conditions can be separated into two categories: difficult flow conditions (e.g., high velocity, air entrainment in the water column, and high sediment concentrations) and difficult site conditions (e.g., high bridges, low clearance under bridges, cold water, floating debris, and ice accumulation) (Schall and Price 2004). These extreme conditions can cause damage and/or interference to the scour monitoring device. According to the survey conducted by Hunt (2005) shown in Figure 2.1, debris (26%) and ice flows (13%) caused the most damage and interference to scour monitoring systems. The damage essentially resulted in repair costs that in some cases doubled the original budget.

**Figure 2.1** Site conditions that cause interference or damage to the fixed scour monitoring systems (Hunt 2005).

To endure extreme field conditions, Lagasse and Price (1997) recommended the
following mandatory criteria to be considered for scour monitoring devices:

**Mandatory Criteria**
- Capability for installation on or near a bridge pier or abutment
- Ability to measure maximum scour depth within an accuracy of ±0.3 m (1 ft)
- Ability to obtain scour depth readings from above the water or from a remote site
- Ability to operate during storm and flood conditions

Where possible, the following desirable criteria should also be considered:

**Desirable Criteria**
- Capability to be installed on most existing bridges or during construction of new bridges
- Capability to operate in a range of flow conditions
- Capability to withstand ice and debris
- Vandal resistance
- Ability to operate and be maintained by highway maintenance personnel

### 2.2 National Practice of Developing Instrumentation for Scour Monitoring

In January 1990, a bridge over the White River, in White River Junction, Vermont, collapsed during a period of ice breakup. A post event inspection of the bridge showed that the piers failed due to progressive deterioration of the foundation caused by scour. The Army Corps of Engineers Cold Regions Research & Engineering Laboratory in cooperation with the FHWA and the Vermont Agency of Transportation instrumented the bridge to monitor the ice force and bed elevation changes due to scour. The instruments implemented for the scour measurements included a Brisco sensor and a matrix of “instrumented fish”, in addition to traditional scour chains (Figure 2.2). The matrix of “instrumented fish” contained wireless transmitters which were attached at increasing
depths to a vertical mast buried in the river bed. During a flood event, the transmitter enclosed within each exposed fish sent out a signal due to the corresponding movement of the fish caused by the water flow. During flood recession, the fish were again buried by the redeposited materials. Therefore, the device was capable of working for multiple scour events. Without cables, which might be damaged by ice and debris, this device has the advantage of resisting these damaging conditions. However, due to the design of the transmitter, the water velocity has to be greater than 4 in/s to even trigger the activity switch. Additionally, the resolution of the scour measurements is dependent on the spacing of buried transmitters as well as the size of the “fish” housings.

![Diagram of river bed with Initial Riverbed, Flow, Redeposited Material, Bottom of Scour Hole, Instrumented Fish, and Sediment Chains.]

**Figure 2.2** Instrumented fish and sediment chains (Zabilansky 1996).

Under the National Cooperative Highway Research Program (NCHRP), the
Transportation Research Center (TRB) initiated NCHRP Project 21-3 entitled, “Instrumentation for Measuring Scour at Bridge Piers and Abutments”. The basic objective of this project was to develop, test, and evaluate fixed instrumentation that is both technically and economically feasible for use in measuring or monitoring the maximum scour depth at bridge piers and abutments (Lagasse and Price 1997). According to the findings of the project literature search, existing fixed scour-measuring and –monitoring devices/instruments can be grouped into the following four broad categories:

- Sounding rods: manual or mechanical devices (rods) to probe the streambed;
- Buried or driven rods: device with sensors on vertical supports, place or driven into the streambed;
- Fathometers: commercially available sonic finders; and
- Other buried devices: active or inert buried sensors (e.g., buried transmitters).

In the research of Lagasse and Price (1997), two instrument systems, sonic fathometers and a magnetic sliding collar device, were selected and tested at various bridge sites under different field conditions. Both instruments met all mandatory criteria and many of the desirable criteria for monitoring and measuring scour. Installation, operation, and fabrication manuals were also developed for these devices.

Portable scour-measuring systems typically consist of four components: (1) instrument(s) for taking the measurement, (2) a deployment system, (3) a method to identify and record the horizontal position for the data collected, and (4) a data-storage device (Mueller and
Landers 1999). Portable instruments can be divided into four categories including: physical probing, such as sounding poles and sounding weights; sonar, such as single-beam sonar, side scan, multi-beam, and scanning sonar; geophysical, such as seismic instruments; and others, such as underwater cameras and green laser sensors (Schall and Price 2004).

The FHWA and the U.S. Geological Survey (USGS) sponsored the first development of portable instruments for bridge scour monitoring (Mueller and Landers 1999). In this research, a low-cost echo sounder and a tethered kneeboard to deploy the transducer were recommended for use in bridge inspection work. An unmanned remote-controlled boat was developed to deploy the measurement sensors (Figure 2.3). The boat was powered by an 8-horsepower (hp) outboard motor and was controlled by recreational remote-control radios and heavy-duty waterproof servos. The boat was successfully used in several floods and has allowed for the collection of data that would not have been able to be safely or efficiently collected with a manned boat.
The Indiana Department of Transportation (INDOT) sponsored a research project based on the deployment of fixed scour monitoring instrumentation in response to bridge scour (Cooper et al. 2000). Two devices, one consisting of a magnetic collar slidably mounted on a rod driven into the streambed, and the other based on a sonar or acoustic principle, were developed, installed, and tested at two bridge sites. These sites included the SR25-Wildcat Creek and the US52-Wabash R. Crossing respectively. The sonar device installed at the US52-Wabash R. crossing site failed a few days after installation during the first flood and by 1999, only a single sonar device remained at both sites. Woody debris was attributed to the failures of the sensors.
To meet the need for effectively measuring scour depth during flooding, under NCHRP Project 21-07, Ayres Associates developed a new portable scour monitoring device (Schall and Price 2004). This device included a streamlined probe designed to position a wireless sonar device, capable of measuring scour depth in high-velocity conditions during flooding. The result of this research was a fully instrumented articulated arm truck (Figure 2.4). The truck provided a solid platform for deployment of various scour measurement devices, even under flood flow conditions. The movement of the crane was able to be measured precisely with mounted instruments. In their final report, Ayers Associates provided specific fabrication and operation guidelines for the sensor and truck system to allow highway agencies to build similar devices.

Figure 2.4 Articulated arm truck making a scour measurement (Schall and Price 2004).
The Nevada Department of Transportation funded a field scour monitoring program for selected bridge piers, crossing the Truckee River, to evaluate the HEC-18 scour prediction equations (Dennett and Siddharthan 2004). The fixed scour monitoring devices used included sonar, sounding rods, and driven rod devices. Portable equipment, used for ground-truthing of fixed scour monitoring instrumentation, included physical probes and sonar devices. According to their findings, “sonar devices appear to be the best option among portable scour monitoring devices. Although their functionality during high flows is suspect, they can be used as secondary devices for confirmation of the results from fixed device during lower flows” (Dennett and Siddharthan 2004).

Hunt (2005) conducted a synthesis study of scour monitoring practices for the Transportation Research Board under NCHRP Project 20-5. During this study, a survey was conducted on transportation agencies’ and bridge owners’ experiences using fixed scour monitoring systems. It was found that approximately 25 out of 50 states use or have employed fixed scour monitoring instrumentation on their highway bridges (Figure 2.5). A total of 93 bridges were instrumented with fixed monitoring systems. The number of bridge sites for each different type of scour monitoring instrument is shown in Figure 2.6. The most popular device was found to be the sonar scour monitoring system, which was used at 51 bridge sites. The next most popular were the magnetic sliding collar and float-out devices, which were installed at 23 and 19 different bridge sites, respectively.
Figure 2.5 States with fixed scour monitoring installations (Hunt 2005).

Figure 2.6 Total number of bridge sites with various fixed scour monitoring instrumentation (Hunt 2005).

Figure 2.7 shows the total number of deployments reported for each type of scour monitoring device. There were a total of 134 float-outs which were installed or which
were to be installed. Sonar devices were second most instruments deployed, with total number of 114. The number of sliding collar and tilt sensor devices were 36 and 37, respectively.

![Figure 2.7 Total number of various fixed scour monitoring instruments (Hunt 2005).](image)

### 2.3 Scour Monitoring Technology

There are many existing devices which use various technologies for bridge scour monitoring, as discussed in the previous sections. In this section, the technical details of the most widely used scour monitoring equipment and the corresponding technologies, i.e. sonar and magnetic sliding collar, are reviewed. The principle of Time Domain Reflectometry (TDR) is presented. Historical development of TDR for scour monitoring technology is also discussed.
2.3.1 Sonar

Sonar is an acronym for SOund NAvigation and Ranging which was largely developed during World War II (Schall and Price 2004). Early sonar systems, called ASDICS (named for the Antisubmarine Detection Investigation Committee), were used during World War I to detect submarines and icebergs. As technology improved over the years, better methods of transmitting and receiving sonar as well as better methods of processing the signal developed, including the use of digital signal processing (DSP). There are currently two types of sonar systems: active and passive. Active sonar consists of a sound transmitter and receiver, while passive sonar solely consists of a receiver. Passive sonar is often employed in military settings and is used in science applications as well, e.g. detecting fish for presence/absence studies in various aquatic environments (Wikipedia n.d.)

Theory

The most widely used instruments based on sonar technology include echo sounders, fathometers, and acoustic depth sounders. These instruments are all active types of sonar. Figure 2.8 shows a low-cost sonic system (fathometer). Figure 2.9 shows a schematic plot of the application of sonar for pier scour monitoring. In this figure, an acoustic pulse propagates out from a transmitter, travels in the water, and is reflected when it reaches the
river bed. The reflected pulse is captured by the receiver. By measuring the elapsed time and calculating the signal propagation speed, the distance from the transmitter to the river bed surface, which reflected the pulse, can be determined.

![Sonar system for bridge scour monitoring](image.png)

**Figure 2.8** A sonar system for bridge scour monitoring (Nassif *et al.* 2002).

Sound wave propagation speed in water is important for the distance measurement accuracy. The sound wave speed is related to the water's bulk modulus and mass density. The wave speed in sea water can be approximated by the following equation:

\[ V = 4388 + 11.25 \times T + 0.0182 \times D + S(2.1) \]
where, $V$ is the wave speed in feet per second, $T$ is the temperature in degrees, $D$ is the depth in feet, and $S$ is the salinity in parts-per-thousand.

Figure 2.9 Schematic of a sonar scour monitoring system over Fire Island Inlet (Hunt 2005).

The generated wave frequency and beam width (Figure 2.10) are two additional parameters which greatly affect the performance of sonar. Determination of the optimum acoustic frequency is influenced in part by two competing factors; background ‘noise’ decreases as frequency increases, however, as frequency increases so too does signal loss. The selected frequency also affects image sensitivity and power requirements (Andrews 1998). For example, most fathometers use a narrow bandwidth 200 kHz acoustic signal. This frequency results in accurate depth information, but provides very little information
about the sediments as it cannot penetrate the sediment layer. With a lower frequency, 20 kHz, fathometers can detect reflections from subbottom interfaces, such as the bottom of an infilled scour hole (fathometer n.d.).

![Illustration of transducer beamwidth](image)

**Figure 2.10** Illustration of transducer beamwidth (Muller and Landers 1999).

*Data Acquisition and Data Processing*

Fathometer surveys are conducted while traveling in a boat at moderate speed. Typically, the transducer is mounted on the boat and submerged in the water. Traces from adjacent source/receiver locations are plotted side-by-side to form an essentially continuous time-depth profile of the stream bottom. The wave speed in water can be used to transform the time-depth profile into a depth profile (Webb *et al.* 2000). With global positioning system (GPS), the horizontal position of each signal location can be determined. Figure 2.11 shows a streambed profile recorded by a fathometer.
Many echo sounders determine the measured streambed or scour hole depth when the reflected acoustic energy first exceeds a predetermined threshold. Beamwidth can greatly affect the accuracy of the measured scour hole depth. Two measurement situations are shown in Figure 2.12. When measuring depressions or holes, the reflected acoustic energy which first exceeds the predetermined threshold will likely come from the edges of the acoustic footprint. If the footprint is large and the width of the hole is small (Figure 2.12 A) or if the bed slopes significantly (Figure 2.12 B), the depth measured by the echo sounder may not be accurate (Muller and Landers 1999).
Figure 2.12 Effect of beamwidth on measured depth (Muller and Landers 1999).

**Limitations**

Echo sounders work well in streams with depths of at least 3 m and velocities less than 4 m/s. However, in shallow streams, with depths of 2 m or less and velocities exceeding 3 m/s, problems have been encountered. Very high levels of turbulence, air entrainment,
and heavy suspended-sediment loads adversely effect the operation of echo sounders (Muller and Landers 1999). The signals are easily contaminated by noise from multiple reflections, as well as echoes from the shoreline, water bottom, and/or piers (Webb et al. 2000). The instrument hardware and software packages are relatively expensive.

2.3.2 Magnetic Sliding Collar

One early sliding collar device is the Scubamouse, originally developed in New Zealand. This device consists of a vertical pipe buried or driven into the stream bed on the upstream side of the bridge pier where maximum scour depth may occur. The horseshoe-shaped collar initially rests on the streambed and slides down the vertical pipe to the bottom of scour hole, during a scour event. The collar contains a low-grade radioactive source, and therefore its position along the rod can be determined by sending a detector down the inside of the pipe after the flood (Lagasse and Price 1997).

Basic Concepts

The magnetic sliding collar (MSC) was developed under NCHRP Project 21-3 by Lagasse and Price (1997). The magnetic sliding collar system (Figure 2.13) consists of a stainless steel pipe and a sliding collar. The pipe is approximately 1.5 m (5 ft) long and 51 mm (2 in) in diameter. The steel pipe is buried or driven vertically into a streambed
with a sliding collar which moves as the scour progresses. The location of the collar is determined by sensing a magnetic field created by magnets attached to the collar. A sensor (probe), consisting a magnetic switch attached to a battery and buzzer on a long graduated cable, was fabricated to determine the position to the collar. The theory of detecting the position of the magnetic collar is explained in Figure 2.14. During operation, the probe is lowered through the annulus of the support pipe and the buzzer is activated when the sensor reaches the magnetic collar. Thus, the collar position can be determined from the reading on the graduated cable. The data acquisition for this device can be automated using modern electronic equipment.

