NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP Report 396

Instrumentation for Measuring Scour at Bridge Piers and Abutments

Transportation Research Board
National Research Council

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Report 396

Instrumentation for Measuring Scour at Bridge Piers and Abutments

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Bridges, Other Structures, and Hydraulics and Hydrology

Research Sponsored by the American Association of State Highway and Transportation Officials in Cooperation with the Federal Highway Administration

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL

NATIONAL ACADEMY PRESS
Washington, D.C. 1997

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Transportation Research Board of the National Research Council was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state and local governmental agencies, universities, and industry; its relationship to the National Research Council is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway and transportation departments and by committees of AASHTO. Each year, specific areas of research needs to be included in the program are proposed to the National Research Council and the Board by the American Association of State Highway and Transportation Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are the responsibilities of the National Research Council and the Transportation Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

NCHRP REPORT 396

Project 21-3, FY'90 and '92

ISSN 0077-5614

ISBN 0-309-06069-9

L. C. Catalog Card No. 97-61382

Price $29.00

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Published reports of the

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

are available from:

Transportation Research Board
National Research Council
2101 Constitution Avenue, N.W.
Washington, D.C. 20418

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http://www.nas.edu/trb/index.html

Printed in the United States of America

FOREWORD

By Staff
Transportation Research Board

This report contains the findings of a study undertaken to develop, test, and evaluate fixed devices for measuring maximum scour depth. Companion manuals provide specific fabrication, installation, and operation guidance for two such devices. This report and the companion manuals will be of immediate interest to hydraulics engineers, bridge management engineers, and bridge maintenance engineers.

Scour is the primary cause of bridge failure in the United States. Because scour holes generally fill in as streamflows diminish, post-flood inspections are not adequate to determine fully the extent of scour damage. Methods of measuring the maximum scour depth are needed in the management of scour-susceptible bridges.

This report and the companion manuals, published as *NCHRP Reports 397A* and *397B*, are the culmination of NCHRP Project 21-3, which consisted of three phases. Phase I, which was reported in *NCHRP Research Results Digest 189*, developed four mandatory and eight desirable characteristics for scour monitoring devices and identified four classes of instruments—sounding rod, sonic fathometer, buried/driven rod, and other buried devices—likely to provide these characteristics.

In Phase II, the most promising devices were evaluated under field conditions. The objective of these evaluations was to determine accuracy, dependability, and durability under a broad range of stream types, flow conditions, and bridge geometries. On the basis of these evaluations, the magnetic sliding collar and the sonar-based devices were identified as appropriate for further refinement. These two types of monitors meet all of the mandatory requirements and most of the desirable characteristics established for scour monitoring devices. There was no report on the Phase II research.

The Phase III effort consisted of additional field testing, improvement of data acquisition techniques, and development of documentation for the sonar and sliding collar devices. This report documents all phases of NCHRP Project 21-3. Laboratory- and field-test findings are presented for each device, and a detailed discussion of the significance of these findings is presented. The companion manuals provide guidance for selecting the device most suitable for a bridge and its location. Detailed instructions, including fabrication drawings and parts lists, are included to permit the fabrication of the monitors in most machine shops. Instructions for operation and maintenance are also given.

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ACKNOWLEDGMENTS

This work was sponsored by the American Association of State Highway and Transportation Officials, in cooperation with the Federal Highway Administration (FHWA), and was conducted through the National Cooperative Highway Research Program (NCHRP), which is administered by the Transportation Research Board (TRB) of the National Research Council (NRC).

The research reported herein was performed under NCHRP Project 21-3 by Ayres Associates, Fort Collins, Colorado. Dr. Everett V. Richardson, Senior Associate, served as Principal Investigator and Dr. Peter F. Lagasse, Senior Vice President, served as Co-Principal Investigator. They were assisted by Dr. James D. Schall, Manager of Sedimentation Engineering, Mr. George Fisher, Field Engineer, and Dr. Jerry R. Richardson (now Assistant Professor, University of Missouri, Kansas City). Mr. Jerry Price and Mr. Don Horton, Electronics Engineers, ETI Instrument Systems, Fort Collins, Colorado, supported Ayres for instrumentation and development of scour measuring devices.

The participation, advice, and support of NCHRP panel members throughout this project are gratefully acknowledged.

A special acknowledgment is made to the state DOTs of Michigan and Minnesota for their participation in the wider deployment task of this project and to the state DOTs of Colorado, Florida, and New Mexico for their assistance and cooperation with the installation of instruments at field sites under their jurisdiction. The state DOTs of New York and Texas and the U.S. Geological Survey installed and reported on scour monitoring instruments with the support of FHWA Demonstration Project 97.

INSTRUMENTATION FOR MEASURING SCOUR AT BRIDGE PIERS AND ABUTMENTS

SUMMARY

This research accomplished its basic objective of developing, testing, and evaluating instrumentation that will be both technically and economically feasible for use in measuring or monitoring maximum scour depth at bridge piers and abutments. Various scour measuring and monitoring methods were tested in the laboratory and in the field, including sounding rods, driven rod devices, sonic fathometers, and buried devices.

On the basis of the mandatory criteria established, the research was limited to fixed instruments that could be installed on or near a bridge pier or abutment. For long-term monitoring, fixed instrumentation offers several advantages over portable instrumentation, including continuous monitoring at a given site, generally low operational cost once the instrument is installed, generally no need for specialized training, and avoidance of deployment and logistics problems associated with portable instruments.

Two instrument systems—a low-cost bridge-deck-serviceable sonic fathometer and a magnetic sliding collar device using a driven-rod approach were installed and tested in the field under a wide range of bridge substructure geometry, flow, and geomorphic conditions. The magnetic sliding collar device consists of a stainless-steel pipe driven into the channel bottom with a sliding collar that drops as the scour progresses. The location of the collar is detected by the magnetic field created by magnets on the collar. The low-cost sonar device consists of a simple fish-finder-type sonar connected to a datalogger that tells the sonar when to turn on, how much data to collect, and when to turn off. Both instruments met all established mandatory criteria and many of the desirable criteria.

Manual-readout magnetic sliding collar devices successfully tracked scour on bridge piers in Colorado, New Mexico, Michigan, Minnesota, and New York. The instruments installed at field test sites performed well, and all but one survived under potentially severe ice or debris conditions. Installations conducted in cooperation with state highway agencies demonstrated that this simple low-cost instrument is adaptable to various field situations and can be installed with equipment and technical skills normally available at the District level of a state highway agency.

Automated magnetic sliding collar devices were successfully installed on a riverine bridge abutment in Colorado and at a tidal bridge pier in Florida. The abutment installation confirmed the installation techniques developed in the laboratory and proved the performance of an automated sliding collar instrument under field test conditions. The automated collar configuration greatly reduces the vulnerability of the sliding collar instrument system to damage from debris or ice impact. This instrument was also used to demonstrate a successful cellular telephone link between the field test site and a base

station 64 km (40 mi) away. Although aggradation, not scour, occurred at the Florida pier test site, the electronic components of the instrument system, including the underwater cable link and datalogger, remained functional in a tidal environment for the duration of the project.

This research also resulted in development of a reliable low-cost sonic fathometer system (consisting of a fish-finder-type sonar, a datalogger/interface, and a solar panel) which can be mounted in a bridge-deck- or above-water-serviceable configuration. Installations on riverine bridge piers and a bridge abutment in Colorado, New Mexico, Texas, and New York, and on a pier of a deep water tidal bridge in Florida proved the adaptability of the instrument system to various bridge substructure geometries and site conditions. At many of the riverine test sites, instrument installation was affected by debris accumulation around the bridge piers and, at several sites, the performance of the instrument was hindered by the accumulation of debris. Three low-cost sonic instrument systems were successfully installed on riverine bridges by a state highway agency using in-house equipment and personnel.

The tidal bridge test site in Florida was selected because it posed substantial challenges for the installation of a low-cost sonar system, including an aggressive tidal inlet with a 14-m (45-ft) water depth on the open (Gulf) coast that had experienced significant scour, a large bascule (moveable) bridge with a complex pier and crutch bent substructure, and a hostile marine environment where corrosion and growth of marine organisms would test the durability of electronic and mechanical components. The low-cost sonic system in an above-water-serviceable configuration performed well over a 2-year period. Anti-fouling paint protected the transducer face for the first year of operation, but by the end of the second year, barnacle growth had begun to interfere with system operation. This instrument provided an excellent continuous record of seasonal scour and fill and performed successfully under hurricane storm-surge conditions.

Installation, operation and fabrication manuals were developed for the low-cost sonic system and magnetic sliding collar devices (*NCHRP Reports 397A* and *397B*) and provide complete instrument documentation, including specifications, and assembly drawings. That information, together with the findings, appraisal, and applications information of this final report provide a potential user of a scour measuring or monitoring device complete guidance on selection, installation, and, if desired, fabrication of two effective systems, one of which could meet the need for a fixed scour instrument at most sites in the field.

A third instrument, a driven rod device with piezoelectric film sensors, was tested in the laboratory and then received limited field testing under this research. This instrument was given a lower development priority than either the low-cost sonar or sliding collar devices, primarily because of its inherent complexity, limited funds, and anticipated difficulty in relating sensor output to scour status. During limited testing of a prototype piezoelectric film device under this project, the sensors proved to be very sensitive to structural as well as hydrodynamic vibration. Sensors buried in the streambed should not have indicated any motion, but apparently responded to vibration of the support pipe caused by flowing water and traffic across the bridge. In a related research effort, the U.S. Geological Survey reported excellent performance of a second prototype piezoelectric film device provided by this project. The device survived impact by large logs and debris and provided good scour data under conditions where data "could not have been collected by any other means." This instrument shows promise. It would not have the same vulnerability to debris or ice as a sonic system and, unlike the sliding collar class of devices, would be able to track both the development of a scour hole and subsequent refill over an unlimited number of scour cycles. This instrument system warrants further research.

An ongoing scour evaluation program being conducted by the Federal Highway Administration and all state highway agencies has identified, to date, more than 10,000 scour-critical bridges and almost 100,000 bridges with unknown foundations. An additional 132,000 bridges that were screened (assessed) as scour-susceptible have not been evaluated. With limited time and funding available, the scour-critical bridges cannot be immediately repaired or replaced, and the scour-susceptible bridges cannot be immediately evaluated. Moreover, the unknown foundation bridges will require monitoring for the foreseeable future. The two instruments developed under this research, a low-cost sonic system and either a manual-readout or automated magnetic sliding collar device, have been tested extensively and are fully field-deployable. Use of these instruments as scour monitoring countermeasures will provide state highway agencies with an essential element of their plans of action for many scour-critical, scour-susceptible, or unknown foundation bridges.

CHAPTER 1

INTRODUCTION

PROBLEM STATEMENT AND RESEARCH OBJECTIVES

There are more than 575,000 bridges in the national bridge inventory. Approximately 84 percent of these bridges are over water. Highway bridge failures cost millions of dollars each year as a result of both direct costs necessary to replace and restore bridges and indirect costs related to disruption of transportation facilities. However, of even greater consequence is loss of life from bridge failures. Stream instability, long-term stream aggradation or degradation, general scour, local scour, and lateral scour or erosion cause 60 percent of these failures.

Research efforts have developed a large body of knowledge on bridge scour, mostly from laboratory model studies. However, field data and measurements of scour at bridges, necessary to better understand the problem of scour and evaluate analytical methods for scour prediction, are limited. This deficiency results largely from the difficulties of field data collection under flood-flow conditions when scour conditions are typically most severe. These same adverse conditions have inhibited development of a reliable scour monitoring device that can automatically or even semi-automatically collect scour data.

There are many scour-susceptible bridges on spread footings or shallow piles in the United States and many bridges with unknown foundation conditions. With limited funds available, these bridges cannot all be replaced or repaired. Therefore, they must be monitored and inspected following high flows. During a flood, scour is generally not visible and during the falling stage of a flood, scour holes generally fill in. Therefore, visual monitoring during a flood and inspection after a flood cannot fully determine that a bridge is safe. A reliable device to measure maximum scour would resolve this uncertainty.

The basic objective of this research was to develop, test, and evaluate fixed instrumentation that would be both technically and economically feasible for use in measuring or monitoring maximum scour depth at bridge piers and abutments. The scour measuring or monitoring device(s) must meet the following mandatory criteria and should meet, where possible, the following desirable criteria.

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
- Operable during storm and flood conditions

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
- Relatively low cost
- Vandal resistant
- Operable and maintainable by highway maintenance personnel

SCOPE OF RESEARCH

This research project was conducted in three phases. The first phase included a literature search, laboratory testing, and limited field testing of instruments and instrument components. A final report on Phase I was submitted to NCHRP in March 1992. NCHRP issued *Research Results Digest 189* summarizing the Phase I Final Report in January 1993.

Phase II of this research concentrated on field testing and wider deployment of scour measuring systems. The objectives of this phase were to modify, improve, and test the most promising techniques for measuring and monitoring scour at bridge piers and abutments. Tasks included the development, installation, testing and evaluation of field prototypes and detailed evaluation of the two most promising low-cost scour measuring systems. The research indicated which devices may work best for differing stream types, flow conditions, and bridge geometries. Inherent in the field testing was the objective of ascertaining the accuracy, dependability, and durability of these devices.

Phase III objectives included refinement and enhancement of the magnetic sliding collar and, to a lesser degree, sonar-based devices through continued field testing, comprehensive documentation of fully operational scour instrumentation, and continued survey of instrument technology and research and development of other promising techniques. During Phase II, the fundamental research and development on the magnetic sliding collar and sonar-based devices was completed, and the utility of these devices was field tested and documented through a few test installations. Phase III research involved ongoing field testing, research on enhancements such as improved data acquisition techniques, and development of instrument documentation, including design drawings and specifications, installation directions, and user's manuals.

Because the mandatory criteria required that the instruments be capable of installation on or near a bridge pier or abutment, the research was limited to fixed instruments only. Portable sonic instrumentation was developed to ground truth the fixed instrument installations and is discussed in *NCHRP Report 397A*.

RESEARCH APPROACH

Phase I of the project (1989–1992) was divided into eight tasks with Tasks 1.1 through 1.4 resulting in an interim report and recommendations to the NCHRP panel regarding devices to be tested under the research program. Tasks 1.5 through 1.8 involved development (or acquisition) of prototype devices, laboratory testing, limited field testing, a cost analysis for each device tested, and preparation of a final report with recommendations for a comprehensive field testing program, during Phase II. The eight specific Phase I tasks were

- Task 1.1. Comprehensive Information Gathering
- Task 1.2. Identification of Potentially Feasible Measurement Devices
- Task 1.3. Evaluation of Feasible Devices
- Task 1.4. Preparation of Interim Report and Test Plan
- Task 1.5. Development of Prototype Devices for Laboratory Testing
- Task 1.6. Initial Testing and Evaluation of Prototype Devices
- Task 1.7. Cost Analysis of Each Prototype Device
- Task 1.8. Preparation of Phase I Final Report

For Phase II (1992–1994), nine tasks were planned to develop, test, and evaluate scour measuring devices through the development, deployment, and testing of field prototype systems. The specific tasks were

- Task 2.1. Complete the installation of instrument systems initiated during Phase I.
- Task 2.2. Test and evaluate instruments at existing field sites, concentrating on the low-cost sonic fathometer and the simple magnetic scour monitor.
- Task 2.3. Perform limited laboratory testing, as required.
- Task 2.4. Identify field sites for deployment and testing of additional scour monitoring systems.
- Task 2.5. Prepare and submit an interim report with a detailed test plan for wider deployment and testing of scour monitoring devices.
- Task 2.6. Upon NCHRP approval of the interim report and test plan, fabricate and install field prototype devices.
- Task 2.7. Perform extensive field testing of the simple magnetic sliding collar scour monitor and a low-cost sonic fathometer system.
- Task 2.8. Provide support for testing and evaluation programs of other agencies (wider deployment), as approved by NCHRP.
- Task 2.9. Prepare and submit a Phase II Final Report.

The final phase of the project (1994–1996) concentrated on completing field testing of selected instruments, a resurvey of scour instrument technology, and development of comprehensive instrument documentation for two instruments—the low-cost sonic system and the magnetic sliding collar device. Specific Phase III tasks were

- Task 3.1. Resurvey scour instrument technology.
- Task 3.2. Develop instrument documentation.
- Task 3.3. Continue monitoring and operation of field test sites.
- Task 3.4. Fabricate, install, and test field prototypes.
- Task 3.5. Develop and document abutment installation techniques.
- Task 3.6. Develop concepts for a warning/monitoring function, placement of instruments, and telemetry of data.
- Task 3.7. Demonstrate and test wireless transmission of scour data.
- Task 3.8. Remove test devices.
- Task 3.9. Attend meetings and prepare a project final report.

Although the research was conducted in phases, this project final report integrates and summarizes the findings, interpretation, conclusions and recommendations for the total research effort. Separate installation, operation, and fabrication manuals have been developed for the magnetic sliding collar device and low-cost sonic instrument system (see *NCHRP Reports 397A* and *397B*).

CHAPTER 2

FINDINGS

LITERATURE REVIEW

Introduction

This section describes equipment and techniques used before this study to measure scour at bridge piers and abutments. Information about earlier studies was obtained mostly from published reports. Information on developments since about 1950 and on current practices was obtained in part from the literature and summarized from experience or from personal communication with researchers. The initial findings in 1990 are supplemented with information from a resurvey of scour technology during the period 1994 to 1996.

Although a vast literature exists relating to bridge scour, only a few reports deal specifically with instrumentation. In this section, only selected references are discussed. A bibliography on equipment for scour measurement is provided as Appendix A.

Initial Findings

Early Observations

The earliest observations of bridge scour probably were carried out by railroad engineers during the first half of the 19th century. By the turn of the century, hydraulic engineers were involved in laboratory model studies of pier scour, but the main responsibilities for design and field studies were borne largely by the railways. The tradition continues today. In the People's Republic of China, bridge scour studies are carried out by the Ministry of Communications and Academy of Railway Sciences (*1*); in India, field observations apparently are carried out by the Ministry of Railways (*2*), and in the USSR, the Ministry of Transport Construction had these responsibilities (*3*).

Historically, equipment used for scour observations was simple: **sounding rods** for shallow flows and lead **sounding weights** on a line for deeper flows. These devices were developed to sound for navigation depths hundreds of years ago and were adapted for depth soundings in connection with streamflow measurements during the 19th century. The main adaptations involved streamlining the sounding weights and using stay lines or vertically supported sounding rods so that the weights or rods would not be swept downstream in high velocities.

Development in the 1950s

Major advances in instrumentation occurred during World War II. By the mid 1950s, many devices became commercially available and were introduced into scientific studies of rivers. The main advances were in **sonar, sonic sounders, electronic positioning equipment, and radar**. Very often, equipment developed for one purpose was modified and adapted to studies in rivers. A dual channel stream monitor (*4*) was used to study alluvial channel bed configurations and the scour and fill associated with migrating sand waves (*5, 6*). The equipment was highly accurate, but could not operate in depths greater than about 1.8 to 2.4 m (6 to 8 ft). Richardson and others (*7*) developed a sonic sounder for use in the laboratory and in shallow flows in the field. The sounder would work in flows from 0.3 to 1.8 m (1 to 6 ft) deep.

Commercial sounders, such as the Bludworth and Raytheon (use of trade names is for identification purposes only and does not imply endorsement by the authors or sponsors), became available about the same time and soon were used extensively in hydrographic surveys. These were also used extensively to monitor scour and fill associated with migrating sand waves (*8*). This equipment was fairly accurate and could cover a great range of depth, but it could not operate in depths shallower than about 0.9 m (3 ft). Consequently, these devices did not find much application in laboratory studies or in studies in small shallow streams.

Much of the impetus of bridge scour studies in the United States came from the pioneering work of Emmett Laursen and his coworkers at the University of Iowa. One extremely important piece of equipment, a **scour meter**, was developed for the model-prototype studies of the Skunk River. It was mounted in the streambed upstream of a bridge pier and could sense the water-sediment interface at the streambed. This device, which operated on the electrode-impedance principle, was developed and designed by Philip G. Hubbard and was described in an appendix to the report on scour around bridge piers and abutments by Laursen and Toch (*9*).

Standard Practices

Standard practices refer to those developed during the past 25 or 30 years and to techniques and equipment that were in use at the outset of this study (1990) in various field studies.

In 1990, there were no accepted methods or off-the-shelf equipment for collecting scour data in the United States. In part, this was because there had been no coordinated long-term effort to study scour processes. Also, most scour studies were site-specific and the equipment and techniques that were used had to be tailored to the geometry of the site and the peculiarities of the existing hydrology and hydraulic conditions. However, a few trends can be identified.

First, **sonic sounders** were standard equipment in most scour studies, but in some cases, they would not work and more traditional methods were employed. Second, **mobile teams**, not fixed installations, were generally considered more effective in collecting scour data. Third, there was a growing interest in the use of **fixed installations**, largely because of improvements in dataloggers, data transmission, and computers which allow the collection and processing of large amounts of real-time data. By 1990, there was interest in scour and bridge failure **warning systems**; whereas, there was very little interest in warning systems just 10 years before (*10*).

Selected Examples

The initial literature review indicated that although **sonic depth sounders** are the most versatile and widely used piece of equipment for detecting the water-sediment interface at the bed of a stream, there are some conditions under which they do not work. For example, along the Yellow River, sediment concentrations near the bed are so high that the standard sonic sounders cannot distinguish between the moving sediment layer and the nonmoving bed.

At the Old River Control structure along the Mississippi River (at the confluence of the Mississippi and Atchafalaya Rivers in Louisiana), scour measurements are made with a **lead weight** on a line because the highly turbulent flows entrain so much air that sonic devices will not work. The literature review indicated that, in general, sonic devices do not perform satisfactorily if there are high sediment concentrations, debris, or air entrained in the flow. For these kinds of flows, simple mechanical devices were considered to be the most satisfactory instruments for measuring local scour.

Vertically supported **sounding rods** have been used in depth soundings for decades and for measuring scour at bridge piers at least since 1921. In 1990, they were being used to monitor scour depth at bridge piers at several locations.

During recent years, many scour studies have been undertaken in New Zealand. One of the instruments used in the field to measure maximum scour depth at bridge piers is called the **Scubamouse**. The device consists of a vertical pipe buried or driven into the streambed in front of the bridge pier around which is placed a horseshoe-shaped collar that initially rests on the streambed. The collar slides down the pipe and sinks to the bottom of the scour hole as scour progresses during a flood. On falling flood stages, the collar is covered with sediments as the scour hole refills. The position of the collar is determined by sending a detector down the inside of the pipe after the flood. Earlier models involved a metal detector inside a polyvinyl chloride (PVC) pipe, but the pipe was sometimes damaged by debris, so the current models use a steel pipe, a radioactive collar, and a radiation detector inside the pipe. This device has been installed on many bridges in New Zealand (*11, 12*).

Findings From a Resurvey of Technology

Concurrent Activities

Scour studies are currently carried out with a great variety of equipment and techniques; however, through the U.S. Geological Survey (USGS) National Scour Study, conducted in cooperation with the Federal Highway Administration (FHWA), efforts are being made to standardize the collection of scour data (*13, 14, 15*). Because pier and abutment scour are major concerns for operation, maintenance, and bridge safety, bridges are inspected regularly. Inspection techniques for determining the extent of local scour include the use of divers and visual inspection, direct measures of scour with mechanical and electronic devices, and indirect observations using ground-penetrating radar (GPR) and other geophysical techniques (*16, 17*).

One of the early successful investigations using fixed installations was conducted at a new bridge on U.S. Highway 101 across Alsea Bay near Walport, OR. Stage, velocity, and scour depth were monitored every 15 min and stored in a datalogger that could be accessed by telephone to enter the data directly into a computer. Velocities were measured with Marsh-McBurney and Montedoro-Whitney electromagnetic flow meters and depth soundings were made using Lowrance and Eagle **sonic sounders**. The transducers for sounding were mounted on brackets attached to the piers and pointed out slightly to avoid interference from the side of the pier. The system worked well, but the installation was not subject to debris, ice, or air entrainment from highly turbulent flows (Milo D. Crumrine, 1990, personal communication; *26, 27*).

The USGS Hydrologic Instrumentation Facility (HIF) has designed several **conductance probes** for bridge scour studies. One was used in the mid-1970s in Arizona, and a more recent model was used in Arkansas. These devices apparently worked, but there were difficulties in collecting ground truth, and installation of the meters was difficult. HIF also has evaluated dataloggers and developed the component circuitry so that signals from sounders could be entered directly to the loggers. Additional laboratory evaluations of conductance probes have been conducted by the USGS (*18*).

Several research activities on bridge scour instrumentation have been conducted concurrently with NCHRP Project 21-3. The USGS/FHWA National Scour Study has included development of **portable instruments** for measuring scour and collecting scour data during high-flow conditions (*19,* *20, 21*). The USGS, in cooperation with the FHWA, has investigated various instruments and techniques for measuring scour. The ability of **low-cost fathometers** to locate the bed accurately was evaluated. Fathometers were found to be superior to sounding weights and were selected as the primary bed-measuring instrument in the National Scour Study. A remote-controlled portable instrument system using a digital fathometer was developed. The system includes range-azimuth-based hydrographic survey capability and an on-board computer and radio to monitor instrumentation, record measured data, and telemeter data to a shore station.

The USGS, in a cooperative scour study with the New York State Department of Transportation (NYSDOT), has installed Brisco monitors (a **sounding rod** device) and Data Sonics **sonar altimeters** to measure scour (*22*). In this study, remote telemetry of data is being tested. The New York Thruway Authority has installed Brisco monitors to monitor their scour-critical bridges. In addition, the Virginia Transportation Research Council has installed sonic devices on the I-95 bridge at the Virginia/North Carolina state line. These field investigations have provided valuable information on sonic sounders and the use of sounding rods and probes to measure scour or provide a warning when scour has occurred.

Geophysical Techniques

Equipment used in geophysical surveys is finding increased applications in scour studies (*16*). Impulse radar, lasers, and multichannel sounders appear to be the most promising techniques, but these devices are expensive and often the results require unique expertise for interpretation (*23*). The USGS has used surface-geophysical techniques with a position-recording system to study riverbed scour near bridge piers (*24, 25*). **Fathometers, fixed- and swept-frequency continuous seismic-reflection profiling (CSP) systems, and a GPR system** were used with a laser-positioning system to measure the depth and extent of existing and infilled scour holes near bridge piers. Equipment was purchased commercially and modified when necessary to interface with the components and/or to improve their performance.

The USGS and Oregon Department of Transportation (DOT) have extended the work at the U.S. 101 bridge across the Alsea Bay referenced above with an investigation of geophysical methods at U.S. 101 and additional sites in Oregon (*26,27*). Three geophysical methods—**GPR, high-frequency continuous seismic reflector (tuned transducer), and a color fathometer**—were used to examine 14 bridge sites in Oregon, in order to determine the usefulness of each method in locating and determining the depth of infilled scour holes around bridge piers in Oregon streams. Bridge piers were studied using one or more of the geophysical methods from a boat. Results of the surface-geophysical methods were verified by measuring the depth from the water surface to the pier footing, existing scour hole, and bottom of the infilled scour hole with a probe.

The USGS and Oregon DOT concluded (*26*) that each surface-geophysical method used was effective in detecting infilling around piers; however, not every method was effective at each site. GPR was limited to depths less than 7.6 m (25 ft) in water with low specific conductance, while tuned transducer and color fathometer methods worked in water depths ranging from 1.5 to 15 m (5 to 50 ft). Interpretations of the surface-geophysical data were complicated by side echoes from the pier and multiple reflections. This required verification of interpreted depths by probing. Interpreting the elevations of the bottom of infilled scour holes using GPR was more difficult than tuned transducer or color fathometer methods, because radar signals travel at different velocities in water and sediments. No one surface-geophysical method proved more valuable than the other during this study, because of the varying conditions of the sites tested.

Other Technology

A unique subbottom profiler, known as the **Chirp Acoustic Profiler**, has been evaluated as a scour-measuring device (*28*). This technology uses a swept frequency acoustic subbottom profiler integrated with the navigation capabilities of an automated hydrographic survey system to provide precise subbottom profiles. Although the current technology of the Chirp system cannot clearly delineate the type of subsurface material, it can definitely define the compactness or relative density of the underlying material. The darker the color, the more dense is the material and hence less susceptible to scour. For evaluation of the scourability of the bed material, the Chirp system can provide excellent data, particularly when it is correlated with actual borings (*28*).

A **Broadband Acoustic Doppler current profiler (BB-ADCP)** is a new instrument being used by the USGS to measure stream discharge and velocities and bathymetry (*29, 30*). Acoustic Doppler current profilers (ADCPs) have been in use for more than 10 years, primarily in the study of ocean currents and estuaries. Within the last 5 years, ADCPs have been used to measure streamflow, especially in rivers or canals where conventional discharge-measurement techniques are either very expensive or impossible. The more advanced ADCP—the BB-ADCP—can measure depths and velocities in shallow waters and with a high degree of vertical resolution. During the 1993 Mississippi River flood, BB-ADCPs were used to measure water velocities and bathymetry upstream from, next to, and downstream from bridge piers at several bridges over the Mississippi River. Bathymetry data were collected by merging location data from global positioning system (GPS) receivers, laser tracking systems, and depths measured by the BB-ADCP. The capability of the BB-ADCP to measure a three-dimensional velocity profile from a moving deployment platform significantly increases the detail at which the hydraulics associated with scour at bridges can be measured.

It has been suggested that **time-domain reflectometry** (TDR) technology can be deployed to detect bridge scour and monitor pier and abutment movement during flood events (*31*). However, application of TDR to bridge foundation monitoring requires development of an innovative means to package and install the cable system underwater as well as a low-power-consumption, intelligent pulser. A TDR scour detection system would measure the length of a buried cable, where flanges attached to the cable are expected to be torn off by high drag forces as the riverbed is scoured away, thus shearing the cable at the flange connection. The shearing process would shorten the cable and a signal reflection produced at the cable break would mark the scour depth. To date, only conceptual designs of proposed applications have been described.

In the United Kingdom, Hydraulic Research Limited of Wallingford has continued development and deployment of a buried rod instrument system to monitor bed scour during flood events (*32*). This **Tell-Tail scour monitoring system** is based on omnidirectional motion sensors, buried in the river or sea bed adjacent to the structure. The sensors are mounted on flexible 'tails' and are connected to the water surface via protected cables. Under normal flow conditions, the detectors remain buried and do not move. When a scour hole develops, the sensors begin to be exposed and transmit alarm signals to the surface. The signals are continually monitored and can also be recorded. The system also indicates whether scour refill has occurred. A basic eight-channel system of sensors is usually used. Since 1990, many scour monitoring installations have been installed, mostly on older high-risk bridges in the United Kingdom. The system is now being considered by British Rail as part of post-construction monitoring or for new bridge construction.

The California Department of Transportation (CALTRANS) and FHWA have developed a conceptual design which would use **buried scour sensors** placed at known depths in drilled holes (*33*). The sensors would tilt when scour reached their depth and they would transmit that information to the surface with a low-frequency radio signal. A design was conceptualized and a proposal was submitted to build the concept system. Although the proposed project was given an excellent chance of success, it was noted that additional features were needed to make it economically attractive for large-scale deployment.

The U.S. Army Cold Regions Research and Engineering Laboratory in a cooperative effort with the FHWA and the Vermont Agency of Transportation developed ice force and scour instrumentation for measuring and monitoring ice forces on a bridge pier and for monitoring the development of bed scour because of ice and open-water floods (*34*). A scour monitoring system was installed on the Route 5 bridge on the White River in Vermont. In addition to traditional scour chains, the system consisted of active scour sensors, including a Brisco sensor and a matrix of "instrumented fish" (**buried transmitters**) attached at incremental depth to a vertical mast buried in the riverbed. A radio transmitter enclosed in each fish was capable of detecting movement when exposed as scour progressed. Reburial of the fish occurred as sediment refilled the scour hole as the flow velocity subsided. Therefore, the fish did not require resetting after each scour event.

Since 1990, several **portable multibeam sonar units** have become available commercially and have been used to evaluate scour conditions at bridges, particularly on an emergency basis during severe flooding. A system developed by Oceaneering International, Inc. (*35*) uses technology developed for offshore applications to detect scour and other structural problems around bridges, dams, piers, and pipelines. The system uses multibeam sonar coupled with a subbottom profiler and can be deployed from the bridge itself, either by a special framework or from a snooper truck. An integrated multibeam sonar system can provide data in various formats, ranging from cross-section and two-dimensional contouring to isometric displays and three-dimensional design files.

Another **multibeam sonar system** has been developed and deployed by American Inland Divers, Inc. (*36*). The Sonar Scour Vision system has three components: a boom truck deployment unit, a control van, and the Scour Fish. The Fish is a winged hydrodynamic vehicle that uses the river's current to remain submerged. It houses a sonar unit, which is deployed over the side of a bridge from the superstructure using a crane from the boom truck. Suspended from the crane and operated from a stationary point, the fish is positioned several feet below the river's surface.

Sonar data gathered from the Scour Fish is relayed to the control van, which is equipped to produce on-site drawings for field evaluation. The data produce two-dimensional contour plots instantly. Three-dimensional graphics of the riverbed can be generated overnight. Contour plots provide real-time representations of subsurface conditions, ranging from 91 m (300 ft) upstream to 91 m (300 ft) downstream. The system's accuracy has been reported to be within ±152 mm (6 in.) (*36*).

Summary of Literature Review Findings

The initial literature search revealed, and the resurvey of technology confirmed, that fixed scour-measuring and -monitoring devices/instruments can be grouped into the following four broad categories:

1. Sounding rods,
2. Buried or driven rods,
3. Sonar, and
4. Other buried devices.

As a result of the literature review, the laboratory testing program was designed to test at least one device from each category and to select devices for field testing that would give the greatest potential for meeting mandatory and desirable criteria.

LABORATORY TESTING

The laboratory testing program was conducted at the Hydraulics Laboratory at the Engineering Research Center of Colorado State University (CSU). A recirculating flume was used for the indoor small-scale laboratory tests, and a large fixed flume was used for the outdoor near-prototype tests. Figure 1 shows the small-scale pier model in the indoor recirculating flume. Figure 2 shows the near-prototype scale pier model in the outdoor flume. These facilities are described in more detail in Appendix B.

Detailed results from the indoor small-scale and outdoor near-prototype scale testing are presented in the Phase I project report, Volumes I and II (*37, 38*). In this section, test data and findings are summarized and condensed. The results of laboratory testing have been reorganized so that each type of device tested is discussed separately, allowing a logical presentation of results from small-scale to near-prototype scale for each class of devices. In some cases, additional data and analysis are presented in this section to supplement the data from the reports submitted by CSU.

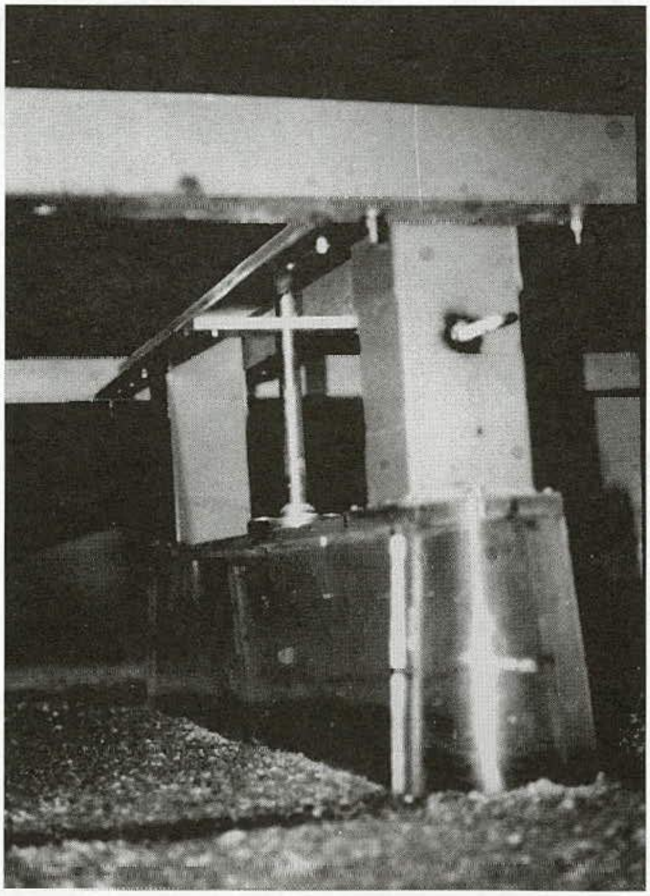


Figure 1. 1:15 scale model pier used in the recirculating flume.

Figure 2. Near-prototype model pier in the outdoor flume.

Sounding Rods

Mechanical sounding rods were tested and evaluated during the indoor tests conducted in the 61-m (200-ft)-long flume and during the outdoor near-prototype laboratory testing. The following sections document chronologically the tests and findings for this class of device during laboratory testing.

Indoor Tests in 61 M (200-Ft) Flume

A model of a sounding rod device was attached to the 1:15 scale model pier and placed in the flume (Figure 3). The model sounding rod consisted of a 1,422-mm (56-in.)-long solid-steel rod with a diameter of 19.56 mm (0.77 in.), supported by a 737-mm (29-in.)-long pipe with an inside diameter of 20.57 mm (0.81 in.). Initially, this device was oriented vertically in front of the pier footing, with the rod bearing on sand with a d_{50} of 4 mm (0.16 in.). For the three discharges tested, it was observed that the sounding rod, without a baseplate, tended to work down into the unconsolidated sand of the bed surface. Furthermore, when the flume was shut down between discharges to measure and contour the bed, it was noted that the depth of rod penetration was not consistent for each discharge.

A similar problem was observed when the sounding rod was oriented vertically through a hole drilled through the pier footing (Figure 4) for the second test of this device, again using 4-mm (0.16-in.) sand. The results of this test indicated that the sounding rod tended to either bury itself or jam with sediment. Furthermore, even if bed penetration or binding had not been observed, the device would have been unable to measure the maximum depth of scour. The maximum scour depth was located near the front of the pier footing and not where the device was located.