**Figure 2.13** A sliding magnetic collar on stainless steel pipe with driving point (Cooper *et al.* 2000).
**Limitations**

This device measures the maximum scour that occurs during a given flood. However, if the scour hole refills, the collar becomes buried. Therefore, it can not measure the refill process. The MSC is well suited for bridges over shallow streams. The device is robust enough to survive severe field conditions. However, barnacle growth can eventually prevent movement of the collar. The measurement accuracy of this device is within ±0.15 m (0.5 ft). It can be used to measure scour at piers and vertical wall abutments. However, it is not generally adaptable for use at spill-throughs or sloping abutments (Lagasse and Price 1997).
2.3.3 Time Domain Reflectometry

TDR was originally used by electrical engineers to locate discontinuities in power and communication transmission lines (Ramo et al., 1965). However, it can also be used to measure a material’s dielectric and electrical properties. In civil engineering, the application of TDR was extended to soil water content and dry density determinations (Topp et al., 1980; Siddiqui et al. 1995, Siddiqui and Drnevich 2000, Yu and Drnevich 2004), concrete strength evaluation (Yu and Drnevich et al. 2004), monitoring of bridge scour (Dowding and Pierce 1994, Yankielun and Zabilansky 1999), evaluation of the field performance of landfill covers, monitoring of water level, detecting petroleum hydrocarbons, monitoring frost depth, determining soil density, monitoring curing of cement-stabilized materials, and measuring displacement and/or deformation etc. (Benson 2006).

The potential of TDR for detection of bridge scour has been explored by a few previous researchers. Dowding and Pierce (1994) developed a TDR scour detection system capable of measuring bridge scour and the displacement of footings. A schematic of this TDR scour monitoring system is shown in Figure 2.15. Little flanges are attached to the TDR cable at regularly spaced intervals. During a scour event, the flanges are exposed to water flow. This flow and flange interaction causes shear deformation of the
TDR cable at the locations of the flanges. This shear deformation causes a reflection in the TDR waveform. By performing signal analysis of the waveform, the location of the flange, and therefore the scour depth can be determined. Unfortunately, this system is not reusable due to the sacrificial characteristics of the designed TDR probe (O’Connor and Dowding 1999).

Figure 2.15 Schematic of a TDR system for scour monitoring (O’Connor and Dowding 1999).

A TDR sensor, made up of steel pipes, was developed by Yankielun and Zabilansky (1999). The laboratory setup for evaluation of the sensor is shown in Figure 2.16. Due to
the dielectric constant change at the water-sediment interface, the TDR signal is reflected. By analyzing the obtained TDR waveform, the location of the reflection, and therefore the scour depth can be determined. Field evaluation of the probe showed that it is sufficiently rugged enough to perform under severe conditions, including flooding and icing. If the two steel pipes are electrically shorted at the ends, the information of the electrical conductivity is lost, which can be utilized to obtain additional information about the river conditions. An analytical method for obtaining the TDR scour signal, using dielectric constants, was presented by Yu and Zabilansky (2006). However the electric conductivity information was overlooked. Thus, TDR signal analysis remains a challenge and is time consuming for nonprofessionals.

![Laboratory setup of the TDR sensor for scour monitoring (Yankielun and Zabilansky 1999).](image)

**Figure 2.16** Laboratory setup of the TDR sensor for scour monitoring (Yankielun and Zabilansky 1999).

**Basics Concepts**
The configuration of a typical TDR system is shown in Figure 2.17. 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, with bandwidth of around 20kHz to 1.5 GHz, to the measurement sensor and measuring the reflections due to the change of system geometry or material dielectric permittivity. The TDR instrument measures the time that the signal takes to travel along the cable and return to the instrument. Knowing the travel speed of the wave, the travel distance can be calculated using the well known equation where distance equals rate multiplied by time. The propagation velocity of the electromagnetic wave can be calculated as

\[ v_p = \frac{c}{\sqrt{\mu_r \varepsilon_r}} \quad (2.2) \]

Where \( c \) is the velocity of light \((3 \times 10^8 \text{ m/s})\) in vacuum, \( \varepsilon_r \) is the relative permittivity, and \( \mu_r \) is the relative magnetic permeability. The magnetic property of nearly all soils does not vary significantly from that of free space so it can be assumed that \( \mu_r = 1\)(Robinson et al. 2003).
Figure 2.17 A schematic diagram of the main components of TDR. The window on the right illustrates two waveforms, one in air and one in water. The dip is caused by an electrical marker in the head of the TDR probe so that the software can locate the starting point for travel time analysis (Robinson et al. 2003).

Figure 2.17 shows a typical TDR signal in soil. By analyzing this signal, the dielectric constant of the material can be determined using Equation 2.3 and the electric conductivity can be determined using Equation 2.4 (Yu and Drnevich 2004).

\[ K_a = \left( \frac{L_a}{L_p} \right)^2 \]  

(2.3)

In Equation 2.3, \( K_a \) is the measured dielectric constant, \( L_p \) is the physical length of probe in the test material, and \( L_a \) is the apparent length of probe in the test material.

\[ EC_b = \frac{1}{C} \left( \frac{V_a}{V_f} - 1 \right) \]  

(2.4)
In Equation 2.4, $EC_b$ is the bulk 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 the probe configuration, which can be obtained by calibration or from theoretical analysis. A schematic presentation of these parameters from a TDR signal is illustrated in Figure 2.18.

![Figure 2.18 A typical TDR waveform for soil (Yu and Drnevich 2004).](image)

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; the mostly widely used of which is Topp’s Equation as shown in Equation 2.5 (Topp et al. 1980). Equation 2.5 was developed based on various types of cohesionless soils and is generally referred to as a “universal” equation. This relationship is utilized to determine the physical properties of sediments in this study.
\[ \theta = 4.3 \times 10^{-6} K_a^3 - 5.5 \times 10^{-4} K_a^2 + 2.92 \times 10^{-2} K_a - 5.3 \times 10^{-2} \] (2.5)

In Equation 2.5, \( \theta \) is the volumetric water content, defined as the volume of water per unit volume of soil, and \( K_a \) is the dielectric constant.

The applicability of TDR in 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 and 7, while that of saturated solids varies depending on the degree of saturation). Due to the large contrast in the dielectric properties, reflections take place at the interface between material layers with different dielectric properties (including the air-water interface and the water-sediment interface).

Signal Analysis

The most important and challenging task of signal analysis is to find the reflections on the waveform. Topp et al. (1982) described a method of interpreting waveforms captured on paper using a chart recorder or by photographing an oscilloscope screen. This analysis consisted of two graphical algorithms. The first algorithm consisted of drawing a horizontal line across the top of the first peak, and drawing another line tangent to the descending limb of the first peak (Figure 2.19). The intersection of these lines defined the first reflection time at the probe head, \( t_1 \). The second algorithm consisted of drawing a
horizontal line tangent to the base line between the first peak and second inflection, and
drawing another line tangent to the second inflection. The intersection of the latter two
lines defined the second reflection at the end of the probe, t2. The travel time of the pulse
in the portion of the wave guide (probe) that was buried in the soil was thus defined as tt
which was equal to t2 minus t1. In Topp et al. (1982) method, peaks and inflections were
subjectively identified by eye and no computer codes or algorithms were implemented.

**Figure 2.19** The TDR waveform (bottom) and its first derivative with respect to time (top)
(Conservation & Production Research Laboratory n.d).

Later, Baker and Allmaras (1990) discussed a computer program for interpretation of
waveforms following the ideas of Topp et al. (1982). The program, which was not
published, included the following steps which were applied to a waveform consisting of
200 data points (Figure 2.20):
1) Smooth and differentiate the data (Savitsky and Golay 1964).
2) Use a loop to search the waveform data for the global minimum, VMIN, and the associated time, t2.1.
3) Find the local maximum, V1MAX, and its associated time, t1p, in the data between the first point and t2.1. This is the time, t1p, of the first peak.
4) Find the most negative derivative, DMIN, the corresponding time, tDMIN, and the waveform value, VtDMIN, in the region of the first 25 points following t1p. The slope of the first descending limb is DMIN.
5) Define a line with the intercept V1MAX and slope of zero that is horizontal and tangent to the first peak. Define a second line with slope DMIN and intercept such that it passes through VtDMIN at tDMIN. Solve the two lines for their intersection point and its associated time, t1, which corresponds to the point where the rods exit the handle.
6) Find the maximum derivative, D2MAX, in the region of the first 25 points following VMIN, and its associated time, t2.2, and waveform value, Vt2.2.
7) Define a line tangent to the second inflection with slope D2MAX and passing through Vt2.2 at t2.2. Define a horizontal line tangent to VMIN. Solve for the intersection of these lines to find t2, the time corresponding to the ends of the rods. The travel time of the pulse through the exposed length of the rods is again \( t_\text{t} = t_2 - t_1 \) (Conservation & Production Research Laboratory n.d.).

**Figure 2.20** The TDR waveform (bottom) and its first derivative (top) with features identified by Baker and Allmaras (1990) (Conservation & Production Research Laboratory n.d.).
TDR shows great potential for application in bridge scour monitoring. It can measure the dynamic scouring process in real-time. TDR sensors can work in the various and severe field conditions. Signal analysis can be automated, which makes data interpretation fairly easy for the operation personnel. The details in exploring the potentials of TDR are presented in the subsequent chapters.
CHAPTER THREE

VALIDATION OF TIME DOMAIN REFLECTOMETRY FOR SCOUR MONITORING

The application of Time Domain Reflectometry (TDR) for scour measurements (monitoring) has been explored by a few researchers, such as Dowding and Pierce (1994), and Yankielun and Zabilansky (1999). Findings by these researchers show that TDR has great potential for real-time scour monitoring. However, there is no algorithm that can automatically analyze the TDR signals and determine scour depth. Additionally, more effort is needed to develop a robust and easily operable scour sensor.

This chapter investigates the potential of using a commercially available TDR moisture probe for taking scour measurements and develops an algorithm for TDR signal interpretation. Therefore, this chapter contains two parts. In the first part, the TDR moisture probe is tested in a simulated scour environment. In the second part, the signal interpretation methods are presented.

3.1 TDR Measurements of Laboratory Simulated Scour

In this section, the capability of a commercially available TDR probe to measure simulated scour in a laboratory setting was tested and evaluated. The TDR probe selected
was the CS605 TDR moisture probe, a product of Campbell Scientific Inc. This probe consists of 3 rods, each 30cm in length and 0.48cm in diameter, with a spacing between the outer rods of 4.5cm (Campbell Scientific Inc. 2008). The TDR 100 Time Domain Reflectometer was used as the pulse generator. The TDR probe was tested in tap water and saline water, using fine sand as the sediment.

3.1.1 Test Setup

3.1.1.1 Test Apparatus

A TDR CS605 moisture probe was selected as the device to evaluate the TDR principle for the measurement of scour. This probe is shown in Figure 3.1. It is connected to a RG58 coaxial cable, which is in turn connected to the TDR 100 pulse generator.

Figure 3.1 Photo of a TDR CS605 moisture probe (Campbell Scientific Inc. n.d.).
The TDR 100 Time Domain Reflectometer, as shown in Figure 3.2, is used for scour measurement. It can generate a pulse output with a rising time of less than 300 picoseconds, amplitude of 250 mV, and duration of 14 microseconds. The imbedded sampling device can sample and digitize the resulting reflection waveform for storage or analysis. Each waveform can have up to 2048 data points with a resulting resolution of 6.1 picoseconds (1.8 millimeters) (Campbell Scientific Inc. 2008).

![Figure 3.2 TDR 100 and data acquisition device.](image)

The digitized TDR waveforms are acquired through a software interface, PMTDR, (current version 1.6, Figure 3.3) developed by Bill Yu. Through this interface, an average of several waveforms (usually 3) can be obtained, which makes measurements in
noisy environments possible. This software is able to automatically determine the average dielectric constant and electrical conductivity of the testing materials along the rods.

![Figure 3.3 Screen shot of PMTDR.](image)

Two transparent polyvinyl chloride (PVC) cylinder tanks, as shown in Figure 3.4 and Figure 3.5, were used for the scour simulation tests. The larger tank (Figure 3.4) was used for the first test only. The rest of the tests mentioned in this dissertation were performed using the smaller tank (Figure 3.5) due to its easy operation compared to the larger one.
Figure 3.4 Larger cylinder tank used for scour simulation tests.

Figure 3.5 Small cylinder tank used for scour simulation tests.
3.1.1.2 Testing Protocol

The experimental setups for this study are shown in the previous Figures 3.4 and 3.5. The simulated scour/sedimentation tests were conducted in the two cylinder tanks. The TDR probe was installed in each tank with the aid of a fixture. The tank was first filled with water to a prescribed level. Dry sand (or other testing sediments) was then gradually poured into the tank. In the meantime, the water level was maintained at a constant height by draining the appropriate amount of water through the base of the tank (for the tank shown in Figure 3.4). For each specified sand layer thickness, the mass of sand used for the layer was recorded, from which the density of the sand layer was calculated. The thickness or height of the sand layer was measured using the ruler as shown in Figure 3.4 and 3.5. For each layer of soil, TDR signals were acquired. This process was continued until the tank was completely filled with sediment.

3.1.1.3 Testing Materials and Solutions

The ASTM standard, fine sand (Figure 3.6), was used as the sediment for the scour simulation tests. The results of a particle size distribution analysis on the fine sand is shown in Figure 3.7, from which it is determined to be a poorly graded sand (SP) according to the unified soil classification system (USCS).

In order to simulate saline river water, additional tests were also performed in tap water
mixed with dissolved 250ppm, 500ppm, and 750ppm Sodium Chlorite (NaCl).

Figure 3.6 Photo of fine sand.

Figure 3.7 Grain size distribution of fine sand.

3.1.2 Test Results

TDR waveforms obtained during the simulated scour tests in tap water are shown in
Figure 3.8. The TDR waveforms change systematically as the thickness of the sand layer increases. A close examination of the waveforms shows the existence of reflections at the water-sand interface. These observations demonstrate the ability of TDR to obtain scour measurements, which allow for further study of TDR for scour monitoring. The waveforms of Figure 3.8 were analyzed automatically, using PMTDR, to obtain the dielectric constants and electrical conductivities of the testing materials.

![Figure 3.8 TDR waveforms of simulated scour in tap water.](image)

The mass of the sand added and the thickness of the sand layer at each increment, along with the measured dielectric constants and electrical conductivities are shown in Table 3.1.
Table 3.1 Test records of simulated scour tests in tap water.