To mitigate the problem with the sounding rod penetrating the bed, the rod was modified by adding a 58.4-mm

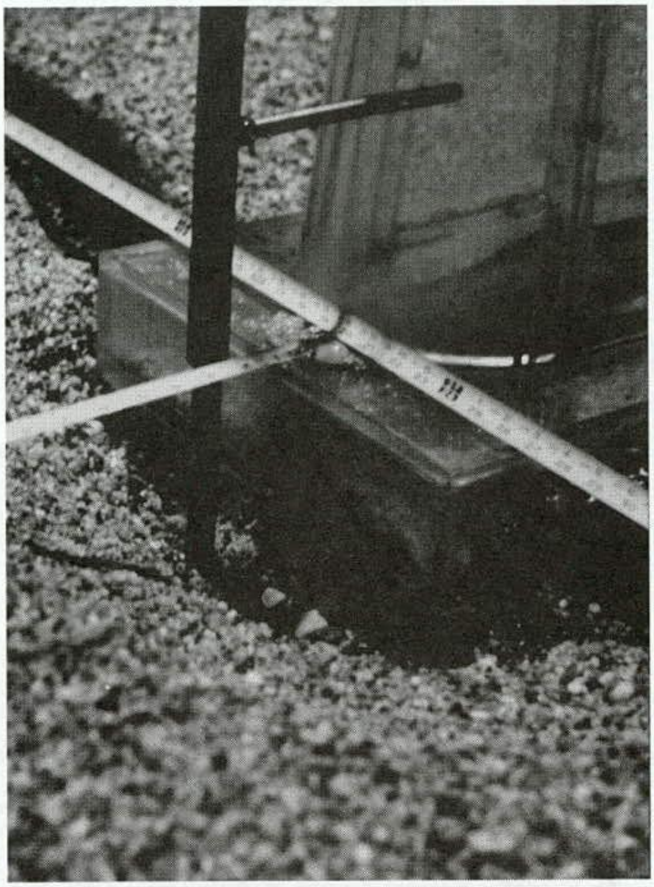


Figure 3. 1:15 scale model pier in recirculating flume with mechanical sounding rod.

(2.3-in.)-diameter circular base plate (3 times the diameter of the rod). Additional tests were conducted using 4- and 2.3-mm (0.16- and 0.09-in.) sand, respectively, with the modified baseplate and with the device oriented vertically in front of the pier footing. These tests indicated that the addition of the baseplate resulted in the ability to measure the actual scour depth to within approximately ±10 percent. Furthermore, the device was observed to move down with the progression of the scour. In no case did the device penetrate the bed, and the presence of the sounding rod did not affect the maximum scour depth. Discrepancies between the measured and actual scour depth occurred because the maximum scour depth was observed at a location which was not exactly where the device was located.

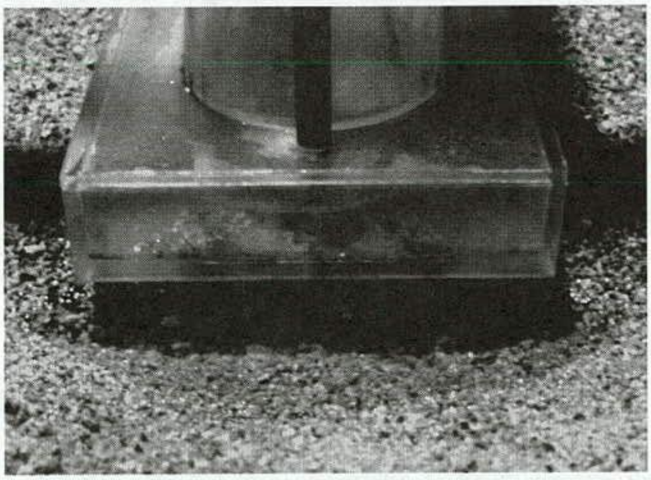


Figure 4. Vertically supported sounding rod installed through pier footing.

For one test, the sounding rod with the enlarged baseplate was oriented at a 45-degree angle. This orientation was used to assess the performance of this class of devices when vertical installations would not be feasible (e.g., at sloping abutments and piers). For this test, the device performed well. The rod followed the progression of the scour hole and did not bind or hang up. However, because the rod was angled, as the scour progressed, the end of the rod moved further away from the zone of maximum scour depth. This problem, combined with the necessity of making a correction on the basis of the angle, would make it difficult to obtain actual maximum scour depth measurements from an angled sounding rod installation in the field.

Outdoor, Near-Prototype Tests

A 2.4-m (8-ft)-long Brisco Monitor was used to test the sounding rod type of device during the outdoor, near-prototype testing phase of the project. The device was a shortened version of the patented Brisco Monitor which has been installed by others elsewhere in the field. This device consisted of a 2.3-m (7.5-ft)-long solid-steel rod with a 51-mm (2-in.) diameter encased in a 51-mm (2-in.)-diameter PVC sheath. The rod and sheath assembly had an outside diameter of 60.45 mm (2.38 in.). The sounding rod was supported by a 2.4-m (8-ft)-long steel pipe with an inside diameter of approximately 73.7 mm (2.9 in.). A heavy piece of 203-mm (8-in.) angle iron protected the upstream end of the device from debris. Figure 5 shows the Brisco Monitor as it was installed in the flume. The instrument weighed approximately 136 kg (300 lb).

Two tests were conducted in the outdoor flume with this device. The first test used the original 76-mm (3-in.)-diameter baseplate, which was fitted to the device at the factory. For the second test, an enlarged 127-mm (5-in.)-diameter baseplate was used. During the first test with the original baseplate, the device exhibited the same problem experienced in the indoor flume tests. During the second test, the Brisco Monitor, modified with an enlarged baseplate, performed well. The rod tended to move down with the progression of the scour hole and did not display the problem with penetration. However, the enlarged baseplate tended to slightly reduce the maximum depth of scour observed as compared with the base flume tests which were conducted without a scour measuring device installed.

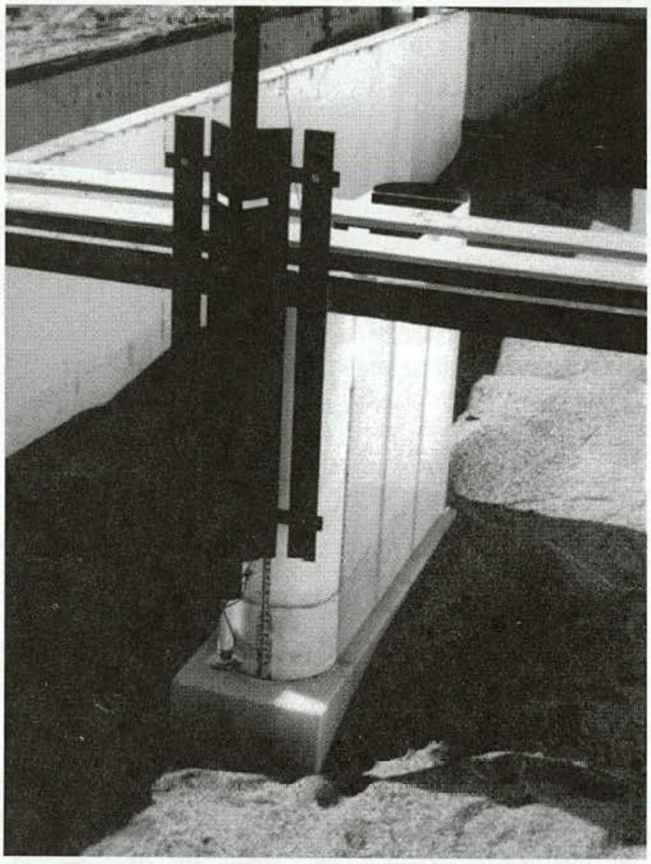


Figure 5. Installation of Brisco Monitor in outdoor flume.

Findings—Sounding Rod Laboratory Testing

- Currently, little or no data are available on the behavior of sounding rod devices in sandbed streams. The results of the indoor and outdoor tests indicate that the weight of the rod and the subsequent bearing stresses applied to the sand must be minimized to prevent settlement or penetration of the rod into the sandbed.
- Although the test data are limited, it appears that the bearing stress of the sounding rod devices needs to be minimized when installing this class of devices in sandbed channels. Because the weight of the rod is directly proportional to the length of the rod, and rod lengths can be up to 6.1 m (20 ft) long or longer, the size of the footplate must necessarily be larger for longer devices. Assuming a 6.1-m (20-ft)-long rod weighing 98 kg (216 lb), a footplate approximately 203 mm (8 in.) in diameter would be required to keep the bearing stress below 28,728 Pa (600 PSF).
- Increasing the baseplate diameter requires that the sounding rod would necessarily need to be mounted farther from the pier or footing. The added distance from the pier will most likely complicate the mounting of the device and the ability to mount the device directly over the location where maximum scour would be expected. Furthermore, because the device would project further into the flow, it would be more susceptible to debris and ice impact and hydrodynamic vibration from vortex shedding off the exposed rod.
- The laboratory test data on the sounding rod class of devices indicate that these devices may be best suited for piers or abutments where the instrument can be mounted in a vertical orientation. If the device is to be mounted in a sandbed channel, the device must be equipped with a footplate large enough to distribute the vertical force to the soil without settlement. In regard to the mandatory criteria to determine maximum depth of scour, and because of the jamming problem experienced in the small-scale flume, installing a sounding rod through a pier footing is not recommended.
- Significant insight into the function and potential problems associated with this class of devices was obtained from the laboratory trials. However, problems associated with debris and sediment jamming, as well as the long-term durability and reliability of these instruments need to be demonstrated in actual sandbed streams. Details of the field testing phase of this study are presented in the Field Testing section of this chapter.

Driven/Buried Rods

This class of scour measuring device includes all sensors and instruments supported by a vertical support member such as a pipe, rail, or column, which could be placed vertically in the bed at the location where scour would be expected to occur. Installation of the support column could be by driving, jetting, augering, or excavation and burying. Examples of this class of device include the New Zealand Scubamouse, the Wallingford Tell-Tail devices, and the USGS conductance probe field tested in Arkansas (see *11, 12, 18, 32*).

The objectives for laboratory testing of this type of device were to ascertain the degree to which the presence of a driven/buried rod would enhance or inhibit scour in front of piers, document how a sliding collar similar to the Scubamouse performs, and develop and test other bed-level sensor concepts.

Indoor Tests in 61-M (200-Ft) Flume

A small-scale model of a driven/buried rod was tested in the 61-m (200-ft)-long flume at CSU's hydraulic laboratory. The tests were conducted in a fashion similar to the tests of the small-scale sounding rods discussed previously. The rod, which was 19.56 mm (0.77 in.) in diameter, was driven into the bed in front of the footing of the 1:15 scale model pier. A sliding collar, consisting of three washers with an inside diameter of 20.57 mm (0.81 in.) (see Figure 6), was installed around the rod when the rod was oriented in front of the pier footing.

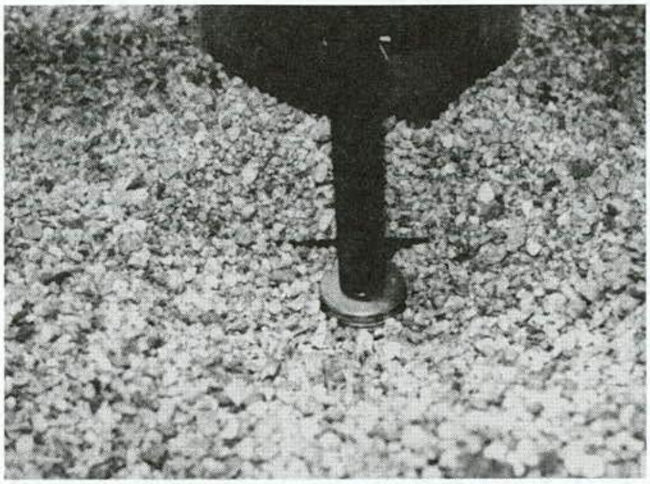


Figure 6. Driven rod with sliding collar in the indoor flume.

Comparison of tests with the driven rod and the base run without a device installed indicated that there was no discernible influence from the presence of the rod on the maximum scour depth. For some tests in bed material consisting of sand with a d_{50} of 4 mm (0.16 in.), the sliding collar was observed to stick and jam. Sticking occurred as a consequence of fine material getting between the collar and the rod, inhibiting the free sliding of the device down the rod as the scour progressed. Jamming also occurred as a consequence of differential sliding of the collar down the rod. Because the scour hole did not have a horizontal surface, the downstream edge of the sliding collar dropped first and the collar jammed.

To rectify this shortcoming, the tolerance between the outside of the rod and the inside of the sliding collar was increased by reaming the inside diameter of the collar to a diameter of 21.59 mm (0.85 in.). When the modified sliding collar was tested again, the sliding collar properly tracked the bed and the progression of the scour hole.

These tests indicated that the design of a sliding collar type of device must be carefully considered so that the smooth mechanical operation of the collar is not inhibited. A competing concern is that the sliding collar must be kept close to the support rod so that any sensors mounted on the rod to track the progression of the falling collar can activate as the collar slides past them.

Outdoor, Near-Prototype Tests

Three different driven/buried rod sensor types were tested during the outdoor, near-prototype testing phase: piezoelectric polymer film, mercury tip switches, and magnetic switches (activated by the sliding collar). All three types of sensing devices were mounted on a single 102 mm (4 in.)-diameter pipe and tested simultaneously. Thus, this single driven rod device had a "redundant" sensing capability. Each sensor type is described separately below.

Piezoelectric Film. Piezoelectric film is a polymer film which is widely used in the electronics industry. The significant property of this film for this application is that when the film is flexed or vibrated, a voltage and current are generated. Conversely, when buried, the strips remain stationary and should not produce a signal. As scour develops, the piezoelectric film sensor would be exposed to the flow and vibrated by turbulence in the flow (see Figure 7). A voltage signal emanating from the piezoelectric film would indicate that the scour had reached a particular sensor's elevation on the driven rod.

One advantage of this device is that the piezoelectric film does not need to be excited by an external power source, which minimizes power drain from the datalogger which records the data. Furthermore, a vertical series of these sensors should be able to measure both the scour and fill process which is a characteristic of local scour. By varying the spacing of the sensors, the accuracy of an array of piezoelectric film sensors could be selected to meet specific local requirements.

For the near-prototype tests, five strips of piezoelectric film, spaced at 0.3-m (1-ft) intervals, were mounted horizontally on a 1.5-m (5-ft) length of a 25-mm (1-in.)-wide stainless-steel channel, which was mounted vertically on the 102-mm (4-in.)-diameter support pipe (see Figures 8 and 9). The channel and strips were mounted on the downstream side of the pipe to protect the sensors from sediment and debris impact. Furthermore the strips were designed so that they would fold up and lay flat against the pipe during field installations using driving, jetting, or augering techniques.

The functioning of the piezoelectric film using two encasement methods was assessed. Three piezoelectric film sensors were encased in a thin plastic laminate using a technique similar to heat lamination used for identification cards. Two other sensors were encased in a 76-mm (3-in.)-long piece of 9.5-mm (0.38-in.)-diameter vinyl tubing.

Mercury Tip Switches. Five electrical mercury tip switches, spaced on 0.3-m (1-ft) centers, were also installed on the stainless-steel channel, which was attached to the lee side of the support pipe (see Figures 8 and 9). The principle of this device is that, as the supporting rod is driven, jetted, or augured into the bed, the tip switches would be folded up against the rod, closing the circuit in the switch. These switches would remain in the up (closed) position until the streambed material holding the switch is eroded away by scour. When the scour exposes the switch, the device would flip into the down position, breaking the circuit.

The main advantage to this type of sensor array is that these switches are easy to obtain from any electronics shop. Because the technology is simple, the construction of a rugged sensor array which would withstand long-term exposure to the elements should be relatively simple. As with the piezoelectric film, the accuracy of a sensor array can be

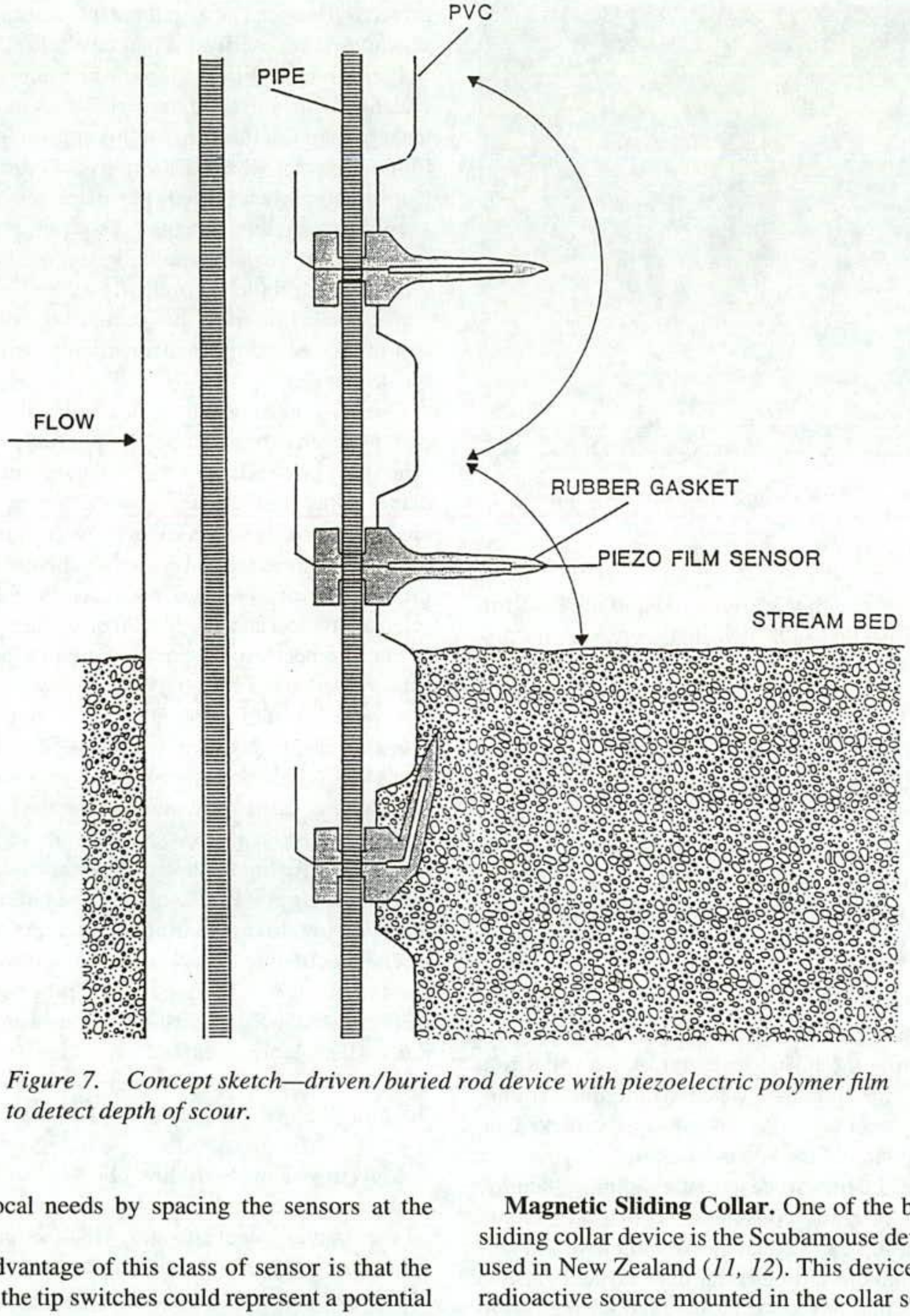


Figure 7. Concept sketch—driven/buried rod device with piezoelectric polymer film to detect depth of scour.

designed to fit local needs by spacing the sensors at the desired interval.

The chief disadvantage of this class of sensor is that the use of mercury in the tip switches could represent a potential or perceived environmental hazard. Although the housing of the sensors is extremely durable, the possibility of damage from debris and sediment impact, from installation, or from long-term exposure to the elements might lead to release of mercury and, consequently, environmental concerns. However, another type of tip switch that does not use a hazardous material could be developed, which could be used in lieu of the mercury switches. Another disadvantage of this type of device, in contrast with the piezoelectric film sensor, is that, once the maximum depth of scour is reached for a given flow event, this sensor will not indicate any subsequent stream bed activity, such as scour hole refill or re-scour.

Magnetic Sliding Collar. One of the best examples of a sliding collar device is the Scubamouse developed and being used in New Zealand (*11, 12*). This device uses a low-grade radioactive source mounted in the collar so that the position of the collar along the rod can be determined.

To avoid the use of undesirable materials, a sliding collar which would activate magnetic switches was designed to slip over the pipe supporting the driven/buried rod. The design of the collar was influenced by the results of the indoor flume studies. The collar was 152 mm (6 in.) high and was designed with minimal contact with the support pipe to prevent jamming and sticking (see Figure 10). A 152-mm (6-in.)-long magnet was attached vertically to the collar. The collar was designed so that the collar and magnet would slide vertically within approximately 12.7 mm (0.5 in.) of the stainless-steel channel described previously. A series of five magnetic

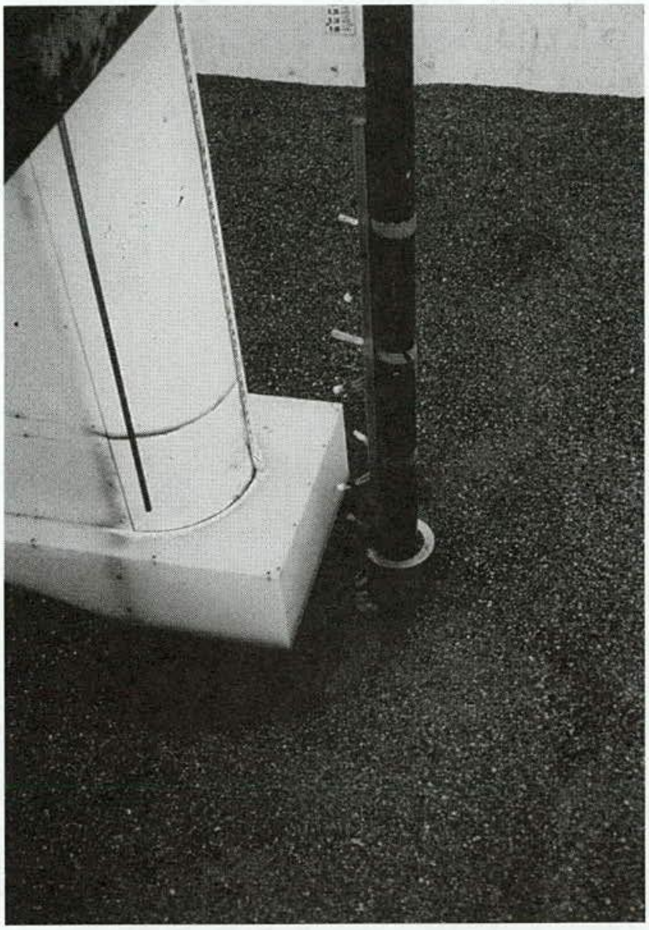


Figure 8. Driven/buried rod with three types of sensors and sliding collar.

switches, installed on 0.3-m (1-ft) centers in the stainless-steel channel of the driven rod, completed the fabrication of this device (see Figures 8 and 9).

The concept of this device is that the collar will slide down the pipe as scour progresses and activate the magnetic switches placed at preset intervals. The advantage of this type of sensor array is that the magnetic switches are simple, readily available, and not hazardous. Because the technology is simple, the construction of a rugged sensor array, which would withstand driving and long-term exposure to the elements, should be relatively easy. However, the sliding collar will not "reset" to indicate subsequent fill and scour activity once the maximum depth of scour has been reached.

Split-Ring Magnetic Sliding Collar. As a refinement to the standard sliding collar (see Figure 10), a split-ring or clamshell magnetic sliding collar was also designed. The split-ring design allows for the installation of the sliding collar around the support pipe instead of sliding it on from the top. With this collar design, it is possible to install a second sliding collar in the event that filling buries the primary collar and removal (scour) of the fill needs to be monitored.

The clamshell (split ring) consists of a sliding magnetic collar similar in dimensions to the original, except that it is in two halves which close around the support structure and are fastened by stainless-steel bolts and nuts once it is in place. With a new magnetic collar at the surface of the streambed, the instrument now functions as it did initially.

Results of Driven/Buried Rod Tests

Figure 9 shows the location of the tip, piezoelectric, and magnetic switches as fabricated for the outdoor tests. On the driven/buried rod, a sensor consisting of either a tip, piezoelectric, or magnetic switch was located every 0.1 m (0.33 ft) along the rod. With this arrangement, the progression of the scour hole could be monitored at accuracies of 0.1 m (0.33 ft). Furthermore, the redundancy allowed evaluation of the performance of one sensor type against the other.

A Campbell 21X datalogger was used to interrogate the voltages and activity of the three types of electrical switches incorporated into the driven/buried rod. The datalogger served to sense voltage from the tip and magnetic switches and to sense low-level AC voltage from the piezoelectric film strips. The status of all switches was ascertained by the datalogger at 5-sec intervals. Time-stamped minimums from the tip switches and maximum readings from the piezoelectric and magnetic sensors were recorded every minute.

Two driven/buried rod tests were conducted in the outdoor flume with the three types of sensors. The first test was conducted to ascertain whether the device would work as expected and to verify that data could be retrieved on the datalogger. The data for the first test with the driven/buried rod indicated that the tip switches tended to release and flip down into an "off" position when, or slightly before, the scour reached the level of the tip switch. Accuracies of 0.3 m (1 ft) were obtained with the tip switches located at 0.3-m (1-ft) intervals on the rod. Accuracies of ± 0.15 m (0.5 ft) or better were obtained using the sliding collar with 0.3-m (1-ft) magnetic switch spacing. This is because the 152-mm (6-in.)-long magnet on the sliding collar would mark when the collar initially arrived and finally left the proximity of the magnetic switch.

The piezoelectric film data indicated that the encasing tubing not only damped transient noise, but blocked much of the signal generated from turbulent buffeting by the flow. Consequently, it was sometimes difficult to ascertain when the tubing-encased piezoelectric film sensors were active. Conversely, the laminated sensors were more easily excited by turbulent buffeting.

The results of the first test with the redundant device showed that the sensors and datalogger performed as expected and followed the progression of the scour hole. In more detailed tests (Tests 1F and 2F), actual scour depth measurements, using a graduated sounding rod, were collected so that data from the redundant device could be com-

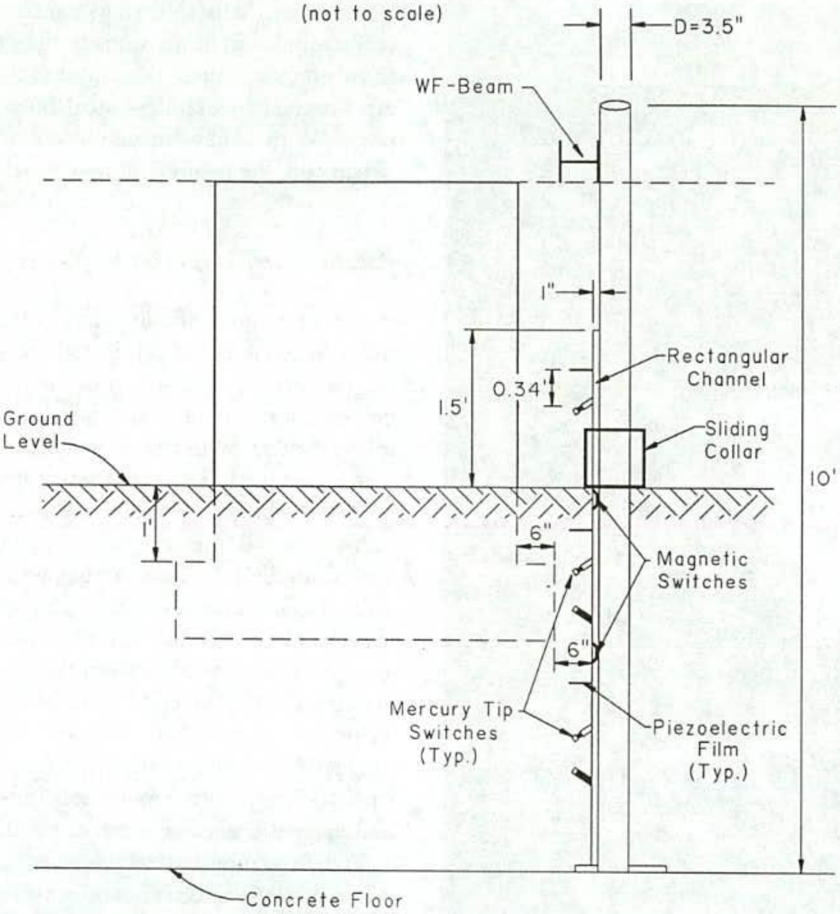


Figure 9. Profile view of the driven/buried device.

pared directly with the actual scour depth. The results from these tests indicated that the individual sensors which produced data performed as expected and accurately indicated the scour depth. However, several individual sensors did not function during this test and, therefore, require additional discussion.

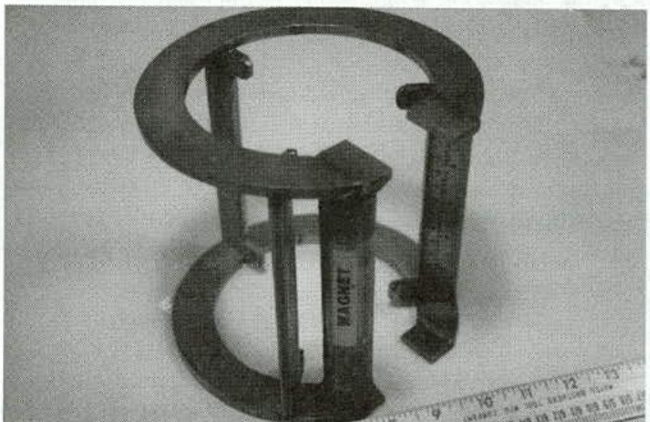


Figure 10. Oblique view of magnetic sliding collar for driven rod scour-measuring device.

During Test 1F, one piezoelectric sensor never flipped to the horizontal position when it was exposed by scour. This was caused by sand compacted against the rail and sensor when the sand was compacted in the flume. This piezoelectric film sensor never indicated activity during Test 1F. Between Tests 1F and 2F, this sensor was cleaned and it then worked properly during Test 2F. A second piezoelectric film sensor was exposed by scour during Test 2F and flipped to a horizontal position, but no signal from this sensor was recorded by the datalogger. This lack of signal was attributed to (1) the sensor's being located in a relatively deep scour hole where turbulence was low and (2) this sensor's being mounted in the less flexible vinyl tubing. With less turbulence available to flex a stiffer sensor, no signal was obtained.

In addition, one magnetic switch did not produce any discernible signal during Tests 1F and 2F. Upon post-test inspection, it was discovered that the wire for this sensor had been crimped and broken during the early portion of the test. Before the beginning of the second test with the driven/buried rod, it was observed that the plastic lamination on the piezoelectric sensors had become brittle and delaminated. Although these sensors still worked during the test, the lack of durability of the lamination is undesirable for field installations.

Piezoelectric Film Sensors

The design criteria for the piezoelectric sensors requires that the piezoelectric film strips be encased in a flexible, durable, water-tight material which would not deteriorate when exposed to sunlight, water, soil, and chemical pollutants. It was found that the encasement techniques such as polyvinyl tubing or laminating the sensor between two pieces of mylar deteriorated and cracked in less than a few months of exposure to sunlight, rain, snow, and freeze/thaw cycles. Alternative encasement materials evaluated included use of a high-grade underwater silicone-based sealant, plastics similar to that used to make in-line skate wheels, and a high-grade silicone tubing. Various sensor shapes and encasement techniques were considered for the piezoelectric film sensor.

It was found that silicone-based sealants were messy and difficult to shape, and skate wheel plastics required significant pressure and heat for curing, which could destroy the piezoelectric film. Discussions with the manufacturer of the silicone tubing indicated that the material was very inert, durable, waterproof, flexible, and resistant to a wide variety of chemical and oil-based solvents. Additional benefits of this material included good bond strength and adhesion with polycarbonate plastics using a silicone sealant and the ability to be stretched with minimal stress-strain hysteresis.

Various shapes of piezoelectric sensors were fabricated using piezoelectric film bonded to mylar and encased in the silicone tubing described above. A plug made of polycarbonate was sealed in one end of the tubing to form the attachment to the support rod. To test sensor response to turbulence, various shapes of 3.1-mm (1/8-in.) polycarbonate plastic were attached to the downstream end of the sensor. These shapes included a straight piece, a piece shaped like a fish tail, and a fish tail which was asymmetrically twisted. Additional sensors were fabricated without the polycarbonate end attachments.

These sensors were attached to a 100-mm (4-in.)-diameter piece of pipe (Figure 11) and tested for output sensitivity in flowing water using a voltmeter. From these tests, it was found that all of the various shapes produced a random voltage output pattern which ranged between 0.002 and 1.8 volts. Because there was no apparent difference in output signal, the sensor design without the polycarbonate end attachment was selected because this design was easier to construct and more durable.

Figure 11. Signal testing apparatus for piezoelectric film sensors.

The weatherability of the silicone tubing sensors was tested by exposure to environmental conditions similar to field conditions. A sensor was buried in a wet environment and left outside for more than 4 years. This sensor was periodically removed and visually inspected and tested with a voltmeter. Results indicated that the sensor had not deteriorated and the voltage signal had not degraded during that period.

Findings—Driven/Buried Rod Laboratory Testing

- The small-scale indoor test of a driven/buried rod indicated that the presence of the rod did not appreciably enhance or reduce scour at the pier. Small-scale tests of a sliding collar installed on the buried rod, indicated that this type of device must be carefully designed to prevent sticking or jamming. This observation influenced the design of the sliding collar for the near-prototype tests, in that the sliding collar was designed to present the smallest cross section to the flow, have sufficient distance between the upper and lower collar segments to ensure that the collar would slide smoothly on the rod, and provide ample clearance for sediment to be flushed through and away from the collar.
- With the exception of the mechanical problems associated with the mounting and encasement of the individual sensors, the driven/buried rod device performed as designed during the near-prototype laboratory tests and provided an accurate indication of the progression of the scour hole. As constructed, the driven/buried rod device measured maximum scour to an accuracy of ± 0.1 m (0.33 ft), better than the mandatory criteria of ± 0.3 m (1.0 ft). By redesigning the array spacing, even greater accuracy could be achieved.
- Although the encasement and mounting of individual sensors required further refinement, the positive results from the laboratory tests indicated that these devices offer a viable method for measuring scour at bridge piers and abutments.
- Further laboratory testing of the piezoelectric film sensors revealed that a high-grade silicone tubing provided the optimal encasement material for the piezoelectric film. When exposed to the flow and turbulence in a scour hole, tubing alone, without any additional shape, such as a fish tail, provided sufficient vibration to generate a detectable voltage. Immersion tests over a period of 4 years proved the durability of this encasement technique.

Sonic Fathometers

Description of Devices

The survey of instrument technology revealed that there are several sophisticated, research-quality sonic fathometers available commercially (e.g., Data Sonics fathometers). Rather than adopt one of these relatively expensive instruments to a scour measuring function, it was of interest to determine if, and to what extent, low-cost sonic fathometers could be used for measuring scour. Such devices are readily available from several manufacturers and are typically used on boats to locate fish. Both low- and high-cost devices are being evaluated by other researchers also interested in measuring scour (see Literature Review, Chapter 2).

Two fish-finder-type instruments were purchased and used for the laboratory testing. The first was an Eagle Corporation Z–9500 equipped with an 8-degree transducer. This device displays a bottom scan and depth on a liquid crystal display (LCD) screen. An advantage to this device is that depth and temperature data can be interrogated from a data relay wire hard-wired into the instrument. The second device was a Lowrance Corporation 3400 sonar fathometer equipped with a 20-degree transducer.

An objective for testing the sonic type devices was to identify which regions of the bed are detected at different mounting angles, and with different transducer cone angles. That is, it was of interest to determine how a sonic device "sees" the scour hole. Furthermore, it was important to determine if, or to what degree, vertical bridge members, such as piers and abutments, interfere with the sonic signal. A final objective was to determine if temperature or other environmental conditions would adversely affect the reliability of the signal. Limitations in experimental apparatus available produced inconclusive results when tests were conducted in the indoor laboratory. These issues were addressed, and more conclusive results were obtained from field testing, final testing, and analytical studies. These results are presented in the sections which follow.

Outdoor Near-Prototype Tests

Following the indoor tests in the sump, the Eagle and Lowrance fathometers were tested in the outdoor flume as part of the near prototype testing phase of this project (see Figures 12a and 12b). Initial tests were conducted to check the test setup. At a discharge of approximately 2 m^3/s (70 cfs) neither of the two fathometers would "lock on" to the bed. This disconcerting behavior led to a set of hypotheses to identify the reason for the loss of signal. Possible factors including equipment failure, minimum water depth requirements, the velocity of the water, flow separation at the transducer head, or air entrainment in the flow were considered. To disprove that equipment failure was the cause, the devices were checked in quiescent water. This check confirmed that the equipment was functioning properly.

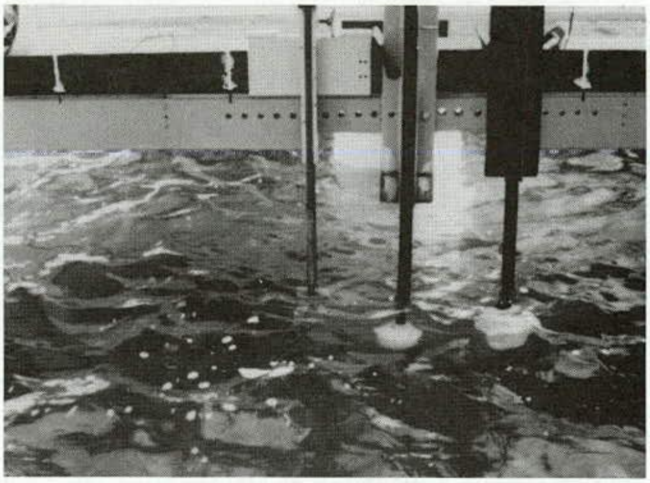


Figure 12a. Sonar transducers submerged during testing.

A preformed scour hole was excavated in the outdoor flume for the second near-prototype test. For this test, a minimum of 0.9 m (3 ft) of water was maintained at the location in front of the pier where the transducers were to measure the scour depth. Both instruments were checked thoroughly and tested in calm water before and during the test to ensure that the instruments were functioning properly. Both instruments functioned properly as the discharge increased to approximately 0.71 m^3/s (25 cfs). When the discharge was increased beyond that point, both fathometers once again lost signal. Upon reducing the discharge, signal was re-established. At no time was any flow separation observed at the transducer heads during this test. Observations of the functioning of the flume head box and energy dissipator (see Figure B-2) as the flow was increased through 0.71 m^3/s (25 cfs) and then

Figure 12b. Sonic fathometers in outdoor (near-prototype) flume.

reduced revealed that there was a threshold for discharges greater than 0.71 m^3/s (25 cfs) where the flow exiting the head box contained significantly more entrained air. It was concluded that the presence of a large amount of entrained air was the most likely cause for the loss of signal from the sonic fathometers.

To verify this conclusion, the fathometers were tested in a nearby irrigation canal. At the location where these instruments were tested, the flow was tranquil with a mean velocity of approximately 1.2 m/s (4 fps) and average depth of approximately 0.9 m (3 ft). A 0.6-m (2-ft)-drop structure in the canal provided a location where the instruments could be tested in both tranquil and highly turbulent air-entrained flow directly upstream and downstream of the drop, respectively. The influence of the velocity on the operation of the instrument could be ascertained because the mean velocity in the canal was comparable to the velocities during the first flume test with the sonic fathometers.

Tests in the canal confirmed the hypothesis that entrained air caused the loss of signal. When the instrument was placed in the flow upstream of the drop structure, accurate and steady readings were obtained. Conversely, when the instrument was located in the plunge pool downstream of the drop, where the flow was turbulent and contained a high proportion of entrained air, no signal could be obtained. Approximately 9 m (30 ft) downstream of the drop, signal from the fathometer was re-established.

Findings—Sonic Fathometer Laboratory Testing

- Testing of the sonic fathometers indicated that this class of low-cost instruments must be mounted so the transducer is aimed at the location where maximum scour will occur and the signal must not be obscured by debris or ice.
- Loss of signal associated with the entrainment of air, which was observed in the laboratory flume, may not be a major concern for most bridge sites, because the entrained air which was introduced into the flume flow by the energy dissipator is atypical of most actual river situations. However, there may be cases in the field where highly turbulent, air-entrained flow conditions will preclude the use of these instruments.
- Testing of the performance of low-cost sonic instruments under varying conditions of turbidity and sediment load was deferred to the field testing phase.

Other Buried Devices

Description of Devices

This class of devices includes sensors which could be buried in the bed of a river at various elevations. Should scour expose these instruments, they would be rolled or floated out of the scour hole. These sensors could be either untethered or tethered to the pier or abutment (*33*).

Obtaining scour data from a tethered device could be as simple as visually inspecting which tethered devices have been removed from the hole by scour. Alternatively, the tether could incorporate the electronic wiring for a motion-activated switch in the sensor head. The untethered devices would most likely incorporate a motion-activated transmitter, with a receiver on the bridge or stream bank sensing when and which transmitter has been moved and activated.

To ascertain the physical interactions of these type of sensors with a scour hole, a set of dummy devices (without electronics) was buried in the bed and tested in the outdoor flume concurrently with the second test of the driven/buried rod device discussed previously.

Outdoor, Near-Prototype Tests

The tethered devices consisted of 25-mm (1-in.) oval fishing bobbers connected to the superstructure of the pier with fishing line. The untethered devices consisted of 0.95-L (1-qt) neoprene wide-mouth sample bottles. This size of bottle was considered necessary to contain a transmitting device with an adequate supply of batteries. The bottles were filled with sand to simulate the weight of an electronics package which would be required for these sensors. The bottles were filled so that they would float with approximately 51 mm (2 in.) of the 178-mm (7-in.)-long bottles above the surface. The placement of the untethered and tethered devices in the outdoor flume is shown in plan and profile view in Figures 13 and 14, respectively.

During the test, the actual maximum scour depth, as measured with a graduated wading rod, was determined directly upstream of the pier and footing. Because of the presence of the driven/buried rod, the buried sensors could not be located where maximum scour occurred. However, the behavior of the buried bottles could be observed from the surface so that a visual record of their performance could augment the data.

Findings—Other Buried Device Laboratory Testing

- Near-prototype testing of dummy buried tethered and untethered devices indicated that these types of instruments could be developed and adapted for measuring scour at bridge piers and abutments. Further research and development would be required in order to design and fabricate prototype devices which would incorporate the required electronics, transmitters, receivers, and power sources.
- Although more work is required so that a prototype device of this nature could be installed in the field, the results of these investigations show that the devices could be designed so that their removal by the flow correlates closely with the development of a scour hole.

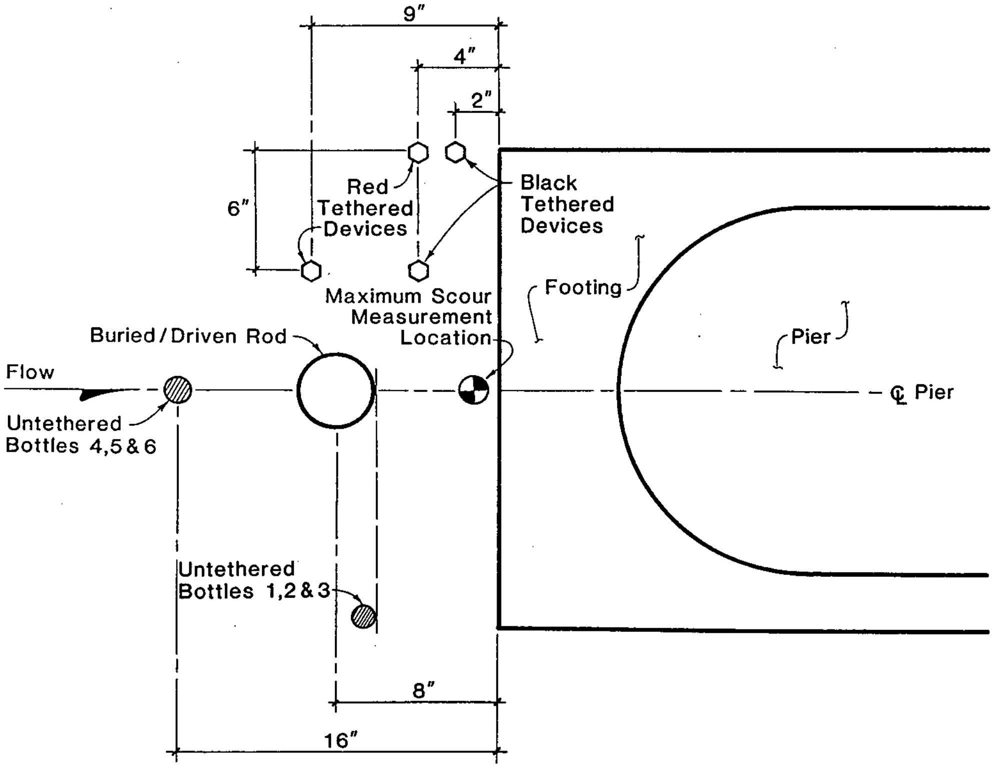


Figure 13. Location of buried devices (plan view).

FIELD TESTING

Introduction

The primary objectives of field testing of scour instrumentation were to build on the experience gained with selected instruments during laboratory testing, test the adaptability of promising instruments to a wide range of bridge pier and abutment geometries, and subject the instruments to various geomorphic and environmental conditions. An additional significant objective was to gain experience in working with local state highway personnel who would ultimately be responsible for installation, maintenance, and collection of data from scour-monitoring devices.

Although field testing was accomplished in phases—limited testing, field testing, and final testing, the findings from these phases are consolidated in this section and presented in relation to the major instrument types tested—sounding rods, driven/buried rods, and sonic devices. Initial results of field testing are presented in the Phase II Final Report (*39*). The research team had direct control of the field installation of a Brisco Monitor sounding rod, simple and automated magnetic sliding collar devices, and low-cost bridge-deck-serviceable sonic instrument systems. Several simple magnetic sliding collar devices were installed under a cooperative "wider deployment" program through which instruments were purchased by the Minnesota and Michigan DOTs and installations were accomplished by the DOT with the advice and assistance of the research team.

Additional field experience with simple magnetic sliding collar devices and low-cost sonar instrument systems was obtained through a cooperative arrangement with the FHWA Demonstration Project 97 (DP97) program. DP97 provides instruction in and demonstration of fixed and portable devices to detect, measure, and monitor bridge scour. To provide a broader experience base for instrument demonstrations, FHWA funding and NCHRP project technical assistance were provided to the Texas DOT and the USGS in New York and Oregon for installation of simple magnetic sliding collar and sonic devices. In addition, limited testing of prototype driven rod devices with piezoelectric film sensors was conducted under this project and by the USGS in Oregon. The results of field testing of instruments directly under this project and through cooperative arrangements with other agencies are reported in this section.

Sounding Rod (Brisco Monitor)

Installation

A bridge site on the South Platte River east of Greeley, CO, (Site CO1), was selected as the site for field testing bridge pier installations of a Brisco Monitor, low-cost sonic

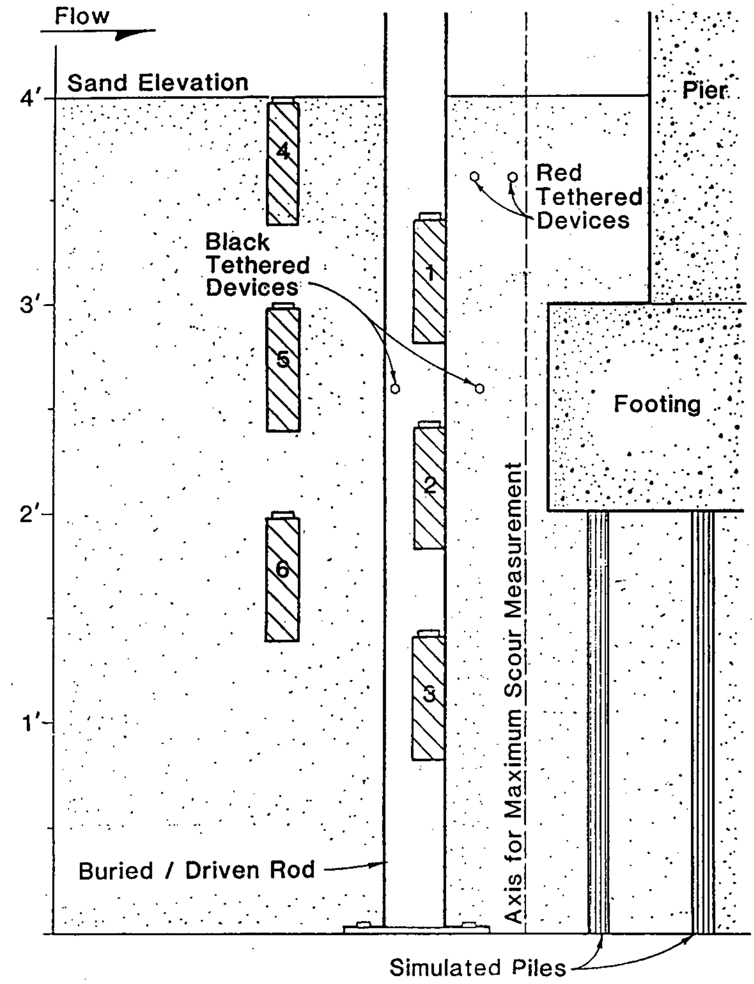


Figure 14. Location of buried devices (profile view).

instrument, and prototype installation of a piezoelectric film driven rod device (see Appendix section B-2 for location map and site description). This site was selected because of the characteristics of the river (which include significant debris, variable flow, sandbed material, and possible icing conditions) and the proximity of the site to Fort Collins, CO. The bridge is on State Highway 144, near the town of Orchard, CO. The bridge is an old wood structure, approximately 122 m (400 ft) long, with wooden stringers and pile bents (Figure B-5). Replacement circular steel piles have been retrofitted to support the bridge, because many of the original wood piles have deteriorated and broken.

The patented Brisco Monitor was loaned to the project by the manufacturer and was tested initially on the near-prototype pier in the outdoor flume at CSU (see Findings - Laboratory Testing). The instrument with an unmodified 76-mm (3-in.)-diameter footplate was installed on the first pile bent from the right (south) abutment (see Figure 15). Mounting took approximately 1 hr. The device was set so that approximately 0.6 m (2 ft) of the shaft, which rests on the bed, extended below the support pipe. The clamping arrangement allowed the sounding rod to rest on the bed within approximately 102 mm (4 in.) of the pile. Because of the proximity to the pile, it was not deemed necessary to skew the device to account for non-aligned flow.

Installation of the Brisco Monitor and sonic instrument was completed on the morning of October 4, 1991. A seven-person crew consisting of four state highway personnel and three research team members completed the installation of the devices. The highway personnel consisted of two flag persons for traffic control, a loader operator, and a supervisor who spotted for the loader operator. Two research team members performed the mounting with help from the third, who served as tool holder, photographer, and coordinator with the highway crew. The sounding rod (Brisco Monitor) and the bridge-deck-serviceable sonic fathometer were installed on the Orchard bridge without a datalogger in October 1991. These instruments were left out through the winter to assess their durability. The electronics packages for these two instruments were installed in April 1992. The installation for the Brisco Monitor consisted of the following equipment:

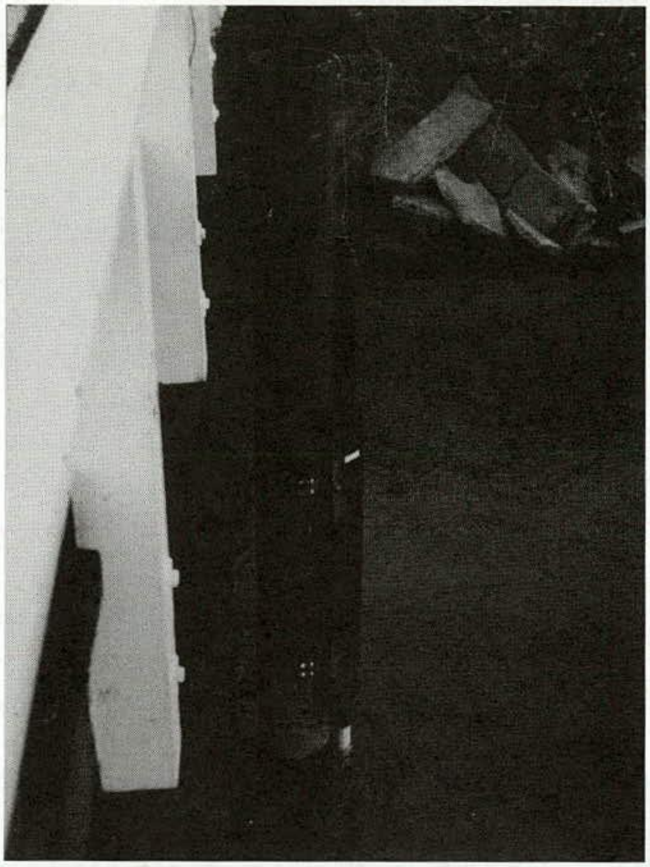


Figure 15. Brisco Monitor installation at State Highway 144 bridge near Orchard, CO.

- A vandal-resistant housing,
- A 12-volt lead-acid battery power source and solar panel for battery recharge,
- The cable reel and pulse counter for measuring distance that the sounding rod extends during scour,
- A datalogger to service both the sounding rod and sonic fathometer, and
- A storage device consisting of a removable data card system.

The datalogger was programmed to sense pulse counts from the Brisco Monitor sounding rod. The datalogger was programmed to store the number of pulses obtained from the counter attached to the cable reel whenever movement of the sounding rod occurred. For this installation, one pulse was equal to 25 mm (1 in.) of movement on the sounding rod.

The overall operation of the instruments and electronic packages was field tested. This field test indicated that although the solar panel's capacity (10 watts) was estimated to be sufficient to compensate for the electrical drain on the battery, it was found that with two instruments connected (Brisco Monitor and sonic fathometer), the battery would drain in approximately 2 to 3 days. The 10-watt solar panel was replaced with an 18-watt solar panel that corrected the power problem.

During installation of the electronic package, an evaluation of the conditions of the sounding rod was conducted to assess any damage or problems with leaving the system on the bridge over the winter. This evaluation indicated that the mountings for the instrument were secure. However, it was found that the sounding rod (Brisco Monitor) was fully extended and buried approximately 1.2 m (4 ft) in the bed. Because there had not been significant flows in the river since October 1991 when the sounding rod was installed, this indicated that the relatively small-diameter footplate was too small to support the weight of the sounding rod on the sandbed. The sounding rod was a "prototype" device not specifically designed for this field application.

The sounding rod was raised and reset three times during summer 1992. Each time the rod was reset, it reburied itself in the bed within a week after resetting. The extension of the sounding rod into the bed did not correlate with periods of high discharge in the river or to the measured scour depths obtained from the sonic fathometer on an adjacent pier.

From these findings, it was concluded that the bearing stress of approximately 78 kPa (1,632 psf) with the existing 76.2-mm (3-in.)-diameter baseplate exceeded the maximum allowable bearing stress of the sandbed. To correct this problem, a modified baseplate was fabricated and installed on the sounding rod (Figure 16). The modified baseplate was semicircular with an area of 12,006 mm^2(18.61 in.^{2}) and a bearing stress of approximately 29.6 kPa (620 psf). When the sounding rod was reset on July 17, 1992, with this modified baseplate, it initially settled approximately 0.15 m (0.5 ft) into the soft upper surface of the bed and stabilized.

Review of the available digital data recorded from the sounding rod by the datalogger indicated that pulse count data from the sounding rod could erroneously increase without limit. The number of pulses recorded would begin at 0 at the beginning of the data record and increase to approximately 4,000 pulses within 1 week's time, suggesting that the

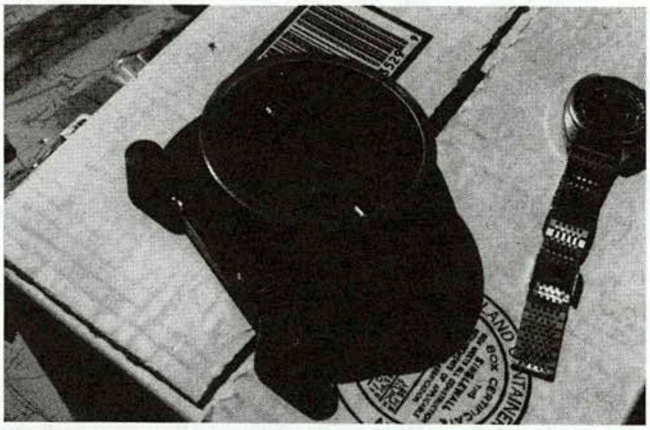


Figure 16. Modified footplate for sounding rod.

rod had descended more than 100 m (333 ft). However, the rod was constrained to move no more than 2 m (7 ft) and ground truth observations indicated there was little or no scour at this pier then.

Although the datalogger at the Orchard site worked well with the sonic fathometer, the input channel from the pulse counter of the Brisco Monitor sounding rod to the datalogger failed, resulting in loss of signal from the pulse counter. Attempts to rectify this problem were not successful. The input channel for the sounding rod was permanently disconnected in August 1992. An interpretation and appraisal of this finding and a suggested solution to this problem are provided in Chapter 3.

Inspection of the Orchard site in February 1993 suggested that flow conditions between November 1992 and February 1993 concentrated flow at the pier equipped with the sounding rod, resulting in significant scour. As a consequence of this scour, the sounding rod had slipped completely out of the guide pipe and pulled the cable completely off the cable reel. Both sounding rod and cable were found buried in the bed adjacent to the pier. This indicates that scour greater than or equal to approximately 1.4 to 1.5 m (4.5 to 5 ft) must have occurred for the sounding rod to have been removed from the guide pipe. Data from the magnetic sliding collar at this bridge pier (see discussion below) confirm approximately 1.5 m (5 ft) of scour between November 1992 and February 1993. Given the problems experienced with the datalogger for the sounding rod, this instrument was not reactivated.

Findings—Sounding Rod Field Testing

- The prototype Brisco Monitor sounding rod did not perform well under sandbed conditions on the South Platte River. Addition of a larger foot plate improved performance, but scour at the site was sufficient to pull the rod and cable completely out of the housing, rendering the device inoperative. The device tested at the Orchard bridge site was a "prototype" device not specifically designed for this field application, successful operation has been reported by the manufacturer and the USGS on coarse bed material streams (cobbles and larger).
- Problems with the electronics of the data storage system for this device were encountered at both the Orchard bridge test site under this research project and at a field installation by the Iowa DOT (*40*). Discussions with the manufacturers indicate that a different pulse count technology is now being used that should correct these problems.

Magnetic Sliding Collar Devices

Overview

Both simple (manual readout) and automated readout magnetic sliding collar devices were installed and tested in various locations in the field. Testing under this project included pier installations of simple sliding collar instruments at the Orchard bridge on the South Platte River in Colorado, and the Bernado bridge on the Rio Grande in New Mexico. Automated magnetic sliding collar devices were installed and tested on a pier of the Nassau Sound bridge near Jacksonville, FL, a tidal site, and on a sloping abutment of the South Platte River bridge near Kersey, CO.

Simple magnetic sliding collar devices were purchased by the Minnesota and Michigan DOTs and installed at bridge piers in these states with the advice and assistance of the research team. This cooperative "wider deployment" program provided feedback from the state DOTs on instrument installation, operation, and maintenance and expanded the range of bridge geometry and geomorphic conditions under which the instruments were tested. Two simple magnetic sliding collar instruments were delivered to the Texas DOT under the FHWA DP97 program for scour instrumentation, but only one was installed. DP97 also provided instruments and technical consultation on installation to the USGS for several installations in New York (*22*).

Installation and testing of devices under this project or through the wider deployment program are described in this section. Findings from all the sliding collar instrument installations, including those where the research team had only an advisory role, are summarized for those sites were documentation is available.

Field Prototype

Laboratory testing of a driven rod with an open architecture magnetic sliding collar indicated that the sliding collar accurately tracked the progression of scour. Using this concept, a field prototype of a magnetic sliding collar was designed and fabricated. This instrument consisted of a 51-mm (2-in.)-diameter stainless-steel support pipe in 1.5-m (5-ft)-long sections. A magnetic collar, similar in design to the original collar used for the prototype testing, was fabricated to slide on the support pipe; however, the externally mounted magnetic switches tested in the laboratory (see Figures 8 and 9) were replaced by a much simpler approach to measuring scour. To determine the position of the collar, a sensor (probe) consisting of a magnetic switch attached to a battery and buzzer on a long graduated cable was fabricated. Photographs of the magnetic collar with the support rod and the magnetic probe are presented in Figures 17 and 18. In operation, the probe is lowered through the annulus of the support pipe and the buzzer activates when the sensor reaches the magnetic collar. Collar position is determined by using the graduated cable to determine the distance from an established datum near the top of the support pipe to the magnetic collar.

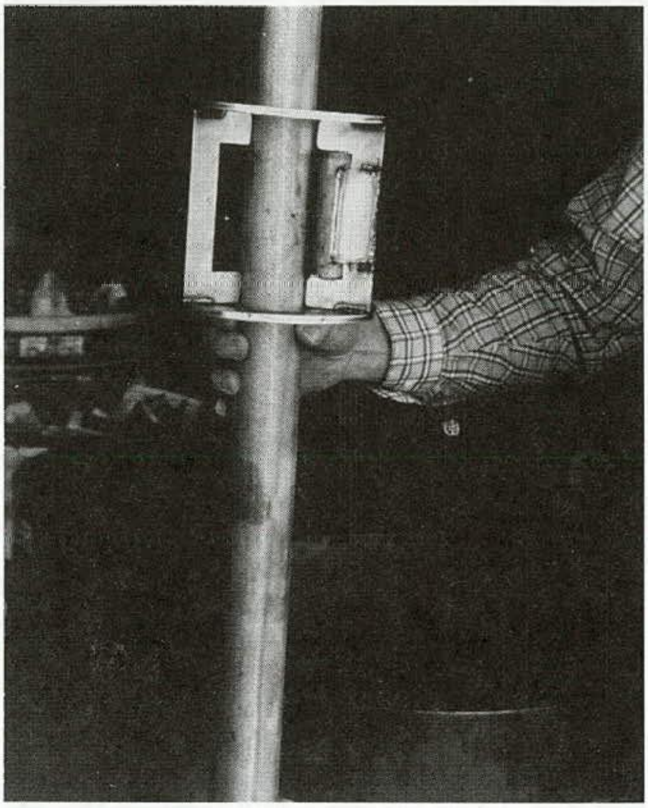


Figure 17. Magnetic collar and support for field installation of magnetic sliding collar device.

Installations Under the NCHRP Project

Orchard Bridge Test Site (CO1). A prototype of the magnetic sliding collar was installed adjacent to the sounding rod on a bridge pier at the Orchard site (see Appendix section B-2, Site CO1) in September 1992, by manually driving a 1.5-m (5-ft)-long section of rod into the streambed, connecting a second section of rod, and resuming the driving process. Four sections of rod were installed in this fashion with a total of 3.0 m (10 ft) of rod driven below the streambed. For this installation, a manual driving technique was employed using a 45.4-kg (100-lb) fence post-type driver.

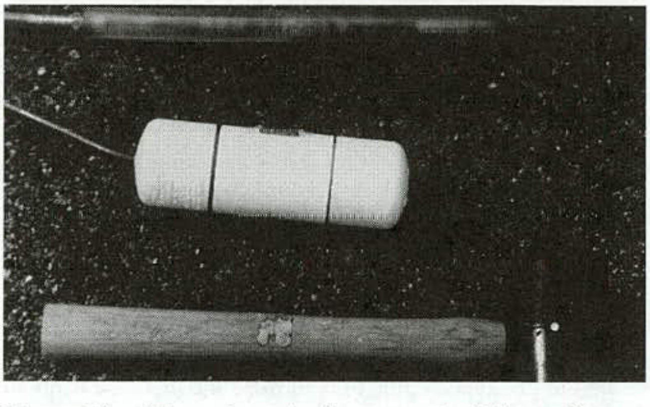


Figure 18. Magnetic probe for magnetic sliding collar device.

At the time of installation in September 1992, the distance from the top of the support rod to the magnetic collar was measured to be 3.75 m (12.3 ft). A week later, the distance was measured to be 3.78 m (12.4 ft). Because the flow in the river was low during this period, this difference in readings was attributed to minor settling of the collar after installation. The flow in the river remained low from September through late November 1992, and no additional motion of the magnetic sliding collar was noted.

In late February 1993, the instruments at the Orchard site were inspected. During this inspection, it was noted that debris had accumulated around the pier and support pipe for the magnetic sliding collar. Further inspection revealed that the buried portion of the support rod had been pushed downstream approximately 102 to 152 mm (4 to 6 in.). Because the upper portion of this rod was anchored, the support rod was bent slightly. Measurements of the location of the magnetic sliding collar in March 1993 showed that the magnetic collar had descended to an elevation 5.2 m (17 ft) below the top of the support rod indicating a change of 1.4 m (4.7 ft) since the last recorded reading in November 1992.

In June 1993, the reading for this instrument was 5.3 m (17.3 ft). Subsequent site visits throughout summer and fall 1993 indicated no further movement of the collar. No additional damage to the instrument was noted and the minor damage to the instrument, which was noted in February, did not adversely affect the performance of this instrument.

Bernardo Bridge Pier Test Site (NM1). In May 1993, a simple magnetic sliding collar device was installed on a pier of the Bernardo bridge on the Rio Grande, south of Albuquerque, NM. The site offered variable flows; a dynamic, shifting sandbed channel, where scour was known to occur; heavy debris loading; and high sediment loads—all factors that would provide field experience with the instrument under very adverse, high-stress conditions. Bridge geometry and hydrologic, hydraulic, and geomorphic conditions at the Bernardo bridge test site are described in Appendix section B-2 (see Figure B-7 for a map of Site NM1). The installation of the sliding collar was completed using a pickup truck equipped for installation/ground truth activities (Figure 19). The basic installation of the device went smoothly, requiring about 1 day for installation by a three-person crew.

One problem encountered during installation at the Rio Grande site was debris that had collected around many of the piers since the reconnaissance site visit, limiting the locations where instrument installation was feasible. At some piers, debris piles were not evident from the water surface and were only detected by probing around the piers. Ultimately, the instrument was installed on the west side of the bridge, somewhat out of the main flow. However, this was not a serious limitation for evaluation of prototype performance.

Figure 19. Pickup truck equipped with boom and personnel bucket for installation/ground truth activities.

Figure 20 shows the upstream face of the Bernardo bridge where the magnetic sliding collar device was installed (this photograph also shows the completed installation on the pier near where the pickup trucks are parked). At this bridge, the piles were vertical, allowing the driven rod of the sliding collar to be vertically driven. The driven rod was a 51-mm (2-in.)-diameter, Schedule 40 stainless-steel pipe in 1.5-m (5-ft) lengths with couplers to add additional length as each section was driven into the streambed. The rod was driven into the streambed with a Rhino air-operated post driver (Model PD-40) to a depth of about 3.7 m (12 ft).

The rod was then attached along the front edge of the pile cap and at the bridge deck. A mounting bracket fabricated to clamp around the pile cap was used to secure the rod rather than anchoring into the concrete of the pile cap (partially visible in Figure 21). Figure 21 also shows the completed installation, looking from the bridge deck down to the water surface; note the offset in the pipe that was necessary to allow for the overhang of the bridge deck over the pile cap. The section of pipe above the pile cap, including the offset, was constructed of 51-mm (2-in.) Schedule 40 steel (black) pipe. The pipe extended above the guard rail with a locking cap that could be removed to take measurements of the collar location (Figure 22).

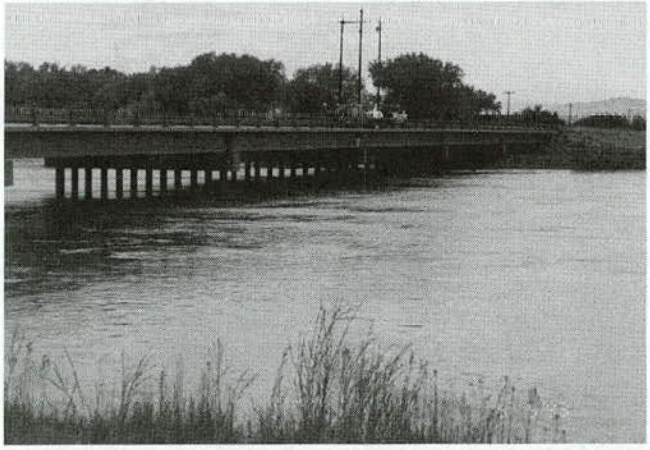


Figure 20. Upstream face of Bernardo bridge (Site NM1).

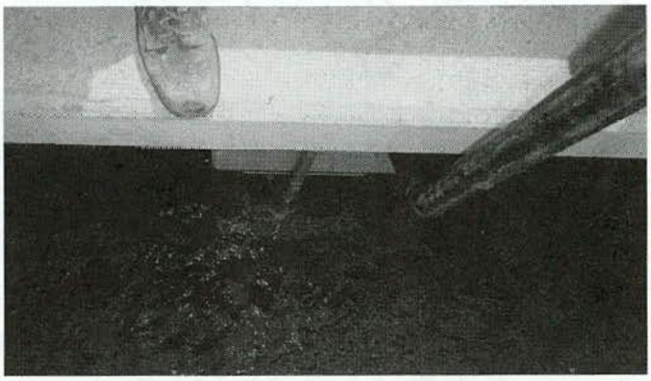


Figure 21. Bernardo bridge sliding collar device (Site NM1).

Beginning in May 1993, New Mexico instrument installations were monitored weekly under a subcontract agreement with New Mexico State University. The weekly monitoring included downloading the datalogger on the sonar unit (see

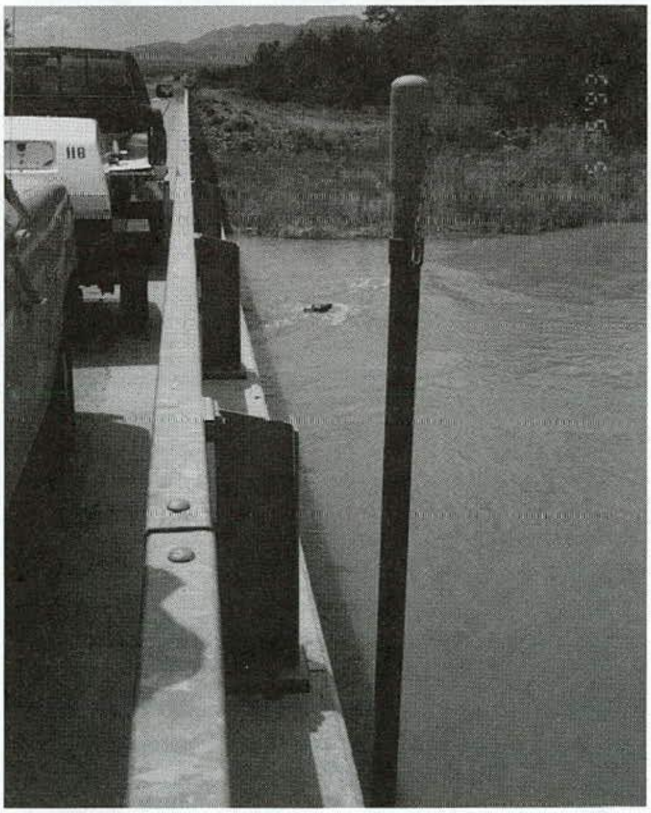


Figure 22. Removable cap on sliding collar device at Bernardo bridge (Site NM1).

discussion Site NM2), measuring the location of the magnetic sliding collar, performing limited ground truthing by probing, and, with a portable sonar unit, taking pictures and recording general observations on flow behavior.

Additional ground truthing consisted of stream gaging at the San Antonio bridge (Site NM2) and sonar measurement and probing of scour holes at each bridge (Sites NM1 and NM2). Stream gaging was not conducted at the Bernardo bridge because this bridge is gaged biweekly by the USGS.

As part of the ground truth effort, the changes in channel cross section over time for the Bernardo bridge were evaluated from USGS stream gaging data (Figure 23). Because of debris problems in the main channel along the left bank, the instrument was installed toward the right (west) bank (about Station 310) on a sand bar that was out of the main flow. (Note: the standard water resource agency convention of designating right and left bank when looking in a downstream direction has been used throughout). Cross-sectional data indicate significant channel bottom activity between Stations 150 and 400 as flows increased from May to June and then decreased; however, the main channel remained along the left bank.

The sliding collar instrument was not in the portion of the cross section showing the most change, but did encounter some scour and fill. Because of the overhang of the bridge deck, the ground truth cross-sectional data developed from stream gaging results represent conditions as much as 0.9 to 1.2 m (3 to 4 ft) upstream of the face of the pile where the instrument was located. Consequently, the cross-sectional data do not represent local scour conditions measured by the instrument, which was installed within about 0.3 m (1 ft) of the pile. The cross-sectional data suggest that between installation (May 6) and May 17, the sand bar height increased, which probably buried the collar. Between May 17 and June 7, the sand bar began to move out again and the bed level dropped back down near the level at installation. By June 17, the bed had dropped about 0.3 m (1 ft) below the level at the time of installation.

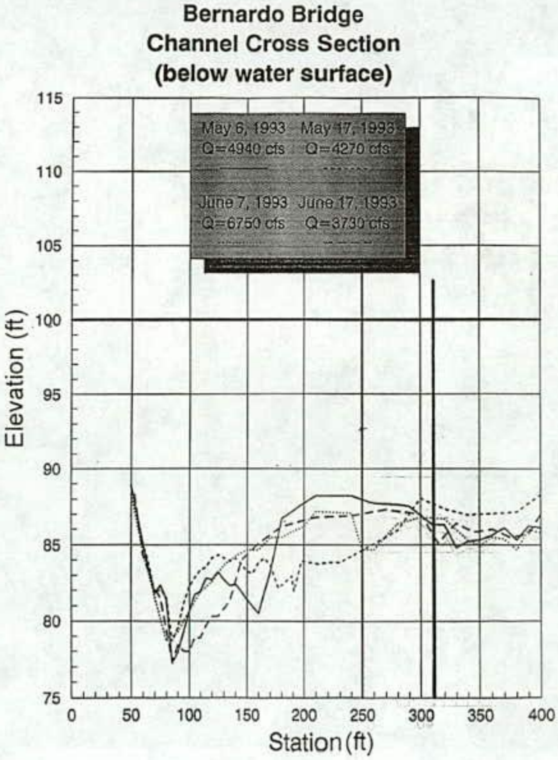


Figure 23. U.S. 60 bridge over Rio Grande near Bernardo (Site NM1) channel cross sections.

Figure 24 illustrates the Bernardo bridge magnetic sliding collar data recorded over this same period and the corresponding ground truth data. The instrument is drawn to scale with the pipe about 3.4 to 3.7 m (11 to 12 ft) into the bed at the time of installation. A sudden drop in the collar was detected on the June 8 weekly visit, when a change of 864 mm (34 in.) occurred from the June 4 visit. Observations on June 4 indicated high flow conditions and a shifting of the sand bar downstream. This activity and the observed sudden drop in the collar correlates with the cross section activity documented from the USGS stream gaging data.

The ground truth data on Figure 24 were determined by physical probing and portable sonar measurements around the sliding collar instrument. The sliding collar data suggest that the sand bar scoured out to a maximum depth and then partially refilled between the June 4 and June 8 readings. On the basis of the available data and observations, the magnetic sliding collar device at Site NM1 worked properly and successfully detected maximum scour occurring between two instrument readings. Subsequent site visits indicated that the Rio Grande continued to migrate away from the instrumented pier. Although the instrument remained functional, no further scour data were obtained from this site.

The manual probe for sensing the location of the magnetic collar was refined during this phase of the research project. The original probe, which was built for the prototype Orchard bridge site, consisted of the sensor end, buzzer end, and a graduated length of electrical cable. Although this design worked adequately, it was not durable enough for general use. A second design encased the cable in a length of 9.5-mm (⅜-in.)-diameter flexible plastic plumbing pipe. This design adequately protected the cable, but was stiff and hard to manage, especially when the weather was cold. A third probe was constructed by encasing the wires for the probe in a length of 9.5-mm (⅜-in.)-diameter spiral-wound spring steel, typically used for "sewer snakes." Although this probe system was heavier, it proved to be easy to use. This probe did not kink when unrolled and by virtue of its weight, slid freely down the annulus of the support rod of the magnetic sliding collar instrument.