<table>
<thead>
<tr>
<th>Increment</th>
<th>Thickness (cm)</th>
<th>K_{a,m}</th>
<th>EC_{b,m}</th>
<th>Sand added</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sand</td>
<td>Water</td>
<td>mS/m</td>
<td>g</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>24</td>
<td>87.27</td>
<td>23.25</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>20</td>
<td>74.43</td>
<td>20.982</td>
</tr>
<tr>
<td>3</td>
<td>8</td>
<td>16</td>
<td>62.92</td>
<td>17.953</td>
</tr>
<tr>
<td>4</td>
<td>12.5</td>
<td>11.5</td>
<td>50.01</td>
<td>14.82</td>
</tr>
<tr>
<td>5</td>
<td>16</td>
<td>8</td>
<td>44.85</td>
<td>13.593</td>
</tr>
<tr>
<td>6</td>
<td>20.5</td>
<td>3.5</td>
<td>31.62</td>
<td>10.394</td>
</tr>
<tr>
<td>7</td>
<td>21.7</td>
<td>2.3</td>
<td>32</td>
<td>9.578</td>
</tr>
<tr>
<td>8</td>
<td>23.5</td>
<td>0.5</td>
<td>28.87</td>
<td>8.374</td>
</tr>
</tbody>
</table>

The measured dielectric constants and electrical conductivities are also presented in Figure 3.9 and 3.10. A linear relationship between the measured dielectric constant and the thickness of the sediment layer is observed in Figure 3.9. Similarly, a linear relationship between the electrical conductivity and the thickness of the sediment layer is observed in Figure 3.10.

![Graph showing linear relationship](image)

**Figure 3.9** $K_{a,m}$ versus thickness of the sand deposit.
The measured dielectric constants and electrical conductivities observed during scour simulation tests in saline water, i.e. 250ppm, 500ppm, and 750ppm NaCl solution, are shown in Figures 3.11 and 3.12. The test results in tap water are also presented in these figures for comparison. As can be seen, the linear relationships still exist, but with different slopes.
Figure 3.11 $K_{a,m}$ versus thickness of the sand deposit in saline water.

Figure 3.12 $EC_{b,m}$ versus thickness of the sand deposit in saline water.
3.2 Algorithms for TDR Signal Interpretation

From the measured dielectric constants and electrical conductivities shown in the previous section, it was found that there exists a linear relationship between these quantities and the sediment (fine sand) thickness. Therefore, from TDR measurements, the sediment thickness can be determined. Thus, the scour depth, i.e. the water depth minus the sediment thickness, can be obtained from TDR measurements.

In this section, the algorithms for determining sediment thickness (scour depth) from measured TDR signals (waveforms) are presented. Additionally, the electrical conductivity of water, dry density of the sediment, and porosity of the sediment are estimated from TDR measurements.

3.2.1 Algorithms based on Mixing Formulas

The water layer and sediment layer in a simulated scour test constitute a mixture system. The dielectric constant and electric conductivity of each component in the mixture system are known values. By applying the mixing formulas of dielectric constant or electrical conductivity to the mixture system, the dielectric constant and electrical conductivity of the system can be estimated from the properties of its components. In combination with
other formulas, information about the water and sediment can also be obtained. The analytical examples presented shown in this section are based on the test results from tap water with fine sand unless otherwise noted.

3.2.1.1 Mixing Formula for Dielectric Constant and its Application

Soil is a multiphase system composed of soil solids, water, and air. Birchak et al. (1974) presented a semi-empirical volumetric mixing model (Equation 3.1) relating the bulk dielectric constant of a mixture to its components.

\[
(K_{a,m})^\alpha = \sum_{i=1}^{n} \nu_i (K_{a,i})^\alpha
\]  

(3.1)

In this equation, \(\nu_i\) and \(K_{a,i}\) are the volumetric fraction and permittivity (dielectric constant) of each component, respectively. \(K_{a,m}\) is the dielectric constant of the mixture. The exponent \(\alpha\) is an empirical constant that summarizes the geometry of the medium with respect to the applied electric field. A value of \(\alpha\) equal to 0.5 is recommended for homogenous and isotropic soils (Birchak et al. 1974, Ledieu et al. 1986).

Apply the mixing formula, Equation 3.1, to the layered system shown in Figure 3.13, consisting of water and sediment, it can be seen that,
\[ L_1 \sqrt{K_{a,w}} + L_2 \sqrt{K_{a,bs}} = L \sqrt{K_{a,m}} \]  \hspace{1cm} (3.2)

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

**Figure 3.13** Schematic of the simulated scour/sedimentation test setup.

If the thickness of the sediment layer \( L_2 \), is assigned to the variable \( x \), then the thickness of water layer, \( L_1 \), is \( L-x \). Substituting \( L_1 \) into Equation 3.2 and normalizing both sides of the equation with \( \sqrt{K_{a,w}} \), the following equation (Equation 3.3) is obtained:
\[
\frac{\sqrt{K_{a,m}}}{\sqrt{K_{a,w}}} = x \left( \frac{\sqrt{K_{a,bw}}}{\sqrt{K_{a,w}}} - 1 \right) + 1 
\] (3.3)

This equation indicates that the square root of the measured bulk dielectric constant is linearly related to the sediment thickness. This equation also explains the linear relationship observed in Figure 3.9. The process of normalization also helps to reduce the potential effects of the measurement system on the results of the dielectric constant. Figure 3.14 plots the ratio \( \frac{\sqrt{K_{a,m}}}{\sqrt{K_{a,w}}} \) versus the sediment thickness from the measured data. Also shown in the plot is the data from the theoretical predictions. For the predicted curve, the \( \sqrt{K_{a,bw}} \) (an average value 26.5 was used) value was estimated from Topp’s equation with the density of the sand layers obtained from experimental records. The measured dielectric constants predicted by Equation 3.3 closely matches that from the actual measurements, which indicates that the mixing formula (Equation 3.1) is valid for studying the layered system during the scour/sedimentation process. Equation 3.3 can also be used to estimate the sediment thickness from the TDR measured dielectric constant of the mixture. Figure 3.15 plots the estimated thickness of the sand layer versus the thickness measured by use of a ruler.
Figure 3.14 Measured and predicted $\sqrt{K_{a,m}}/\sqrt{K_{a,w}}$ versus sediment thickness.

Figure 3.15 Thickness of sand layer estimated by the dielectric constant mixing formula.
From Equation 3.2, $K_{a,bs}$ can be solved as follows

$$K_{a,bs} = \left( \frac{L}{x} \sqrt{K_{a,m}} - \frac{L - x}{x} \sqrt{K_{a,w}} \right)^2$$  \hspace{1cm} (3.4)

The mixing formula (Equation 3.1) can also be applied to the saturated sediment layer using,

$$n \sqrt{K_{a,w}} + (1 - n) \sqrt{K_{a,s}} = \sqrt{K_{a,bs}}$$ \hspace{1cm} (3.5)

where $K_{a,bs}$ is the dielectric constant of the saturated sand layer, $n$ is the porosity, and $K_{a,s}$ is the dielectric constant of the soil solid and is typically in the range of 3 to 7 (a value of 4 is used for $K_{a,s}$ in this study).

The bulk dielectric constant, $K_{a,bs}$, of saturated sand can be estimated from either Equation 3.4 or 3.5 by substituting the measured values from experimental tests. $K_{a,bs}$ can also be estimated using Topp’s equation with known porosity. The porosity of the sand layer can be estimated from measured quantities assuming a specific weight of 2.65. The estimated dielectric constant of the sand layer for the scour tests in tap water using these different approaches is compared in Figure 3.16.
Figure 3.16 Estimation of $K_{a,b}$ for saturated sediments from TDR measurements.

From Figure 3.16, it can be seen that the dielectric constants of saturated sand obtained by three different approaches are similar to each other. Values determined from Equation 3.4 vary from the results of the other two methods at one point (15cm layer thickness). This might be caused by the error in the porosity estimation due to the uneven sediment surface. As in most cases, the porosity (volumetric water content) of the sediment is unknown. Topp’s equation is the most practical equation to apply to estimate the bulk dielectric constant of saturated sand. With this information, the physical properties of the sediments including the porosity, water content, and density can be estimated.
3.2.1.2 Mixing Formula for Electrical Conductivity and its Application

The electrical resistance of a hollow cylinder filled with homogeneous material is related to its electrical conductivity and geometry by Equation 3.6 (Ramo and Whinney 1965).

\[
R = \frac{1}{2\pi L \times EC} \ln \left( \frac{b}{a} \right)
\]  

(3.6)

where \(a\) and \(b\) are the inner and outer diameter of the cylinder respectively, \(L\) is the length of the cylinder, and \(EC\) 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 to each other. The total resistance can thus be calculated using the electrical circuit principle:

\[
\frac{1}{R} = \sum_{i=1}^{n} \frac{1}{R_i}
\]

(3.7)

Substituting Equation 3.6 into Equation 3.7,

\[
EC = \frac{1}{L} \sum_{i=1}^{n} L_i EC_i
\]

(3.8)

The bulk electrical conductivity is thus related to the electrical conductivity and geometry
of the constituent layers by Equation 3.8, which can be regarded as the mixing formula for the electrical conductivity.

For a two-layered system consisting of water and saturated sediment layer (Figure 3.17), the mixing formula for electrical conductivity can be written as:

\[ EC_{b,w}L_1 + EC_{b,s}L_2 = EC_{b,m}L \]  \hspace{1cm} (3.9)

where \( EC_{b,w} \) is the electrical conductivity of water, \( EC_{b,s} \) is the electrical conductivity of saturated sand layer (sediment), \( EC_{b,m} \) is the measured overall electrical conductivity of the water and saturated sand layer system, \( L_1 \) is the thickness of water, \( L_2 \) is the thickness of sediment, and \( L \) is the total water and sediment thickness.

Figure 3.17 Schema of TDR electric field distribution for deducing the mixing formula for electrical conductivity (Yu and Yu 2006).
Equation 3.9 can be normalized by dividing both sides by $\sqrt{EC_{b,w}}$, i.e.:

$$\frac{EC_{b,m}}{EC_{b,w}} = \left( \frac{EC_{b,bs}}{EC_{b,w}} - 1 \right) \frac{x}{L} + 1 \tag{3.10}$$

Archie (1942) introduced the concept of the formation factor, $F$, which is defined as the ratio between the conductivity of pore fluid, $EC_1$, and the measured soil conductivity, $EC_m$, in a direct current (DC) or low frequency alternating current (AC) field.

$$F = \frac{EC_1}{EC_m} \tag{3.11}$$

The formation factor, $F$, can be related to the porosity, $n$, of the material by Equation 3.12 as presented by Arulandan and Sybico (1992).

$$F = n^{-f} \tag{3.12}$$

where $f$ is the form factor. A value of 1.2 for $f$ is recommended for fine sandy material such as Nevada sand. From Equation 3.11 and 3.12,

$$\frac{EC_{b,bs}}{EC_{b,w}} = \frac{1}{F} = n^f \tag{3.13}$$
Substituting Equation 3.13 into 3.10,

\[
\frac{EC_{b,m}}{EC_{b,w}} = \left( n' - 1 \right) \frac{x}{L} + 1
\]  

(3.14)

Equation 3.14 shows that the measured electric conductivity normalized by the electric conductivity of water is approximately linearly related to the sediment thickness. Figure 3.18 is a plot that validates this observation. Also shown in the plot is the theoretically predicted relationship obtained directly from Equation 3.14, where the porosity, \( n \), was obtained from experimental data, and a value of 1.2 was used for the factor \( f \). This comparison indicates that the mixing formula (Equation 3.14) for the electrical conductivity of the sediment system is valid.

Figure 3.18 Comparison of the measured and predicted relationship between \( EC_{b,m} / EC_{b,w} \) and sediment layer thickness.
The electrical conductivity mixing formula (Equation 3.14) can also be used to estimate the thickness of the sand layer using the assumed $f$ and calculated porosity of the sand layer. The estimated sediment thickness is shown in Figure 3.19. The estimated results match the physical measurements very well, which indicates the validity of using the electrical conductivity mixing formula for scour measurements.

![Figure 3.19 Estimated thickness of the sand layer by use of the electrical conductivity mixing formula.](image)

The electrical conductivity of water, $EC_{b,w}$, can be obtained from Equation 3.14, i.e.:
\[ EC_{b,w} = \frac{EC_{b,m}}{n_f \frac{x}{L} + \frac{L-x}{L}} \]  

(3.15)

where the porosity, \( n \), sediment layer thickness, \( x \), and the total length of the water layer and sediment layer, \( L \), can be estimated from measurements. Results of the calculated electrical conductivity of water are compared with those of the actual measurements by the electrical conductivity meter (Figure 3.20). It shows that the estimation of the electrical conductivity of water is reasonably accurate.

\[ \text{Conductivity of Water (ms/m)} \]

\[ \text{Thickness of Sand Layer (cm)} \]

**Figure 3.20** TDR estimated electrical conductivity of water versus the actual values.

### 3.2.2 Empirical Equation Procedures for Application in Bridge Scour Monitoring

The test results for the dielectric constant and electrical conductivity are summarized in
Figures 3.21 and 3.22, respectively. The measured overall dielectric constant is normalized by the dielectric constant of saline water. The plots shows that most of the measurement data fall within a similar trend after the thickness of the sediment layer is normalized by the total length of the probe. Since the dielectric constant of river water is not strongly influenced by the electrical conductivity of the river water (in the range of consideration), it can be used as a reference to estimate the scour thickness. Subsequently, the electrical conductivity of river water can be estimated. The idea is summarized to generate the design plots and application procedures discussed below.

![Graph](image)

**Figure 3.21** $\sqrt{K_{a,m}} / \sqrt{K_{a,w}}$ versus the normalized thickness of the sediment layer.
Design Plot and Procedures for Application in Bridge Scour Monitoring

Two general linear equations were obtained by fitting the experimental data shown in Figure 3.21 and 3.22, i.e.,

\[
\frac{\sqrt{K_{w,m}}}{\sqrt{K_{w,w}}} = -0.43x_r + 1 \quad (3.16)
\]

\[
\frac{EC_{b,m}}{EC_{b,w}} = -0.67x_r + 1 \quad (3.17)
\]

where \(x_r\) is the ratio of the thickness of the sand layer to the total thickness of the water.
and sand. The other symbols represent the same physical quantities discussed in previous sections.

**Figure 3.23** Design diagram for determining the sediment thickness and water conductivity
By using these two empirical equations and referring to the fact that the dielectric constant of water is approximately constant (81), the following procedures were designed to obtain information on the scour status:

Step a) Determine the scour depth, $x$, from the measured bulk dielectric constant $K_{a,m}$ (Figure 3.23a);

Step b) Determine the electrical conductivity of the river water, $EC_{b,w}$, from the obtained scour depth and the measured bulk electrical conductivity (Figure 3.23b);

Step c) Determine the dielectric constant of the sediments using Equation 3.4 based on the estimated scour depth; dry density of the sediments can therefore be calculated with the known specific gravity of the sediments.

Figure 3.24 and 3.25 show the results of the calculated thickness of the sand layer and the electrical conductivity of saline water following the application procedures outlined above. The estimated values closely match those from actual measurements, within around a 5% error range. The dry density of the sediments is determined from step c, which is shown in Figure 3.26. The results are typically satisfactory with the exception of a few points. These exceptional points correspond to test results from very thin sediment layers, which tend to generate errors in the TDR signal interpretation and direct measurements of the thickness. The fact that the sediment surface is not flat, particularly with thin sediment layers, leads to error in the determination of the density of...
the sediment layer.