Kersey Bridge Abutment Test Site (CO2). An automated readout sliding collar instrument system and a sonic fathometer were installed on a sloping abutment at the

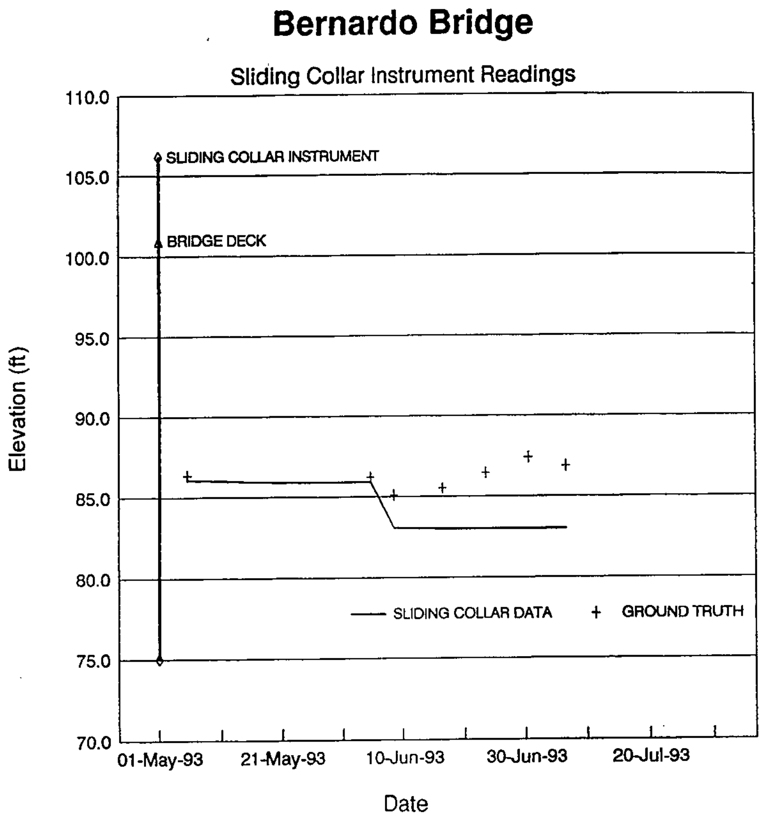


Figure 24. Site NM1 magnetic sliding collar readings.

Kersey bridge over the South Platte River east of Greeley, CO. A site description is provided in Appendix section B-2 (see Figure B-4 for a map and Figure B-6 for an overview of the bridge site).

Following field testing of manual-readout magnetic sliding collar devices at the Orchard and Bernardo test sites, it was apparent that the support pipe or extension conduit, normally fastened to the upstream face of a bridge pier, can be vulnerable to debris impact. Development of an automated-readout magnetic sliding collar device could reduce this vulnerability to debris and ice impact if only the head of the device protrudes from the streambed in front of a pier or adjacent to an abutment. A waterproof conduit could carry the signal by a less vulnerable route, such as along a pile cap or pier footer and up the *downstream* face of a pier to a datalogger.

To automate the operation of the magnetic sliding collar, a laboratory prototype electronic insert (probe) was developed. The design of this insert uses a string of 523-ohm resistors—each followed by a magnetically actuated reed switch—located at 152-mm (6-in.) intervals along the length of a stainless-steel support structure. The number of resistors used corresponds to the length of the probe. Magnets on the sliding collar actuate the reed switch at a given position as it comes in proximity. A datalogger provides excitation voltage for a brief sampling period.

The probe is encased with waterproof flexible tubing and is then inserted into the stainless-steel pipe section on sections that constitute the support rod for the instrument. This sensing unit could be inserted into the stainless-steel section of most existing sliding collar devices or included as an enhancement feature at new installations of the device, upgrading the readout capability from manual to automatic using a datalogger. The insert was designed so that each magnetic sensor has a unique resistance value; that is, when a voltage potential is applied to two wires at the datalogger, the array of magnetic sensors will produce a unique output amperage (i.e., depending on which magnetic sensor is active [closed]). Sensors at different levels are activated as the magnet on the sliding collar around the stainless-steel pipe slides down the pipe as scour develops. The automated insert was bench tested and appeared to perform as designed.

An automated-readout sliding collar device was installed on a sloping abutment at the Kersey bridge over the South Platte River in early April 1995. A first attempt to install the driven rod encountered rock, possibly riprap placed earlier as a scour countermeasure, and the rod had to be withdrawn. It was found that a better technique is to drive a small-diameter solid rod until an unobstructed location is found, if the presence of rock or riprap below the surface is suspected. Figure 25 shows a sketch of the installation site. Figure 26 shows the sonic device and sliding collar installed on the upstream side of the left abutment. The details of the cellular phone link from this instrument are discussed in a later section.

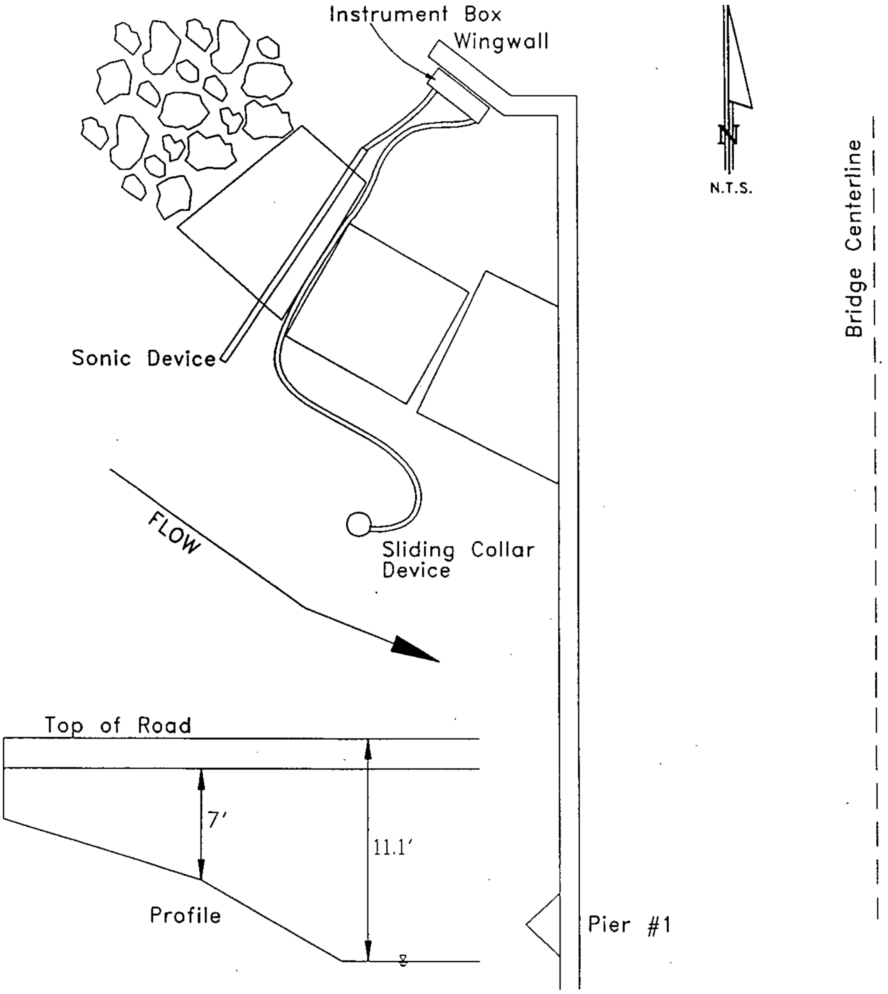


Figure 25. Abutment scour monitors, sonar, and sliding collar at Highway 37 bridge over the South Platte River near Kersey, CO (Site CO2).

During May, datalogging was accomplished in a manner similar to a sonic unit as described in the Datalogging and Telemetry section. The abutment sliding collar and sonic devices were monitored with increasing frequency during late May when heavy rain produced significant runoff. A visit to the site in late May revealed high water conditions well up on the sloping abutment, but still below the low chord of the bridge. At that time, both devices were operational, but no significant scour was recorded.

The site was revisited on June 1 when flows had increased to about 680 m^3/s (24,000 cfs) and pressure flow conditions existed at the bridge. The USGS was on the bridge making measurements and Colorado DOT maintenance crews were engaged in removing debris from the upstream face of the bridge. Both instruments showed 0.6 to 0.9 m (2 to 3 ft) of scour at the abutment, possibly related to the pressure flow conditions. This confirmed the automated operation of the sliding collar and the ability to log data with this device. The scour hole was contoured with a portable sonic device during this visit and the sliding collar device was monitored during June with site visits and via a cellular phone link.

By late June, flow on the South Platte River had receded to the point that no further scour was anticipated. In addition, the concrete slab slope protection at this abutment displaced downslope about a meter, possibly as a result of the scour recorded during the flood of June 1. It was decided to decommission the instrument (see related discussion, Kersey bridge sonic instrument).

The automated sliding collar device at the Kersey bridge was selected to demonstrate the feasibility of telemetry of scour instrument data by cellular phone. The link from the Kersey bridge to Fort Collins, a distance of about 64.4 km (40 mi), was completed in April 1995, and instrument data were monitored from that time through June 1995. No problems were encountered. Telemetry concepts are discussed in the Datalogging and Telemetry section.

Figure 26. Sonic instrument (black rod), sliding collar (cable), and data box at Kersey bridge (Site CO2).

Nassau Sound Pier Test Site (FL2). An automated sliding collar device was installed in Florida at the Nassau Sound bridge near Jacksonville in May 1995 (see Appendix section B-2 for a site description, location map, and overview of the bridge). The use of a Reach All vehicle and boat, which were provided by the Florida DOT, District 2, contributed greatly to the successful installation.

This device was the first automated sliding collar device to be installed in a marine environment. It consisted of a 3-m (10-ft)-long stainless-steel pipe encased by a 3.2-mm (⅛-in.)-thick plastic sheath (see Figure 27 for an overview of the device and Figure 28 for a close-up). The sheath was heat-shrunk and glued to the pipe in order to minimize barnacle growth. The sheath also acted as further protection against corrosion. Because this device requires the collar to slide uninhibited along a pipe, barnacle growth that might impede the collar's movement was a concern.

The collar was a standard magnetic collar painted with anti-fouling paint to prevent barnacle growth (Figure 28). This device used magnetically activated switches to determine the position of the sliding collar and could locate it within ± 0.15 m (0.5 ft). This device was completely automated and data were logged in a manner similar to that of the sonar unit (see Datalogging and Telemetry section).

Figure 27. Overview of Nassau Sound automated sliding collar with driving extension (Site FL2).

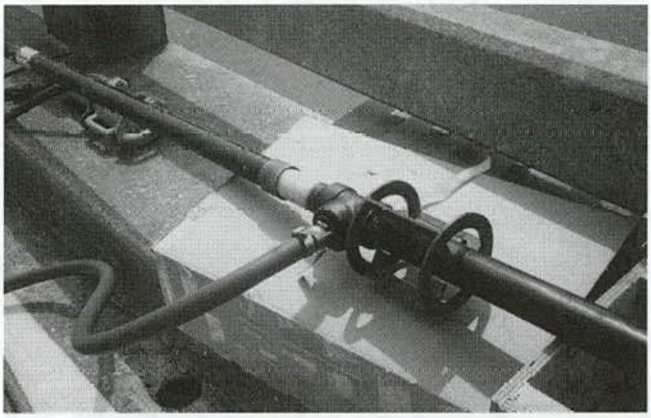


Figure 28. Close up of Nassau Sound automated sliding collar device.

Installation of the pipe on the ocean side of the bridge went smoothly (see Figures 29 and 30). Using a pneumatic air driver, the pipe was driven 2.6 m (8.5 ft) into the bed. The water depth at Bent 46 was about 3.7 m (12 ft), so an extension pipe was used for driving purposes and then removed when the instrument was in place. With the help of two people in a boat and one in a Reach All vehicle, the entire process was quick and simple. About 5 min were required to prepare the pipe and place it next to the pile, and an additional 10 min were needed to actually drive the pipe into the bed. The procedure was done at slack low tide, which prevented high-water velocities from interfering with the installation process.

The instrument shelter was mounted to the bridge rail with stainless-steel brackets (Figure 31). The shelter was designed to hang low off the rail so as to limit potential vandalism. Also, the solar panel, which recharges the system batteries, was mounted directly to the shelter's lid, thus not requiring a separate mount and saving considerable time and effort during the installation. The device was programmed to take a reading at 1-hr intervals. To facilitate data retrieval, a small compartment housing an RS-232 data cable was built into the instrument box. This allowed the downloading of data to a laptop computer and servicing of the unit without having to expose the electronic equipment to accidental damage or the elements.

Data from the magnetic collar at Nassau Sound was downloaded periodically from June 1995 to February 1996. In February 1996, the site was visited to inspect and recondition the instrument. The sliding collar instrument was in excellent condition, and the data were downloaded. This instrument showed no change in bed elevation since installation, within its ± 0.15-m (0.5-ft) accuracy. The available ground truth data also suggested no significant change in bed elevation had occurred, and yet there was some concern

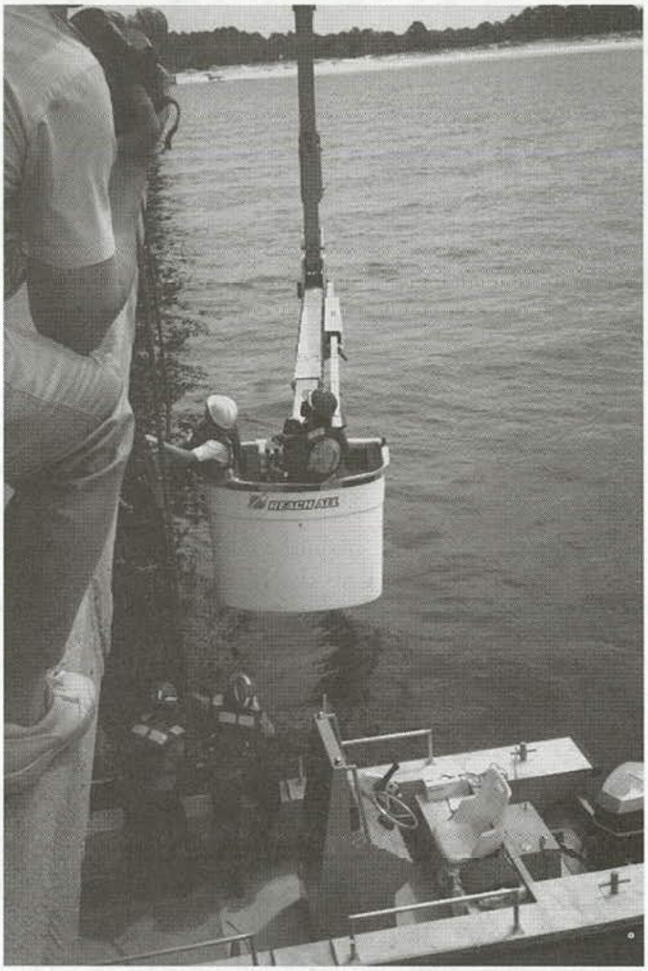


Figure 29. Nassau Sound tidal site automated sliding collar being driven with assistance of FDOT District 2 personnel from Reach All (Site FL2).

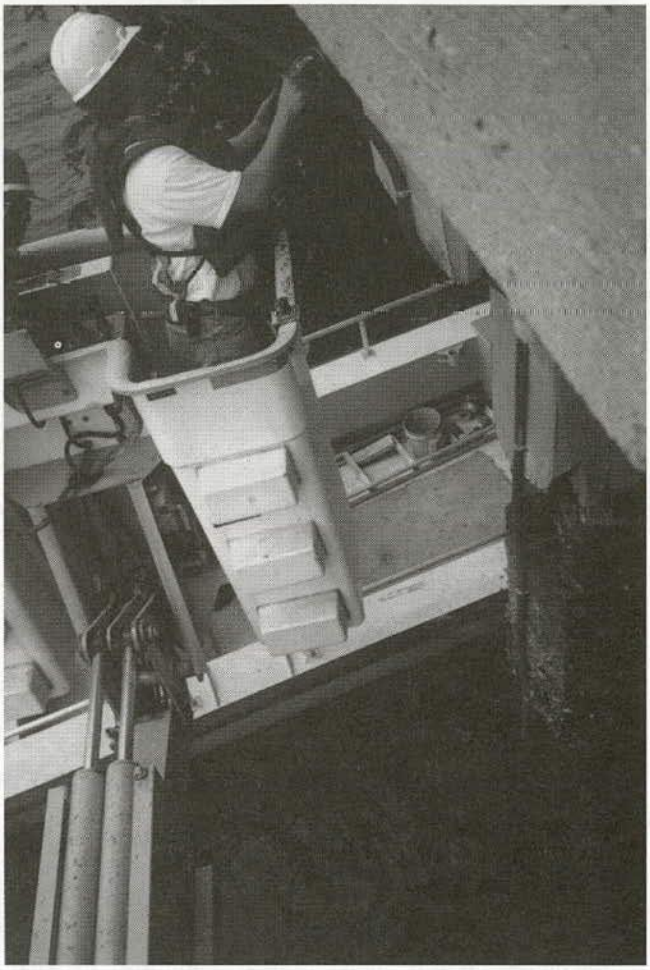


Figure 30. Nassau Sound sliding collar—fastening flexible conduit to bridge pier (Site FL2).

that the collar might have become immobile because of barnacles or binding or perhaps because of a problem created during installation.

Inspection by Florida DOT divers found that the collar had been buried by sand. At the time of installation, the stainless-steel pipe was driven into the bed about 2.6 m (8.5 ft), leaving about 0.46 m (1.5 ft) extending above the bed. In February 1996, the divers found only 0.15 m (0.5 ft) of pipe extending above the bed, implying that the collar was now buried about 0.3 m (1 ft). The divers found a few barnacles attached to the heat-shrunk tubing that was exposed above the channel bottom and reported that they were relatively easily removed. It is difficult to be conclusive on the basis of this limited information, but these results tend to confirm that barnacles do not adhere as readily to plastic/rubber surfaces and would not have inhibited the free movement of the sliding collar if it had been exposed. Readings during the test period showed that the collar remained covered by sand and no scour occurred.

Wider Deployment of Sliding Collar Instruments

Approach. The objective of wider deployment activities was to expand the field testing program by facilitating wider deployment of selected scour measuring/monitoring systems. This task allowed for the testing and evaluation of scour measuring systems that had progressed to the level that their installation and operation could be managed by agencies not directly associated with the NCHRP project. The research team worked with cooperating agencies that desired to purchase and install scour monitoring systems by providing an evaluation of bridge sites, a recommendation of the most applicable system, and limited on-site technical assistance. Costs for purchase or fabrication of the scour measuring device and ancillary equipment (e.g., dataloggers), as well as installation costs, were the responsibility of the cooperating agency.

A great deal of interest in scour monitoring instrumentation was encountered during this project. Most of the interest was focused on the magnetic sliding collar device, primarily

Figure 31. Nassau Sound sliding collar—datalogger housing and solar panel (Site FL2).

Figure 32. Installation of magnetic sliding collar device at Muskegon River bridge (Site MI1).

because of the simplicity of the design and the fact that this device moved quickly from the drawing board to field deployment. Early success of this instrument at the Colorado and New Mexico field test sites enhanced this interest.

Following a request for information, a standard information package describing the bridge-deck-serviceable sonic fathometer and the magnetic sliding collar instruments was forwarded to the interested agency/individual. These forms were used to document the preinstallation, installation, and local evaluation of the instrument, as well as to provide a standardized format for measuring scour with these instruments. The DOTs of Michigan and Minnesota agreed to purchase magnetic sliding collar devices and assist in deploying these instruments for field testing.

Wider Deployment Site in Michigan (MI1). The first wider deployment of a manual-readout magnetic sliding collar device was completed in March 1993, on the U.S. 31 (north-bound) bridge over the Muskegon River near the city of Muskegon in cooperation with the Michigan DOT (Site MI1). The instrument was installed with an 18.1-kg (40-lb) pneumatic post driver operated from an under-bridge inspection crane. This installation also marked the first attempt to incorporate an offset into the design so that the extension collar of the device could be anchored to the bridge deck.

The installation process is shown in Figures 32 and 33. The burial depth of the support rod was designed to be approximately 6 m (20 ft). However, the rod could only be driven approximately 3.4 m (11 ft) into the bed of the channel with the 18.1-kg (40-lb) pneumatic post driver. The inability to install the rod deeper was attributed to the tip and skin resistance of the soil surrounding the support rod because subsurface soil properties were silty sand. A heavier pneumatic driver would be needed to achieve deeper burials in this type of streambed.

Installation was completed in less than half a day using the bridge inspection crane. Because the support rod could not be driven to the desired depth, the offset to the bridge deck was set well above the water surface. This installation was, therefore, more susceptible to debris and ice than originally planned. Additional bracing of the support rod (Figures 34 and 35) was subsequently installed by the Michigan DOT during summer 1993.

A breakdown of installation and equipment costs for this site was compiled by the Michigan DOT. The estimated installation cost for DOT equipment and personnel support was $2,568. The material, hardware, and fabrication cost for this instrument was $2,495 and the technical assistance site visit cost $2,000, which resulted in the total cost to the DOT to build and install this instrument of approximately $7,000. This estimated cost does not include the cost incurred to

Figure 33. Installation of offset for sliding collar device (Site MI1).

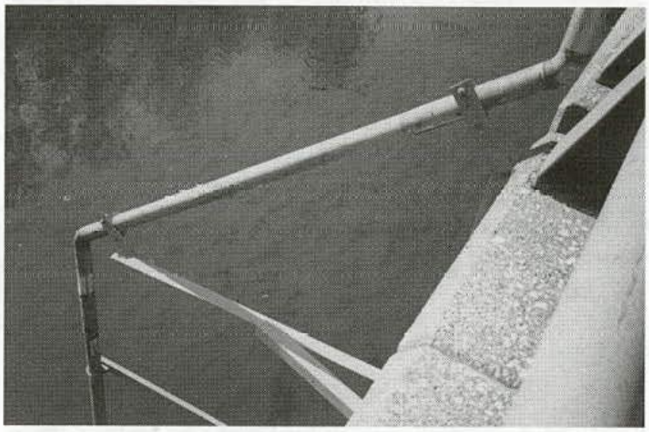


Figure 34. Additional bracing of support rod (Site MI1).

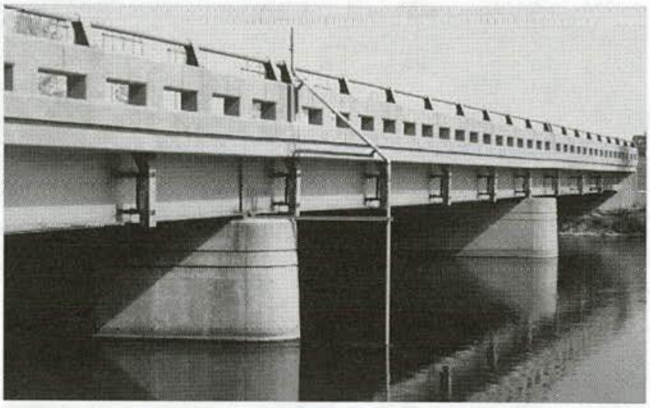


Figure 35. Additional bracing of support rod (Site MI1).

design the instrument for the site and provide pre- and post-installation coordination and support (approximately $3,000). Also, this cost does not include additional markups which would be necessary for a commercial enterprise to successfully market, sell, and support this instrumentation.

Scour and flow data were collected during summer 1993 by the Michigan DOT. A tabulation and plot of the data collected during the 1993 flow season are presented in Table 1 and Figure 36. Scour at this site in 1993 was less than approximately 0.46 m (1.5 ft).

The data collected by the Michigan DOT indicate that the magnetic sliding collar instrument as installed is susceptible to debris. Although this debris has not damaged the instrument to date, this finding underscores the need to set the horizontal offset for the driven rod as close to the bed as possible. Figure 37 shows schematically the horizontal offset designed for the Michigan wider deployment site. A similar offset will normally be required when installing this instrument at any site with a spread footer or pile cap near the streambed.

Wider Deployment Sites in Minnesota. Three manual-readout magnetic sliding collar scour monitors were installed in Minnesota during June 1993. The installation of these three instruments was preceded by a week of heavy rains and high flow on all of the rivers in the area. At the time of installation, the Minnesota River was cresting at higher flood stages than had been witnessed in over 30 years. Although the installation sites on the Straight and Root rivers had been above flood stage, the stage had dropped to below bankfull by the time the field crews had mobilized at each site.

The three installations in Minnesota marked the first time that the magnetic sliding collar was installed with a pneumatic jackhammer. Although more difficult to handle, the 61.2-kg (135-lb) hammer provided significantly more driving force than previously attained in Michigan with the pneumatic post driver. The jackhammer was used because a heavier post driver was not locally available. For all three installations, the instruments were installed in less than a full working day. After performing the initial installation at Structure 74004 (US14 over the Straight River), the installation

TABLE 1. Data from Michigan Installation (Site MI1) of Magnetic Sliding Collar, 1993

Date	Time	Tracker Reading		Maximum Scour Depth		Maximum Scour Elevation		Water Elevation		Comments
		(ft)	(m)	(ft)	(m)	(ft)	(m)	(ft)	(m)	
Initial				1.88	0.57	582.48	177.54	585.16	178.36	
3/15	11:08 AM	19.54	5.96			580.60	176.97	585.16	178.36	initial installation reading
3/30	11:00 AM	19.58	5.97	0.04	0.01	580.56	176.95	585.16	178.36	
4/20	1:32 PM	19.92	6.07	0.38	0.12	580.23	176.85	585.16	178.36	
5/06	12:17 PM	19.92	6.07	0.38	0.12	580.23	176.85	585.16	178.36	
5/21	11:36 AM	20.17	6.15	0.63	0.19	579.98	176.78	585.31	178.40	lateral bracing installed
5/28	12:30 PM	20.33	6.20	0.79	0.24	579.81	176.73	585.31	178.40	heavy debris surrounds rod
6/11	10:50 AM	20.33	6.20	0.79	0.24	579.81	176.63	585.21	178.37	removed debris
6/25	12:56 PM	20.33	6.20	0.79	0.24	579.81	176.73	585.31	178.40	
7/14	12:01 PM	20.63	6.29	1.08	0.33	579.52	176.64	585.41	178.43	more debris develops around rod
7/23	10:35 AM	20.92	6.38	1.38	0.42	579.23	176.55	585.41	178.43	removed heavy debris
8/06	11:45 AM	21.00	6.40	1.46	0.46	579.14	176.52	585.51	178.46	more debris develops around rod
8/20	1:30 PM	21.00	6.40	1.46	0.46	579.14	176.52	585.41	178.43	

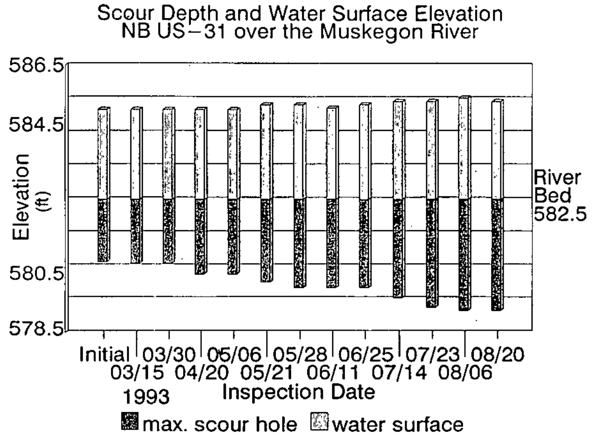


Figure 36. Plot of magnetic collar and water depth, Michigan installation 1993 (Site MI1).

crews could have performed the remainder of the installations without further technical assistance.

All three of these installations required that 6.1 to 9.1 m (20 to 30 ft) of extension conduit be installed for each instrument to reach the bridge deck. In some cases, several 45-degree bends and 90-degree sweeps were also needed. Rigid electrical conduit with a diameter of 51 mm (2 in.) was used for the extension conduit. The field crews demonstrated that field cutting and threading of extension conduit was not difficult or time consuming. Extension conduit was anchored to the bridge piers and concrete superstructure using conduit clamps and concrete anchors.

The magnetic probe supplied with these instruments was 15.2 m (50 ft) long and constructed of 9.5 mm (3/8-in.)-diameter wound spring steel (sewer snake). Although heavy, this probe negotiated the various bends and curves of these three installations without problems, including the installation on the bridge over the Straight River, which consisted of four 45-degree bends and one 90-degree sweep. Another advantage of this probe was that it did not kink and was easy to coil.

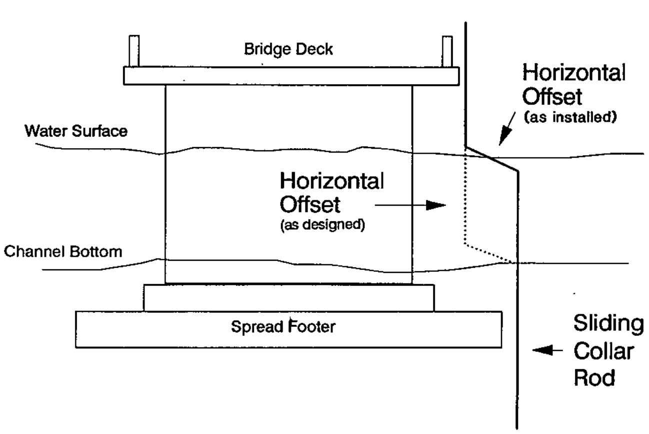


Figure 37. Schematic of horizontal offset of sliding collar rod at Michigan wider deployment site.

Site-Specific Factors in Minnesota.

U.S. 14 over the Straight River (Site MN1)
Minnesota DOT Structure No. 74004
Location: Approximately 50 km (30 mi) west of Rochester, MN, (Region 6).

Photographs of the completed installation at this location are shown in Figures 38 and 39. At the time of installation, the water level was approximately 0.6 m (2 ft) below bankfull. The water depth at the pier was approximately 1.83 m (6 ft) and it was believed that there was some contraction and pier scour occurring. It was anticipated that 0.3 to 0.6 m (1 to 2 ft) of refill would occur when the flow receded. No debris or riprap were encountered, and the support rod was easily driven into the bed approximately 3.9 m (13 ft).

One 90-degree sweep and four 45-degree bends (see Figure 39) were required to route extension conduit from the water surface to the bridge deck because of the large spread footing and cantilevered overhang of the bridge deck. The total length of support rod and extension conduit was approximately 14.3 m (47 ft). The collar was initially located at 10.4 m (34 ft) from the top of the locking end cap. Subsequent measurements made in December 1993 indicated that the collar had not moved. The steel-wound magnetic probe slid smoothly through the annulus of the conduit and support rod. The end cap was located below the top of the guard rail so that it could not be seen easily from the bridge deck.

T.H. 16 over the Root River (Site MN2)
Minnesota DOT Structure No. 23015
Location: Approximately 8 km (5 mi) west of Rushford, MN

Photographs of the completed installation at this location are presented in Figures 40 and 41. This instrument was installed adjacent to an upstream pile bent on the bridge. The support rod was driven into the bed at an angle conforming to the batter of the pile bent (2H:12V). This angle of installation caused difficulty in obtaining the full motive force of the jackhammer to drive the support rod.

This bridge has significant debris problems and a large amount of debris had to be removed from the pile bent before installation. At the time of installation, the stage was near bankfull and the water depth at the pier was approximately 3.7 m (12 ft). It was determined that there was a 1.2- to 1.5-m (4- to 5-ft)-deep scour hole at the pile bent at the time of installation. Water velocities in excess of 1.8 m/s (6 fps) combined with the depth made it difficult to position the instrument for driving.

Rock was encountered while driving at depths of approximately 0.9 and 2.1 m (3 and 7 ft) below the streambed. After passing the first rock, no further driving progress could be made beyond the second rock. Although the instrument burial depth was minimal, it is expected that the scour hole will

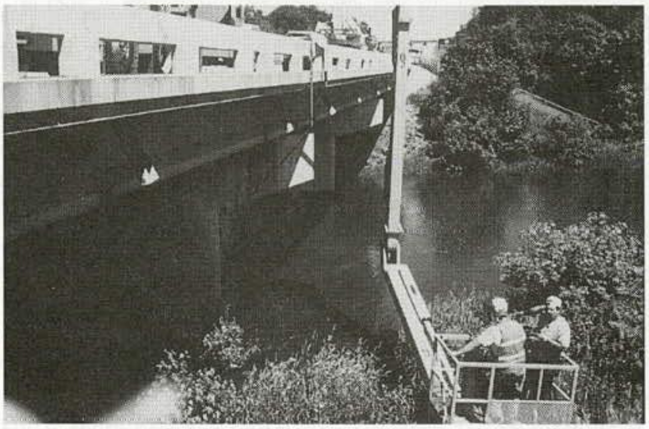


Figure 38. Installation of sliding collar device at Minnesota bridge no. 74004 (Site MN1).

refill approximately 1.2 to 1.5 m (4 to 5 ft). Consequently, a second split-ring magnetic sliding collar was fabricated and shipped to Minnesota to determine the amount of refill and for tracking future scour events.

No bends were required to route extension conduit from the water surface to the bridge deck. The total length of support rod and extension conduit was approximately 13.1 m (43 ft). The steel-wound magnetic probe slid smoothly through the annulus of the conduit and support rod.

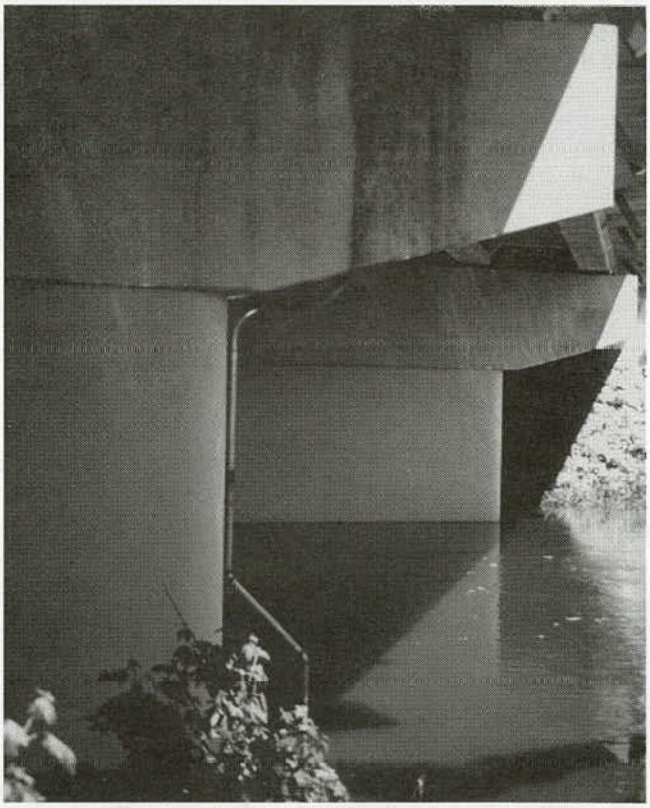


Figure 39. Installation of sliding collar device at Minnesota bridge no. 74004 (Site MN1).

Figure 40. Installation of sliding collar device at Minnesota bridge no. 23015 (Site MN2).

Of the three Minnesota installations, this site was the most vulnerable to debris because of the persistent accumulations of large debris rafts. Potential debris damage was minimized to the extent possible by securely anchoring the instrument to the pile bent using collar clamps, by routing extension conduit as close to the pile bent as possible, and by anchoring the extension conduit to the bridge deck using concrete anchors.

Subsequent data collected at the site in November 1993 indicated that debris had bent the extension rod (Figure 42).

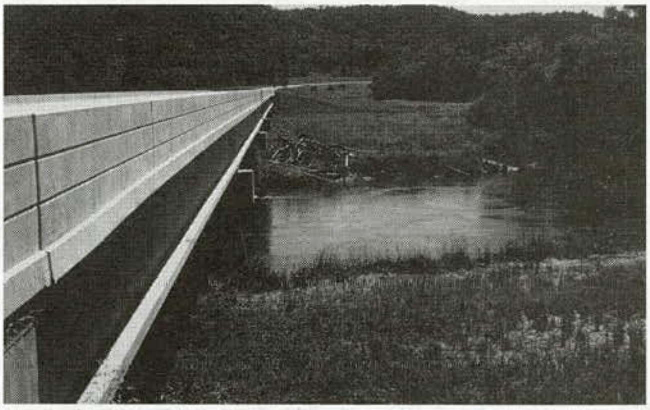


Figure 41. Installation of sliding collar device at Minnesota bridge no. 23015 (Site MN2).

Figure 42. Debris accumulation on sliding collar device at Minnesota bridge no. 23015 (Site MN2).

No reading was taken on this date. A second visit was made on December 17, 1993. Once again, the rod appeared to be damaged by debris, but readings were possible and the collar was located 0.24 m (0.8 ft) lower than when installed.

T.H. 76 over the Root River (Site MN3)
Minnesota DOT Structure No. 9003
Location: Houston, MN

Photographs of the completed installation at this location are shown in Figures 43 and 44. This installation was of particular interest to the Minnesota DOT (MNDOT) because the bridge constricts flood flows and causes significant backwater. It was expected that significant contraction scour could be occurring at this site during flood flows. Of all the three Minnesota sites, this installation is most susceptible to vandalism as evidenced by a large amount of graffiti on the bridge and the proximity of the bridge to downtown Houston, MN.

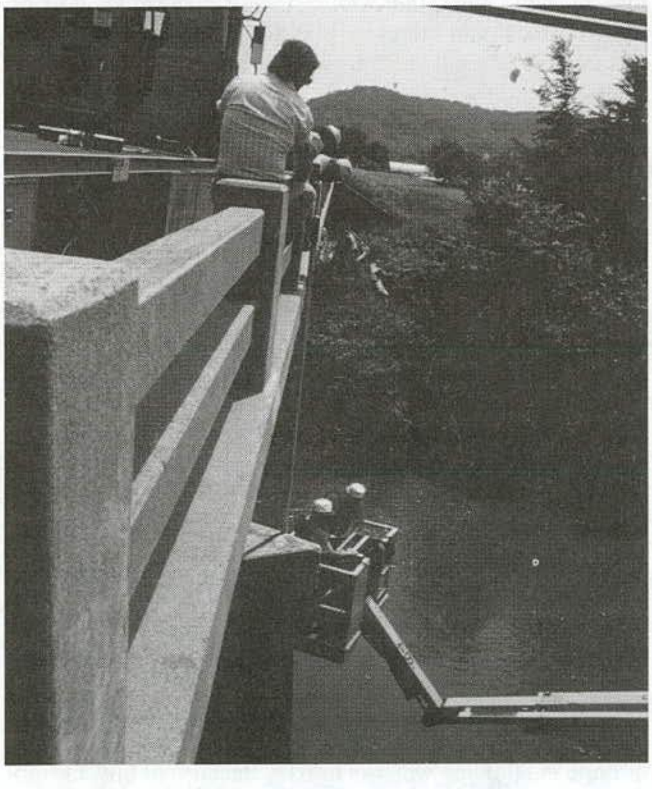


Figure 43. Installation of sliding collar device at Minnesota bridge no. 9003 (Site MN3).