These results indicate that TDR can accurately be used to determine the scour depth and obtain the status of the sediments with a simple application algorithm. As this method normalizes the effects of the electrical conductivity of river water, it can be applied to various river conditions. The estimated electrical conductivity of river water can be used, for example, as an environmental quality indicator for contaminant detection. Potential application in this aspect can further be explored by incorporating more advanced analytical methods.

Figure 3.24 TDR estimated depth of sediment versus the actual sediments thickness.
Figure 3.25 TDR estimated electrical conductivity of water versus the actual electrical conductivity.

Figure 3.26 TDR estimated dry densities of sediments versus the actual dry densities.
3.2.3 Scour Estimate Based on Water-Sediment Interface Reflection

The pulse generated by the TDR tester travels in the coaxial cable and the probe in the form of an electromagnetic wave. A portion of the traveling waves are reflected when there is a change in the impedance. The most challenging part of TDR signal analysis is to locate these reflections. For simplification, all the analyses in this section are based on the assumption that the testing probe is submerged in the water. Therefore, the reflections of interest are at the probe head, water-sediment interface, and at the end of the probe. In the PMTDR software, a well established automatic algorithm is used to locate the reflections at the probe head and end of the probe. Compared to the reflection at the water-sediment interface, these two reflections are fairly easy to locate. PMTDR is not able to locate the reflection at the water-sediment interface. In this section, an algorithm is developed to locate the reflection at the water-sediment interface, which can be used to estimate scour depth.

There are two generally accepted methods (Topp et al. 1982, Baker and Allmaras 1990) for locating the reflections at the probe head and end. These two methods are illustrated in Figure 3.27. Both of these methods pick the first local maximum point as the reflection at the probe head. The Topp et al. method uses two linear sections of the TDR waveform, while the method by Baker and Allmaras proposes the intersection of the
horizontal line tangent to the local minimum point and the line tangent to the local maximum slope point with the local maximum slope as the second reflection point.

Difficulties have been encountered when applying these two methods:

Although it could give satisfactory results in some case, it is more prone to be influenced by the operator’s personal preference. Besides, the time and effort needs in the process of manual operating the cursor under field condition are intolerable (Drnevich, Yu, and Lovel 2003).

![Figure 3.27 Two methods to manually identify the second reflection point.](image)

Drnevich et al. (2001) developed an algorithm that could locate the two reflection points under common conditions automatically and satisfactorily. This algorithm is also applicable for locating the two reflections for scour tests. In this study, an algorithm has been developed to locate the third reflection point (at the water-sediment interface) as
well the other two reflection points. The flow chart for this algorithm is shown in Figure 3.28. Figure 3.29 shows an example of using this algorithm to calculate scour depth. Figure 3.30 presents an example of scour depth determined using this algorithm.

**Figure 3.28** Algorithm for determining scour depth.
Figure 3.29 An example of locating reflection points using the algorithm presented in Figure 3.27.

Figure 3.30 TDR measured scour depth based on reflection detection method.

From Figure 3.30, it can be seen that the TDR measurements for the results of fine sand in saline water is much more accurate than the results of fine sand in tap water. This is caused by the complexity of the reflection detection in the latter case. The section of the
TDR probe exposed in air cause an extra reflection at the air-water interface. The length of the exposed section is fairly short (around 7cm), which makes the detection of the reflection at the air-water interface challenging. When the scour depth is very small, the reflection at the water-sediment interface is close to the reflection at the probe head and the air-water interface. This makes the detection at this condition more complex due to the interference of the reflected waves. Therefore, TDR measurements for shallow scour are not as accurate as for deep scour. To minimize this effect, the TDR scour sensor should be submerged in water.

3.3 Summary

In this chapter, the TDR measurements of simulated scour with fine sand in water were performed to evaluate the potential for scour monitoring. Three methods, mixing formulas, empirical equations, and reflection detection, have been presented to determine the scour depth from the TDR waveforms. Mixing formulas and empirical equations are easier to operate because only two reflection points at the probe head and at the end are necessary. Besides, turbidity makes the reflection at the water-sediment less distinctive. More test data are required to conclude that the general empirical equations are applicable to different field conditions.
CHAPTER FOUR

TDR SCOUR MEASUREMENTS IN VARIOUS ENVIRONMENTS

In Chapter 3, the application of TDR for scour measurement was evaluated by simulated scour tests with fine sand in fresh and saline water. Algorithms for signal interpretation were presented and evaluated with the test results. It is shown that TDR measurements of scour are accurate and the mixing formulas and empirical equations for TDR signal interpretation are applicable and easy to implement. However, further evaluations of the analytical algorithms are necessary to make it applicable in various field conditions.

In this chapter, the empirical scour estimation algorithm is evaluated by different simulated scour experiments. The effects of river conditions (including the salinity of river water, water level, suspended sediments, and trapped air bubbles) on TDR measurements are also studied.

4.1 Measurements of Scour in Different Sediments

The empirical TDR scour estimation equations (3.16) and (3.17) are based on the test results from fine sand. Verification of these equations on different types of soils is needed to determine their range of application. For this purpose, laboratory simulated
scour tests using various soils were performed in a transparent cylindrical tank. The various soils included fine sand, coarse sand, gravel, and a mixture of coarse sand and gravel. A TDR sensor was placed vertically in the center of a 30.5cm deep cylindrical tank. The TDR sensor was totally immersed under water. A TDR measurement was taken at the beginning of each test. The testing soils were gradually poured into the tank. TDR signals were acquired corresponding to different thickness of sediment layer. The thickness of the sediment layer was measured using a ruler. This process was continued until the cylinder was filled with soil. The test results shown in Chapter 3 are also presented in this chapter as a reference for comparison.

4.1.1 Test Materials

A particle size distribution (sieve) analysis was performed on all test materials. Photos and the grain size distribution of these testing materials are shown in Figure 4.1. According to the sieve analysis results, the fine sand and coarse sand used were classified as poorly graded sand (SP), while the gravel was classified as poorly graded gravel (GP) using the USCS.

4.1.2 Test Results

Test results from TDR measurement were organized in the format of Equation 3.16 and
3.17, and plotted in the following figures, Figures 4.2 through 4.5.

a) Photo of fine sand

b) Grain size distribution of fine sand

c) Photo of coarse sand

d) Grain size distribution of coarse sand

e) Photo of gravel

f) Grain size distribution of gravel

**Figure 4.1** Photo and grain size distribution of testing materials.
Figure 4.2 Normalized TDR measurements for fine sand.

Figure 4.3 Normalized TDR measurements for coarse sand.
4.1.3 Accuracy of TDR Scour Equations for Various Soils

It is clear from the above figures that different soils have different regression lines. This
can be explained by Equations 3.3 and 3.14. The slope of the regression curve is a function of the soil properties (mainly the porosity). For a specific soil and water condition, the linear relationship holds reasonably well. Under the natural water environment, the electric conductivity of water varies due to turbidity, pollution, and other factors. To investigate the effects of such factors, simulated scour tests were conducted using water with different sodium chloride (NaCl) concentrations; the variation of salinity partly accounts for the variations of the electrical conductivity in a stream. Figures 4.2 through 4.5 show the results of this investigation. As can be seen from these figures, the TDR measured dielectric constant is not significantly affected by the change in the electrical conductivity of the water. Data points for the bulk dielectric constant are less scattered than those of the bulk electrical conductivity (Figures 4.2 through 4.5).

Applying Equation 3.1 to the saturated sediment, the following equation is obtained,

\[ n\sqrt{K_{a,w}} + (1-n)\sqrt{K_{a,s}} = \sqrt{K_{a,bs}} \]  \hspace{1cm} (4.1)

where \( K_{a,bs} \) is the dielectric constant of the saturated sediment, \( K_{a,w} \) is the dielectric constant of water, \( n \) is porosity, and \( K_{a,s} \) is the dielectric constant of the soil solid. \( K_{a,s} \) is typically in the range of 3 to 7 (a value of 6 is used for \( K_{a,s} \) in this study). During the
scour simulation test for each soil, the dielectric constant of water was measured by the first TDR measurement and the dielectric constant of the saturated sediment was measured by the last TDR measurement. By assuming a constant $K_{a,s}$ of 6 for the different soils, the average porosity for each soil was solved using Equation 4.1 as follows,

$$n = \frac{\sqrt{K_{a,bs}} - \sqrt{K_{a,s}}}{\sqrt{K_{a,w}} - \sqrt{K_{a,s}}}$$

(4.2)

With a known porosity for each soil, the slope of the design Equations 3.3 and 3.14 can be calculated. The slope of the lines from the theoretical calculation and those from fitting the actual measured data are shown in Table 4.1.

The results of Table 4.1 show that the theoretically predicted slope from the scour estimation equations closely match that obtained by linear regression of the testing data. Using the theoretically predicted slope from the design equations, the predicted thickness of the sediment layer and that of the physically measured result is plotted in Figure 4.6 and 4.7. Scour depth can be easily obtained by subtracting the predicted thickness of the sediment layer from the total length of the TDR probe. It can be seen from Figure 4.6 that all of the predicted normalized thicknesses are within a 5% percent error range, which means, for example, that the absolute error for a 30.5cm length probe is less than
1.5cm. This accuracy is sufficient for practical aspects. However, TDR measurements based on the electrical scour estimation equation (3.17) are far less accurate than the results based on the dielectric scour estimation equation (3.16). This is caused by the salt concentration, which has a greater effect on the electrical conductivity than the dielectric constant.

Table 4.1 Theoretically predicted and empirically fitted slope of the design equations.

<table>
<thead>
<tr>
<th></th>
<th>Average porosity</th>
<th>Slope of equation 3.3</th>
<th>fitted slope of equation 3.3</th>
<th>Slope of equation 3.14</th>
<th>fitted slope of equation 3.14</th>
</tr>
</thead>
<tbody>
<tr>
<td>fine sand</td>
<td>0.417</td>
<td>-0.424</td>
<td>-0.434</td>
<td>-0.670</td>
<td>-0.667</td>
</tr>
<tr>
<td>coarse</td>
<td>0.422</td>
<td>-0.421</td>
<td>-0.421</td>
<td>-0.666</td>
<td>-0.598</td>
</tr>
<tr>
<td>gravel</td>
<td>0.569</td>
<td>-0.314</td>
<td>-0.318</td>
<td>-0.511</td>
<td>-0.548</td>
</tr>
<tr>
<td>mix</td>
<td>0.356</td>
<td>-0.468</td>
<td>-0.489</td>
<td>-0.730</td>
<td>-0.768</td>
</tr>
</tbody>
</table>

Figure 4.6 TDR measurements (dielectric constant) versus physical measurements (cm ruler) of thickness of sediment layer for all sediments.
4.2 Scour Monitoring in Water with High Electrical Conductivity

The electrical conductivity of water has a significant influence on TDR signals. TDR signals are attenuated faster in water with a high electrical conductivity. When the water conductivity is above a certain value, it becomes impossible to obtain a complete TDR waveform. Therefore, no scour information can be determined from the signal. The workable length of the TDR probe and the quality of the TDR signals are determined
by the value of the electrical conductivity of water. A special design of a TDR sensor is
needed for it to work in a tidally affected or brackish environment.

A concentration of 2000ppm NaCl solution was prepared to simulate a sea water
environment. The regular TDR sensor is not applicable in water with such a high
electrical conductivity. To reduce the signal attenuation, the center probe of the regular
TDR sensor was insulated using commercially available shrinking tubes. This insulated
TDR sensor is shown in Figure 4.8. A similar scour simulation test procedure as that of
the previous section was followed. The measured TDR signals are shown in Figure 4.10,
zoomed in on portion of interest. It was found that the insulation layer surrounding the
center probe reduces the signal attenuations and ensures clear TDR signals under even
high salinity conditions. This insulated TDR sensor still has a high enough sensitivity to
detect the scouring process as can be seen from the TDR waveform responses in Figure
4.9. By analyzing the TDR waveforms, the dielectric constant at different scour depths
can be obtained. A good linear relationship, similar to that of an uninsulated probe is
observed (Figure 4.10).
**Figure 4.8** Insulated TDR sensor.

**Figure 4.9** TDR waveforms during scouring process by insulated probe.
The dielectric constants obtained from the coated TDR probe are related to the dielectric constant of the testing material and coating material by Equation 4.3 (Ferré et al. 1996).

\[ K_c^n = wK_{coating}^n + (1-w)K_a^n \]  

(4.3)

In this equation, \( K_c \) is the dielectric constant by the coated TDR probes, \( w \) is a weighting function, \( K_{coating} \) is the dielectric constant of the coating, and \( K_a \) is the dielectric constant of the testing materials. Persson et al. (2004) calibrated their probe using \( n \) equal to -1.

According to the measurements of saline water by the uncoated probe, the dielectric constant of the saline water (2000ppm solution) can be assumed to be 86 and the
dielectric constant of the saturated sediment can be assumed to be 26. The dielectric constant of the water sand sediment mixture can be calculated by using the mixing formula. The dielectric constant of the shrink tube (polyolefin) can be chosen as 2.27 (Tyco Electronics 2008). The best fit of $w$ from Equation 4.3 is 0.037. The dielectric constants predicted from Equation 4.3 are presented in Figure 4.11 and compared with the TDR measured dielectric constant obtained from the coated probe. It is shown that the theoretically predicted dielectric constants match the measured values very well. Thus, Equation 4.3 can be used to describe the dielectric constant obtained from the coated probe and that of the real value of the testing materials.

![Figure 4.11 Predicted dielectric constant versus that measured by coated probe.](image-url)
4.3 Scour Monitoring in Turbulent Flow

Flow at scour sites sometimes involves a complex turbulent flow, which evolves air entrainment and high sediment concentration, especially during floods. Therefore, the performance of the TDR sensor under these turbulent flow conditions needs to be evaluated.

4.3.1 Effect of Air Entrainment

An air bubble generation tube was fabricated to generate air-entrained water. Several holes were opened on the tube and the tube was connected to an air valve. During the scour test (Figure 4.12), the air valve was opened and the amount of air bubbles generated was controlled by adjusting the air pressure. Two different air bubble generation rates were used and are referred to herein as low and high. The effects of air bubble on the TDR waveforms are shown in Figure 4.13. By visual inspection of TDR waveforms in Figure 4.13, the effect of air bubbles on the TDR signal was minimal for both low and high air bubble concentrations. The results of the TDR measured dielectric constant with and without air entrainment are compared in Figure 4.14. It can be seen that the existence of air entrainment does have a slight influence on the measured dielectric constant. This effect increases as the air bubble concentration increases.
However, considering the range of air bubble concentration that is likely in the field, which lies in the low end of our simulations, the air entrainment effect on TDR scour measurement is negligible from practical considerations.

Figure 4.12 Scour simulation with air entrainment.

Figure 4.13 Effects of air entrainment on the TDR waveform.
Suspended solids are another potential factor affecting the performance of the scour monitoring system. For example, suspended sediments tend to attenuate the ultrasonic signals. A “hydrometer” test was performed to study the effect of suspended sediments on TDR measurements. In this procedure, 50g of sandy soil was mixed with water. The soil slurry was placed into a standard cylinder for hydrometer testing. A similar procedure to that of the hydrometer test was followed, except that no dispersing agent was added to the solution. After shaking, the cylinder containing the soil slurry was placed upright onto a desk. A TDR sensor was place into the cylinder and monitoring of
The dielectric constant was immediately started. The test setup is shown in Figure 4.15. The measured dielectric constant of the solution along with time is also shown in Figure 4.16. It can be observed from the test that the dielectric constant of the solution increased from 90.6 in the beginning to 92.2 in the end. At the end of monitoring, all the soil particles settled and the solution became clear. A similar test was repeated with 100g of soil. This time, the dielectric constant of the solution increased from 90.0 to 94. This shows that a higher concentration of sediments has a slightly larger influence on the TDR measurement. The differences in the final values of the two tests might be caused by the change of electrical conductivity due to the dissolution of salt minerals contained in the soil particles. Such effects should be minimal with use of a coated probe as discussed in the previous section of this dissertation.
4.4 Scour Monitoring in Water with Varying Water Level

4.4.1 Varying Water Level

The water level in a river and/or tidal environment may vary with the seasons. The scour estimation equations in the previous sections are valid when the sensor is totally submerged in water. However, it is possible that part of the probe will be exposed to the air due to the fluctuation of the water level. A simulated scour test was conducted with part of the TDR probe exposed to the air (Figure 4.17). With a known length of probe exposed to the air, the measured dielectric constant of water and the sediments can be easily calculated by the developed automatic algorithm. A screen shot of the waveform
analysis is shown in Figure 4.18. The air-water interface can be easily detected since it is the first peak in the waveform. Once this is determined, the remaining procedure for scour depth estimation is similar to that when the probe is completely submerged.

Figure 4.17 Scour simulation with part of the sensor exposed to the air.

Figure 4.18 Screen shot of waveform analysis.
4.4.2 Dry scour

In some cases, the river bed might be completely dry. Then the TDR sensor is surrounded by only two layers of materials: air and sediments. In this case, although no scour would happen, scour detection is used to find the length of probe exposed in the air. A dry scour simulation test was performed. The same tank that was used in the wet scour simulation test was also used in this test. A wet sand with a 6% water content was used to simulate the sediment. A procedure similar to the wet scour simulation was followed. The measured TDR waveforms are shown in Figure 4.19. The air-wet sand interface was determined using the method presented by Siddiqui and Drnevich (1995). Thus, the length of probe in the air (and subsequently the dry scour depth) could be calculated. The dry scour depth obtained by TDR measurement is shown in Figure 4.20. The reflection coefficient at air/wet sand interface is small, which makes it difficult to accurately locate the interface reflection. Therefore, the accuracy of the TDR measurements could be affected.
Figure 4.19 Waveforms of dry scour in wet sand.

Figure 4.20 Dry scour depth measured by TDR probe.
4.5 A Comparison of TDR and Ultrasonic Methods

4.5.1 Background of Ultrasonic Method

The configuration of a typical ultrasonic testing system is shown in Figure 4.21. The traditional method of ultrasonic testing is called pulse echo. In the pulse-echo system, the transmitting transducer introduces a wide-band acoustic signal into the test object. The pulse propagates in the material and is scattered or reflected by the interfaces or inhomogeneities within the object. Because of a large acoustic contrast, the interface between water and sediment will cause a large amount of acoustic energy to be scattered or reflected. The reflections are picked by the receiving transducer where the returning signal can be displayed as amplitude versus time (an A-scan). The depth of the interface can be determined by sending the impulse on the surface of the water and recording the transit time between the pulse reflections. A new testing method called direct-sequence, spread-spectrum, ultrasonic evaluation (DSSSUE) was recently introduced. This new method has the advantages of better sensitivity and larger scan area compared to the traditional method. More details about the ultrasonic method can be found in the literature (Rens et al. 1997). A typical signal recorded during application of the ultrasonic method for scour measurement is shown in Figure 4.22.
Figure 4.21 Schematic of a typical ultrasonic testing system.

Figure 4.22 A typical ultrasonic signal.
4.5.2 Theory and Application Procedure of Ultrasonic Method for Scour Detection

The application of the ultrasonic method for scour detection is based on determining the reflections at the water-sediment interface. Ultrasonic waves are reflected at interfaces where there is a difference in acoustic impedances of the materials on each side of the boundary. This difference in acoustic impedance is commonly referred to as the impedance mismatch. The greater the impedance mismatch, the greater the percentage of energy that will be reflected at the interface or boundary between one medium and another (NDT Resource Center webpage 2008). The reflection coefficient is given by Equation 4.4

\[ R = \left( \frac{Z_2 - Z_1}{Z_2 + Z_1} \right)^2 \]  \hspace{1cm} (4.4)

where \( Z_1 \) and \( Z_2 \) are the acoustic impedance of the materials on each side of a boundary.

The acoustic impedance \( Z \) of a material is defined as the product of the density \( \rho \) and acoustic velocity \( V \) of that material (Equation 4.5).

\[ Z = \rho V \]  \hspace{1cm} (4.5)
The compression wave in water is 1482 m/s at 20°C. The acoustic impedance is $1450 \times 10^2$ g/cm²/s for water and it ranges from 2000 to approximately $4000 \times 10^2$ g/cm²/s for silty clay to sandy gravel (Hamilton 1970). The difference in acoustic impedance will cause appreciable reflections at the water-sediment interface. The location of the interface, which is a direct measure of scour depth, can be determined by analyzing the travel time of the reflected signals.

### 4.5.3 Laboratory Test for Comparing TDR Method and Ultrasonic Methods

#### Experimental Setup

Simulated scour/sedimentation tests were conducted in a cylindrical tank. Figure 4.23 shows the experimental setup for this study. Both the ultrasonic sensor and the TDR sensor were installed and connected to their respective testing electronics. A mixture was prepared with coarse sand and gravel mixed at a 1:1 mass ratio. The tank was first filled with water of a 500ppm salt concentration to a prescribed level just under the probe head. The dry mixture was then gradually poured into the tank. The water level was maintained constant by draining the appropriate amount of water through the base of the tank. At each specified sand layer thickness, the mass of sand placed for that layer was recorded. From this, the density of the sand layer was calculated. TDR and ultrasonic signals were acquired at each depth of sediment deposit. This process proceeded until
the mixture completely filled the tank. Figure 4.24 shows variations of the TDR and ultrasonic signals with the sedimentation process. Both the TDR and ultrasonic signals change systematically with the scour/sedimentation process.

Figure 4.23 TDR probe, ultrasonic transducer, and the experimental tank.
Figure 4.24 a) Variations of TDR signals with scour depth; b) Variations of ultrasonic signals with scour depth.
4.5.4 Experimental Results and Analysis

The analysis of TDR measurements followed the newly developed procedures outlined in the earlier part of this chapter. The scour depths were directly estimated from the TDR measured dielectric constant. The measured dielectric constant was also used to estimate the dielectric constant of the sediment, from which the porosity and density of the sediment were determined. The electrical conductivity measured from the same TDR signal was used to estimate the electrical conductivity of the water.

The analyses of ultrasonic measurements were based on picking the travel time difference of ultrasonic reflections. Figure 4.24b has shown that the travel time for ultrasonic reflections was closely related to the depth of the water-sediment interface. The travel time was determined by picking the peaks in the recorded signal. This was the round trip travel time between ultrasonic transducer and the surface of the sediments. The distance of the ultrasonic transducer to the surface of the sediment, which was also the thickness of the water layer for the ultrasonic transducer located at the surface of the water, was then calculated with the speed of the ultrasonic wave in the water.

The measured scour depth by both the TDR and ultrasonic methods are presented in Figure 4.25. The results by both methods are compared with the results of direct
measurements. Results show that both the TDR method and ultrasonic method can accurately estimate the scour depth. But the trends of the slight change in accuracy for both methods are different. TDR is more accurate when the thickness of the water layer (or distance to the surface of scour) is thicker. The ultrasonic method, however, is more accurate when the water layer thickness is thinner. The increased accuracy of TDR for larger water layer thickness is attributed to the improved accuracy in determining the reflection points under longer travel time. The observed trend for the ultrasonic method is attributed to the fact that there is a lesser amount of attenuation and scattering of the ultrasonic signal at shorter distances; thus, reflections can more precisely be determined.

Two different equations are used for scour depth estimation based on TDR measurements. These include the use of Equation 3.3 by assuming a dielectric constant of 4 for soil solids (denoted as TDR method 1) and the use of the general Equation 3.16 (denoted as TDR method 2). The TDR method 1 has relatively better performance than method 2 in this case. This is attributed to the fact that a mixture of coarse sand and gravel was used in this study, while the parameters of Equation 3.16 were derived from measurements in fine sand. Thus determination of parameters embracing a wide range of sediment materials is warranted for improved accuracy in using the general equation.
The electrical conductivity of water can be estimated from the TDR method by use of Equation 3.14 (\(f = 1.2\)). The calculation results are shown in Figure 4.26 and compared with the results from an electrical conductivity meter. There is reasonable agreement between the TDR estimates and the electrical conductivity meter measurements. Comparison is not available for the electrical conductivity meter measurement at the final step because there is no water layer at that step.
The dry density of the sediments is determined from step c of the newly designed TDR method application procedure. The results are shown in Figure 4.27. The dielectric constant of the soil solid, $K_{a,s}$, is assumed to be 4 and the specific gravity of the soil solids is assumed to be 2.65. Also shown in the figure is the dry density by direct measurement. The comparison indicates that the measured density of the sediment by the TDR method is accurate.

Figure 4.26 Prediction of electrical conductivity of water versus depth.
4.5.5 Comparison of TDR and Ultrasonic Methods

This study indicates that both the TDR and ultrasonic methods can provide accurate measurement of scour depth. The TDR system is advantageous in that it is inexpensive and amenable to automation. These are desirable for deployment of a real time scour monitoring and surveillance system. The ability of real time surveillance is important since the most severe scour typically happens near the peak flood discharge, which poses a big threat to the safety of bridge structures. As sediments deposit in the scour hole during flood recession, post flood measurement might not truly describe the severity of historical scour during the flooding process. The application procedures for TDR scour
measurement developed in this dissertation, can measure the scour depth with ease. Information on the sediment status (density) and water conditions (electrical conductivity) can be obtained simultaneously. These could be used to enable a mechanistic understanding of the scour phenomena. However, the accuracy of TDR can be affected by the electromagnetic interference and signal attenuation in the cable length. In addition, the TDR sensor only measures scour at a given point. Multiple TDR probes are needed to map the scour hole shape. This requires the designed field TDR probes to be rugged and inexpensive. The deployment of the TDR probes also needs to be well planned.

The ultrasonic method is usually used for post-event scour measurement. Coupling the ultrasonic transducer with water is needed, which requires the ultrasonic transducer to be maintained below the water surface. The ultrasonic method is also a local measurement. However, as it is a non-intrusive technology, the ultrasonic transducer can be moved to determine the shape of the river bed after a scour event. With the progress in ultrasonic signal processing (such as the new DSSSUE testing method), it is possible to scan a large area from a single test. The interpretation of the ultrasonic signal can be challenging, especially for complex river bed territories. Experience from this research indicates that there could be a significant amount of background noise in the ultrasonic signal. Experience in ultrasonic signal analysis is needed to ensure a sound interpretation of the
measurement results.

4.6 Summary and Conclusions

The development of an instrument for automatic real time scour monitoring under field conditions is a pressing task for the research community. In this chapter, the CS605 TDR probe was tested and evaluated in simulated scour tests under various conditions. TDR measurements of simulated scour show that the dielectric constant based scour estimation is accurate for different types of sediments and different river conditions. The TDR sensor and algorithm works reasonably well in measuring scour under high electrical conductivity, high sediment concentration, and high air bubble entrainment, which might occur during a typical flood event. Scour measurements under different water level fluctuations also show promising results. The evaluation has resulted in an automatic scour estimation algorithm that is robust and easy for field implementations. This automation algorithm will help in the development of an accurate, rugged, and inexpensive bridge scour monitoring system. Deployment of such a system will help to manage effectively the risk associated with scour induced bridge failures. In the following chapter, the development of a field TDR scour sensor will be discussed.

Additionally, the performance of TDR for scour measurement was compared with the
ultrasonic method using the physical measurement as a baseline reference. It is found that both TDR and the ultrasonic method can accurately measure the scour depth. More information about the status of the sediment and water, however, can be obtained from the TDR measurement. The advantage of the TDR scour monitoring system is that it is rugged and can provide real time surveillance. The ultrasonic method, on the other hand, can rapidly measure the scour contour. On-site monitoring with the TDR method in conjunction with survey by the ultrasonic method will enable an accurate determination of the status of bridge scour during and after a major flood event. This will ensure the long term safety of bridge structures.
CHAPTER FIVE
DEVELOPMENT OF A FIELD TDR SCOUR SENSOR

In the previous chapters, the evaluation and analysis of TDR were based on a commercial moisture probe which might not be applicable for field employment. Due to possible severe field conditions, a field worthy TDR scour sensor needs to be resistant to damage caused by debris as well as be resistant to corrosion. This chapter discusses the development of a field TDR scour and validates its sensing capability using a laboratory evaluation program.

A coated TDR probe helps to reduce energy loss, and therefore gives it the ability to work in lossy materials, i.e. materials of high electric conductivity and causing significant attenuation of the EM waves. By coating the moisture probe, it is able to measure the dielectric constant of a material with a high electric conductivity. According to the sampling theory of Ferré et al. (1996), the effective measured dielectric constant by a coated probe can be calculated from the finite element analysis results of the electrical field. The electric field of the TDR sensors is essential to the understanding the measurement mechanism. Besides analyzing a coated moisture probe, a coated metallic strip TDR sensor has been developed for scour measurements in the field. This strip sensor is tested in simulated scour in a laboratory setting. The sampling area of the strip
sensor is determined based on finite element analysis of the electric energy density. The measured effective dielectric constant by the strip sensor is also studied based on the numerical simulation results.