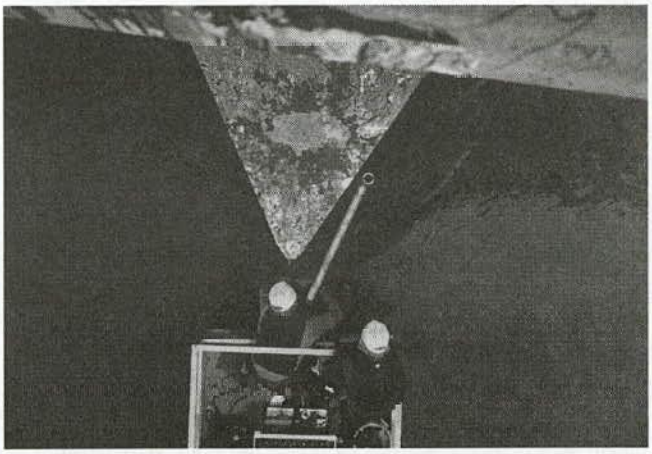


Figure 44. Installation at Minnesota bridge no. 9003 (MN3).

A USGS gaging station (Gage ID No. 05385000) is located at this bridge. The records in the gage house indicated that the discharge at the time of installation was approximately 96.3 m³/s (3,400 cfs). The stage was approximately 0.6 m (2 ft) below bankfull and the water depth was approximately 3.1 m (10 ft). The velocities were slower than for the installation at bridge number 23015 (MN2) and there was no problem in positioning the rod for installation. During driving, a firm layer of material was encountered approximately 1.5 m (5 ft) below ground surface. After penetrating this layer, the rod was driven approximately 1.8 m (6 ft) further into the bed before progress was arrested by a second layer of firm material. Review of the bridge plans indicated that these layers were composed of cohesive material.

Two 45-degree bends were required to route extension conduit from the water surface to the bridge deck. The total length of support rod and extension conduit was approximately 15.2 m (50 ft). The collar was initially located at 11.9 m (39 ft) from the top of the locking end cap. Again, the steel-wound magnetic probe slid smoothly through the annulus of the conduit and support rod.

This installation was inspected in November 1993, and no debris accumulation or damage to the instrument was noted. The site was visited again on December 17, 1993. During this visit, it was noted that debris had impacted the extension conduit and damaged it, although it was still possible to sense the collar location with the magnetic probe. The distance to the collar was noted to be 12.2 m (40 ft) below the top of the extension conduit indicating a change of approximately 0.3

m (1 ft). During a site visit in February 1994, it was discovered that this instrument had been destroyed by impact from large floating tree trunks.

Other Installations of Sliding Collar Devices

The USGS in cooperation with the New York State Department of Transportation (NYSDOT) and the FHWA evaluated a sliding collar device for the FHWA Demonstration Project on Scour Instrumentation (DP97) (*22*). A manual-readout magnetic sliding collar device (Figure 45) was installed by the USGS at State Route 30/145 over Schoharie Creek at Middleburg, NY, in September 1994. Before installation, NYSDOT backfilled a scour hole that partly exposed the footing with sand, gravel, and cobbles and used a drill rig to lower the stainless-steel pipe into a 3-m (10-ft) borehole at the upstream side of the footing. The collar (Figure 45) was mounted near the top of the stainless-steel pipe, about 7.6 m (25 ft) below the bridge deck and 0.15 m (0.5 ft) below the streambed. Schedule 40 galvanized pipe was attached to the stainless-steel pipe and supported by a steel bracket at the base of the pier. Schedule 80 galvanized pipe was mounted to the upstream side of the pier from the steel bracket to the bridge deck. Rubber O-rings and a waterproof compound prevented seepage into the pipe.

During the four inspections at State Route 30/145 over Schoharie Creek in the 1995 water year, the distance from the top of the pipe to the collar ranged from 8.78 to 8.84 m (28.8 to 29.0 ft). The range between measurements was not a result of scour, but was attributed to accumulation of excess cable at two bends in the pipe as the sensor was lowered to the magnetic collar. The July 1995 inspection found the collar to be uncovered but not undermined. The USGS found that the cable used to position the collar broke during shipment and was cumbersome to store. Also, it stiffened in cold temperatures (see discussion of an improved sensor probe at Bernardo bridge site, NM1, above). The sliding collar was not damaged by ice or debris during the first year of operation, but the USGS noted that it was a low-flow year.

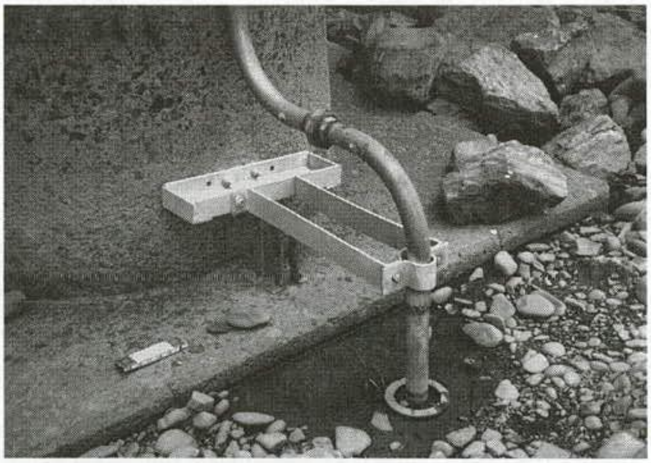


Figure 45. Sliding collar installed upstream of bridge pier at State Route 30/145 over Schoharie Creek at Middleburg, NY.

With funding from FHWA DP97, the Texas Department of Transportation (TXDOT) installed a manual-readout sliding collar device on a pier of the U.S. 380 bridge over Double Mountain Fork of the Brazos River in Haskell County, TX. In the past, more than 6.1 m (20 ft) of scour had been reported at this bridge. The stainless-steel pipe was driven into the bed 5.8 m (19 ft) with a gasoline power driver and connecting conduit was bent and fastened to the bridge pier. The instrument successfully recorded a scour episode of approximately 1.5 m (5 ft) during the test period.

Driven Rod Installation Techniques

For either the magnetic sliding collar or the piezoelectric instruments to be viable, it was necessary to investigate practical methods for installing instruments into the streambed. An overriding concern was that these installation techniques be simple, practical, and, if possible, completed using the capabilities and equipment of state DOTs and their bridge maintenance crews. Early investigations focused on standard driving and augering techniques. These techniques were determined to be less desirable because highway departments usually must contract these services out when needed.

Mechanical and vibratory pile-driving techniques require a crane and vertical leads to support the pile while driving. Because pile-driving hammers are designed to drive large-diameter foundation piles, the forces generated from these machines would be much greater than required for installation of small-diameter driven rods into the streambed. Consequently, it would be difficult to control the force generated by these techniques to a degree that they would not destroy the instruments. Further, driving techniques using pile drivers would be costly and require third-party contractors to install the instruments.

Hollow-stem augering or drilling is typically performed by geotechnical engineers to collect subsurface samples and install down-hole instruments and wells. These installation techniques showed promise as a viable method for installing scour monitoring instrumentation. On the basis of this discussion with operators of this equipment, it was determined that scour monitoring instruments could probably be installed using these techniques, provided the drilling or augering rig could be positioned at the location where the instrument was to be installed. However, these rigs were not designed to cantilever over a bridge deck, drill or auger from an elevated platform such as a bridge deck, or drill or auger through the flowing water in a river. Because of this, most of the rig operators contacted were unwilling to attempt drilling in a river from a bridge deck. One operator was willing to try, but expressed doubt that it could be done. These installation techniques could be successful for installations in ephemeral rivers which could be accessible when the channel was dry, or during bridge construction activities requiring a coffer dam and diversion of the river.

Pneumatic fence post drivers were investigated for installation of driven rod instruments. These drivers, basically inverted jackhammers, are designed for driving fence posts of a wide variety of shapes and sizes. The most common manufacturer of these drivers is Rhino, which markets drivers ranging in size from a light-duty 15.9-kg (35-lb) to a heavy-duty 68-kg (150-pound) driver. Energy is supplied to these drivers using a standard trailer-mounted air compressor. These drivers are relatively inexpensive (approximately $1,000), can usually be rented from most equipment rental shops, are portable, and use power from an air compressor (which highway crews typically have).

In some cases, pneumatic driving alone will not be sufficient to drive the buried rods deep enough into streambeds consisting of dense materials. However, for reasons stated above, it is desirable to limit the installation techniques to equipment which is portable and available to bridge maintenance crews. For the more dense soil conditions, a technique of simultaneous jetting and pneumatic driving was investigated. A special driving anvil/manifold was designed and fabricated to fit onto the uppermost section of the support pipe for the magnetic sliding collar. This anvil was designed to inject high-pressure water into the annulus and out of the driving tip of the support rod while simultaneously driving the rod into the bed using either a pneumatic post driver or jackhammer. As designed, water for jetting could be obtained from a portable gas-powered pump with water taken from the river.

Although a prototype driving/jetting system was developed, it was not tested in the field. It is anticipated that this installation equipment may be necessary for increasing the applicability of the magnetic sliding collar and for installation of the piezoelectric instrumentation. The jetting technique alone was successfully used to install the prototype piezoelectric film device at the Orchard bridge site (see Figure 46), but the combined jetting and driving technique should be field tested.

Findings—Magnetic Sliding Collar Device Field Testing

- A manual-readout magnetic sliding collar device successfully tracked scour at the Orchard bridge test site (CO1) and met all established mandatory criteria and most desirable criteria. Although this instrument system could be vulnerable to ice and debris impact, under field conditions on the South Platte River involving both ice and debris, only moderate damage was experienced and the instrument remained operational for the 4-year duration of the project.
- A magnetic sliding collar device was installed on the Bernardo bridge over the Rio Grande in New Mexico (NM1) using a mounting bracket clamp on a pile cap. This instrument successfully tracked a significant scour event involving a major shift in location of a sand bar in the channel at a site vulnerable to heavy accumulations of debris. Selection of instrument location was influenced by debris accumulation around the bridge piers. Although no further scour occurred at the instrumented pier, the sliding collar instrument remained functional for the duration of the project (3.5 years).
- An automated magnetic sliding collar instrument was successfully installed in a riverine environment on a bridge over the South Platte River near Kersey, CO (CO2). This installation confirmed the installation techniques developed in the laboratory, proved the performance of an automated sliding collar instrument under field test conditions, and contributed to development of concepts for instrumenting a sloping abutment. The instrument was also used to demonstrate a successful cellular phone link between the field test site and a base station 64 km (40 mi) away. The instrument recorded scour at the toe of the abutment sufficient to cause dis-

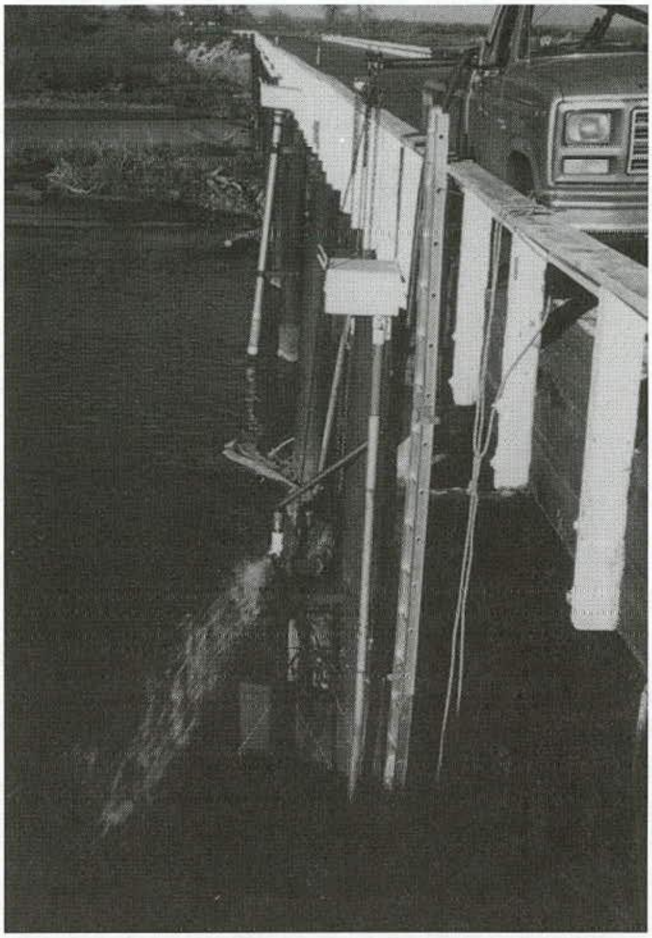


Figure 46. Installation of prototype piezoelectric device using jetting techniques.

placement of the concrete slab slope protection during a period of extreme high flow 680 m^3/s (24,000 cfs) with pressure flow conditions at the bridge. The instrument remained operational for 3 months until removed.

- An automated magnetic sliding collar instrument was installed in a tidal environment on the Nassau Sound bridge near Jacksonville, FL (FL2). The availability of a Reach All vehicle and a boat, which were provided by Florida DOT, District 2, contributed significantly to the successful installation. The use of anti-fouling paint on the collar and a plastic sheath on the driven rod appeared to reduce the potential for barnacle growth on instrument operation. Although some fill, not scour, has occurred at this site, the electronic components of the instrument system, including the underwater cable link and datalogger remained functional for the duration of the project (1.5 years).
- Simple (manual-readout) magnetic sliding collar devices were fabricated and installed in Michigan (one site) and Minnesota (three sites) in cooperation with the respective state DOTs. These installations demonstrated that this instrument system is adaptable to various field conditions, can be installed with the equipment and technical skills normally available at the District level of a DOT, and can perform and survive under severe conditions of ice and debris. The Michigan installation provided a clear record of the instrument's ability to track a moderate scour event.
- The estimated total cost (instrument cost, DOT installation cost, and NCHRP project support) for the Michigan installation was about $10,000.
- The Michigan and Minnesota installations demonstrated the vulnerability to ice and debris impact of the simple sliding collar system. The instrument at one site in Minnesota was destroyed by impact from a large floating log. Conversely, another site remained operational even after significant debris had accumulated on the instrumented pier.
- Results from the post-installation questionnaires received from Michigan and Minnesota indicated that both agencies felt that the magnetic sliding collar instrument was simple in design, easy to assemble, and simple to operate. All participating agencies indicated that there was adequate manpower and equipment to install the devices, that they felt that the instrumentation would be useful in monitoring scour, and that they would be inclined to install additional magnetic sliding collar scour monitoring instrumentation in their respective regions. Although the results of the questionnaire were predominantly positive, the participating agencies indicated that better driving techniques would be desirable for installation of these instruments.
- The simple magnetic sliding collar device installed on a coarse-bed stream in New York by the USGS performed well. It was not damaged by ice or debris during the first year of operation, but it was a low-flow year. The cable for the sensor probe was difficult to use and excess cable, accumulated at pipe bends, caused a slightly erroneous reading. On the basis of these results and experience at other sites, the sensor probe cable was improved.
- A simple magnetic sliding collar device was successfully installed at a scour-prone site by TXDOT. The instrument recorded approximately 1.5 m (5 ft) of scour.
- Pneumatic fence post drivers or pneumatic jackhammers were used to successfully install small-diameter driven rod devices in the field. The depth of installation may be limited by skin friction, cohesive layers, or rocks. Exploratory driving with a small-diameter, expendable rod is useful at sites where buried rock or riprap may be present. Simple water jetting techniques should extend the range of conditions under which pneumatic driving will be successful.
- Standard pile driving techniques and hollow-stem augering may be adaptable to the installation of driven rod devices, but positioning the crane or rig over the desired point at most bridge sites would be difficult, if not impractical, except on ephemeral streams or during new bridge construction involving coffer dams or stream diversion (i.e., where the equipment can be positioned on a dry streambed).
- As a refinement to the standard magnetic sliding collar, a split ring or clamshell sliding collar provides flexibility in field installation and the option to track a second scour episode after the first collar has been buried.

Low-Cost Sonic Fathometer Instrument Systems

Overview

Laboratory testing of two low-cost fish-finder-type sonic fathometers produced inconclusive results, primarily because of limitations in the experimental apparatus available. Consequently, field testing was crucial to the evaluation of these instruments for scour measuring and monitoring.

Field testing of sonic fathometers under this project included pier installations at the Orchard bridge on the South Platte River in Colorado, the San Antonio bridge on the Rio Grande in New Mexico, and the Johns Pass bridge over a tidal inlet on Florida's Gulf Coast. A low-cost fathometer was also configured and installed on a sloping abutment at the Kersey bridge over the South Platte River in Colorado. Two sonic fathometer systems were provided to TXDOT under the FHWA DP97, and one of these was installed with technical assistance from the research team. Additional consultation on installation of sonic systems was provided to both the USGS and NYSDOT. Installation and testing of low-cost sonic fathometers under this project are described in this section. Findings from installations when the research team provided advice and consultation are summarized, where documentation is available.

Installations Under the NCHRP Project

Orchard Bridge Pier Test Site (CO1). Standard practice for installation of sonic fathometers to monitor bridge scour has been to mount the sonic transducers into a small durable steel encasement which is then bolted to the pier of the bridge below water level. A heavy gage electrical conduit, approximately 1 to 2 in. in diameter is then routed from the transducer to the data box, located either on the bridge deck or stream bank. Using this method for mounting, transducers could usually be installed without the need for heavy lifting equipment; however, maintenance to clean the transducer head and check for damage required that maintenance personnel be lowered to the transducer mount. This could require specialized equipment, such as scaffolds, bridge inspection and maintenance cranes, or the use of divers, rafts, or boats.

This research project developed an alternative which permits mounting the transducer so that it can be serviced from the bridge deck. The mounting for the sonic transducer at the South Platte River bridge is an example of a bridge-deck-serviceable transducer (see Figure 47). In this arrangement, the transducer was encased in a PVC "pig" (see Figure 48) which was pushed down through a 127-mm (5-in.)-diameter steel conduit. At the bottom of the conduit, the pig snapped into position so that it protruded through a fitting at the bottom of the support pipe. With this arrangement, the transducer is serviceable from the bridge deck.

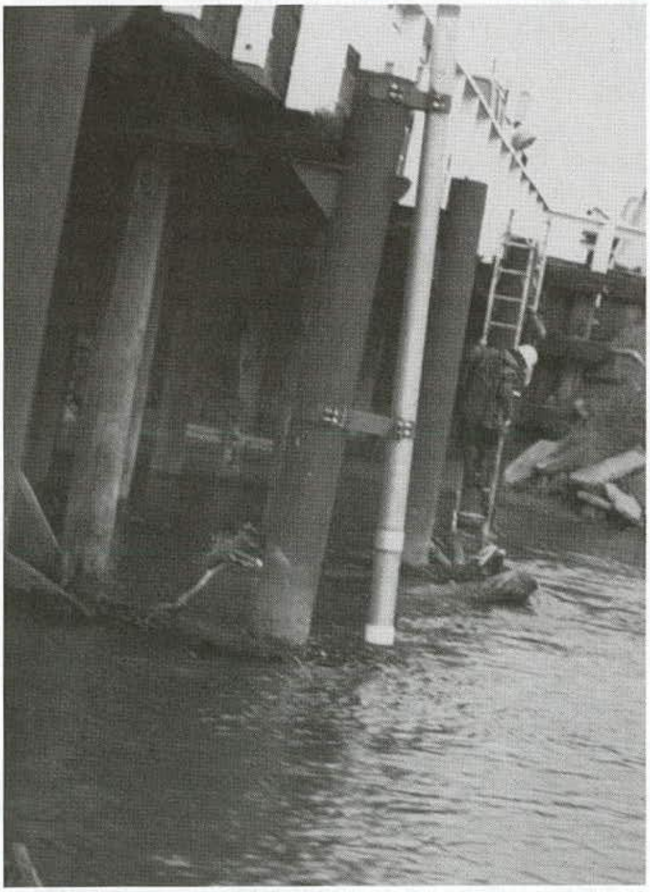


Figure 47. Sonic device support installation at State Highway 144 bridge near Orchard, CO (CO1).

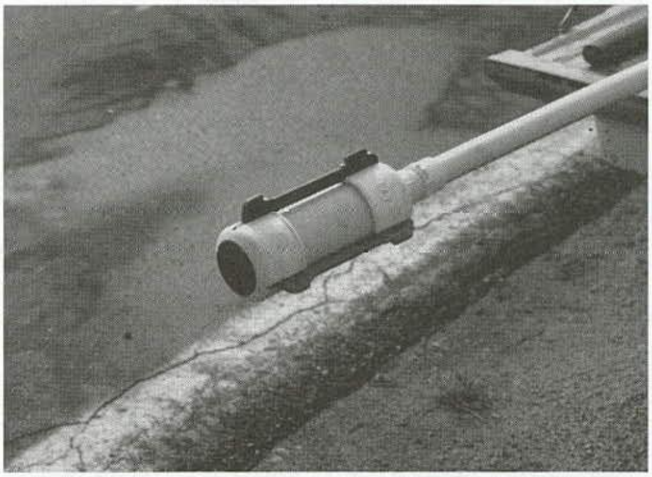


Figure 48. Sonic transducer mounted in PVC "pig" for bridge-deck-serviceable transducer mounting.

The disadvantage of the bridge-deck-serviceable transducer mount is that the mounting hardware (in this case a 3-m [10-ft] piece of 127-mm [5-in.] electrical conduit) is heavy and required the use of a front-end loader to suspend and position the mounting hardware so that it could be bolted into position. However, subsequent servicing will not require the use of scaffolding, inspection cranes, or other specialized equipment.

As noted in the Sounding Rod section, the Brisco Monitor and the sonic fathometer at the Orchard bridge test site were connected to the same datalogger. These instruments were installed without electronics in October 1991 and left out through the winter to assess their durability. The electronics packages for these two instruments were installed in April 1992. The installation for the sonic fathometer consisted of the following equipment:

- A vandal-resistant housing for the electronics package,
- A 12-volt lead-acid battery power source and solar panel for battery recharge,
- An Eagle Z-9500 fathometer,
- A datalogger to service both the sounding rod and sonic fathometer, and
- A storage device consisting of a removable data card system.

During installation of the electronic packages, an evaluation of the conditions of the instruments indicated that the mountings for both instruments were secure. The face of the sonic transducer was clean, but there was silt accumulation around the transducer housing.

The overall operation of the instrument and electronics package was field tested. As noted in the Sounding Rod section, a 10-watt solar panel was replaced with an 18-watt panel to compensate for the electrical drain both instruments imposed on the battery.

Testing of the bridge-deck-serviceable sonic fathometer was conducted at the Orchard site from spring 1992 through fall 1993. Testing during the 1992 flow season focused on evaluation of the overall operation of the datalogging and storage electronics, the functioning of the sonic fathometer, and the ability of this instrument to measure scour. The instrument was left in place during winter 1992-1993 to assess its durability to winter weather conditions. Upon reactivation of the site in spring 1993, testing continued through fall 1993. During this period, significant improvements were made to the data acquisition and data storage functions (see discussion, Datalogging and Telemetry section, below).

The sonic fathometer and datalogger at the Orchard site were replaced with an upgraded electronics package in June 1993. Upgrading included replacement of the Eagle Z-9500 fathometer with a Lowrance LMS200 fathometer, replacement of the data card with 64 kilobytes of on-board system memory, addition of an industry-standard RS-232 output port, and modifications to the datalogging software. These upgrades allowed the user to connect a laptop computer via the RS-232 port to (1) alter the sampling intervals and threshold resolution; (2) set the internal clock/calendar; (3) download data directly from the datalogger to the laptop computer; and (4) perform checks of the electronics, voltage supply, and memory.

Operation of the datalogger during the 1993 flow season indicated that the upgraded datalogger system provided greater flexibility in setting sampling protocol and provided a better standardized method to download data. The larger memory capacity extended the length of time between data retrieval visits from a few days to several weeks depending on the sampling protocol used.

The sonic fathometer at the Orchard site performed well. The sonic sounder was able to obtain a consistent reading of the distance between the transducer and bed whenever the transducer was submerged (during periods of high flow). Furthermore, reliable readings were obtained when the distance between the bed and transducer was greater than 0.43 m (1.4 ft), which is less than the minimum distance of 0.61 m (2 ft) indicated by the manufacturer. Although there was not a spread footing or pile cap at this site, the angle of the transducer conduit can be adjusted to "aim" the sonic signal away from such substructure elements (see Figure 47). At the Orchard bridge test site the angle was designed to point the transducer at the expected area of maximum scour.

Clear indications of the scour and fill during high-flow events were observed in the data record. A sample of the scour and fill process is presented in Figure 49. Approximately three similar scour-and-fill occurrences were recorded during the 1992 flow season at the Orchard site.

The first prototype sonic fathometer system deployed at the Orchard site was designed around the Eagle Z-9500. However, when additional sonic fathometer systems were fabricated, it was found that the design and capability of this fathometer had been significantly changed and that the 1993 version of the Lowrance LMS200 was identical to the Eagle Z-9500 (purchased in early 1992). Because manufacturers of sonic fathometers are continuously modifying their product line, no specific manufacturer or model number can be specified for interfacing with datalogging and storage equipment. Developers of sonic fathometer scour monitoring instrumentation using commercial low-cost fish-finders must be cognizant of the tendency for the specifications and capabilities of commercially available sonic fathometer systems to change (see additional discussion on Datalogging and Telemetry, below).

San Antonio Bridge Pier Test Site (NM2). In May 1993, a low-cost sonic fathometer was installed in a bridge-deck-serviceable configuration on a pier of the San Antonio bridge on the Rio Grande south of Albuquerque, NM (see Appendix section B-2, Figures B-7, B-10, and B-11). The site was selected for specific geomorphic and environmental characteristics, including recorded episodes of significant scour and fill, heavy debris loading, and location below the confluence with the Rio Puerco, a notorious sediment-producing tributary.

Figure 50 shows the upstream face of the San Antonio bridge where the sonar device was installed. As can be seen, this bridge had battered piles. The 102-mm (4-in.) pipe for the bridge-deck-serviceable sonar transducer was attached vertically to the front edge of the pile cap and the last 0.61-m (2-ft) section of the pipe was angled out so that the angle of the transducer cone matched the pile batter. As with the sliding collar device on the Bernardo bridge (NM1), a mounting bracket that clamped around the pile cap was used instead of anchoring into the concrete, although the sonar-mounting bracket was significantly larger and stronger to support the weight of the 102-mm (4-in.)-diameter pipe. Figure 51 shows the assembly of the mounting bracket.

The transducer pipe was a piece of 102-m (4-in.)-diameter, Schedule 40 black pipe that was 5.5 m (18 ft) long and weighed nearly 91 kg (200 lb). Figure 52 shows this pipe attached to the pile cap-mounting bracket, with the angled portion (to match the pile batter) under the water surface. The instrument shelter was attached to the transducer pipe near the guard rail. The instrument shelter was a single-wall steel enclosure that contained the sonar unit, the datalogger, and a 12-volt battery. The battery was recharged by a solar panel mounted on the other (south) side of the bridge using a lighter weight pile cap bracket.

Figure 53 illustrates the change in channel cross section at the San Antonio bridge, as developed from stream gaging data for ground truth purposes. The U.S. Bureau of Reclamation (USBR) had previously indicated that the water surface at this bridge does not change much as flow increases and decreases, suggesting significant bed scour and deposition. Ground truth data, as illustrated on Figure 53, confirmed

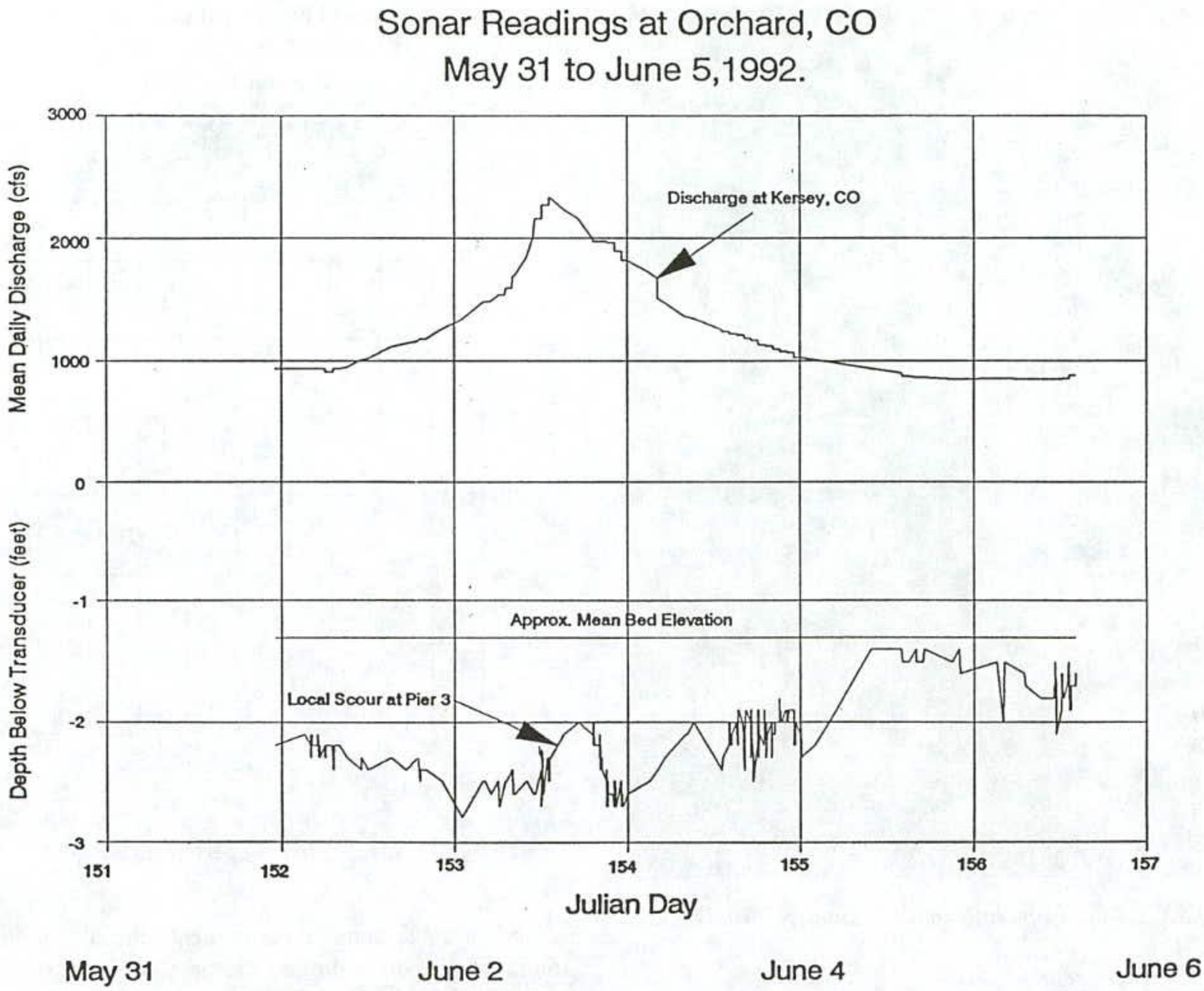


Figure 49. Plot of depth reading versus time from sonic fathometer at Orchard bridge site (CO1), 1992 field season.

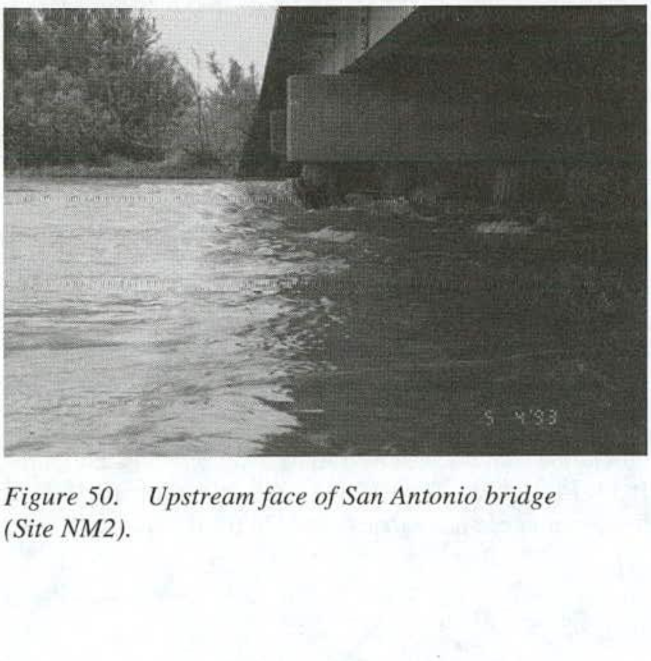


Figure 50. Upstream face of San Antonio bridge (Site NM2).

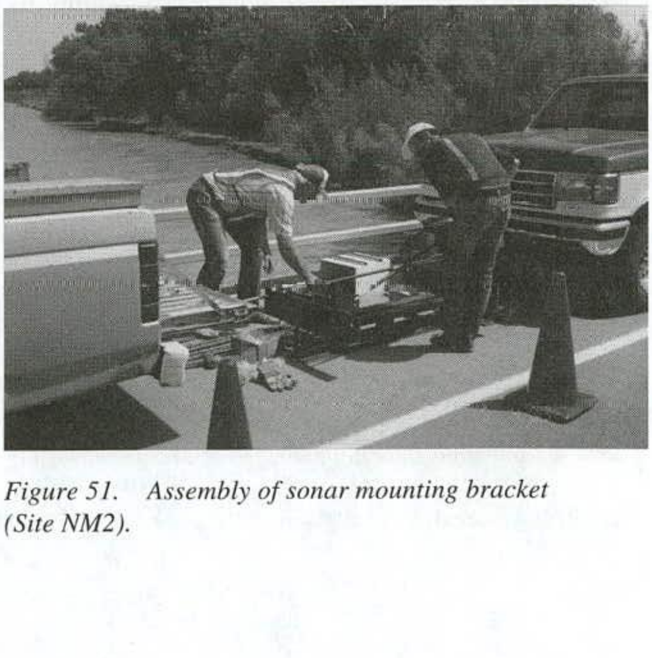


Figure 51. Assembly of sonar mounting bracket (Site NM2).

Figure 52. Sonar pipe attached to mounting bracket (Site NM2).

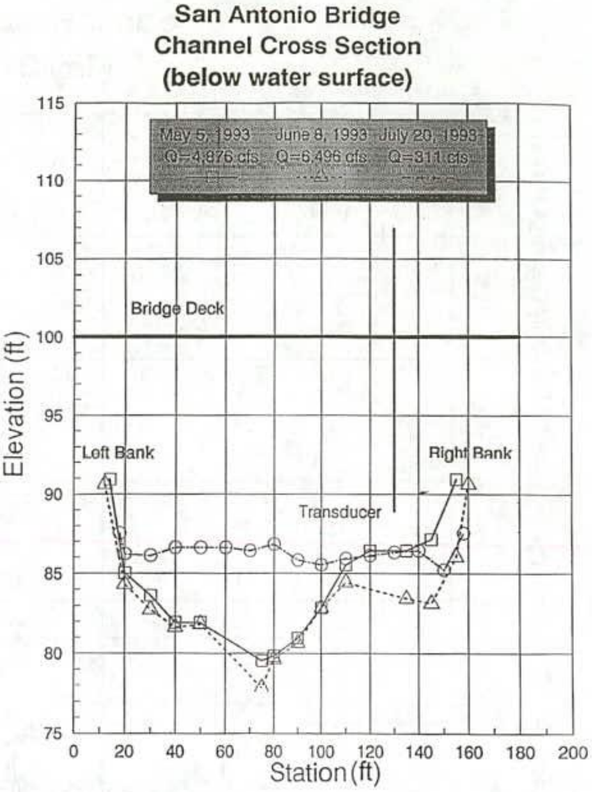


Figure 53. U.S. 380 bridge over Rio Grande at San Antonio (Site NM2) channel cross sections.

this behavior of the streambed. At the time of installation (May 5), the flow was already high and a relatively deep channel cross section had developed, particularly on the left bank (left and right defined looking downstream). Between May 5 and June 8, the right portion of the channel enlarged more, with as much as 0.9 to 1.2 m (3 to 4 ft) of scour at the location of the sonar instrument (at about station 130). By July 20, after the flow had receded, the entire cross section was filled back in with sediment. The sonar unit is drawn to scale in Figure 53 with the transducer approximately 0.8 to 0.9 m (2.5 to 3.0 ft) above the streambed on May 5, increasing to approximately 1.5 m (5.0 ft) by June 8, and then returning to approximately 0.8 to 0.9 m (2.5 to 3.0 ft) by July 20, 1993, thus providing a definitive cycle of scour and fill for the sonar instrument to track.

Figure 54 illustrates the sonar data record over this period and the corresponding ground truth data. Immediately after installation, the sonar unit was working properly with nearly perfect agreement with the ground truth data collected during installation. However, discrepancies occurred with the June 8 ground truth measurement. On the basis of weekly monitoring notes, a large log was caught on the sonar pipe on May 27, and more debris collected by the June 4 visit. Probing and portable sonar measurements during the June 8 ground truth visit confirmed the presence of a significant debris pile about 0.8 m (2.5 ft) below the transducer, with the streambed another 0.8 to 0.9 m (2.5 to 3.0 ft) below the debris pile. It was concluded that the sonar unit was sounding off the debris pile most of the time, and only occasionally as a log shifted did the sonar unit actually detect the streambed. Figure 55 shows the debris problem on June 16, 1993. Although much of the debris was visible above the water surface, a significant amount of debris was also present under the water surface. This condition persisted throughout the rest of the monitoring period. Although the instrument system remained fully functional, no further reliable soundings of the stream bed were obtained.

Figure 56 shows the debris accumulated and resulting scour hole on a pier adjacent to the instrumented pier after flow on the Rio Grande receded. This figure demonstrates the potential problems with using a sonic fathometer in a debris-prone environment.

Johns Pass Bridge Pier Test Site (FL1). In February 1994, a low-cost sonic instrument system was installed on a bascule bridge over Johns Pass, a deep, aggressive tidal inlet on Florida's Gulf Coast (see Appendix section B-2, Figures B-13, 14, and 15). The site was selected because this bridge had experienced more than 6.1 m (20 ft) of scour and it pro-

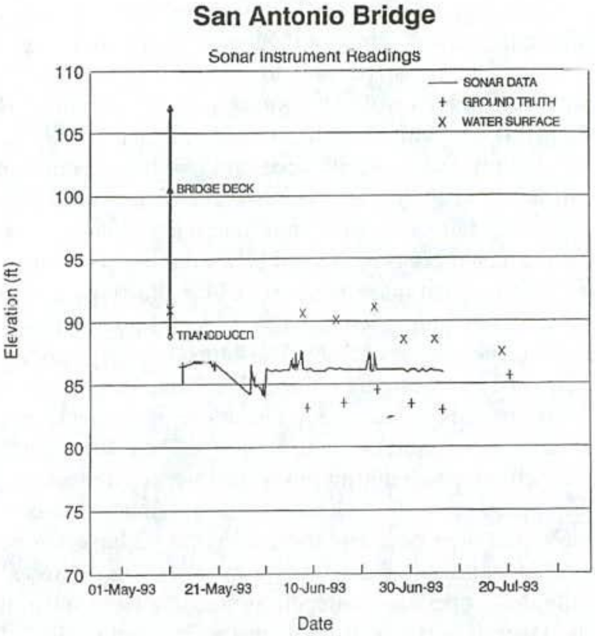


Figure 54. Site NM2 sonic sounder readings.