5.1 Introduction

5.1.1 TDR Measurements in Highly Conductive Materials

The dielectric constant measured by TDR is the real part of the complex dielectric permittivity at the effective TDR frequency of low gigahertz (Heimovaara et al. 1994). The electrical conductivity of materials can also affect the TDR measurements of the dielectric constant. For measurement of normal soils, whose electrical conductivity is small, the effect of electrical conductivity on the measured dielectric constant is also small. However, in saline soils, the overestimation of the dielectric constant by TDR due to this effect was reported by many researchers (Campbell et al. 1999, Dalton 1992 cited in Persson et al. 2004, Persson et al. 1999, Sun et al. 2000). While some other researchers found that the overestimation due to high conductivity was not significant (Nadler et al. 1997 cited in Persson et al. 2004).

The significant amount of attenuation of the TDR waveform in highly conductive
materials makes it impossible to find the reflection at the end of the TDR probe. Two possible solutions to this problem have been studied: 1) remote diode shortening of the TDR probe and 2) coated TDR probes (Persson et al. 2004). Nichol et al. (2002) compared these two methods and found that coated probes had more accurate measurements in high saline salt solutions. However, there were some shortcomings with the use of coated TDR probes. First, the sensitivity of the coated probes was lower compared to the uncoated probes. Second, measurements of electrical conductivity was impossible. Persson et al. (2004) designed a three rod probe with a coated central rod. The shields of the two coaxial cables were connected to a common outer rod as the ground rod and the conductor. The two coaxial cables were connected to the center rod and the other outer rod separately. The dielectric constant and electrical conductivity can thus be determined using two TDR measurements.

5.1.2 Sampling Area of Coated TDR Probe and Measured Effective Dielectric Constant

By measuring the wave propagation velocity, TDR is able to determine the dielectric constant of materials being tested. If the material being tested is uniform throughout the measured volume, the determined dielectric constant is the true value of the material. If the dielectric constant of the material varies along the direction of the electromagnetic
wave propagation, the determined dielectric constant is the average value of the material in the measured volume. The average value can be determined using the mixing formula. Topp and Davis (1982 cited in Knight et al. 1997) have shown in their study that the measured dielectric constant of non-uniform material in the direction parallel to the testing rods is the length weighted average value, even in the presence of a sharp contrast of the dielectric constant. If the dielectric constant varies in the plane perpendicular to the direction of the wave propagation, the measured effective dielectric constant depends on the spatial distribution of the dielectric constant in the measured volume. The variation of the dielectric constant can be caused by the variation of water content, soil, and the existence of an air gap. Therefore, in this case, the effective measured dielectric constant is a function of the value of the dielectric constant and its distribution, and the measured volume or the sampling area.

Spatial sensitivity and sampling area of the TDR probes were studied by several researchers (Knight 1992, Ferré et al. 1996, Knight et al. 1997, Ferré et al. 1998). The sample area is an important aspect for design of the TDR sensors and for the determination of the effective measured dielectric constant. The sample area was defined by Ferré et al. (1998) as follows:

“The sample volume is the region of the porous medium that contributes to the total probe response: changes in the properties of the porous medium outside this volume do not have significant influence on the response of this instrument. We determine sample areas in the plane perpendicular to the long axis of the rods. Ignoring end effects, the three dimensional volume is defined as the projection of
this two dimensional sample area along the length of the rods. Rather than assume an arbitrary shape for the sample area, we will choose the sample area enclosing the regions of greatest spatial sensitivity, thereby uniquely defining the smallest region contributing to the probe response.”

It can be seen from this definition that the material outside of the sample area still has an influence on the probe measurements, but in a negligible amount. In order to determine the sample area, it is necessary to quantify the contribution of each sub area to the overall measured effective dielectric constant. This can be realized by using a spatial weighting function.

The effective measured dielectric constant of heterogeneous materials in the plane perpendicular to the direction of the wave propagation can be calculated using a weighted average method by Equation 5.1 (Knight 1992).

\[
K_{a,e} = \iint_{\Omega} K_a(x, y) w(x, y) dA
\]  

(5.1)

In this equation, \( K_a(x, y) \) is a function of the dielectric constant distribution in the perpendicular plane, \( w(x, y) \) is the spatial weighting function, and \( \Omega \) is an area surrounding the test probe which is large enough to nearly include all the area contributing to the total energy. The heterogeneous material can be treated as a uniform material with the dielectric constant \( K_{a,e} \). This uniform material is equivalent to the heterogeneous material in terms of total electric energy. The stored energy per unit length
of a TDR probe in heterogeneous materials is given by Equation 5.2 (Knight 1992).

\[ W = \frac{1}{2} \varepsilon_o \int \int \limits_{\Omega} K_o(x, y) |E|^2 \, dA \]  \hspace{1cm} (5.2)

In this equation, \( W \) is the stored energy by the TDR probes, \( \varepsilon_o \) is the permittivity of free space, and \( E \) is the electric field intensity. The stored energy of a TDR probe in uniform materials is given by Equation 5.3.

\[ W = \frac{1}{2} \varepsilon_o \int \int \limits_{\Omega} K_o(x, y) |E_o|^2 \, dA \]  \hspace{1cm} (5.3)

\( E_o \) is the electric field intensity for a uniform dielectric constant. Combining Equations 5.2 and 5.3, the effective measured average dielectric constant, \( K_{a,e} \), giving the same capacitance as the actual distribution of \( K_a(x, y) \) is,

\[ K_{a,e} = \frac{\int \int \limits_{\Omega} K_a(x, y) |E|^2 \, dA}{\int \int \limits_{\Omega} |E_o|^2 \, dA} \]  \hspace{1cm} (5.4)

Comparing Equation 5.4 and 5.1, the spatial weighting function in two dimensions is given by,
Using finite element method programs, Equation 5.5 can be used to determine the effective measured dielectric constant of heterogeneous materials.

\[
w(x, y) = \frac{|E(x, y)|^2}{\iint_{\Omega} |E_o(x, y)|^2 \, dA}
\]  

(5.5)

Ferré \textit{et al}. (1998) first presented a method based on the spatial weighting function to numerically determine the sample area of the TDR probes. Starting from the point of highest weighting, the summation of the product of the weighting function for a small element and its area is calculated. When the summation is close to a certain percentage, for example 90\%, of the summation over the whole calculation domain, the corresponding area is the sampling area. The calculation of the percentage is shown in Equation 5.6.

\[
f = \frac{100 \times \sum_{wh} w_i A_i}{\iint_{\Omega} w_i dA}
\]  

(5.6)

In theory, each point in the entire calculation domain contributes to the probe response. A percentage of the total contribution should be chosen to characterize the sample area of the probes. In the study by Ferré \textit{et al}. (1998), 50\%, 70\%, and 90\% were chosen to compare the corresponding sampling areas. Figure 5.1 shows the calculated sample
areas of the coated rods. The probe configuration is defined by the separation of outer rods, $S$, the rod diameter, $D$, and the outer diameter of the rod coatings, $G$. Following the example of Knight et al. (1997), constant potentials 1 and -1 V were set on the rods of two-rod probes; and constant potential 1 V was set on the center rod of three-rod probes and -1 V was set on the outer rods. The vertical axes and horizontal axes in the figures are lines of symmetry. One subplot represents four probe configurations. The sampling area of the coated probes is a function of both the probe configuration and the dielectric constant of the coating materials and the medium. More details on the findings can be found in the reference.
The measured effective dielectric constant by coated probes can be determined using Equation 5.1. The analytical solution of Equation 5.5 is difficult. It is only possible under several special conditions (Annan 1997, Zegelin et al. 1989). Computer programs for ground water flow models were used by Knight et al. (1997) to solve the electric field of TDR probes. The numerical results of several special cases were compared with analytical solutions. Results showed a close agreement. The effect of the coatings and an air gap on the dielectric constant measurements were studied using the results from the computer programs. It was found that an air gap and coating with a low dielectric constant has a great impact on the measured dielectric constant. An increase in the ratio of the rod diameter to the rod separation can reduce the impact of the coating and air gap.

5.2 Use of FEMLAB for TDR Probe Design

The electric field of TDR probes can be treated as an electrostatic problem. It can be determined by solving Poisson’s equation (Equation 5.7). Except for a few cases, the solution of Poisson’s equation can only be solved numerically. The numerical solutions can easily be obtained by the powerful multispsychics modeling tool FEMLAB. Its powerful post processing functions offer a fast and easy way of solving the electric field.
of a TDR probe. Based on the provided integration capability, the measured effective dielectric constant by coated TDR probes of different geometries can be determined. Combined with other available programming platforms, such as MATLAB, the sampling area of the TDR probes can also be determined.

\[ \nabla \cdot (\varepsilon \nabla \varphi) = -\rho \]  \hspace{1cm} (5.7)

In equation 5.7, \( \varepsilon \) is the permittivity of the medium, which can be a function of space coordinates, \( \rho \) is the space charge density, which can also be a function of space coordinates. In this study, the charge density is assumed to be 0.

### 5.2.1 Effective Measured Dielectric Constant

To validate the performance of FEMLAB, two simple cases that have analytical solutions have been studied. As shown in Figure 5.2, two non-uniform material distributions are studied. In Case I, the dielectric constant is distributed in parallel with the rod surfaces. The material interface is the plane of symmetry. The equipotential lines do not cross the interface. Thus, this case has an identical electric field to that of homogenous materials. The resulting effective measured dielectric constant is the arithmetic average of \( K_{a,1} \) and \( K_{a,2} \), as shown in Equation 5.8 (Ferré et al. 1998).
In equation 5.8, \( K_{d,e} \) is the effective measured dielectric constant, and \( K_{a,1} \) and \( K_{a,2} \) are the dielectric constants of the materials.

The probe configuration shown in Case I of Figure 5.2 can be modeled in FEMLAB as shown in Figure 5.3. The two circles are the rods of the TDR probe. The calculation domain was selected to be large enough so that the increase in the size of the domain did not have an obvious effluence on the electric field. The upper half of the calculation domain has a dielectric constant (relative dielectric permittivity) of 5; the lower half
domain has a dielectric constant of 10. The material interface is the internal continuous surface. Following the recommendation in the literature (Knight *et al.* 1997), the electric potential of the left rod was set as 1 V and the electric potential of the right rod was set as -1 V. The magnitude of the voltage only affects the level of the electric field, not the shape of the electric field. The electric displacement ($D$) at the outside boundary was set as 0. There were a total of 1882 triangular elements in the calculation domain. The space charges were set as 0 in this study. The solved electric potential and electric field are shown in Figure 5.4. The plot of the electric energy density is shown in Figure 5.5. From the obtained numerical results, it can be seen that the solutions are symmetric about the axes of symmetry.
Figure 5.3 FEMLAB model of two-rod probe.

Figure 5.4 Solved electric potential (color and contour line) and electric field (arrow).

Figure 5.5 Electric energy density (contour and color) and electric field (arrow).
It can be seen from Figure 5.5 that the area with the high dielectric constant contributes more to the total energy generated by the TDR probe. The electric energy density, \( W_e \), can be expressed as follows:

\[
W_e = \frac{1}{2} ED = \frac{1}{2} \varepsilon_r \varepsilon_0 E^2
\]  
(5.9)

where \( \varepsilon_r \) is the relative electric permittivity (dielectric constant), and \( \varepsilon_0 \) is the electric permittivity of vacuum. From Equation 5.4, the effective measured dielectric constant \( K_{a,e} \) can be expressed as,

\[
K_{a,e} = \frac{W_{e,n}}{W_{e,o}}
\]  
(5.10)

where \( K_{a,e} \) is the measured effective dielectric constant, \( W_{e,n} \) is the electric energy for non-uniform materials, and \( W_{e,o} \) is the electric energy for uniform materials with a dielectric constant of 1. Based on the FEMLAB solutions, \( W_{e,n} \) for Case I is 2.39E-10 (Joule/m) and \( W_{e,o} \) is 3.18E-11 (Joule/m). Substituting these two values into Equation 5.10, \( K_{a,e} \) can be obtained as 7.51. The analytical solution obtained from Equation 5.8 is 7.5. Thus, the numerical solution based on FEMLAB is accurate. The results can be improved by refining the mesh.
Similarly, the electric field of the probe shown in Case II of Figure 5.2 can also be solved using FEMLAB. The obtained electric potential, intensity, and energy density are shown in Figures 5.6 and 5.7. From Equation 5.10, the effective measured dielectric constant is 6.95. The analytical solution for the electric field of the probe shown in case II of Figure 5.2 can be determined from Equation 5.11 (Ferré et al. 1998).

\[
K_{a,e}^{-1} = 0.5K_{a,1}^{-1} + 0.5K_{a,2}^{-1}
\]  

(5.11)

Using this equation, the effective measured dielectric constant is 6.67. This agrees reasonably well with the value based on the FEMLAB solution.

**Figure 5.6** Case II: solved electric potential (color and contour line) and electric field (arrow).
5.2.2 Sampling Area

Equation 5.6 introduces a method to determine the sampling area in the plane perpendicular to the axes of the rods. Instead of using a weighting function, electric energy density is proposed. Energy is a direct term describing the contribution to the TDR probe measurements. Therefore, Equation 5.6 can be modified as,

$$f = \frac{100 \times \sum_{i \in \mathcal{W}_b} W_{ei} A_i}{\int_{\Omega} W_{ei} dA}$$  \hspace{1cm} (5.12)
A MATLAB code was implemented to find the sampling area at the values of interest. This code searches for the numerical solution of the electric energy density by FEMLAB from the element with the highest value until the integration over an area reaches the specified value. The sampling area of the probe shown in Case I of Figure 5.2 is shown in Figure 5.8. The sampling area is 0.0306 m$^2$. The rod with a diameter of 0.03 m has a cross section area of 7.0686e-004 m$^2$. The ratio of the sampling area to the cross sectional area is 43.3. From Figure 5.8 it can be seen that the lower half, with a higher dielectric constant, contributes more to the overall probe measurement.

Figure 5.8 Sampling area of Case I at 90% energy level.
Similarly, the sampling area of the probe shown in Case II of Figure 5.8 can be obtained as shown in Figure 5.9. The sampling area is 0.0409 m². The ratio of the sampling area to the rod cross sectional area is 57.9. This sampling area is larger compared with Case I. So the sampling area is not only dependent on probe geometry, but also on the dielectric constant distribution.

5.3 Coated TDR CS605 Moisture Probe

The center rod of a CS605 moisture probe was coated with heat shrink tubes to reduce energy loss in highly conductive media. This probe, as shown in Figure 4.8 in Chapter
4, is able to measure the dielectric constant of highly conductive media. In this section, the multi-physics computer program FEMLAB is used to study the measured effective dielectric constant by the coated TDR probe and its effective sampling area.

The center rod of the probe was coated with heat shrink tubes. According to the supplier of the heat shrink tube, the material is polyolefin with a referenced dielectric constant of 2.27. The saline solution had a sodium chloride concentration of 2000 ppm (mg/L). The dielectric constant of this saline solution was assumed to be 86. The dielectric constant of the saturated sediment was assumed to be 26.

5.2.1 TDR Probe in Saline Water

The rods had a diameter of 0.48 cm and a center-to-center spacing of 2.25 cm. The center rod was coated with back heat shrink tubes made of polyolefin. The thickness of the coating was approximately 0.03cm. The outer calculation boundary of the calculation domain was a circle of radius 4 times the rod spacing. The model setup in FEMLAB is shown in Figure 5.10. The red ring encircling the center rod is the coating tube. In order to clearly show the coating tube, only the center portion of the model is shown in this figure. The electric potential at the center rod is 1 V and the electric potential at outer rods is -1 V. The electric displacement at the outer circle boundary is 0.
From the FEMLAB solution, the measured effective dielectric constant can be determined using Equation 5.10. The total electric energy for a uniform material with a dielectric constant of 1 is 3.71E-11 (Joule/m); the total electric energy for saline water with a dielectric constant of 86 is 1.38E-09 (Joule/m); and the total electric energy for saturated sand with a dielectric constant of 26 is 7.05E-10 (Joule/m). Therefore, using Equation 5.10 the effective measured dielectric constant of water is 37.2 and the effective measured dielectric constant of saturated sand is 19.0. The electric energy density and sampling area for saline water is shown in Figure 5.11. The sampling area is 6.65 cm². The ratio of the sampling area to the rod cross sectional area is 36.8. It can be seen from Figure 5.11 that the coating area has the highest electric energy density.

The electric energy density distribution and sampling area for the uncoated probe in saline water is shown in Figure 5.12. In saline water, this probe has a sampling area of 12.9 cm², which is much larger than that of the coated probe. Coating with a low
dielectric constant can reduce energy loss.

**Figure 5.11** Electric energy density for saline water and sampling area (90% total energy).

**Figure 5.12** Electric energy density for saline water and sampling area (90% total energy, uncoated probe).

The electric energy density distribution and sampling area for the uncoated and coated probe in saturated sand are shown in Figures 5.13 and 5.14. As shown in Figure 5.13,
the sampling area is 9.8 cm$^2$ and the ratio of the sampling area to the rod cross sectional area is 54.0. The sampling area is much larger than that in saline water. The sampling area is affected by the dielectric constant of the materials being tested. The uncoated probe in saturated sand, as shown in Figure 5.14, has a sampling area of 12.9 cm$^2$. The ratio of the sampling area to the rod cross sectional area is 71.5. Again, it shows that the coating reduces the effective sampling area.

For the mixture composed of a water layer and a sediment layer in the scour simulation tests, the overall dielectric constant can be calculated using the dielectric mixing formula. The calculated effective dielectric constant agrees well with the TDR measurements, as shown in Figure 5.15. The comparison shows that the method is effective.

**Figure 5.13** Electric energy density for saturated sand and sampling area (90% total energy, coated probe).
Figure 5.14 Electric energy density for saturated sand and sampling area (90% total energy, uncoated probe).

Figure 5.15 Calculated effective measured dielectric constant by the coated TDR probe.
5.4 A New Field TDR Scour Sensor

An innovative TDR strip sensor (Figure 5.16) has been designed to study the moisture distribution in soil (Zhang et al. 2007) as well as the freeze/thaw status of frozen soil (Yu et al. 2008). These studies have shown that this sensor is durable, sensitive, and accurate. This strip sensor has been modified for scour monitoring purposes.

Figure 5.16 Photo of a TDR strip sensor.
This sensor has great potential for bridge scour monitoring. In order to be able to be installed at bridge sites to resist flow and debris, the sensor needs to have a certain rigidity and stiffness. A fiber glass U-channel was selected to provide the strip sensor with enough support to aid with installation through a drilled hole. To test the performance of the U-channel supported strip sensor, a prototype sensor was fabricated as shown in Figure 5.17.

![Prototype strip bridge scour sensor](image)

**Figure 5.17** Photo of the prototype strip bridge scour sensor.

### 5.4.1 Lab Evaluation of Strip Scour Sensor

A prototype strip bridge scour sensor was used for lab evaluation purposes. In a field model, the U-channel will be longer than the strip sensor used in lab evaluation. This prototype was first tested in a cylindrical tank with different water depths to verify its function. The waveforms recorded during this test are shown in Figure 5.18. The
dielectric constant from this sensor is calculated as shown in Table 5.1. From Table 5.1, the average dielectric constant of water measured by this sensor is 26.6.

**Figure 5.18** TDR waveforms for various water levels.

**Table 5.1** Calculations of the dielectric constant of water measured by the strip scour sensor.

<table>
<thead>
<tr>
<th>Reflection at Air-water interface (point index)</th>
<th>Reflection at end of probe (point index)</th>
<th>Water depth (cm)</th>
<th>Wavelength (la)</th>
<th>$K_{a,w}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1094</td>
<td>1193</td>
<td>19.8</td>
<td>0.967</td>
<td>23.9</td>
</tr>
<tr>
<td>1060</td>
<td>1278</td>
<td>40.3</td>
<td>2.13</td>
<td>27.9</td>
</tr>
<tr>
<td>1034</td>
<td>1344</td>
<td>58.5</td>
<td>3.03</td>
<td>26.8</td>
</tr>
<tr>
<td>1008</td>
<td>1411</td>
<td>74.5</td>
<td>3.937</td>
<td>27.9</td>
</tr>
<tr>
<td>973</td>
<td>1492</td>
<td>98.5</td>
<td>5.071</td>
<td>26.5</td>
</tr>
</tbody>
</table>
Simulated scour tests were also performed in the laboratory to test the performance of this prototype sensor (Figure 5.19). The test procedure is the same as that in Chapter 3. During the test, the water surface was in level with the top of the cylindrical tank. The obtained waveforms during the scour tests are shown in Figure 5.20. The calculations of the dielectric constants of water, sand, and the water and sand mixture are shown in Table 5.2. The average measured dielectric constant of the saturated sand is 13.3 and the average measured dielectric constant of water is 27.2. The normalized measured dielectric constant of the water and sand mixture is plotted on Figure 5.21. Similarly to that shown in the previous two chapters, there is good a linear relationship between the normalized measured dielectric constant of the mixture and the normalized thickness of the sand layer.
Figure 5.19 Photo of simulated scour test.
Figure 5.20 TDR waveforms of simulated scour tests.

Table 5.2 Calculations of the dielectric constants measured by the strip scour sensor.

<table>
<thead>
<tr>
<th>Reflection at Air-water interface (point index)</th>
<th>Reflection at Water-sand interface (point index)</th>
<th>Reflection at end of probe (point index)</th>
<th>water depth (cm)</th>
<th>sand depth (cm)</th>
<th>$K_{a,w}$</th>
<th>$K_{a,s}$</th>
<th>$K_{a,mix}$</th>
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<tr>
<td>972</td>
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<td>1450</td>
<td>63.1</td>
<td>35.9</td>
<td>26.59</td>
<td>15.6</td>
<td>22.3</td>
</tr>
<tr>
<td>972</td>
<td>1270</td>
<td>1435</td>
<td>54.8</td>
<td>44.2</td>
<td>28.23</td>
<td>13.3</td>
<td>20.9</td>
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<td>976</td>
<td>1201</td>
<td>1408</td>
<td>43.2</td>
<td>55.8</td>
<td>25.90</td>
<td>13.1</td>
<td>18.2</td>
</tr>
<tr>
<td>972</td>
<td>1105</td>
<td>1381</td>
<td>25</td>
<td>74</td>
<td>27.02</td>
<td>13.3</td>
<td>16.3</td>
</tr>
<tr>
<td>976</td>
<td>1046</td>
<td>1368</td>
<td>12.9</td>
<td>86.1</td>
<td>28.11</td>
<td>13.4</td>
<td>15.0</td>
</tr>
<tr>
<td>971</td>
<td>N.A.</td>
<td>1343</td>
<td>N.A.</td>
<td>99.0</td>
<td>N.A.</td>
<td>13.5</td>
<td>13.5</td>
</tr>
</tbody>
</table>
5.4.2 FEMLAB Analysis of the Performance of the Strip Scour Sensor

The metal strip is made of a high-carbon steel and is 0.5 inches wide and 0.01 inches thick. The metal strips are separated by a 2 mm gap. This gap is filled with Polytetrafluoroethene (PTFE) Teflon. The top and bottom surface are covered with tape. The width and spacing of the strips make it have close to a 50 ohm impedance in the air. This strip sensor is bonded onto the flat surface of a fiber glass U-channel with dimensions of 2 x 9/16 x 1/8 (inch) using adhesive tape. This sensor configuration can be modeled using FEMLAB as shown in Figure 5.22. A zoomed in view of Figure 5.22
(of the strip sensor) is shown in Figure 5.23.

**Figure 5.22** FEM model of the strip scour sensor.

**Figure 5.23** A zoomed in view of the strip scour sensor.
The tape used is made of a layer of film and a layer of adhesive. It is reasonable to assume that the dielectric constant of the tape is 3.0 (Berilla, Jim 2008, pers. comm., 7 December). The dielectric constant of Teflon was chosen to be 2.1 (Dielectric Properties of Polymers 2008). The dielectric constant of air is 1. There is no clear recommendation for the dielectric constant of the fiberglass U-channel. Reviewing relative materials, its dielectric constant can be assumed to be 6. The electric potential at the center strip is set as 1 V and the electric potential at outer strips is set as -1 V. The electric displacement at the outer rectangular boundary is set as 0. The electric field of the strip scour sensor submerged in water is solved using FEMLAB as shown in Figure 5.24. The field of energy density in log scale is shown in Figure 5.25.

**Figure 5.24** Electric potential of the strip scour sensor submerged in water.
Figure 5.25 Field of energy-density and sampling area (filled with tap water).

The highest energy-density occurs at the metal strip tips between the center strip and the outer strips. The plot is shown in log scale in order to clearly show the energy density distribution. The enclosed area by the curves shown in Figure 5.25 is the sampling area at a 90% total energy level. The sampling area is 4.68 cm$^2$. The sampling is mainly in the area facing the metal strip side with an outermost distance of 1 cm. The total energy is 2.04e-09 Joule/m. The total energy for a uniform dielectric distribution (all the materials surrounding the metal strips have a dielectric constant of 1) is 7.79e-11 Joule/m. Therefore, the effective measured dielectric constant is 26.2, which agrees with the measured dielectric constant 26.6 very well.
For saturated sand with a dielectric constant of 26, the strip scour sensor has a similar electric potential field to that shown in Figure 5.24. The energy density field (in log scale) is shown in Figure 5.26. Similar to the energy density field shown in Figure 5.25, the highest energy-density occurs at the metal strip tips between the center strip and outer strips. The sampling area is 4.37 cm$^2$, which is very close to the sampling area shown in Figure 5.25. In this case, the sampling area shifts to the back of the U-channel. The total energy for saturated sand is 1.04e-9 Joule/m. This energy is smaller than that of the sensor submerged in water. The effective measured dielectric constant is 13.3, which is very close to the measured dielectric constant of saturated sand from this strip scour sensor.

**Figure 5.26** Field of energy-density and sampling area (filled with saturated sand).
As shown in the previous analysis, the measured dielectric constant by this strip scour sensor is not the real dielectric constant of the material. Thus a calibration equation is needed to relate the real value to the measured value. For the mixture composed of a water layer and a sand layer, the above method for the determination of the effective measured dielectric constant is not appropriate. Using the mixing formula, the effective measured dielectric constant of the water layer and sand layer mixture can be determined as shown in Figure 5.27.

![Figure 5.27 Calibration of dielectric constant by the strip scour sensor.](image)

By fitting the data shown in Figure 5.24, the calibration equation can be obtained as,
\[ K_{a,r} = -59.50 + 7.93K_{a,m} - 0.12K_{a,m}^2 \]  

(5.13)

where \( K_{a,r} \) is the real dielectric constant of the water and sand layer mixture and \( K_{a,m} \) is the measured dielectric constant by the strip scour sensor. Using this equation and the scour prediction equation for fine sand (Equation 3.16), the scour depth can be determined (Figure 5.28). The TDR measured scour depth agrees with the physically measured scour very well.

**Figure 5.28** TDR measured scour versus physically measured scour.
5.5 Summary

In this chapter, the performance of a coated CS605 moisture probe was first analyzed using the multi physics platform FEMLAB by calculating the sensitivity around the TDR probes using the procedures presented by Ferré et al. (1998). Instead of being based on the spatial weighting function, the sampling area of the TDR probes was determined based on the energy contribution. Particularly, when testing materials with large dielectric constants using coated probes, this method offers more reasonable results than the method based on the weighting function. The effective measured dielectric constant and the sampling area of the coated probe can be accurately calculated with integrated functions of FEMLAB in combination with a MATLAB code. Numerical results of the effective measured dielectric constants agree very well with TDR measurements. A comparative study shows that coating can reduce the sampling area of the TDR probes as well as result in energy loss. Thus, measurements in lossy materials using coated probes are feasible.

A strip scour sensor was developed and tested in simulated scour tests. With its design, this sensor can easily be installed at bridge sites. Laboratory tests show that the sensor can measure scour depth with satisfying accuracy. Similar to the coated probe, numerical simulations were performed to study the sensitivity of this sensor using
FEMLAB. Again, the numerically calculated effective dielectric constant agrees very well with the TDR measurements by the prototype sensor. Also, the sampling area of the sensor was determined. In tap water, the sampling area was mainly located in the flat front side of the sensor, while in saturated sediments (with lower dielectric constant), the sampling area shifted to the back of the sensor, although the majority of the sampling area was still in the front. The measured dielectric constant by this sensor can be easily converted to the actual value by using a calibration equation. Using the scour estimation equation and the analysis algorithm developed and validated in Chapter 3, the scour depth can be easily and accurately determined.
CHAPTER SIX

DEPLOYMENT AND EVALUATION OF THE FIELD TDR SCOUR MONITORING SYSTEM

6.1 Introduction

The TDR bridge scour sensors were installed adjacent to bridge piers on the BUT-122-0606 bridge on SR 122 over the Great Miami River in Butler County, just west of the City of Middletown. Photo of this bridge is shown in Fig. 6.1. The bridge has seven piers. According to Brandon Collett, ODOT District Engineering, “The dive survey in 2007 and 2004 indicated a significant increase (around 2 ft) of local scour around the piers located in the western side of bridge while the eastern side remains essentially unchanged. This structure also serves as a USGS gage location (Station number 0237100). Typically, several measurements are taken daily of the discharge (cfs), gage height, and water temperature. This will allow significant correlation between scour depth and flow.”

Figure 6.1 The BUT-122-0606 bridge on SR 122 over the Great Miami River in Butler County
6.2 Installation of TDR Bridge Scour Sensors

The field installations were completed at the assistance of J&L laboratories with consultation from GRL Engineers Inc. Figures 6.2 illustrates the sequence of field installation. In summary, the following steps were involved:

Step 1) coring through bridge deck;

Step 2) drilling in river bed to design depth;

Step 3) lowering TDR scour sensing probe into borehole;

Step 4) backfilling borehole with sand and sealing the coring hole in the bridge deck.