Figure 55. Debris collection at San Antonio sonar site (Site NM2).

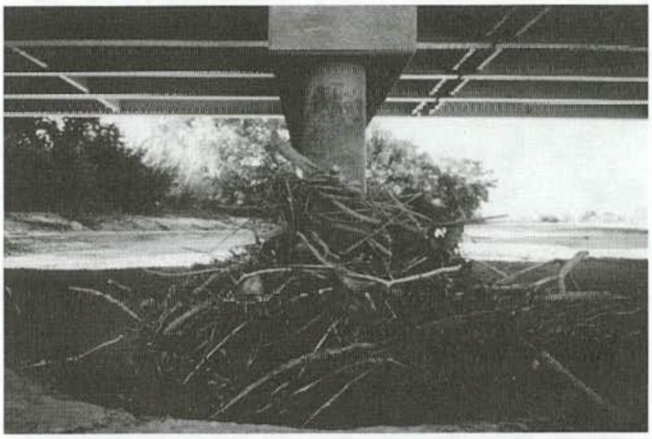


Figure 56. Debris and scour hole "in the dry" on San Antonio bridge pier on Rio Grande, NM (Site NM2).

vided the opportunity to test the sonic fathometer system in a tidal environment.

The basic installation went smoothly, requiring about 1.5 days to install by a three-person crew. This installation differed from the installation of the riverine sonar device in that it was necessary to design and build all the components to withstand the corrosive seawater environment.

Figure 57 shows the Gulf side of the Johns Pass bridge where the sonar device was installed. The instrument was installed on the second intermediate bent south of the southerly bascule pier (see Figure B-15). This bent is one of four where crutch bents have been installed as a result of undermining of the original bridge piles. The 102-mm (4-in.)-diameter pipe for the sonar transducer was installed on the vertical crutch pile, as shown in Figure 58. A bridge-deck-serviceable installation was not attempted, in part because of the height of the bridge deck off the water surface (approximately 10.7 m [35 ft]). Rather, an above-water-serviceable transducer installation was used, which

Figure 57. Gulf side of the Johns Pass bridge (Site FL1).

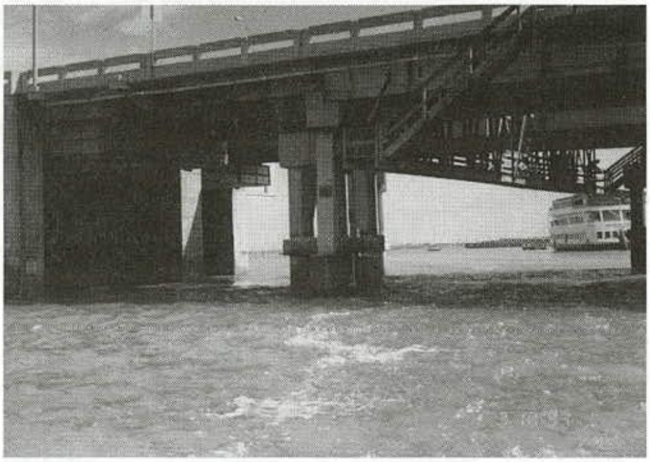


Figure 58. Crutch pile where the instrument was installed (Site FL1).

offers the same advantages as the bridge-deck-serviceable (i.e., easy installation and removal for cleaning or replacement), except that, in this case, any servicing requires the use of a boat to give access to the instrument at the pile cap. The 102-mm (4-in.)-diameter pipe, constructed of Schedule 40 PVC, was 3.0 m (10 ft) long and extended below mean sea level about 0.9 m (3 ft).

Different mounting brackets for the 102-mm (4-in.)-diameter pipe were also used, given the large diameter of the crutch piles (0.9 m [3 ft]) and the corrosion factor. Rather than the steel band clamps used on riverine sites, stainless-steel bands and eyebolts were used to secure a stainless-steel mounting bracket for the PVC pipe.

Given the configuration of the bridge and concerns about potential vandalism, a different mounting arrangement than riverine sites was selected for the instrument shelter. A catwalk was available under the bridge, and the instrument shelter could have been mounted adjacent to the walkway for easy access; however, to minimize potential vandalism, the instrument shelter was mounted to the top of the crutch pile cap (Figure 59), which is not accessible from the catwalk. To facilitate the downloading of data, a cable was run from the instrument shelter to a second, smaller instrument box located near the catwalk containing just the download RS-232 port. If the instrument itself needs servicing, the top of the crutch pile cap is easily accessible by boat (Figure 60). The instrument shelter is a single-wall stainless-steel enclosure that contains the sonar unit, datalogger, and a 12-volt battery. The battery is recharged by a solar panel mounted to one of the original piles that has a batter and slope that provided an acceptable orientation to the sun (Figure 61).

During the periods March 1994 through July 1995 and December 1995 through February 1996, monthly visits were made to the Johns Pass site to check the instrument, download data, and ground truth the readings. The instrument system functioned well during this 2-year period, and as shown in Figure 62, provided an excellent, continuous record of depth to the inlet bed. The data in Figure 62 have not been corrected for seasonal temperature variations, as discussed in relation to temperature compensation for sonar later in this section (see also Figure 76). The instrument was subjected to a storm surge and successfully recorded inlet response to this episode in November 1995 when Hurricane Opal passed along Florida's Gulf Coast (see Figure 62).

A field inspection in February 1995, about 1 year after installation, found that the transducer anti-fouling paint on

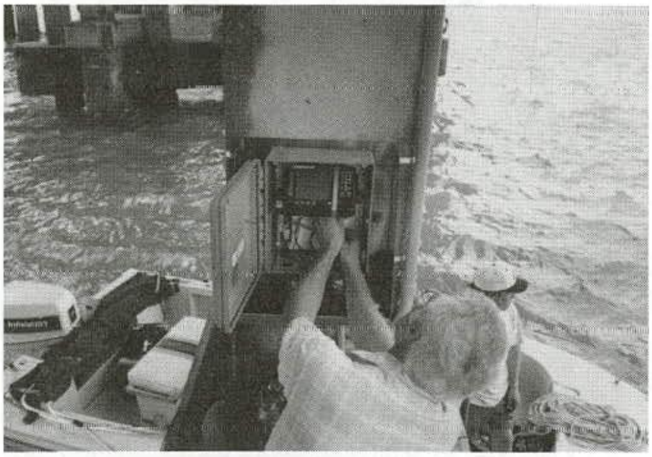


Figure 59. Sonic instrument enclosure at Johns Pass bridge (Site FL1).

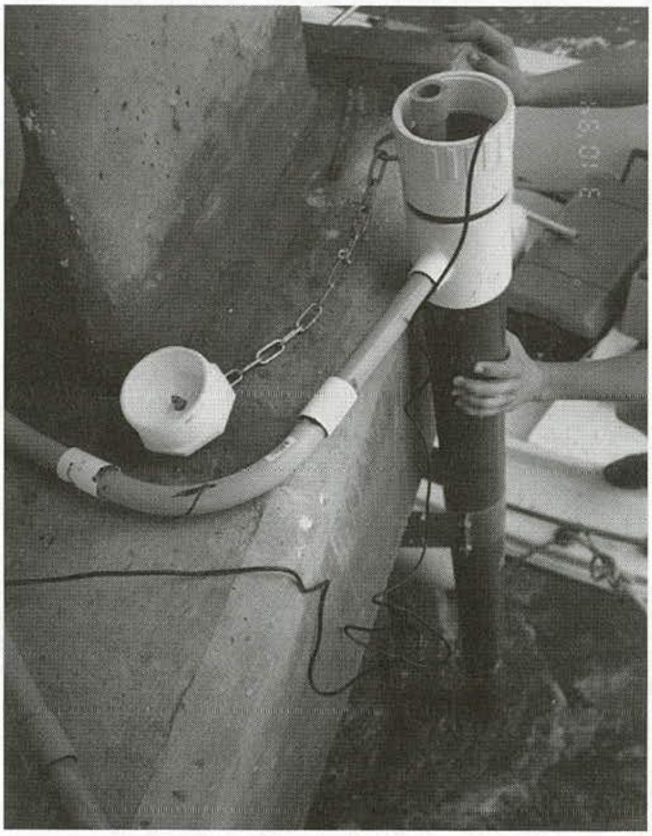


Figure 60. Transducer housing at Johns Pass bridge (Site FL1).

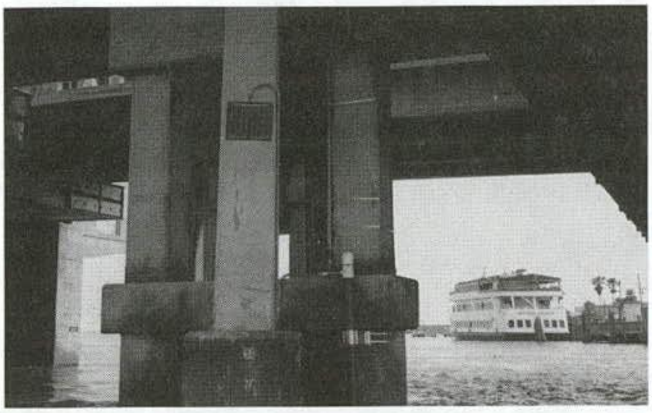


Figure 61. Solar panel installation at Johns Pass bridge (Site FL1).

this instrument was just beginning to wear away at the center of the transducer, but there was no marine growth yet. The decision was made then not to replace or re-paint the transducer, in order to evaluate the maximum useable life of the anti-fouling paint treatment. By early 1996, the instrument had developed a problem "locking on" and getting reliable data and it was thought that barnacle growth on the transducer might be the cause.

Dive inspection in February 1996 found that barnacles were built up around the entire end of the transducer and the 102-mm (4-in.)-diameter mounting pipe, to a thickness of about 51 to 76 mm (2 to 3 in.). Before having the diver chisel off the barnacles, the cap on the transducer pipe was removed to see if the transducer could be extracted by pulling on the rod connected to the transducer inside the mounting pipe. After turning the transducer slightly, and applying a steady pull, the transducer broke free of the barnacles. Figure 63 shows the transducer immediately after being removed.

After a new transducer was installed, the instrument had no problem getting a reading. Therefore, it was apparent that the barnacle growth had impaired the ability of the instrument to function. It is interesting to note that even with this much marine growth on the face of the transducer, the instrument could still occasionally get an accurate reading. On the basis of these results and the results of the field inspection in February 1995, it is recommended that the anti-fouling paint should be replaced every year for sonic fathometers installed in a marine environment.

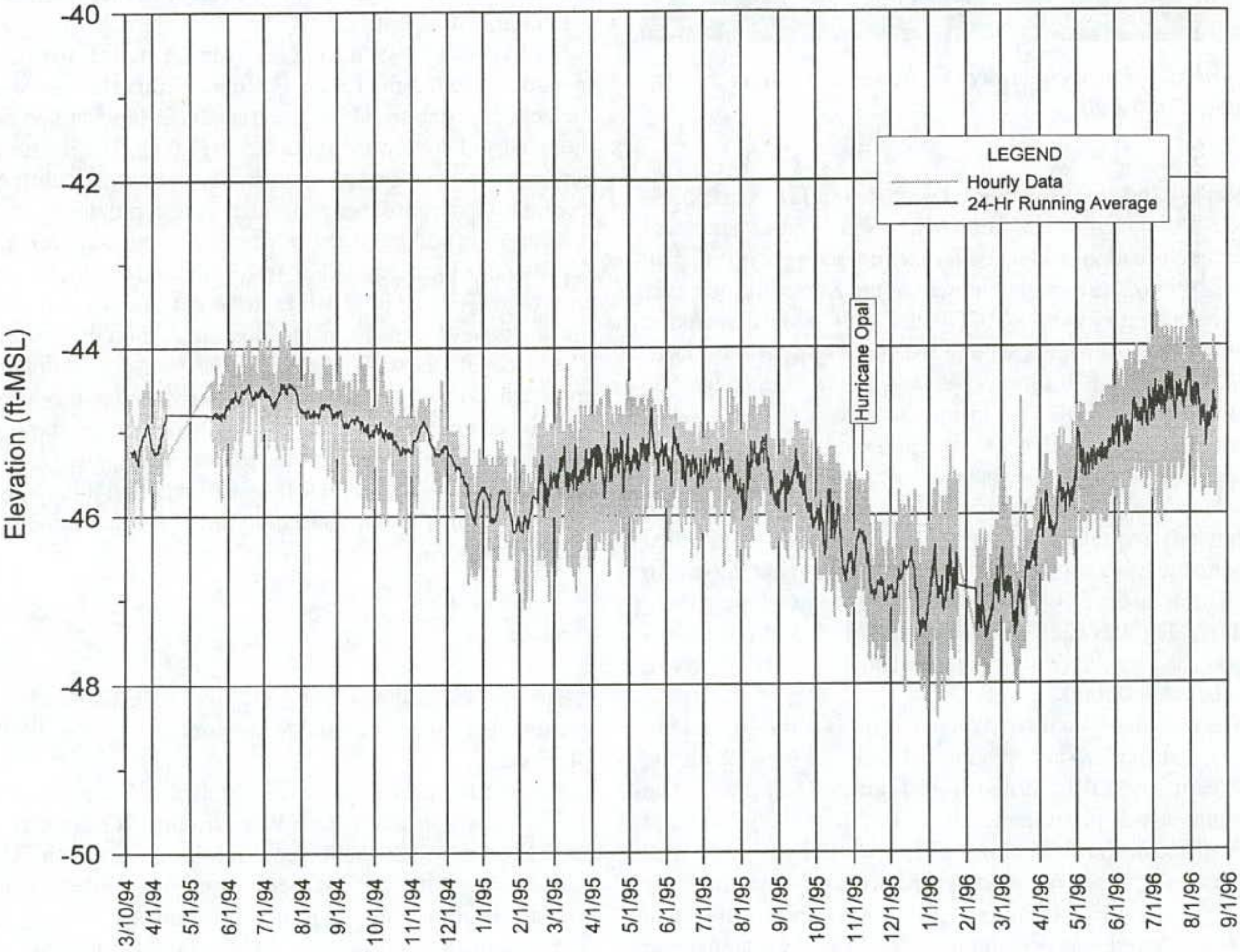


Figure 62. Uncorrected sounding data, Johns Pass bridge (Site FL1).

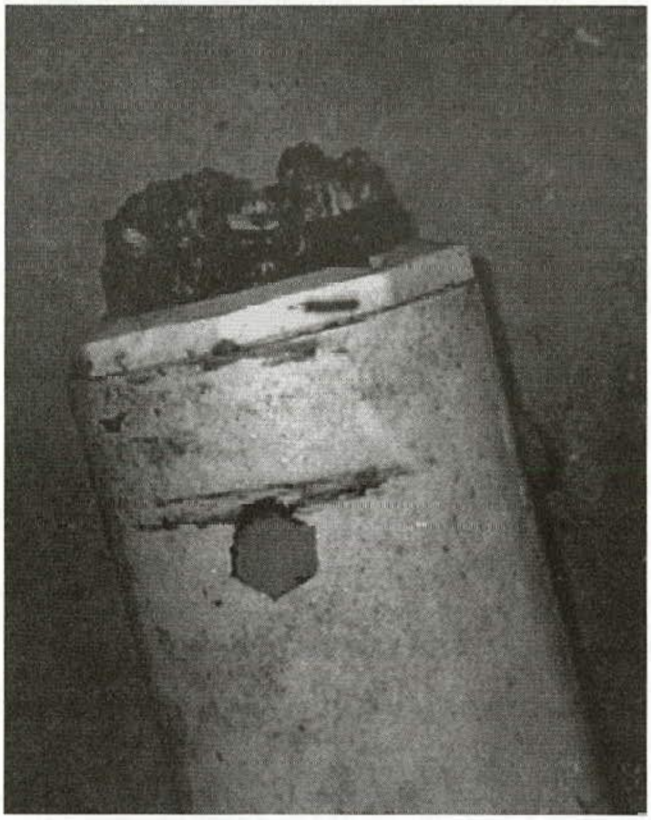


Figure 63. Barnacle growth on transducer—John's Pass bridge (Site FL1).

Kersey Bridge Abutment Test Site (CO2). As reported under sliding collar instruments, a sonic fathometer and automated-readout sliding collar instrument were installed in April 1995 on a sloping abutment at the Kersey bridge over the South Platte River east of Greeley, CO. A site description is provided in Appendix section B-2 (see Figure B-4 for location and Figure B-6 for an overview of the bridge site. See also Figures 25 and 26 for installation layout).

At the Kersey bridge site, the potential for heavy debris loading adjacent to the abutment was not thought to be a problem, and the use of a transducer mounting bracket (see Figure 64) was selected, in part to get the transducer elevated beyond the minimum depth capability of the sonar 0.5 m (1.6 ft). The transducer bracket was bolted to the slope paving with the leg elevating the transducer located at the toe-of-slope. The transducer was positioned about 0.6 m (2 ft) above the channel bottom.

The transducer cable was routed through a flexible conduit to the instrument shelter mounted to the wingwall on the upstream side of the bridge (see Figures 25 and 26). The instrument was programmed to collect data every hour and store the data on a datalogger. The instrument performed well initially; however, after several weeks of operation, the readings became intermittent. Field inspection found that grass and weed debris being transported in the channel had collected on the transducer and was interfering with the transducer operation. After removing this debris, the instrument began to function properly.

Figure 64. Close up of sonic device support bracket-Kersey bridge abutment installation (Site CO2).

In early June 1995, the South Platte River experienced a flow of about 680 m^3/s (24,000 cfs), creating pressure flow conditions at the bridge (see discussion of Kersey bridge sliding collar instrument).

On May 30, 1995, during high spring runoff, the instrument detected 0.5 m (1.6 ft) of scour. Within the next week, the concrete slab to which the transducer bracket had been mounted slid downward about 0.5 m (1.6 ft). The instrument continued to function (at a new datum); however, debris collection on the transducer continued to be a problem.

Therefore, although there was not a concern for large debris at this location, such as tree limbs and trunks, the presence of grass/weed type debris in the channel was a problem for this type of transducer installation. Although not tested, it was concluded that an alternative transducer-mounting approach, consisting of a modified above-water-serviceable transducer housing, might perform better under these circumstances (see additional discussion in Chapter 3, Abutment Installation Concepts). The instruments at this site were decommissioned in late June 1995 following the spring high-flow episode.

Other Installations of Sonic Fathometers

The USGS, in cooperation with NYSDOT and FHWA, evaluated a low-cost sonar instrument for the FHWA DP97 (*22*).

A low-cost sonar device was installed at State Route 418 over the Hudson River near Warrensburg, NY, in October 1994 to monitor the stability of rock installed by NYSDOT at the base of the pier. A permanent shield was installed around the transducer to protect the transducer and cable from ice and debris (Figure 65). The transducer was mounted

Figure 65. Protective shield for transducer mounted in bridge pier at State Route 418 over Hudson River near Warrensburg, NY.

0.9 m (3 ft) from the streambed in a 102-mm (4-in.) inside diameter Schedule 40 galvanized pipe angled 10 degrees upstream from the pier. The pipe was angled upstream so that the signal path between the transducer and streambed would be unobstructed by the pier footing. The transducer cable extended 82 m (270 ft) to an instrument shelter and was installed in a groove cut into the pier for added protection. This installation tested the adaptability of the instrument system to be incorporated directly into the bridge structure either as, in this case, part of a retrofit or rehabilitation, or as part of a new bridge design.

The USGS reports that the sonar system performed well. It was not damaged by ice or debris during the first year of operation. The site was inspected nine times during 1995 and no scour was observed. The field-measured distance between the transducer and streambed ranged from 0.85 to 0.91 m (2.8 to 3.0 ft), and the median sonar depth ranged from 0.91 to 0.98 m (3.0 to 3.2 ft).

An initial problem was encountered when a measurement time of 20 sec was used on the datalogger. This was apparently too short to activate the sonar and compute an average depth. A 45-sec measurement time was ample to process the signal; it also improved streambed detection when floating ice momentarily obstructed the signal path. The 82-m (270-ft)-long transducer cable and the 10-degree transducer angle did not adversely affect the signal because the shallow depth and solid streambed minimize signal attenuation. Despite a malfunctioning relay, the solar panel provided adequate power at 29°C (–20°F) to maintain continuous operation of the sonar.

With support from FHWA DP97, TXDOT installed three low-cost sonic instrument systems on bridge piers in the southeastern part of the state. The research team provided technical assistance for the first installation. TXDOT completed the remaining installations with District and Design Division personnel, including divers, technicians, and engineers. The following equipment was used for installation:

- A snooper truck (Reach All) to install the conduit, datalogger, and transducer housing;
- A drill to secure the conduit and datalogger to the bridge;
- A pneumatic hammer drill to anchor the transducer and conduit under water;
- An air compressor to operate the pneumatic hammer drill; and
- Miscellaneous equipment (e.g., pipe wrenches and sockets).

Each installation required an average of 2 days. The scour monitors were installed from the top of the bridges at the bent locations and traffic control was set up to close the outside lane of the bridge. A brief description of each site and instrument performance follows. Most streams in southeast Texas are subject to severe flooding, have significant debris problems, and high turbidity.

Instrument No. 1 was installed in March 1994 at the U.S. 59 crossing on the Trinity River. Before installation, heavy debris was removed from the pier. Divers were used to install the transducer approximately 0.6 m (2 ft) above the streambed in an effort to minimize the debris problem. This instrument was installed with the on-site assistance of the research team. After a period of successful operation, the instrument was damaged, apparently by a barge during the October 1994 flooding.

Instrument No. 2 was installed in August 1994 on the U.S. 90 bridge crossing the Trinity River near Liberty, TX. At this site, the sonar transducer was installed near the water surface because of high-velocity flows at the time of installation. The system was operational throughout the test period, but no scour has been recorded. During the October 1994 flooding on the Trinity River, TXDOT had difficulty obtaining safe access to the instrument box—safe access would have required a lane closure.

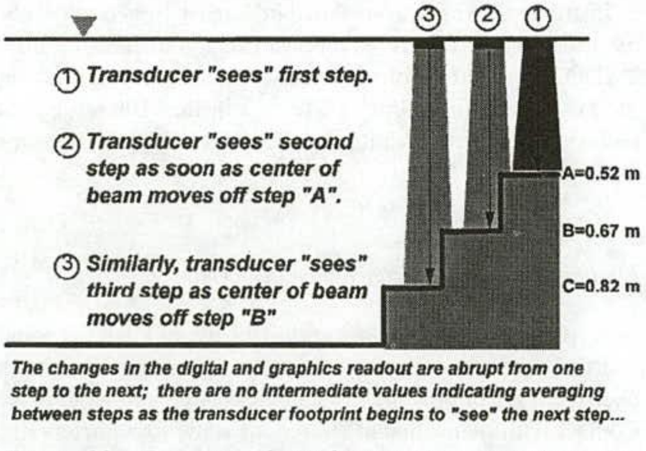
Instrument No. 3 was installed in August 1994 on the U.S. 59 bridge on the Brazos River near Sugarland, TX. Initially, TXDOT reported problems with downloading the data from the instrument, but during a site visit in July 1996, the data recorder appeared operational. The site has been dry for about 18 months.

Evaluation of Sonar Transducer Performance

A significant unknown regarding the use of low-cost sonic instruments for a scour measuring or monitoring function has been the issue of how the sonic device "sees" the scour hole. Contact with major manufacturers of sonic fathometers did not clarify the issue, as manufacturers treat such detailed information as proprietary. Consequently, several simple tests were completed in a swimming pool and on site at the Johns Pass installation in Florida (Site FL1). These tests used a Lowrance X-25 sonar with an 8-degree transducer. During the first test in a swimming pool, the transducer was floated over the steps leading into the pool. An immediate change in both the digital readout and LCD screen was observed as the center of the transducer passed over the edge of each step (see Figure 66). The depths changed from 0.52 to 0.67 to 0.82 m (1.7 to 2.2 to 2.7 ft), resulting in a "footprint" for the transducer of about 70, 90, and 110 mm (2.8, 3.5, and 4.3 in.), respectively. Obviously, there were times when the transducer footprint was "seeing" a portion of both the upper and lower step, and yet the sonar did not display any sort of average reading between the two steps. Rather, either the depth to the upper or the lower step was displayed, depending on the location of the center of the transducer. This test demonstrated the ability of the sonar to identify and resolve abrupt changes in bed topography and verified that the depth measured with a Lowrance sonar is located at the centerline of the transducer.

In the second test, the transducer was located in the relatively steep-sloped transition to the deep end of the pool, in about 2.44 m (8 ft) of water. At this depth, the transducer produces a footprint of about 340 mm (13.4 in.), and the depth change from the upper edge of the footprint to the lower edge was about 120 mm (4.7 in.) (see Figure 67). On the basis of this test, it was again concluded that the sonar was measuring the depth to the center of the transducer and neither the deeper or shallower depth represented by the lower or upper portion of the footprint. This test indicated that a Lowrance sonar "looking" at the steep side slope of a scour hole would measure the depth to the center of the transducer and not the deepest or shallowest point "seen" at the edges of the footprint.

In the third test, the transducer was pointed across the pool at the opposite side and slowly rotated down toward the bottom of the pool. The distance across the pool was accurately measured until the angle of the transducer caused the sound wave to reflect off the bottom. The longer depth that was then displayed was apparently the result of the longer distance the sound wave traveled as it reflected off the bottom, up to the side of the pool, and then back to the transducer. This test indicated that as long as the sound wave has only one direct reflection, an accurate measurement can be made. Therefore, applications such as shooting the transducer at an angle from a pier to an abutment might work for a vertical wall abutment, but would be questionable for sloping wall abutment where the sound wave would not always have a direct reflection back to the transducer.



The changes in the digital and graphics readout are abrupt from one step to the next; there are no intermediate values indicating averaging between steps as the transducer footprint begins to "see" the next step...

Figure 66. Detecting abrupt bottom changes with a sonic fathometer.

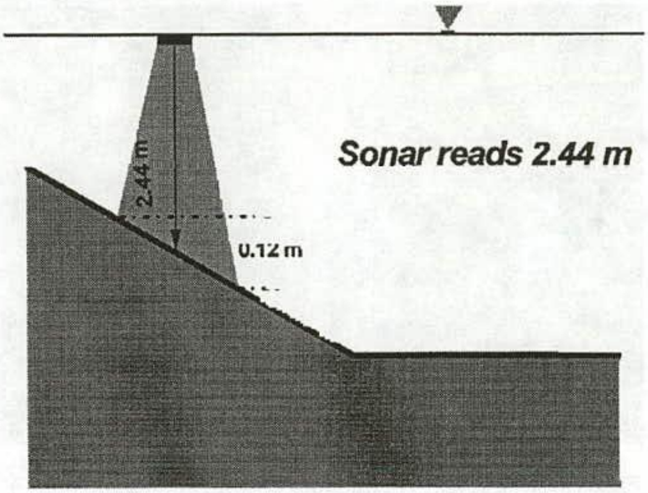


Figure 67. Measurement on a steep slope with a sonic fathometer.

The final test was completed at the Johns Pass sonar instrument site (see Figures 57 and 58). The transducer was attached to the end of a long pole so that it could be positioned immediately next to a pile. The water depth was about 14.3 m (46.9 ft), making the footprint about 2 m (6.6 ft) across. The depth measurement when the transducer was oriented vertically and positioned between 0.5 to 1.0 m (1.6 to 3.3 ft) from the pile was the same as the depth measured when the transducer was positioned vertically against the pile. Furthermore, the LCD screen did not indicate any extraneous reflections or noise when the transducer was positioned next to the pile. At an angle of about 15 degrees into the pile, the depth measurement increased slightly, about 60 mm (2.4 in.), and at an angle of 30 degrees into the pile the measurement increased about 150 mm (5.9 in.) and became more unstable. As the angle became greater, the sound wave apparently began to bounce off the pier and into open water, resulting in less and less of the sound wave returning to the transducer (see Figure 68).

These tests suggest that it is not necessary to position or angle the transducer away from the pier; however, in a marine environment, this may still be desirable to avoid erroneous readings from the large accumulations of barnacles

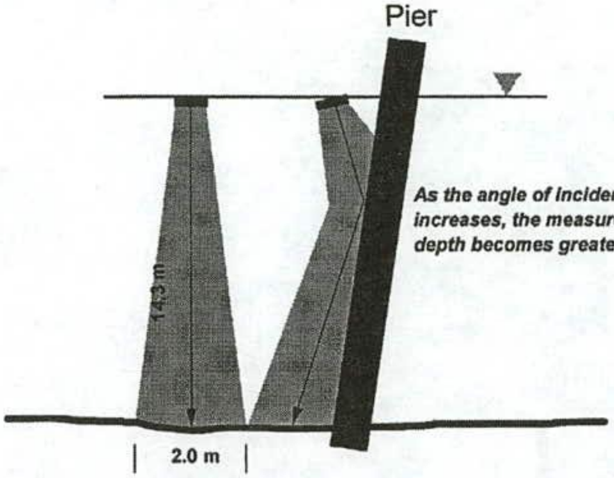


Figure 68. Measurement near a pier with a sonic fathometer.

often present on a pier below the waterline and to prevent completely encapsulating the transducer to the pile with barnacles.

These results are for Lowrance sonar equipment, similar to that used for the portable and fixed instruments during this project. However, other sonar manufacturers may use different analysis and filtering schemes to interpret the sound wave returns, which might change the way the sonar "sees" conditions over a step or along a steep slope. During a telephone call to Lowrance, the manufacturer indicated that their procedure involved "digital averaging of the strongest returns." They would not elaborate on the type of averaging or how they identify the strongest returns; however, on the basis of the test results discussed above, a Lowrance sonar does provide the type of information needed for scour-monitoring applications.

Temperature Correction—Low-Cost Sonic Fathometer

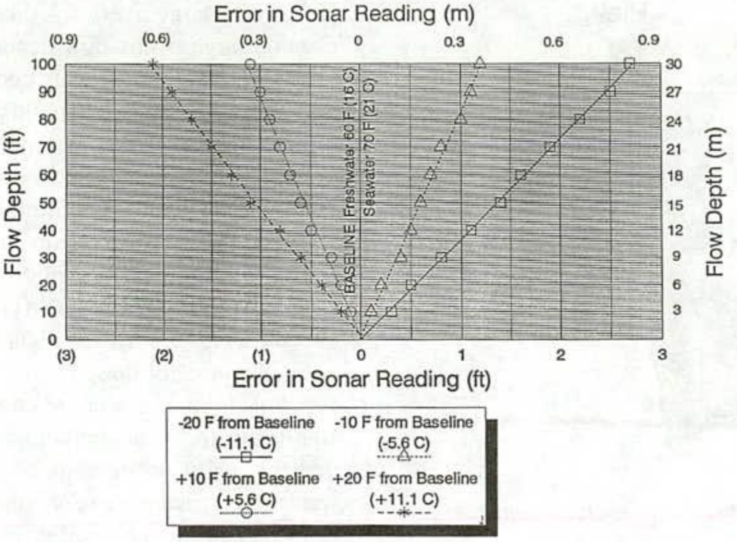
Temperature Compensation in Sonar Devices. A theoretical investigation was completed to determine the effects of temperature variation on the potential error in the sonar reading over a wide range of temperature and flow depths. Specifically, when the water temperature is near freezing, the maximum flow depth that can be measured without exceeding an error of 0.3 m (1 ft) is about 9.1 m (30 ft). Similarly, when the water is quite warm (e.g., near 27°C [80°F]), the maximum flow depth that can be measured without exceeding an error of -0.3 m (-1 ft) is about 12.2 m (40 ft). These results suggest that these error conditions are probably not a serious limitation in practical application of low-cost sonar devices at most sites (see Appendix section B-3).

One significant factor in interpretation of these results is recognition that a 9.1 to 12.2 m (30 to 40 ft) flow depth is typical of very large rivers or a tidal inlet. Another factor is that even on large rivers, flow depths in excess of 9.1 to 12.2 m (30 to 40 ft) would typically occur during flood season when the water temperature would probably be close to 16°C (60°F). In other words, during flood season, there would be minimal temperature effect on the assumed speed of sound. For example, a deviation in the speed of sound of 15.2 m/s (50 fps), representing a temperature change of about a 5.5°C (10°F) from baseline conditions, would not exceed the error criteria even in 24.4 m (80 ft) of flow depth (sonar error of about 0.24 m [0.8 ft]; see Figure B-21).

On the basis of these results and their interpretation, it is concluded that temperature compensation is not normally a significant factor or limitation in the use of low-cost sonar devices. Only under extreme conditions (e.g., very deep water at very warm or very cold conditions) would temperature compensation be warranted or necessary for purposes of scour monitoring. For example, interpretation and appraisal of the Johns Pass sonar installation, located at a relatively deep tidal inlet on the Gulf of Mexico where water temperatures can exceed 30°C (85°F), found temperature (and salinity) correction necessary for accurate results (see Chapter 3 discussion and Figure 76).

The effect of density on the speed of sound also raises concerns about the accuracy and use of a low-cost sonar unit in a seawater environment. Results of theoretical investigation indicated that the assumed speed of sound for a low-cost sonar unit at 1463 m/s (4,800 fps) occurs at about 21°C (70°F) in seawater, rather than the approximate 16°C (60°F) in freshwater. At many tidal bridge sites, it would be unusual for the water temperature to be much warmer than 24°C (75°F), for which the approximate 7.6 m/s (25 fps) increase in the speed of sound would result in an error in the sonar depth of about -0.1 m (-0.4 ft) in 24.4 m (80 ft) of water. The primary exception to this may be the Gulf Coast region, as determined during the Johns Pass testing. Similarly, even in a colder climate at a tidal bridge site, the water temperature would seldom be below 10°C (50°F), for which the approximate 30.5 m/s (100 fps) decrease in the speed of sound would result in an error of about 0.3 m (1.0 ft) in about 12.2 to 15.2 m (40 to 50 ft) of water (Figure B-21). Therefore, as with sonar use in a freshwater environment, it is concluded that density compensation is generally not a significant factor or limitation in the use of low-cost sonar devices in a tidal environment.

If it is desirable to adjust the low-cost sonar results for the effects of temperature or seawater, Figure 69 can be used. This figure was derived from theoretical considerations and indicates the potential error in the sonar reading over a range of 17°C (20°F) and for flow depths up to 30.5 m (100 ft). Interpolation between temperature curves and reading the sonar error to the nearest tenth of a meter would provide a first order correction for temperature or salinity effects.



Example:

Measured conditions:
- Sonar depth reading 9.0 m in freshwater
- Water temperature 21°C

Temperature corrected value:
- Temperature deviation 21-16 = +5°C
- Error in sonar measurement (from graph) = -0.1m

Therefore, the measured value is 0.1 m lower than the true depth; the temperature corrected sonar depth is 9.0 + 0.1 = 9.1 m

Figure 69. Low-cost sonar correction factors for temperature.

Findings—Low-Cost Sonic Device Field Testing

- Research resulted in development of a reliable low-cost sonic system (consisting of fish-finder-type sonar, a datalogger/interface, and a solar panel) which can be mounted in a bridge-deck- or above-water-serviceable configuration. This system exceeded the initial expectations for this type of instrument and met all established mandatory criteria and most desirable criteria.
- A low-cost sonic system performed well on a bridge pier on the South Platte River in Colorado under variable flow conditions, with ice and debris. A specific scour-and-fill episode was documented and correlated with stream-gaging data.
- A low-cost sonar system in a bridge-deck-serviceable configuration was successfully fabricated and installed on a pier of the San Antonio bridge over the Rio Grande in New Mexico using a mounting bracket clamp on a pile cap. Instrument installation was affected by debris accumulation around the bridge piers and, at this site, the performance of the instrument was hindered by the accumulation of debris. Although the sonar unit continued functioning normally during a full flow season, the instrument was able to acquire a reading off the streambed only intermittently because of the accumulation of debris. The instrument was, however, able to successfully track a significant episode of scour and fill, on a reach of the Rio Grande known for its high turbidity. Sonar readings were correlated with cross-section and stream-gaging data.
- A low-cost sonar system was successfully fabricated and installed on a tidal bridge pier on Florida's Gulf Coast. The site was selected because it posed substantial challenges for the installation of a low-cost sonar system, including an aggressive tidal inlet on the open (Gulf) coast that had experienced significant scour, a large bascule (moveable) bridge with a complex pier and crutch bent substructure, a hostile marine environment where corrosion and growth of marine organisms could test the durability of electronic and mechanical components, and a 14-m (45-ft) water depth. The system performed well over a 3-year period. Anti-fouling paint protected the transducer face for the first year of operation, but by the end of the second year, barnacle growth had begun to interfere with system operation. This instrument provided an excellent continuous record of seasonal scour and fill and performed successfully under storm-surge conditions.
- A workable configuration for installing a low-cost sonic fathometer on a sloping bridge abutment was developed

and installed at a bridge on the South Platte River in Colorado. The mounting bracket elevated the transducer above the minimum depth capability of the instrument and directed the transducer cone to the most likely area for scour at the toe of the abutment slope. The instrument performed well initially, but after several weeks of operation, grass and weed debris collected on the bracket and interfered with transducer performance. Successful operation required frequent removal of this debris.

- The USGS successfully installed a low-cost sonic fathometer on a bridge pier in upstate New York. The bridge-deck-serviceable instrument was embedded in a concrete pier during rehabilitation and demonstrated system adaptability to integration into the structural design of a bridge for new construction or retrofit. The system performed well and was not damaged by ice or debris during the first year of operation; however, flow conditions throughout the year did not produce scour at the site.
- Three low-cost sonic instrument systems were successfully installed by TXDOT using in-house equipment and personnel. All three sites were on debris-prone streams with high turbidity. One instrument transducer was installed close to the bed to avoid debris and initially performed well, but was damaged by impact from a barge during a flood. A second instrument was operational, but recorded no scour. In addition, TXDOT had difficulty accessing the datalogger on this bridge during a flood. Initially, there were problems downloading data from the third instrument. This problem was corrected, but the site has been dry for most of the test period.
- Tests of sonic transducer performance under controlled conditions demonstrated that the sonic fathometer "sees" the portion of the bed *directly* under the center line of the cone for both a stepped configuration and steep-sloping bottom. Transducer performance deteriorates if more than one direct path of reflection exists, such as off a sloping wall (or abutment). Instrument performance was not affected significantly when reading adjacent to a vertical object, such as a wall or pile, as long as the transducer was not pointed into the wall or pile at an angle greater than about 30 degrees. Thus, directing a transducer cone parallel to a wall or pier should not produce interference. However, it is necessary to angle a transducer away from a wall or pier if a footing or pile cap exists. The centerline of the transducer cone must strike the streambed in front of a footing or pile cap to measure scour.
- A study of temperature and salinity effects on the speed of sound found that there should not be a concern for most installations, within the limits established by the mandatory criteria (0.3 m [1 ft] accuracy) and for the depth and temperature ranges expected at most riverine and tidal bridge sites. If necessary, the corrections for temperature and salinity can be made as a post-processing step.

Piezoelectric Film Devices

Overview

Although a driven rod with piezoelectric film sensors was tested successfully in the laboratory (see Figures 7, 8, and 9), only limited field testing on a prototype device was conducted under this research project. Limited testing of a "piezoelectric array" was completed by the USGS with support from FHWA DP97 (*27*). Results of limited testing of piezoelectric film devices by both the research team and USGS are presented in this section.

Installations

Orchard Bridge Pier Test Site (CO1). In November 1993, a prototype piezoelectric instrument was installed adjacent to the magnetic sliding collar at the Orchard bridge site (CO1). A concept sketch of the piezoelectric device is shown in Figure 7. The prototype piezoelectric instrument consisted of a 102-mm (4-in.)-diameter steel pipe with six piezoelectric sensors attached to the exterior of the pipe. The four sensors which are lowest on the pipe are spaced at 0.15-m (0.5-ft)-long increments and the two upper sensors are spaced at 0.3- m (1-ft) increments. The lowest sensor of the instrument was placed 1.5 mm (0.5 ft) from the bottom of the steel pipe. The prototype piezoelectric instrument was fabricated with a 25- mm (1-in.)-diameter PVC pipe installed inside the steel pipe for transmission of jetting water for installation. The annulus of the steel pipe was then filled with foam to waterproof and protect the wiring leading to the sensors.

The piezoelectric instrument was jetted (but not driven) approximately 0.6 m (2 ft) into the bed of the river using water from a gas-powered pump and a downward force applied manually (see Figure 46). This depth of insertion ensured that two sensors were buried in the bed, one sensor was near the sand/water interface, and three sensors were located between the streambed and water surface. At the time of installation, the uppermost sensor was approximately 25 mm (1 in.) below the water surface.

The instrument was bolted to the bridge pier with collar clamps similar to the clamps used to install the sonar scour monitor at this bridge (see Figure 47). The electrical output from these sensors was then examined using a volt meter and Campbell 21X datalogger.

Preliminary testing of the electrical signal from the sensors of the device installed at the Orchard bridge test site indicated that *all* of the sensors produced output, although two of the sensors were buried in the channel bed. The output from each of the sensors was transient and varied with time. Over a period of 1 to 2 sec, the voltage output ranged from approximately 0.005 to 1.8 volts. In general, higher and more frequent peak voltages were observed for the sensors exposed to the flow than for sensors buried in the bed. However, occasional high peak voltages of approximately 0.9 to 1.2 volts were observed for the sensors buried in the bed. These occasional peak voltages for the buried sensors occurred at random intervals of approximately 5 to 10 sec. Voltage output from the sensors buried in the bed was attributed to vibration of the support pipe caused by the flowing water and from vehicle traffic on the bridge. The interpretation and appraisal relative to this finding are discussed in Chapter 3.

USGS Testing in Oregon. With support from FHWA DP97, a prototype piezoelectric film driven rod was installed by the USGS as part of a project to monitor performance of bridge scour instrumentation at nine sites in Oregon (*27*). Scour was initially monitored at these sites using a sonar device, but during fiscal year 1994, various new methods were tested.

A piezoelectric driven rod array was installed at the Sandy River bridge near Troutdale, OR. A field memorandum on performance and short data record are included in Appendix section B-4. The instrument was hit by debris (large logs) during a small flood in November 1995. Although the conduit was bent, the instrument array remained intact and operational. The USGS concluded that the instrument provided good scour data under conditions where data "could not have been collected by any other means" (see Figures B-23 and B-24).

Findings—Piezoelectric Film Device Field Testing

- During limited field testing of a prototype piezoelectric film device, the sensors proved to be very sensitive to structural as well as hydrodynamic vibration. Sensors that were buried in the streambed should not have indicated any motion, but apparently responded to vibration of the support pipe caused by flowing water and traffic across the bridge.
- The USGS reported excellent performance of a prototype piezoelectric film device. The device survived impact by large logs and debris and provided good scour data under conditions where data "could not have been collected by any other means."

Datalogging and Telemetry of Data

Overview

For most classes of scour measuring or monitoring devices, current datalogging systems are adequate to meet the needs of the sensors being used. Indeed, currently available dataloggers can be used for most of the scour measuring devices described and tested in this report. However, commercially available dataloggers are more sophisticated and costly than is generally necessary. For the low-cost sonic fathometers, commercially available dataloggers provide too many unused input channels, but data processing capability to adequately and efficiently filter out the non-useable data is too limited. Conversely, commercially available dataloggers have all the functionality required to process data from sensors used on the driven/buried rod devices, but lack adequate input channels unless add-on multiplexers are used. More sophisticated dataloggers with transmit-receive capability from the sensors would be required for untethered buried devices.

Evolution of Scour Datalogging Capabilities

The datalogger developed during summer 1992 for this project wrote data directly to a removable data card which could store approximately 8 kilobytes of data. The data card was then downloaded to a portable computer at the site, erased, and reinstalled in the datalogger. Two problems arose with this arrangement. First, any data stored on the data card would be lost if a power failure occurred. Although this problem did not occur once the solar panel was adequately sized, it represented a weakness with the original datalogger and storage design. The second problem concerned the physical storage size of the data card. The data card would fill with data from the two instruments at the Orchard bridge test site (CO1) in about 1 week when data were stored on a 5-min interrogation cycle.

The data retrieval and storage software was installed in the electronics package by using a programmable read-only memory (ROM) chip. This chip could be reprogrammed to revise the data processing and retrieval function of the datalogger. The datalogger was initially programmed to power up every 5 min, initialize the sonic fathometer, and measure the distance from the bed to the transducer. This was accomplished by sensing the digital data from the fathometer until three consecutive identical readings were obtained. Measured data were stored if there was a change in the measured reading from the previous datalogging cycle.

Testing during the 1992 season included assessing the effects of different sampling frequencies. Sampling frequencies of 1.5, 5, and 10 min were used. These tests indicated that the temporal resolution of the scour data was not significantly degraded within this range of sampling frequencies. However, decreasing the sampling frequency from 1.5 to 5 min increased the storage life significantly.

The programming of the datalogger was designed to record data when the streambed elevation changed by more than a predefined value, defined as the "threshold resolution." The threshold resolution was modified to assess the effect of this value on data resolution. When the threshold resolution was set to record any change from the previous reading, large quantities of data within the range of the accuracy of the sonic fathometer (30 mm [0.1 ft]) were recorded. As a result, considerable storage space was consumed to record redundant data. Conversely, when the threshold resolution was set at 0.15 mm (0.5 ft), large gaps in time were noted in the data record between recorded readings, and the temporal resolution of the data was poor. A third threshold resolution of 0.06 m (0.2 ft) resulted in a concise data record which maintained the temporal resolution of the data.

Although the datalogger worked well with the sonic fathometer at Site CO1, the input channel from the pulse counter of the Brisco Monitor sounding rod to the datalogger failed, resulting in loss of signal from the pulse counter. Attempts to rectify this problem were not successful. The input channel for the sounding rod was permanently disconnected in August 1992. An interpretation and appraisal of this finding and a suggested solution to this problem are provided in Chapter 3.

The Orchard bridge site was inspected in October 1992, November 1992, and February 1993. During these visits, the status of the electronics was determined and sonic fathometer data were downloaded. These inspection trips revealed that the battery was fully charged and the solar panel was clean and providing recharge energy at normal levels. From these site visits, it was determined that there was no degradation of the electronics during winter 1992–1993.

The sonic fathometer and datalogger at the Orchard bridge site were replaced with an upgraded electronics package in June 1993. Upgrading included replacement of the Eagle Z-9500 fathometer with a Lowrance LMS200 fathometer, replacement of the data card with 64 kilobytes of on-board system memory, addition of an industry-standard RS-232 output port, and modifications to the datalogging software. These upgrades allowed the user to connect a laptop computer via the RS-232 port to (1) alter the sampling intervals and threshold resolution; (2) set the internal clock/calendar; (3) download data directly from the datalogger to the laptop computer; and (4) perform checks of the electronics, voltage supply, and memory.

Operation of the datalogger during the 1993 flow season indicated that the upgraded datalogger system provided greater flexibility in setting sampling protocol and provided a better standardized method to download data. The larger memory capacity extended the length of time between data retrieval visits from a few days to several weeks depending on the sampling protocol used.

In February 1995, the circuit board in the datalogger at the Johns Pass site (FL1) was replaced with upgraded software. The new software implements revised logic and has an improved menu from a user's point of view. For example, the new logic can be programmed to look for three sonar readings in a row within 0.3 m (1.0 ft) and then average those values to define the measurement value. The old logic required three in a row that were identical, which was too restrictive. In the new logic, the number of readings in a row and the tolerance interval are both programmable. Additional memory on the datalogger also permits logging information every sample period. Previously, a given measurement was compared to the previous reading and logged only if it exceeded the last value by 0.15 m (0.5 ft). Experience during the period 1995 to 1996 showed that the new logic was easier for the user to understand and was implemented with a simpler menu.

Datalogging/Interface Requirements for Scour Instruments

The sonar device used in scour instruments developed for this project is a low-cost fish-finder manufactured by Lowrance Electronics, Inc. (**Use of trade names is for identification purposes only and does not imply endorsement by the authors or sponsors.**) Other fish-finder-type sonar devices are available and could be used, provided they have digital output capability. Many fish-finder-type devices do not have the output capability necessary to connect to a datalogger. The signal output from these sonar devices conforms to the National Marine Electronics Association (NMEA) standard. This standard provides a serial data string that includes heading, position, speed, sonar data, and other information in a near ASCII form transmitted at a 4800 baud rate. This standard, and consequently the form of the output data string, is different from other available standards. Other common standards include EIA-232-C, ANSI X3.4-86, and Serial Digital Interface-12 (SDI-12). To collect and record data with any of these standards, the datalogger must be able to recognize and interpret the output string provided by that standard. Companies manufacturing dataloggers include Campbell, Sutron, Handar, and others.

Of particular interest is the SDI-12 standard. SDI-12 communicates at 1200 baud. This standard was developed by Campbell Scientific, Inc., at the request of the USGS, to provide a new standard for hydrologic and environmental sensors. This standard was developed along with a new datalogger, referred to as a Basic Data Recorder (BDR). The BDR was developed to replace the aging Automatic Digital Recorder (ADR) used for many years by the Water Resource Division of the USGS in support of their streamflow data collection program. The BDR is being widely implemented in hydrologic and environmental data collection. During this same time, Campbell developed the CR10, which has more channel inputs and additional control capabilities.

Initial evaluation of commercial dataloggers indicated that none of the available dataloggers, including the BDR, were easily implemented in a low-cost sonar device. Problems included compatibility with the NMEA standard used in low-cost sonar devices, baud rate differences, and the desire to program the sonar device to turn on at selected times and to screen the data before storage. For any commercially available datalogger, some type of interface would be required to allow operation with fish-finder-type sonar devices. Most off-the-shelf dataloggers had much greater capability than required for a single transducer sonar instrument, which unnecessarily added cost and complexity to the instrument. A viable low-cost approach was to modify the existing ETI Memory Datalogger (MDL), a relatively simple datalogger commercially available from ETI Instrument Systems, Inc., and originally developed to log digital output data from a precipitation gage.

Consequently, the MDL was modified to provide an interface that would accept the NMEA 4800 baud code. The modified device was called the Electronic Interface/Memory Datalogger (EI/MDL). In addition, the EI/MDL provided power-on control to the sonar unit and software algorithms to process the data before storage. This capability minimized the recording of erroneous and/or extraneous data. The preprocessing error checking provided by the interface includes

- A maximum depth change comparison before logging (e.g., a 6.1-m [20-ft] change from the last reading could be rejected as erroneous),
- The ability to program the number of readings in a row with a given tolerance before logging the result (e.g., five depth soundings in a row within 0.09 m [0.3 ft] could be required to ensure the sonar has locked on and is getting good results before logging the depth; the depth logged is the average of the string), and
- The number of times the sonar tries to get a good reading before turning off.

Power-on control and the ability to program the sample interval minimize battery drain and limit collection of extraneous data. Extraneous data collection is also minimized by requiring a minimum change from the last reading before logging the result, with at least one reading per day recorded (e.g., a depth reading with a change less than 0.15 m [0.5 ft] from the last reading could be programmed to not be logged).

Recently, the EI/MDL was modified to allow datalogging by a Campbell type device using SDI-12 protocol. Campbell Scientific has now developed an interface that will allow the output from a low-cost sonar unit to connect to their CR10 datalogger.

Telemetry

Once data have been logged in a datalogger, the telemetry of the data is relatively straightforward because the protocols for data transmission using telephone modem, radio, and satellite transmission are well established. However, additional effort is required to refine the interface between the scour data logger and the various telemetry options.

Although the testing of telemetry systems was generally beyond the scope of this research, a basic telemetry capability for scour data was demonstrated with the automated-readout magnetic sliding collar device installed on the Kersey bridge abutment (Site CO2). A cellular phone link from the Kersey bridge to Fort Collins, CO, a distance of about 64 km (40 mi), was completed in early April 1995, and the instrument data were monitored and downloaded without problems until the instrument was decommissioned in late June 1995 (see additional discussion on telemetry in Chapter 3).

Findings—Datalogging and Telemetry

- The upgraded datalogger/interface developed for the low-cost sonar device represents a substantial improvement over earlier systems. Refinements include additional on-board system memory, addition of an industry-standard RS-232 output port, and modifications to the datalogging software. Enhanced software permits the setting of sampling frequency, threshold resolution, exceedance threshold, and other sampling protocol characteristics. Such software was installed in the field to increase system longevity and reduce errant or erroneous readings. The system proved to be both survivable under harsh environmental conditions and adaptable to other scour monitoring systems, such as the automated magnetic sliding collar device.
- The sonic fathometer selected for scour monitoring applications must have a digital output and the datalogger must be able to recognize and interpret the output data string. For any commercially available datalogger, some type of interface will be required to allow operation of low-cost fish-finder-type sonar devices. Functions of the interface include recognition of the digital data produced by the instrument, power-on control, and software algorithms to screen the data before storage.
- Once data are logged, telemetry of the data is relatively straightforward using telephone modem, radio, or satellite transmission. A cellular phone link between an automated sliding collar device and monitoring station 64 km (40 mi) away was demonstrated successfully during this project.

Underwater Wireless Transmission of Data

Overview

The link between the scour sensors and datalogger/interface is often vulnerable to physical damage by ice and debris. Consequently, it was desirable to investigate and demonstrate the feasibility of transmitting (through water) data signals similar to those produced by a scour monitoring instrument (such as an automated sliding collar device) and acquiring these data at an above-water location, such as on a bridge deck.

Test Equipment

To demonstrate this capability, the following equipment was fabricated and assembled:

- An underwater transmitter and unity gain antenna (4 watt RF @ 151.625 Khz),
- Microcontrolled electronics,
- A 12-volt sealed gel battery,
- A matching receiver and demodulator unit with 2dB-gain omni antenna, and
- An RS-232 interface to laptop computer.

The transmitter, micro-controlled electronics, battery pack, and antenna were housed in a 102-mm (4-in.) cylinder, 610 mm (24 in.) in length (see Figure 70). The demodulator provided output through the RS-232 cable to the portable personal computer (PC).

Test Procedure

In June 1996, a demonstration was completed of underwater transmission of digital data and the ability to record and log these data above water. The system shown in Figure 71 was tested, and a digital data string (composed of time; unit code; 3-digit internal counter; battery voltage; temperature; and two switch positions, which emulate the function of a scour-monitoring device) was transmitted and received successfully. Before lowering the transmitter unit into the water, power was applied to the receiver and demodulator unit to check for proper operation and for any external interference. It was observed that others operating on the same frequency caused some disturbance in the received signal. Specifically, a cyclical interfering signal about 3 to 4 sec long occurred about every 10 sec.

The transmitter unit was activated by attaching a magnetic key device that closed an internal magnetic reed switch and connected the battery to the electronics. A tether was attached to the transmitter casing, and the unit was manually lowered into the water until it rested on the bottom, about 11.3 m (37 ft) deep. The antenna end of the underwater test unit was positioned toward the receiver.

The receiver unit was located approximately 6.1 m (20 ft) horizontally from the point where the transmitter was vertically tethered. The receiver antenna was placed horizontally and directed toward the transmitter. Signals received were captured and recorded on the portable PC.

Test Results

The system was tested for several minutes at the initial location. Most records were received error-free. When interfering signals (described above) occurred, the result was sometimes seen as dropped, added, or changed characters in the received record. Even with the interfering signals, less than 10 percent of the ASCII words received had errors.

The tethered transmitter was then moved horizontally away from the receiver unit to ascertain maximum reliable separation. Even through the percentage of errors increased as separation increased, the system continued to operate favorably for some distance. As long as the horizontal separation remained less than 30.5 m (100 ft), the received signal was readable and reliable. Total elapsed time for the system test was approximately 22 min.

Findings—Underwater Transmission of Data

- In the absence of interfering signals, the underwater unit in the tested configuration, orientation, and environment should provide reliable operation with few errors. Suggestions to improve performance and operational considerations are discussed in Chapter 3.

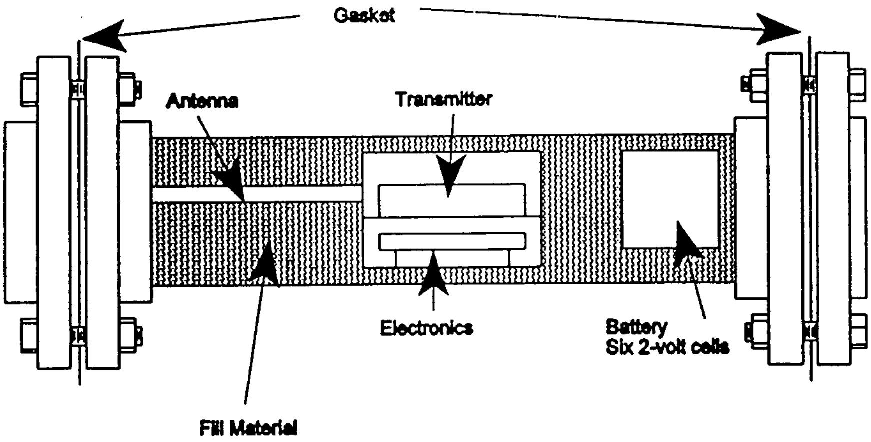


Figure 70. Configuration of underwater wireless transmitter.

Figure 71. Underwater transmitter, receiver, and laptop computer.

Instrument Documentation

A significant objective of this research was to develop comprehensive, detailed documentation of fully operational scour monitoring instruments. This requirement is met by documentation in this report and in installation, operation, and fabrication manuals (see *NCHRP Reports 397A and 397B*) for two instrument systems: (1) a low-cost sonic fathometer, and (2) magnetic sliding collar device (manual and automated). The installation, operation, and fabrication manual available for each of these instrument systems gives design, fabrication, and installation specifications.

NCHRP Report 397A, "Installation, Operation and Fabrication Manual—Sonar Scour Monitor" has two major sections:

- Part I Installation and Operation and
- Part II Fabrication.

NCHRP Report 397B, "Installation, Operation and Fabrication Manual—Magnetic Sliding Collar Scour Monitor" has three major sections:

- Part I Installation and Operation,
- Part II Fabrication of Manual Readout Device, and
- Part III Fabrication of Automated Readout Device.

System schematics, specifications, and enhancements and a list of suppliers are provided in each manual. Discussion of scour instrumentation includes abutment installation techniques and guidelines, warning/monitoring functions, telemetry concepts, wireless (underwater) transmission of data, datalogging and telemetry, and ground truth instrumentation; however, these are discussed primarily in this report in the findings in this chapter and in the interpretation, evaluation, and appraisal in Chapter 3. The most significant findings for the two instrument systems developed and tested under this research project and considered fully operational and ready for field deployment are summarized in the following section.

Summary of Findings

Overview

Findings from laboratory and field testing of two fully operational scour monitoring instrument systems are summarized below. For more detailed findings and findings on other instruments or instrument concepts tested, see the appropriate sections of this chapter.

Magnetic Sliding Collar Device

- Small-scale laboratory tests of the magnetic sliding collar device indicate that the driven rod does not appreciably enhance or reduce scour at a pier, but the sliding collar must be carefully designed to prevent mechanical sticking or jamming.
- Near-prototype laboratory tests indicate that the driven rod configuration can function successfully with various collar position sensors, including mercury tip switches, magnetic trip switches, and piezoelectric film strips.
- A manual-readout magnetic sliding collar offers the simplest configuration for this type of device. Because the collar position is determined manually, no sensors on the driven rod are necessary. Field testing indicates that this device can successfully track scour events under various geomorphic conditions on bridge piers with varied geometry on both riverine and tidal bridges and meets all mandatory criteria and most desirable criteria.
- Although ice and debris impact can damage the simple magnetic sliding collar device, instruments installed at bridge piers in Colorado, New Mexico, Michigan, Minnesota, New York, and Texas proved the survivability of this device under severe environmental conditions.
- Field installations of automated magnetic sliding collar devices at a riverine bridge abutment and tidal bridge pier demonstrated the viability of this more sophisticated instrument system. This device is not as vulnerable as the manual-readout instrument to potential damage by ice and debris and, except for smaller bridges and the simplest installations, the automated sliding collar configuration is the preferred installation mode for this instrument system.
- An automated magnetic sliding collar device was successfully installed on a sloping abutment and was adapted to demonstrate a successful cellular phone

link between the field test site and a base station 64 km (40 mi) away.

- Field experience and post-installation questionnaires indicate that state highway agencies consider the manual-readout sliding collar device simple in design, easy to assemble, and simple to operate. The instrument is adaptable to various field conditions and can be installed with equipment and skills normally available at the District level of a highway agency. Agencies involved in initial installations indicated a need for better driving techniques for the rod.
- Manual and pneumatic fence post drivers and pneumatic jackhammers were used to successfully install small-diameter driven rods in the field. The depth of installation may be limited by skin friction, cohesive layers, or rock. Exploratory driving with a small-diameter expendable rod provides a useful technique where buried rock or riprap may be present. Simple water jetting or augering techniques could extend the range of conditions under which pneumatic driving will be successful.
- As a refinement to the standard magnetic sliding collar, a split-ring or clamshell sliding collar provides flexibility in field installation and the option to track a second scour episode after the first collar has been buried.

Low-Cost Sonic Fathometer Systems

- Laboratory testing of low-cost sonic systems indicated that the fathometer must be mounted so the transducer is aimed at the location where maximum scour is expected to occur. For low-cost instruments, the fathometer must be mounted a specified minimum distance from the bed, normally 0.6 to 0.9 m (2 to 3 ft), to obtain a reading.
- The signal must not be obscured by ice or debris. Loss of signal because of entrainment of air in the flow, which was encountered in the outdoor near-prototype flume tests, should not be a problem at most bridge sites, unless separation of the flow occurs across the face of the transducer.
- Tests of sonic transducer performance under controlled conditions demonstrated that, for the instrument tested, the sonic cone "sees" the portion of the bed directly under the centerline of the cone. Mounting a sonic transducer to point parallel to a vertical wall abutment or pier should not interfere with the accuracy of the reading, but transducer performance deteriorates when the transducer is pointed into a vertical object or there is more than one path of reflection for the sonic cone.
- Temperature and salinity effects on the speed of sound should not be a concern at most installations within the established accuracy criteria ±0.3 m (1 ft) for the depth and temperature ranges expected at most riverine and tidal bridge sites.
- Low-cost sonic systems developed under this research proved to be both durable and reliable under a wide range of field testing situations. A system (consisting of fish-finder-type sonar, a datalogger/interface, and a solar panel), which can be mounted in a bridge-deck-serviceable configuration, met all established mandatory criteria and most desirable criteria.
- System design proved adaptable to various geomorphic and hydraulic conditions on bridges having varied geometry. Short-term scour episodes and long-term scour trends at riverine and tidal sites were monitored.
- Although the instrument can survive impact from ice and debris, interference with the sonic transducer by ice or debris can degrade instrument performance or completely obstruct the signal. Except for problems with debris, low-cost sonic systems performed well at riverine test sites in Colorado, New Mexico, New York, and Texas, and at a deep tidal inlet in Florida.
- High turbidity or sediment in transport did not interfere with sonic system performance at field test sites for this project; however, problems with turbidity have been reported by others (*27*).
- Low-cost sonic systems were successfully installed by the USGS and state highway agencies with equipment and skills normally available at the District level of a highway agency.
- A workable configuration for installing a low-cost sonic system on a sloping bridge abutment was developed and installed at a riverine bridge site. Successful operation required frequent removal of an accumulation of grass and weedy debris. Alternative concepts for abutment installations are presented in Chapter 3.

CHAPTER 3

INTERPRETATION, APPRAISAL, APPLICATION

OVERVIEW

This chapter presents interpretation, appraisal, and applications for scour monitoring instruments tested under this project. Although all instruments tested are discussed, Chapter 3 concentrates on the two instruments considered to be fully operational: (1) a magnetic sliding collar (driven rod) device and (2) a low-cost sonic system. Applications-related information for these instruments include warning and monitoring functions, placement and installation concepts, datalogging, wireless (underwater) transmission of data, and telemetry. The next section presents basic scour concepts, because an understanding of these concepts is essential to the interpretation, appraisal, and application of the findings from laboratory and field testing of scour monitoring instrumentation.

BRIDGE SCOUR CONCEPTS

Scour is the result of the action of flowing water excavating and carrying away material from the beds and banks of streams. Different materials scour at different rates—loose granular soils are rapidly eroded by flowing water; cohesive or cemented soils are more scour-resistant. However, ultimate scour in cohesive or cemented soils can be as deep as scour in sandbed streams. Scour will reach its maximum depth in sand and gravel bed materials in hours; cohesive bed materials in days; glacial tills, sand stones, and shales in months; limestones in years, and dense granites in centuries (*41*).

Total scour at a highway crossing has three components as follows:

1. **Aggradation and Degradation**. These are long-term streambed elevation changes, resulting from natural or man-induced causes within the reach of the river on which the bridge is located. Aggradation is the deposition of material eroded from other sections of a stream reach; degradation is the lowering or scouring of the streambed.
2. **Contraction Scour**. Contraction scour in a natural channel involves the removal of material from the bed and banks across all or most of the channel width. This component of scour results from a contraction of the flow, such as a natural constriction of the bridge reach or constriction caused by bridge substructure elements. Scour is caused by increased velocities and a resulting increase in bed shear stresses. Contraction of the flow by bridge approach embankments encroaching onto the floodplain is a common cause of significant contraction scour.
3. **Local Scour**. Local scour involves removal of material from around piers, abutments, spurs, and embankments. It is caused by an acceleration of flow and resulting vortices induced by the flow obstructions.

In addition to the types of scour mentioned above, naturally occurring lateral migration of a stream may erode the approach roadway or change the total scour by changing the flow angle of attack. Factors that affect lateral movement also affect the stability of a bridge. These factors are the geomorphology of the stream, location of the crossing on the stream, flood characteristics, and the characteristics of the bed and bank materials (*42*).

The failure of the U.S. Highway 51 Hatchie River bridge near Covington, TN, on April 1, 1989, cost eight lives. This failure has been attributed to a combination of lateral shifting of the stream channel in the bridge reach (induced by contraction of the flow) and local scour at bridge piers that had originally been on the floodplain (*43, 44*). The failure of the New York State Thruway bridge over Schoharie Creek on April 5, 1987, which cost 10 lives, has been attributed directly to local scour at the bridge piers (*45*).

A scour measuring device at a bridge pier or abutment would measure the net effect of long-term aggradation or degradation, contraction scour, and local scour. Total scour is assumed to be the sum of these factors. Local scour depths are generally much larger than either long-term degradation or contraction scour depths; therefore, local scour effects are the focus of a scour measuring/monitoring program.

The basic mechanism causing local scour at a pier or abutment is the formation of vortices at their base (see Figure 72). The formation of these vortices results from the pileup of water on the upstream surface and subsequent acceleration of the flow around the nose of the pier or embankment.

The action of the vortex removes bed material from the base region. With the transport rate of sediment away from the base region greater than the transport rate into the region,

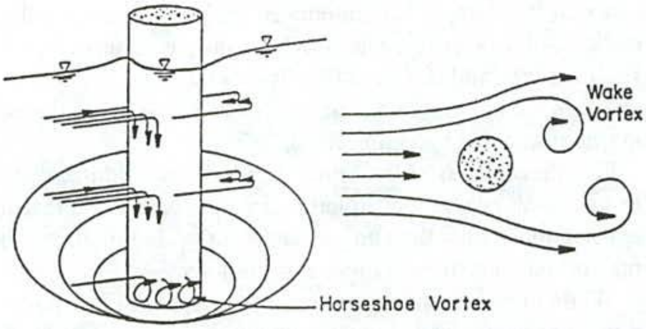


Figure 72. Schematic representation of scour at a cylindrical pier.

a scour hole develops. As the depth of scour increases, the strength of the vortices is reduced, thereby reducing the transport rate from the base region, and eventually equilibrium is reestablished and scouring ceases.

In addition to a horseshoe vortex around the base of a pier, there is a vertical vortex downstream of the pier called the wake vortex (see Figure 72). Both vortices remove material from the pier base region. However, the intensity of these wake vortices diminishes rapidly as the distance downstream of the pier increases. Therefore, immediately downstream of a long pier, there is often deposition of material.

Factors affecting local scour are width of the pier, projected length of an abutment into the flow, length of the pier if skewed to flow, depth of flow, velocity of the approach flow, size and gradation of bed material, angle of attack of the approach flow to a pier or abutment, shape of a pier or abutment, bed configuration, ice formation or jams, and debris.

The temporal change of the configuration of a scour hole at a bridge pier or abutment also presents complications in measuring or monitoring the maximum depth of scour. As shown in Figure 73, a scour hole forms and increases in size and depth as flow increases during a runoff event. The scour hole generally reaches its maximum depth near the peak of a flood hydrograph and then partially refills during the recession of flow from the peak. Thus, post-flood measurements of the bed surface in the scour hole will not reveal the maximum depth of scour nor be indicative of the maximum threat to the integrity of the bridge foundation.

Figure 74 shows the maximum depth of scour developed in the 1:50 scale model of the Schoharie Creek bridge at Colorado State University. Physical modeling of the local scour process was integral to the investigation of the Schoharie Creek bridge failure for the National Transportation Safety Board (*45*). Figure 75 shows the extent of the scour hole at Pier 2 as observed in the field following the failure of the Schoharie Creek bridge. Using currently available equations, maximum local scour depth at the bridge was calculated as 7 m (23 ft). The maximum depth of the scour hole as measured from the 1:50 scale model (Figure 74) was 4.3 m (14 ft), and the maximum depth measured in the field was 4.6 m (15 ft). Scour monitoring and measuring devices must be capable of detecting maximum depth of scour of this magnitude under the adverse and complex conditions that exist at a bridge pier or abutment during a flood event.

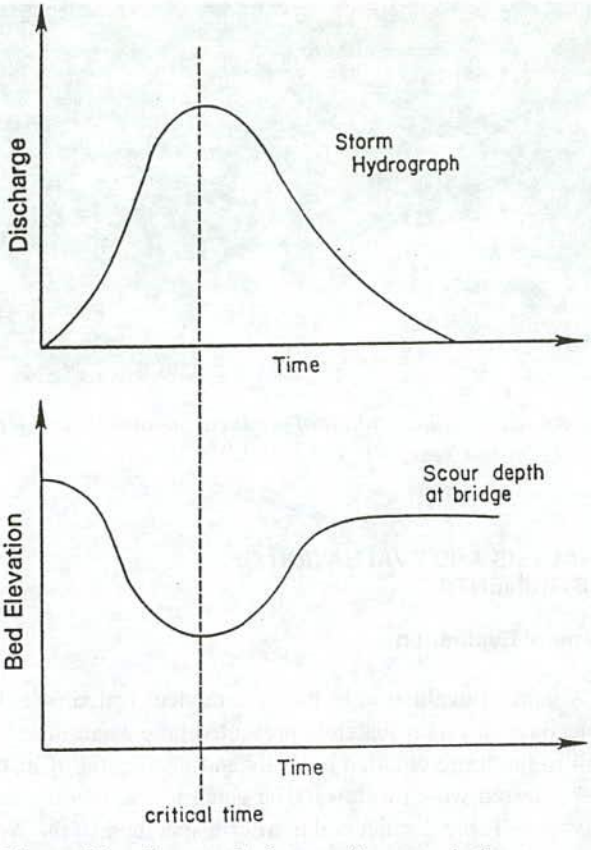


Figure 73. Temporal change of a scour hole at a bridge pier or abutment.

Figure 74. Schoharie Creek Pier 3 from the right bank showing the scour hole in the dry channel for 1987 flood conditions.

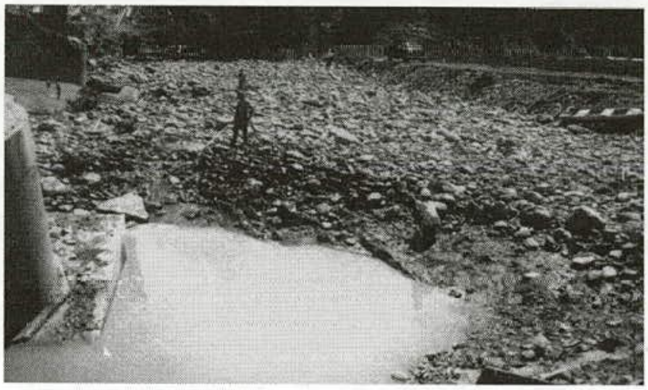


Figure 75. Configuration of the local scour hole at Pier 2, Schoharie Creek, NY, 1987.

ANALYSIS AND EVALUATION OF INSTRUMENTS

General Evaluation

A general evaluation of how the devices tested meet the objectives of this research is presented here as an introduction to the more detailed analysis and evaluation of instruments tested which follows. The general evaluation matrix shown in Table 2 reflects the criteria specified in the work plan as follows:

- Primary Criteria (Mandatory):
  - —Item 1. Capability for installation on or near a bridge pier or abutment,
  - —Item 2. Ability to measure maximum depth of scour within an accuracy of ± 0.3 m (1 ft),
  - —Item 3. Ability to obtain scour depth readings from above the water or from a remote site,
  - —Item 4. Operable during storm and flood conditions
- Secondary Criteria (Desirable):
  - —Item 5. Capability for and ease of installation both on most existing bridges and/or during construction of new bridges,
  - —Item 6. Capability to operate in a range of flow conditions,
  - —Item 7. Capability to withstand ice and debris,
  - —Item 8. Relatively low cost,
  - —Item 9. Vandal resistant,
  - —Item 10. Operable and maintainable by highway maintenance personnel.
- Additional criteria:
  - —Item 11. Reliability, and
  - —Item 12. Operable when subsurface or foundation conditions are not known.

Table 2 also summarizes the results of research on the three instrument systems that have been the focus of this research (the simple and automated magnetic sliding collar devices, a low cost sonar device, and the piezoelectric sensor-driven rod device). The Brisco Monitor, which was tested in the laboratory and at one field site, is also included in this summary (Sounding Rod).

The piezoelectric film device has had only limited field testing and evaluations relative to this device represent expectations rather than proven capabilities. Future research may or may not support these expectations.

While Item 1 (mandatory) rated the *capability* for installation on or near a bridge pier or abutment, Item 5 (desirable) evaluated the *ease* of installation. For instance, a device may be capable of being installed and can be rated high under Item 1, but if the device is difficult to install it would rate low under Item 5. Moreover, a device that would be easy to install on *both* existing and new bridges would rate higher under Item 5 than one that could be easily installed on *only* a new bridge.

The appraisal of Item 8 (desirable) was arbitrary and was based on the estimated cost of procurement, but not installation costs. For purposes here, costs under $2,000 were rated good and costs over $20,000 were rated as poor. In practice, costs need to be evaluated relative to the cost of the structure or relative to the cost of failure of the structure (see the cost evaluation section in this chapter).

A significant number of bridges exist in the United States for which bridge plans are not available (i.e., the foundation and soil properties are unknown). Item 12 evaluates the ability of the device to perform successfully and provide scour data where foundation and soil conditions are unknown. Specifically, this criterion rates as less desirable those devices requiring a particular pier or foundation geometry for installation or requiring detailed knowledge of soil and substrate conditions underlying the bridge. **A device that could provide additional information on the below-ground structural foundation of the bridge would be highly desirable, but none of the devices tested has this capability.**

The first mandatory criterion, which considers capability of installation at piers and abutments, was divided into four subdivisions to better represent the range of pier and abutment geometries at typical bridges and to highlight the problems associated with installing sonic fathometers and sounding rods on nonvertical piers and abutments. The third mandatory criterion was subdivided so that the ability to obtain scour data and to log and transmit these data could be considered separately.

The mandatory criteria evaluation matrix presented is a synthesis of all the information gathered and analyzed during the course of this project. Consequently, the reasoning associated with the classification of good, fair, poor, or unknown reflects the findings reported in Chapter 2 and the evaluation and analysis presented in this chapter.

The evaluation matrix for the desirable criteria is also presented in Table 2. Criterion 7, which considers debris and ice, was subdivided into whether the device could survive debris and ice buildup and could continue to measure scour depths with debris and ice loadings.

As with mandatory criteria, the evaluation matrix for the desirable criteria presented in Table 2 is a synthesis of all the information gathered and analyzed during the course of this project. Again, the reasoning associated with the classification of good, fair, poor, or unknown reflects findings reported in Chapter 2 and the evaluation and analysis presented in this chapter. The reader is referred to these sections in this document for clarification of the determinations presented in the desirable criteria evaluation matrix.

In the following sections, each instrument tested is evaluated in relation to specific factors that affect installation and operation.