Among these procedures, Steps 1, 2 and 4 are commonly used for geotechnical site investigation on bridges. Therefore, the installation of the new TDR bridge scour sensor can be implemented in conjunction with routine geotechnical investigation equipment and procedures. Five scour sensors were installed adjacent to bridge piers. Figure 6.2 illustrate the major steps involved in the field installations.
Figure 6.2 a) coring through bridge deck; b) drilling in the river bed; c) lowering TDR scour sensing probe into borehole; d) backfilling borehole and sealing the bridge deck
Five TDR scour sensors were installed adjacent to bridge piers. The schematic locations of these sensors are shown in Figure 6.3. These sensors are typically located around 1 ft away from the pile cap and 6 ft away from the sidewalk, as illustrated in Figure 6.3.

Figure 6.3 Schematic of locations for TDR scour sensors

6.3 Installation of Automatic Scour Monitoring Station

The automatic monitoring station was also installed on the bridge. Figure 6.4 shows example procedures for installing the automatic monitoring station. The box housing the monitoring station includes controller (field computer), TDR unit, multiplexer, rechargeable battery and wireless modem. In addition, a small solar panel was used to charge the battery. Installation of the electronics was accomplished in April 2010. The cold weather posed major challenges for installation activities. However, these challenges were successfully addressed through the preparation and dedication of engineers assisting the installation activities. Figure 6.4 illustrates major steps involved in installing the automatic monitoring station.
The controller is set to read TDR data at preset time interval (e.g. 1 hour) and wirelessly transmit the data via cellular phone service. It also monitors the battery level and charging current by the solar panel, all of which are stored and displayed on the internet. Figure 6.5 shows the screen shot of the measured TDR signals, the voltage levels and power consumption.
Figure 6.5 a) example of internet display screen for TDR scour signals; b) monitoring data of battery and power consumption
6.4 Preliminary Analyses of TDR Scour Sensor Signals

Figure 6.6 illustrate a typical TDR scour signal. It also describes the information contained in a typical TDR scour signal. This figure clearly shows the locations when EM wave arrives at scour sensor, when reflection of EM wave occurs at water-sediment interface, and when reflection of EM wave occurs at the end of TDR scour sensor. Details of these information can be determined with an analyses algorithm.

![Figure 6.6 illustration of information contained in TDR scour sensor signals](image)

**Figure 6.6** illustration of information contained in TDR scour sensor signals

Figure 6.7 shows examples of measured signals by the TDR scour sensors. The signals show systematic trends that are indicative of the scour process occurring within a two month time span (e.g., Figure 6.7a).
Increasing trend of scour development
Figure 6.7 Example of TDR scour sensor signals at different time after installation.
The TDR scour sensor signals were analyzed using the algorithm developed in previous chapter, i.e.:

1) Analyze TDR signals to determine the reflections from the end of TDR sensor (using commonly used tangent line method). From this determine the apparent travel length $L_a$

2) Calculate the measured dielectric constant $K_{a,m}$ using Equation 2.3

3) Calculate the actual dielectric constant of water-sediment system, $K_{a,r}$, from the measured dielectric constant, $K_{a,m}$, using Equation 5.13

4) Using the scour prediction equation for fine sand (Equation 3.16), replacing $K_{a,m}$, with the actual dielectric constant of water-sediment system, $K_{a,r}$, to determine normalized sediment thickness $x$

5) Estimate the scour depth from normalized sediment layer thickness $x$

Table 6.1 shows examples of data analyses from TDR scour signals.

**Table 6.1 Example calculation for scour depth estimation at location 1**

<table>
<thead>
<tr>
<th>Day</th>
<th>1st reflection (m)</th>
<th>2nd reflection (m)</th>
<th>Apparent length (La)</th>
<th>$K_{a,m}$</th>
<th>$K_{a,r}$</th>
<th>$x_r$</th>
<th>$x$ (m)</th>
<th>Incremental Scour (m)</th>
<th>Total Cumulative Scour (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>26.29</td>
<td>32.2</td>
<td>5.91</td>
<td>15.04</td>
<td>32.42</td>
<td>0.85</td>
<td>1.30</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>2</td>
<td>26.29</td>
<td>32.3</td>
<td>6.01</td>
<td>15.55</td>
<td>34.60</td>
<td>0.81</td>
<td>1.23</td>
<td>0.07</td>
<td>0.07</td>
</tr>
<tr>
<td>3</td>
<td>26.29</td>
<td>32.36</td>
<td>6.07</td>
<td>15.86</td>
<td>35.90</td>
<td>0.78</td>
<td>1.18</td>
<td>0.04</td>
<td>0.12</td>
</tr>
<tr>
<td>4</td>
<td>26.29</td>
<td>32.43</td>
<td>6.14</td>
<td>16.23</td>
<td>37.40</td>
<td>0.75</td>
<td>1.14</td>
<td>0.05</td>
<td>0.17</td>
</tr>
<tr>
<td>58</td>
<td>25.74</td>
<td>32.03</td>
<td>6.29</td>
<td>17.03</td>
<td>40.56</td>
<td>0.68</td>
<td>1.04</td>
<td>0.10</td>
<td>0.27</td>
</tr>
</tbody>
</table>

The results of scour depth evolution are plotted in Figure 6.8. It clearly showed the trend of scour development was higher in the initial stage (possibly due to soil
disturbance during scour sensor installation). The rate of scour decreases and becomes stable in long time.

![Cululative Scour vs Time](image)

**Figure 6.8** Monitored evolution of scour after sensor installation at location 1

Table 6.2 summarizes the results of cumulative scour adjacent to the bridge piers in 58 days measured by the 5 TDR scour sensors. Around 0.5 to 1.5 ft scour occurred since sensor installation. Scour is larger in the middle spans (i.e. piers 3 and 4), which is reasonable considering the higher flow velocity in these locations.
Table 6.2 Summary of measured scour by the sensors at different locations after 58 days of installation

<table>
<thead>
<tr>
<th>Location</th>
<th>Total Cumulative Scour After 58 days (m)</th>
<th>Total Cumulative Scour After 58 days (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.27</td>
<td>0.89</td>
</tr>
<tr>
<td>2</td>
<td>0.16</td>
<td>0.52</td>
</tr>
<tr>
<td>3</td>
<td>0.41</td>
<td>1.35</td>
</tr>
<tr>
<td>4</td>
<td>0.47</td>
<td>1.54</td>
</tr>
<tr>
<td>5</td>
<td>0.21</td>
<td>0.69</td>
</tr>
</tbody>
</table>

6.5 Technical Challenges and Countermeasures

*Installation of TDR probe*

An important issue during the placement of the TDR probe is to make sure it stay in place when withdraw the boring casing. The following measures were used to ensure proper TDR scour sensor installation:

a.1) To prevent the TDR probe to be pulled up while removing the boring case, a plastic shoe was attached to the bottom of the e-glass U-channel that mounted the TDR sensor strip. The plastic shoe was intended to help hold the TDR sensor in place through the weight of backfilled sand.

a.2) Another important lesson is the right amount of sand to hold the sensor in place. Too small amount of sand is not sufficient to hold the U-channel in place. On the other hand, too large an amount of sand will generate large friction force between the U-channel and boring casing; consequently the U-channel will be pulled up when removing the boring casing.

*Installation of Automatic Monitoring Station*
There were no major technical challenges encountered during the installation of the automatic monitoring system. Most challenges come from the weather and freezing temperature. An impact drill was used to drill the holes in the concrete.

**Protection of Lead Wire**

Impact of debris is a major challenge in fixed scour monitoring devices. Figure 6.9 shows an example photo of conduits for electronic cables of USGS river monitoring devices. The conduits survived severe floods for many years. The deformation of the conduits illustrates the magnitude of forces that can be generated by debris, especially wood trunks. This is a major issue that needs deliberation.

Vandalism is another factor that needs to be considered during the installation of a monitoring station. Figure 6.10 shows an example of connection cable that was suspected to be damaged deliberately.
Figure 6.9 Deformation of USGS instrument conduits by debris

Figure 6.10 Example of connection cable damaged by vandalism

For the TDR scour sensor, the following measures are adopted to mitigate debris impacts:
1) bury most of the TDR scour sensor under the river bed. Only a small portion of the sensor probe (less than 1 ft) was exposed. During floods, the water level in the river
raises and therefore the wood trunk raises, this further reduces the chance the sensor was impacted by debris such as a wood trunk; 2) run the cables in rugged conduits and fix the conduits on the pile cap and bridge pier.

The cable connection was found to be a weak spot in the scour sensor. The purpose of cable connection is to provide a communication channel between monitoring device and scour sensor. Alternative communication methods such as by radio wave or acoustic wave might overcome the limitations of cable connections. For example, communications via acoustic wave have been used in geotechnical Cone Penetrometer Test (CPT) to eliminate the time-consuming procedure of cabling through the center of the penetrometer rod. A similar idea might be utilized for the scour monitoring system to reduce the requirements on cabling. This, however, requires further research to look into the feasibility and reliability under flood conditions.

6.6 Summary

The new TDR bridge scour sensors were installed adjacent to the piers of an operating bridge. The installation was conducted using common geotechnical site investigation tools and procedures. TDR sensors gave good quality signals. Signals by the TDR scour sensors were acquired by installation of an automatic monitoring unit. The unit took TDR scour sensor signals at preset time intervals and wirelessly transmitted the sensor data through cellular data service. Preliminary results of sensor signal analyses showed that the TDR scour sensors were able to measure the development of bridge scour. The results of magnitude and distribution of scour were reasonable. The preliminary results of field evaluation are encouraging. Study of the longer term performance is highly recommended to further evaluate this new technology.
CHAPTER SEVEN
SUMMARY, CONCLUSIONS, AND FUTURE WORK

7.1 Summary and Conclusions

This report consisted of four major components: 1) validation of the scour sensing capability of TDR and development of algorithms for signal analyses from laboratory experiments; 2) evaluation of the performance of TDR sensors and analyses algorithms under various conditions; 3) development of a field strip scour sensor and validation of its performance from numerical simulation and laboratory experiments, and 4) deployment and evaluation of the TDR automatic bridge scour monitoring system.

7.1.1 Laboratory Observations and Algorithm for Signal Interpretation

A pilot experiment was first conducted to evaluate the potential of using TDR technology for bridge scour measurement. Simulated scour in a laboratory setting was monitored by a commercial TDR probe. The simulated scour experiments were performed in water of different salinity. The measured waveform at different levels of scour showed a clear systematic pattern of change. It was found that there is linear relationship between the normalized thickness of the sediment layer and the normalized square root of the measured dielectric constant of water and sand. A similar relationship was observed in the measured electrical conductivity. Therefore, it was concluded that TDR can confidently be used for scour monitoring.

The sediment-water system was described by the dielectric mixing model. From this model, a linear relationship was observed between the normalized dielectric constant and the normalized scour depth. A mixing formula for the electrical conductivity was
developed. Using this model, the electrical conductivity of the water and sediment mixture was determined. Combining the formula for the dielectric constant and the electrical conductivity, the dry density of the sediment and the electrical conductivity of the water were also determined.

By fitting the measured data of the dielectric constant and electrical conductivity, two empirical equations for scour measurement were established. An application procedure was presented, based on the empirical equations, to determine the scour depth, the dry density of the sediment, and the electrical conductivity of water. This algorithm can be easily implemented in a computer code to automate the signal interpretation process.

7.1.2 Evaluation of TDR Sensing Capability and Signal Analysis Algorithm under Various Conditions

The performance of TDR scour sensing and the signal analysis algorithm were further validated under different simulated scour conditions. The TDR sensor and algorithms worked reasonably well to measure scour under high electrical conductivity, high sediment concentration, and high air bubble entrainment, all of which might occur during a typical flood event. Scour measurements were accurate under different water level fluctuations. The evaluation validates that the automatic scour estimation algorithm is robust and ready for field implementations. This automation algorithm will be essential for the development of an accurate, rugged and inexpensive bridge scour monitoring system.

The performance of TDR for scour measurement was compared with that of the ultrasonic method using the physical measurements as baseline references. It was found that both TDR and the ultrasonic method can accurately measure the scour depth. More
information about the status of the sediment and water, however, can be obtained from the TDR measurement. The advantage of the TDR scour monitoring system is that it is rugged and can provide real time surveillance. The Ultrasonic method, on the other hand, can rapidly measure the scour contour. On-site monitoring with the TDR method in conjunction with survey by the ultrasonic method will enable accurate determination of the status of bridge scour during and after a major flood event. These technology would ensure the long term safety of bridges.

7.1.3 Design of a Field Worthy Scour Sensor and Validation of its Performance by Numerical Analysis and Laboratory Experiments

A field deployable strip scour sensor was developed and tested in simulated scour tests. Laboratory tests showed that the sensor can measure scour depth with satisfying accuracy. Numerical analyses of the performance of the sensor were performed using the finite element method software FEMLAB. The numerically calculated effective dielectric constant agreed very well with the TDR measurements. Also, the sampling area of the sensor was determined. In tap water, the sampling area was mainly located in the flat front side of the sensor, while in saturated sediments (with a lower dielectric constant), the sampling area shifted to the back of the sensor, although the majority of the sampling area was still in the front. The measured dielectric constant, by this sensor, can easily be converted to the true value based on a calibration equation. Scour depth can be easily and accurately determined by use of the algorithm developed from this research.

7.1.4 Installation and Evaluation of the Automatic Scour Monitoring System

Five TDR scour sensors were installed at the BUT-122-0606 bridge over the Great Miami River in Butler County. The sensors were installed adjacent to bridge piers with traditional geotechnical investigation procedures. Preliminary analyses of sensor signals indicated that
the sensors provided high quality signals and were responsive to the scour process. An automatic data acquisition system was installed on bridge structure to automatically acquire TDR scour signals and wirelessly transmit data via cellular phone service. The results of magnitude and distribution of scour measured by the TDR scour sensors were reasonable. The cable connection was found to be a weak spot in the scour sensor. Development of alternative communication method (such as by radio wave or acoustic wave) could potentially address this problem.

7.2 Future Work
This project developed a new TDR bridge scour monitoring system that is easy to install using routine geotechnical procedures and equipment. The preliminary results are very encouraging. However, due to the time and financial constraints of this project, a number of worthy issues associated with this new bridge scour monitoring system have not been completely evaluated. It is highly recommended that a regular ODOT research project be initialized to assess the long term performance of the new TDR bridge scour monitoring system. It is suggested that the new project focus on further assessment of the accuracy of this new TDR scour monitoring technology, comparison with direct scour measurement, and integration of the scour sensing data into a risk-based bridge management system.
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