Sounding Rods

Hydraulic and Hydrodynamic Factors

Before testing sounding rod devices in the indoor or outdoor laboratory, there was concern as to whether or not vortex shedding around the sounding rod would cause the rod to vibrate. Such vibration could cause the rod to work down into the bed. Although tests without an enlarged baseplate indicated that the rod would penetrate the bed, this was not attributed to vibration or vortex shedding. High velocities at actual field installations where long sections of rod are exposed to the flow could induce vibration of the sounding rod.

Cayuga Industries, which manufactures the Brisco sounding rod, indicated that the early models of the Brisco Monitor tended to rotate at some sites. This rotation was probably caused by the fluid forces of the flowing water. As a result, this rotation tended to twist and kink the cable connected to the sounding rod and data box. Because of this problem, Brisco Monitors are supplied with a swivel connection which attaches the cable to the sounding rod.

Although no rotation of the sounding rod was noted during the indoor or outdoor laboratory tests conducted for this research, the rotation of the rod in a field situation could enable the rod to penetrate the bed more easily, because of the drilling action of a rotating shaft. A final hydrodynamic concern relates to the potential for bending of the sounding rod because of hydrodynamic drag on the rod when it is extended substantially from the guide sleeve of the support pipe. The bending could be severe enough to push the sounding rod back to the point where it rubs or binds on the adjacent footing, pier, or abutment. During field testing of prototype instruments provided by Cayuga Industries, the entire rod and cable assembly was extracted from the guide sleeve by scour.

Operating Conditions/Ranges

The operating range of the instrument depends on the length of the sounding rod used at any particular installation. For the 2.4-m (8-ft)-long rod tested in this study, it is anticipated that the rod can withstand up to 1.5 to 1.8 m (5 to 6 ft) of scour before it is extended to the point where the support pipe cannot align or guide the sounding rod. The range to which the Brisco Monitor can provide data is also determined by the length of cable which can be wrapped around the spool in the data box.

The sounding rod class of devices should not be adversely affected by temperature because they are mechanical devices which have no sophisticated electronics. Temperature concerns for this class of devices, center primarily on the ability of the datalogging system to withstand variability in daily and seasonal temperature fluctuations.

Temperature could have an indirect influence on the functioning of the sounding rod in regard to ice and ice buildup. Although the device as it was tested is well armored and protected from ice impact, the formation of ice between the support and sounding rods could bind the shaft.

The angle iron on the leading edge of the Brisco Monitor will protect the device from floating debris impact. It is not known to what degree submerged debris or impact of large debris may affect the operation of the rod itself. Furthermore, it is not known whether or to what degree suspended sediment would have an adverse impact on the operation of sounding rod devices, although some binding was noted during the small-scale laboratory tests and some sediment accumulation between the rod and sleeve was experienced during the field testing program.

The sounding rod—composed of very durable, heavy-gage steel—will probably be fairly vandal-resistant. However, the data box must be installed in a durable vandal-resistant enclosure and securely anchored.

Geotechnical Factors

From the laboratory investigations, it is clear that rod penetration of the bed is a significant concern when this device is used in sand- and noncohesive bed materials. It appears that bed penetration depends primarily on the bearing stress which the soil must withstand to support the sounding rod. This geotechnical problem with sounding rod devices can be corrected by adding a footplate. Sizing of the footplate will depend on the weight of the sounding rod and the maximum bearing stress that the bed material can withstand without failure (i.e., penetration by the rod). At the field test site for this instrument, this problem was resolved by reducing the bearing stress of the sounding rod on sandbeds to approximately 2.96 kPa (620 psf). The sounding rod class of devices can be used on perennial or ephemeral streams with a wide variety of streambed types, provided the footplate is sized to avoid bed penetration. Successful installations have been reported on coarse-bed streams by the manufacturer and USGS.

TABLE 2 Comparison of Devices Tested With Mandatory and Desirable Criteria

	Mandatory Criteria								Desirable Criteria								
	1a	1b	1c	1d	2	3a	3b	4	5	6	7a	7b	8	9	10	11	12
Device	Install on or near Vert. Pier	Install on or near Sloping Piers or Piers w/Footings	Install on or near Vert. Abut.	Install on or near Spill-thru Abut.	Measure Scour to ± 1'	Read from Above Water Line	Remote Data Collection	Operable During Floods	Ease of Installation	Range of Discharges	Withstand Ice and Surface Debris Impact	Obtain Scour Data with Ice/Debris	Low Cost	Vandal Resistant	Operation and Maintenance	Reliability	Unknown Foundation or Sub-Surface Condition
Sounding Rod	G	F	G	P	G	G	P	G	F	G	G	F	F	F	G	P	F
Sliding Collar																	
Manual	G	G	G	P	G	G	NA	G	G	G	F	F	G	G	G	G	F
Automated	G	G	G	G	G	G	G	G	G	G	G	G	G	F	G	G	F
Low-Cost Sonar	G	G	G	F	G	G	G	G	G	G	G	P	G	F	G	G	G
Piezo Electric Driven Rod	G	G	G	U	G	G	G	G	U	G	G	G	U	F	U	U	F

G = Good
F = Fair
P = Poor
U = Unknown at present
NA = Not Applicable

- Mandatory Criterion 1b—The sounding rod was rated fair because this class of devices is not recommended categorically for all piers with spread footings or sloping piers.
- Mandatory Criterion 1d:
    - — A sounding rod when placed on an angle on spill-through abutments will not measure maximum scour.
    - — A manual-readout magnetic sliding collar would be difficult to use on a spill-through abutment without special mounting arrangements.
    - — A sonic sounder may be difficult to use on spill-through abutments without special mounting arrangements.
- Mandatory Criterion 3b—As tested, the sounding rod had serious data collection problems. The manufacturer indicates that these problems have been resolved.
- Desirable Criterion 5—The sounding rod tested was heavy and required special equipment for installation (winch or crane).
- Desirable Criterion 7a—The connecting conduit to the bridge deck for the manual-readout device can be vulnerable to ice and debris impact. Debris impact damaged several manual-readout sliding collar devices during field testing.

- Desirable Criterion 7b:
  - Because ice could bind the rod, item 7b for sounding rod devices was rated fair.
  - Because ice or debris could affect the connecting conduit of the manual-readout sliding collar, item 7b was rated fair.
  - Because ice and debris may block the signal for sonic fathometers, item 7b was rated as poor. Debris problems were experienced at several field test sites.
- Desirable Criterion 8—Basic equipment costs (not including installation) less than $2,500 were categorized as good for item 8. Equipment costs less than $5,000 for devices with datalogging were categorized as good.
- Desirable Criterion 9—Although all of the devices can be installed to be vandal-resistant, only those devices which can be buried and do not require a datalogger, were classified as good. Vandalism to solar panels and an instrument box were experienced at several test sites.
- Desirable Criterion 10—Sonic fathometers were rated as good for bridge-deck-serviceable configuration but would be rated fair for transducers which are not serviceable above water.
- Desirable Criterion 11:
  - The sounding rod as tested was not considered reliable, primarily because of datalogger problems.
  - The low-cost sonic fathometer instrument itself proved to be very reliable during field testing, but for the sonic system, reliability is poor on debris-prone streams.
- Desirable Criterion 12
  - Information on a buried pile cap or spread footer would be required for proper operation of a sounding rod.
  - The installation of driven rod devices is difficult where rock, buried debris or resistant layers are encountered. Pre-driving an expendable solid rod can alleviate this problem.

Datalogging and Telemetry

A data box for the Brisco Monitor was also provided by Cayuga Industries of Schenectady, NY. A cable connected to the sounding rod extends up into the data box and is wound around a spool. As the sounding rod descends, the spool turns a shaft encoder, which produces an electronic pulse at fixed increments of angular rotation of the spool. By counting pulses and computing the length of cable unwound, data are displayed in inches on an LCD.

As noted in the findings, the electronics used to sense and record pulse counts from the Brisco Monitor sounding rod did not correlate with the actual movement of the sounding rod. This problem was difficult to isolate, but it is believed that it may have been the result of two independent problems with the method and equipment used to obtain and record pulse counts from the sounding rod. The first problem was associated with static electrical noise from the transmission wire between the pulse counter and datalogger. The second problem is believed to be associated with the pulse counter itself.

Data from the pulse counter on the sounding rod were transmitted to the datalogger through approximately 12.2 m (40 ft) of unshielded cable, which was attached to the deck beam on the upstream face of the bridge. This long length of exposed, unshielded cable may have acted as an antenna, transmitting static voltage to the datalogger. At best, this problem resulted in false pulse counts being recorded by the datalogger. At worst, the input channel to the datalogger from the sounding rod could burn out because of voltage spikes. The input channel of the device at the Colorado test site was repaired several times over the course of the field season. Various attempts to ground the cable and provide for isolation of the interface to the datalogger proved unsuccessful.

The pulse counter which was supplied with the Brisco Monitor sounding rod generates a pulse whenever one of the equally spaced magnets attached to the shaft of the cable reel is moved in proximity to a detector switch. Because of this, multiple pulses can be generated from a single magnet because of vibration caused by traffic on the bridge without any progressive rotation of the cable reel. It is believed that most of the errant pulse counts observed in the data record were attributable to vibration caused by passing traffic (see summary discussion below).

Installation

Mechanical sounding rod devices such as the devices tested in this research program are heavy by virtue of their design and function. The short 2.4-m (8-ft) Brisco Monitor, which was used for the near-prototype and limited field tests, weighed approximately 136 kg (300 lb) and had to be installed in the outdoor flume with a small crane. Heavy equipment is necessary in order to install these devices in the field.

Installation can be accomplished from the bridge deck using either a scaffold or an inspection and maintenance crane. A crane or other heavy lifting equipment will be required to position the device for mounting. Experience gained from the limited field testing indicates that the installation is easier with installers working from the streambed below, although this is not always possible. For perennial streams, a barge or raft may aid in the installation of this class of devices.

This class of devices must be mounted to a fixed structure such as a bridge pier or abutment. The device needs to be mounted vertically (or at least near vertically) over the location where maximum scour is expected in order to ensure that the device measures the maximum depth of scour. To measure maximum scour depths and avoid binding, mounting the sounding rod so that it will extend through a footing is not recommended.

Another installation problem concerns bridge piers with footings or pile caps which extend in front of the piers. In some cases, where the footing extends a minimal distance, the device can be mounted by extending the mounting hardware from the pier to the device so that the device is positioned beyond the footing or pile cap. Alternatively, the device could be mounted on an angle, provided that the angle was small, so that the correction for the angle is minimal and the end of the sounding rod could be oriented so that it measures maximum scour for the full range of sounding rod movement. For larger angles, such as on a sloping abutment, the base of the sounding rod will move away from the location of minimum scour as scour progresses.

For larger footings which extend further upstream from the bridge pier, or for sloping piers and abutments, the use of the vertical sounding rod becomes impractical because the mounting hardware must be cantilevered to maintain a vertical or near-vertical orientation. It may be difficult to design the mounting with adequate strength, given the weight of these devices and the susceptibility of the device to debris impact and hydrodynamic forces when the mounting and device extend away from the pier or abutment.

It is not recommended that the device be mounted so that the sounding rod slides through a hole drilled in a footing or pile cap. This arrangement positions the sounding rod at a location other than the point of maximum scour and is prone to sticking from sediment. Furthermore, it would be very difficult to mount the device with a footplate in this fashion without drilling a large, oversized hole through the footing.

Summary Evaluation—Sounding Rods

The sounding rod class of device, as represented by the Cayuga Industries Brisco Monitor, is strong, durable, simple, and can be used to measure scour at a wide variety of vertical and near-vertical bridge piers and abutments. Datalogging can be easily accomplished, but currently available dataloggers have encountered problems.

Datalogger problems were also reported by the Iowa DOT where the performance of two Brisco Monitors installed on a bridge over the Mississippi River at Burlington, IA, was evaluated *(40)*. Persistent problems with the electronic readouts from both of these sounding rods was cited. Specifically, Iowa DOT noted problems with the electronics failing, presumably during electrical storms, and Iowa DOT personnel noted that when the electronics were working, the digital readouts for these two instruments would register "extremely large numbers" which were obviously in error.

Comparison of the Iowa and Orchard site data indicate that all three installations of this device had similar problems with very large erroneous data readings and electronic failure. Given that these data were independently obtained and that the Iowa data were from an installation by the manufacturer, it is apparent that fundamental problems existed with the cable reel, pulse counter, and associated electronics of these commercially available instruments. The basic concept of using a sounding rod-type device is sound, and successful instrument performance has been reported on coarse-bed material streams. The manufacturer has indicated that the data retrieval and storage systems for the Brisco Monitor have been improved.

Magnetic Sliding Collar Device

Hydraulic and Hydrodynamic Factors

The driven rod which supports this class of device must be strong and durable to withstand hydraulic forces, including debris and ice impact. In the automated sliding collar device, the rod must be watertight and large enough to protect the sensors and electronics from flow conditions which could cause damage. A competing concern is to minimize the size of the support rod so that it can be easily installed and so that the presence of the rod does not enhance scour. The original concept of 1.5-m (5-ft) pipe sections joined by a special union has been superseded by the use of a continuous section of pipe cut to the desired length. This eliminates the possibility of leakage at the unions and the expense of specially fabricated fittings.

The automated sliding collar device permits the driven rod to be installed with the top of the support rod flush or slightly above the ground or bed surface. Data from the sensors can be transmitted either through electronic cables buried below the streambed, or alternatively via a radio transmitter-receiver system (see findings and discussion on wireless transmission of data). This concept minimizes the cross section presented to the flow and, therefore, minimizes hydrodynamic forces on the driven rod supporting the sensors, as well as the potential for debris and ice impact.

The sliding collar must be heavy enough so that hydrodynamic lift forces will not suspend the collar, and the design of the collar must be rugged enough to withstand hydraulic forces, including impact from ice and debris. The open cross section of the collar tested for this project tends to minimize hydraulic forces on the falling collar because it presents a minimal cross section to the flow. The collar is also designed with point contacts on the support rod to reduce the potential for jamming with sediment or sticking.

Debris impact either destroyed or rendered the manual-readout sliding collar devices inoperable at 2 of 11 field test sites. Site CO1 on the South Platte River in Colorado is typical of field test experience. At this site, debris impact during a February flood caused damage to the support rod of the magnetic sliding collar. This resulted in a bent support rod, but the ability to locate the magnetic collar with the probe was not compromised and the instrument detected 1.42 m (4.7 ft) of scour during the flood event. Although the magnetic sliding collar device can withstand some bending without losing the ability to monitor scour, it is necessary to protect those portions of the support rod which extend above the streambed from damage from ice and debris. Whenever possible, the rod and any extension conduit should be placed firmly against the bridge substructure and securely anchored.

Operating Conditions/Ranges

Temperature has little or no influence on the effectiveness of the sliding collar and driven rod, except for the extreme condition of a totally frozen shallow stream. However, temperature will be a factor in maintaining battery life for the datalogger responsible for interrogating the sensors of the automated-readout device.

Sediment transported in suspension should not adversely affect the sliding collar, provided the collar allows the flow to flush transported sediments through an open architecture similar to the sliding collar tested. A larger concern is the transport of large contact loads such as gravel and cobbles. These transported sediments could damage the sliding collar and it may not be advisable to use the sliding collar on streams which transport large bed material.

When the driven rod is installed at or just above the bed surface, as with the automated device, floating debris should not have an adverse effect on the instrument; however, submerged debris in the scour hole could snag on and inhibit the free sliding of the collar.

On the basis of extensive field trials, the durability of the sliding collar driven rod device is good, particularly for the automated device when installed so that the top of the rod is at or slightly above the bed surface. This minimizes forces from the flow and impact from transported sediment and debris. This also discourages vandals, in that the driven rod would be mostly out of sight. However, buried electrical cables are susceptible to debris and vandals if they are excavated and exposed. Data boxes and solar panels can be made vandal-resistant, but not vandal-proof.

Geotechnical Factors

Geotechnical factors influence the methods and techniques required to install any device requiring a driven rod. If the soils at the site have a low blow count, it may be possible to drive the device into the bed with a manual or pneumatic fence post driver. For soils which are primarily fine-grained, noncohesive materials, jetting techniques may be applicable. For cohesive soils, a pneumatic jackhammer, hollow-stem augering, or predrilling and driving may be necessary. Cohesive soils could also stick to the support rod and could inhibit the free sliding of the collar. Where possible, site-specific geotechnical investigations should be conducted to document the engineering properties of the soil before installation of this class of devices.

Installation of a driven rod device could be incorporated into a drilling program to determine geotechnical conditions at a site. The opportunity to place a driven rod in a geotechnical investigation borehole once the core is removed offers an interesting avenue for investigation which was not pursued beyond the conceptual stage in this research.

Datalogging and Telemetry

The manual-readout sliding collar device has no datalogging capability. For the automated sliding collar, the datalogging requirements are similar to the sonic device. These are discussed in the Datalogging and Telemetry section of Chapter 2. For the automated sliding collar, the possibility of underwater transmission of data to a datalogger on or near the bridge could significantly reduce the vulnerability of the automated sliding collar to damage by ice or debris. The results of an underwater wireless transmission test are presented in Chapter 2 and discussed in the Datalogging and Telemetry section below. An automated sliding collar instrument was used to demonstrate telemetering of scour data via cellular phone (see Chapter 2).

Installation

For new or replacement structures, it should be possible to install driven rod devices during construction. Installation for large perennial rivers can be accomplished while the construction coffer dam is in place and the location where the device is to be installed has been excavated.

It is apparent that the impact forces associated with driving could be damaging to the electrical connections and sensors incorporated into the support rod for the automated sliding collar. However, this device was successfully driven into a sandbed at a tidal site (Site FL2) and into a coarser riverbed (Site CO2) without damage to the sensors. Several alternative installation techniques could also be considered.

One alternative would be to jet the device into the ground. In discussions with geotechnical engineers, this technique is possible, albeit for a limited range of conditions. Jetting is practical only in sand and fine-grained noncohesive materials. Jetting is not viable for cohesive materials or where there are large cobbles or boulders in the soil. Jetting technology is common in coastal delta regions of the southeastern United States. Another installation alternative would be to use hollow-stem augering techniques. This technology is generally available throughout the United States because it is used to install well casings and other groundwater and geotechnical instrumentation.

A drawback to hollow-stem augering is that the drill rigs used to install instrumentation must be able to drill from directly above the location where the device is to be installed. It is not possible to suspend the auger over the bridge or work in water depths greater than approximately 0.3 m (1 ft) with commonly available drill rigs. As such, this method of installation will be limited to ephemeral streams and overbank areas at abutments where the devices can be installed in the dry.

Finally, it may be possible to predrill a guide hole using a conventional drill rig, and then drive the device into the predrilled hole. By predrilling, the driving forces could be reduced to protect the sensors from damage.

Corrosion

Because the sliding collar devices require free movement between the collar and support rod for proper operation, corrosion, particularly at a tidal site, could be a problem. The material used for the driven rod support structures is Type 304L Schedule 40 stainless-steel pipe, 50.8 m (2 in.) in diameter. The sliding collar is fabricated from the same material. Type 304 is the most widely used of the austenitic chromium-nickel stainless steels. It is characterized by a very low carbon content and higher corrosion resistance than that found in other common stainless steels, such as Type 302. Type 304L has even lower carbon content than Type 304, which results in minimal carbide precipitation when welding. The lower carbide content results in less susceptibility to intergranular corrosion.

Type 304L stainless steel is highly resistant to the corrosive atmospheres of city, rural, and seaside locations and quite resistant to most organic acids. It is especially recommended for welding construction where severe corrosive conditions are encountered, as are found in the dairy, chemical, paper, and textile industries. In laboratory comparative analyses, Type 304L is rated "satisfactorily resistant to sea water." Corrosion problems were not experienced at any sliding collar test site for this project, including a tidal site and riverine sites that encompassed a wide range of environmental conditions.

Summary Evaluation—Magnetic Sliding Collar Device

The investigations into the driven rod class of devices indicate that this class of scour measuring devices is well suited to measuring scour at bridge piers and abutments. However, the installation methods and the design of the device in terms of withstanding installation forces and surviving operational conditions, require careful consideration for each site.

The field prototypes of a driven rod with a magnetic sliding collar met or exceeded the established mandatory criteria. The advantages of this device include the following:

- The instrument is corrosion resistant, allowing the instrument to be installed in tidal areas.
- The driven rod can normally be installed using common manual, vibratory, and mechanical techniques.
- Scour depths can be easily determined by inexperienced personnel.
- The manual-readout instrument can be upgraded to provide automated retrieval, storage, and telemetry of data.
- The instrument is easy to fabricate and ship.
- The manual-readout instrument can be installed in front of footers with an offset extension pipe routed up the pier or abutment to the bridge deck; the automated device does not need this conduit extension. This latter feature reduces, but does not eliminate, the vulnerability of the instrument to floating debris or ice. The device was tested more widely on piers, but proved to be adaptable to a sloping abutment configuration.

Additional abutment installation concepts are discussed below.

The magnetic sliding collar is relatively inexpensive, easy to install and operate, and can be upgraded to provide an automated readout capability. This instrument system can be readily adapted to small county and local bridges, where the need to monitor the bridge for scour competes with other needs for available financial resources. The magnetic sliding collar is also useful in the monitoring of scour for larger bridges because of the instrument's flexibility and potential to be upgraded; however, in larger or deeper rivers, the length of unsupported pipe for the manual-readout device will need to be carefully evaluated. Additional underwater-mounting brackets may be required to withstand hydrodynamic loading, vibration, and ice/debris impact. For larger rivers, assistance by divers will be required for installation of the automated device or a wireless transmission capable instrument. Although a sliding collar device cannot track the refill of a scour hole, it will register the maximum depth of scour for multiple events and a second collar can be installed to monitor subsequent events, if desired.

With the development of the automated sliding collar, the manual-readout device probably will be used only for smaller bridges and the simplest installations. The advantages of the automated-readout device (which is less prone to ice and debris damage) makes this the preferred installation mode, and it would be difficult to use a second collar on an automated device, except possibly on an ephemeral stream. A single collar will track the *maximum* depth of scour which was one of the mandatory criteria. The need to track scour episodes relates more to scour research requirements rather than monitoring, and the sonic system or a piezoelectric film device would be better suited to this application.

Low-Cost Sonic Fathometer

Hydraulic and Hydrodynamic Factors

It has been demonstrated by this research, and by others, that the presence of air bubbles in the water interferes with the sound wave transmission to and from the transducer. Croad (*46*) indicates that the damping of the sound waves is not particularly sensitive to the radius of air bubbles, but is sensitive to the concentration of air in the water. This damping prevents the transducer from receiving a clear signal and can result in the total loss of signal. This leads to two principal concerns for the use of sonic fathometers for measuring scour at piers and abutments.

First, if the flow is highly turbulent, as in the case of steep mountain streams or directly below drop structures, dams, or locks, it is unlikely that the sonic fathometer will be able to receive accurate and reliable return signals from the bed. Turbulence can also adversely affect the signal if the transducer is located in the lee of obstructions or in a zone where there is significant vortex shedding. Examples of these locations include, but are not limited to, the downstream faces of piers or downstream of sudden contractions or expansions of the flow.

Second, the design of the transducer mount must not produce flow separation at the transducer head. Therefore, the transducer must be angled slightly to the oncoming flow so that flow streamlines are maintained over the transducer head. The mounting head of the transducer should be streamlined to minimize flow separation.

From the results presented in this study and research published by others (*46*) there is no evidence that the velocity of the flow will adversely affect the signal return from sonic fathometers. However, if the flow velocities are accelerated in a manner which entrains air or causes flow separation, reliable depth readings may not be obtained.

Neither laboratory nor field installations for this project experienced loss of signal because of separation on the transducer face. The loss of signal experienced in the laboratory flume was because of air entrainment in the inlet box, not separation. Streamlined through-hull transducers for boats are designed to perform under high-speed conditions without separation. For the fixed sonic instrument, separation on the mounting brackets or bridge substructure itself could be a problem and should be avoided.

Others have reported that high turbidity and sediment in transport, particularly as a bed layer, can interfere with sonic sounders (*1, 27*), but that problem did not occur at any field test site under this research. Site NM2 (San Antonio bridge) on the Rio Grande was selected because of the historically high turbidity levels contributed by an upstream tributary, but debris, not turbidity, created the only problems encountered at this site.

Operating Conditions/Ranges

The speed of a sound wave in water is affected by water temperature and density. A study of temperature and salinity effects on the speed of sound indicates that these will not be a factor at most installations, within the limits established by the mandatory criteria ±0.3 m (1 ft) and for the depth and temperature ranges expected at most riverine and tidal bridge sites.

At the Johns Pass site (FL1) with a depth of 13.7 m (45 ft) and a seasonal temperature range of 13°C to 31°C (55°F to 88°F), the correction for temperature would increase depths by at least 0.46 m (1.5 ft). Figure 76 shows a first order correction to the plot of Figure 62 using an estimate of probable seasonal temperature change. The corrected data show a deeper inlet bottom and the seasonal fluctuations have leveled out, but a very large water depth and an extreme temperature variation were necessary to produce this amount of correction.

To obtain a reading, the sonic transducer face must be in the water. The low-cost sonic fathometer transducer generally must be placed no closer than 0.6 to 0.9 m (2 to 3 ft) to the streambed. Maximum sounding depth is essentially unlimited, considering depths normally encountered at most riverine or tidal bridge sites. The low-cost sonic fathometer performed well in 13.7 m (45 ft) of water at Johns Pass (Site FL1).

Floating debris will adversely affect the effectiveness of both the low-cost and more expensive fathometers. This is a physical constraint relating to where the transducers must be located to measure maximum scour and where the debris will likely build up. Buildup of debris on the nose of piers is a common problem. As debris becomes more water-logged, it

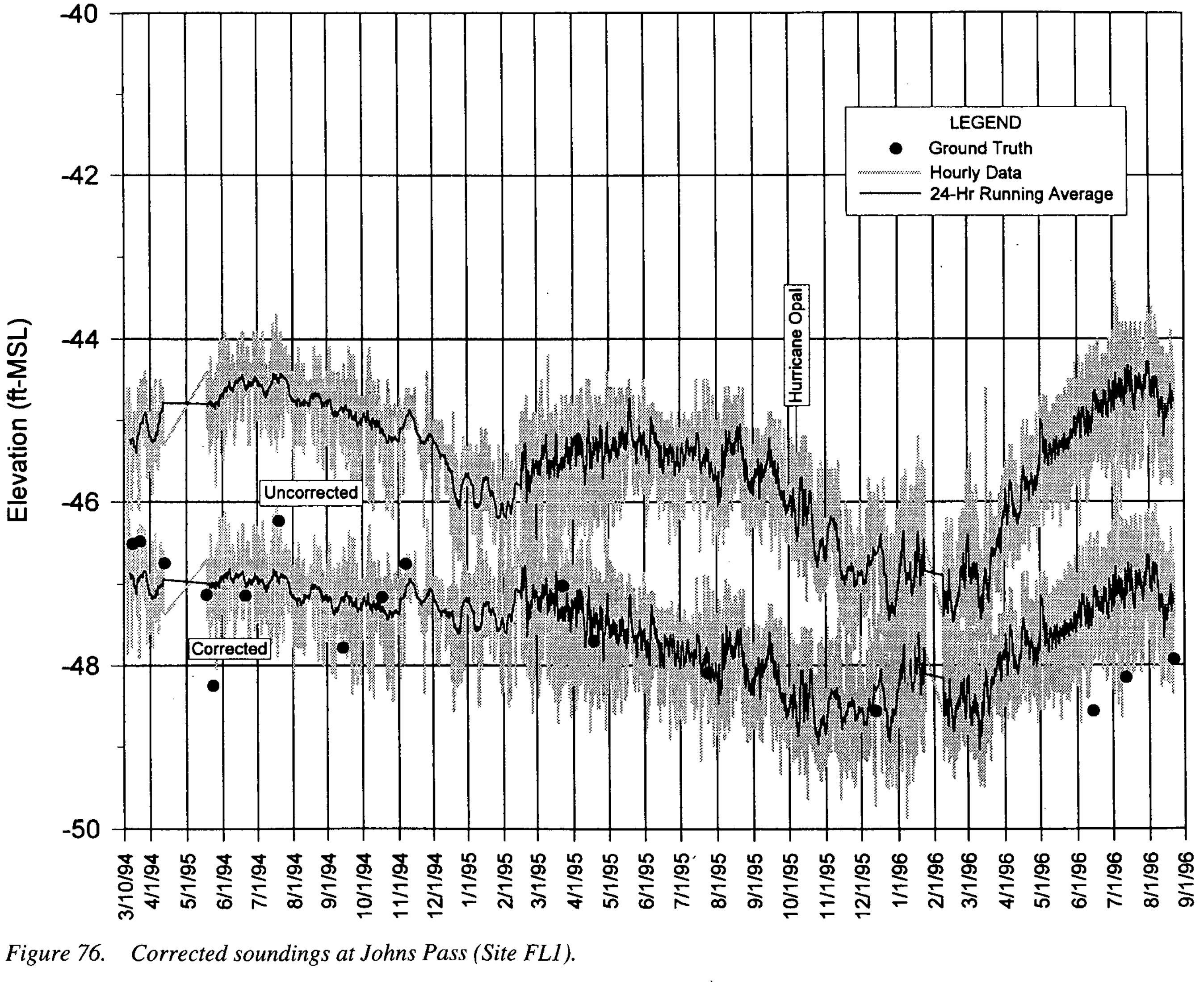


Figure 76. Corrected soundings at Johns Pass (Site FL1).

can sink or be pushed down on the pier nose. If the debris blocks the ability of the fathometer to sense the bed, the instrument will be rendered useless for measuring scour. For example, persistent accumulations of debris eventually rendered the sonic instrument at the San Antonio site inoperative (see Figures 55 and 56). Ice can cause the same problem—the transducer will be unable to sense the bed if the transducer is located above or in the ice block.

One strategy to counter the debris or ice problem is to locate the transducer as close to the bed of the stream as possible, out of the normal range of influence of debris or floating ice. For the bridge-deck-serviceable fathometer installations, this implies a longer support conduit and diver support for installation. This strategy was implemented at a low-cost sonar site in Texas installed under FHWA DP97, and the instrument functioned well until it was damaged by impact from a floating barge during a 1994 flood.

Another potential problem with this class of sensor is that the signal can be degraded by the accumulation on the transducer face of moss or other biologic organisms—this attenuates the sonic signal. To correct this problem, the transducer must be cleaned periodically so that accurate, reliable scour depth readings can be obtained. This can be accomplished as routine maintenance if the sonic instrument is installed in a bridge-deck-serviceable configuration. Experience from field test sites indicates that, for tidal environments, anti-fouling paint should be applied on installations to the transducer face and reapplied at least annually. Figure 63 shows the accumulation of barnacles on the transducer face at Johns Pass (Site FL1) after approximately 2 years of service. Even under these extreme conditions, the sonar instrument was able to obtain a reading occasionally.

The durability of this class of device depends primarily on the durability of the mounting hardware which holds the transducer to the pier or abutment. The mounting must be strong to withstand the impact forces of ice and debris, but streamlined so that flow separation cannot occur at the face of the instrument. The cabling to the electronics and data box must be protected from impact forces as well. Because all of the components to this device will be exposed, the transducer's electrical conduit and data box must be securely anchored, and the data box must be sufficiently armored to protect this class of device from vandalism.

Geotechnical Factors and Unknown Foundations

The strength of the return signal from the scour hole depends on the soils composing the bed of the river. Bedrock would be expected to return a strong reflection while a soft mud would be expected to attenuate the signal. The degree of signal scattering from the bed may be a concern. Sand or gravel can scatter the signal and return only a fraction of the incident signal back to the transducer. At the range of conditions encountered at field test sites for this project, which included sand-, cohesive-, and coarse-bed material, signal strength and scatter were not a problem. As noted above, others have reported erroneous readings where a moving layer of bed material in transport has interfered with instrument accuracy.

The low-cost sonic fathometers tested during this project do not have the capability to detect subsurface features and cannot be considered viable for sensing unknown foundations. As the scour hole progresses during an extreme flow event, it may be possible to identify exposed foundations and footers, although it will be difficult to identify these subsurface features without the ability to articulate the transducer mount and scan the scour hole.

Datalogging and Telemetry

If datalogging or telemetering were not required, low-cost fish-finder sonic fathometers, such as those tested during this study, could be used as purchased to provide scour data without datalogging. Without datalogging, these instruments would have to be monitored at the bridge site. Hard copy printouts of the time sequence of scour could be obtained using a fathometer equipped with a strip-chart recorder.

Datalogging and interface requirements for low-cost sonic fathometers are discussed in detail in the datalogging section of the findings (Chapter 2). Additional discussion of current state DOT capabilities for datalogging and telemetry is presented below.

Because manufacturers of sonic fathometers are continuously modifying their product line, no specific manufacturer or model number can be specified for interfacing with datalogging and storage equipment. Developers of sonic fathometer scour monitoring instrumentation using commercial low-cost fish-finders must be cognizant of the tendency for the specifications and capabilities of commercially available sonic fathometer systems to change.

Installation

An advantage of the sonic fathometer over other scour monitoring devices is that this device is not installed in or on the bed of the stream. Rather, for piers, sonic transducers can be mounted directly on the bridge pier and oriented so that they point directly at the bed where the maximum depth of scour is expected to occur. Installation can be accomplished from the bridge deck at low flow, using scaffolding or a truck-mounted bridge inspection and maintenance platform. The transducers can be mounted so that they are out of the water during low flow and submerged during runoff periods.

For vertical abutments, the sonic fathometers can be installed in a similar fashion as for piers. The transducers could also be suspended from a vertical support from the bridge deck so that they are oriented over the bed where scour could be expected at spill-through (sloping) abutments.

However, this mounting arrangement could be vulnerable to the forces of flood flow and debris. One approach to a sloping abutment installation was tested at field test site CO2 (see Figure 64). Other alternatives for abutment installations are discussed in the later section on Abutment Installation Concepts.

In the past, it was standard practice to mount the sonic transducer into a small durable steel encasement which was bolted to the pier of the bridge. A heavy-gage electrical conduit, approximately 25.4 to 50.8 mm (1 to 2 in.) in diameter, was routed from the transducer to the data box, which was located either on the bridge deck or streambank. With this method for mounting, the transducers were installed without the need for heavy lifting equipment; however, maintenance to clean the transducer head and check for damage required that maintenance personnel be lowered to the transducer mount. This usually required specialized equipment, such as scaffolds, bridge inspection and maintenance cranes, or the use of divers, rafts, or boats.

The alternative developed under this research project is to mount the transducer so that it can be serviced from the bridge deck. The mounting for the sonic transducer at the South Platte River bridge (Site CO1) is an example of a bridge-deck-serviceable transducer (see Figure 47). In this arrangement, the transducer is encased in a PVC "pig" (see Figure 48) which is pushed down through a 127-mm (5-in.)-diameter steel or PVC conduit. At the bottom of the conduit, the pig snaps into position so that it protrudes through a fitting located at the bottom of the support pipe. Thus, the transducer can be retrieved and serviced from the bridge deck.

The disadvantage of the bridge-deck-serviceable transducer mount is that the mounting hardware, (in this case, a 3.0-m [10-ft]-long piece of 127-mm [5-in.]-diameter electrical conduit) is heavy and may require the use of heavy equipment to suspend and position the mounting hardware so that it can be bolted into position. However, with this arrangement, subsequent servicing will not require the use of scaffolding, inspection cranes, or other specialized equipment. At sites where little or no debris (or ice) is anticipated, the heavy steel conduit can be replaced with PVC conduit, which can easily be mounted without heavy equipment (see Site FL1, Figure 60).

Summary Evaluation—Sonic Fathometers

Sonic fathometers for the measurement of scour at bridge piers and abutments for fixed installations are represented by two price ranges of equipment. The low-cost devices are represented by the Eagle and Lowrance fathometers, and the more expensive, moderate-cost devices by the Data Sonics fathometer. Both categories can be considered relatively inexpensive in comparison with the more sophisticated sonic devices, such as tuned transducers, color fathometers, and other devices identified during the literature search phases of this project.

Although the low-cost devices are limited in their capability and functionality compared with the more sophisticated moderate-cost sensors, extensive testing of low-cost instruments augmented with dataloggers and data processing software confirms that they can provide a level of capability and functionality comparable to the moderate-cost devices. Low-cost instruments installed under a wide range of conditions proved extremely reliable and durable and were able to meet the mandatory criteria and most of the desirable criteria established for this research.

The results of laboratory testing, field testing, and literature review indicate that the use of sonic fathometers to measure scour from a fixed installation may be limited by entrained air and, possibly, high concentrations of suspended sediment. Accumulations of floating debris that block the sonic transducer can render this instrument inoperative. It is expected that ice could have the same effect. In practical application, debris will be an ongoing problem for sonar instruments. Test results suggest that the transducer should be installed as close to the streambed as possible, yet, even then, submerged debris may make its way down to where it interferes with the sonar signal. Periodic maintenance is possible, but this is not very feasible from practical and/or economic considerations.

At tidal sites and some riverine sites, growth of marine organisms on the transducer face is to be expected. Periodic coating of the transducer with anti-fouling paint can control this problem.

Piezoelectric Film and Other Driven Rod Sensors

Hydraulic and Hydrodynamic Factors

As with any driven rod which supports sensors to monitor streambed level, the rod must be strong and durable to withstand hydraulic forces, including debris and ice impact. The rod must be watertight and large enough to adequately protect the sensors and electronics from flow conditions which could damage the sensors, but not so large that the presence of the rod creates or enhances scour.

To mitigate these concerns, the driven rod could be installed with the top of the support rod flush or slightly above the ground or bed surface. Data from the sensors can be transmitted either through electronic cables buried below the streambed, or alternatively via a radio transmitter-receiver system (see the findings and discussion on wireless transmission of data). This concept minimizes the cross section presented to the flow and, therefore, minimizes hydrodynamic forces and the potential for debris and ice impact on the driven rod supporting the sensors.

For this project, three types of sensors were tested in the outdoor flume on a driven rod: piezoelectric film, tip switches, and a sliding collar with magnetic switches. To obtain a signal from the piezoelectric film, the flow and turbulent velocities must be strong enough to flex the film and any protective coating or jacket encasing the film. As tested, the film was located in the lee of the driven rod, where the wake vortices buffeted the film. It is apparent that the encasement and length of the film projecting from the driven rod need to be carefully examined in regard to the flow velocities expected in the field. A stiff, or short piece of piezoelectric film may not be excited by the flow if the flow and turbulent velocities are low. Conversely, damage to the film could result if the film was too long and flexible and the velocity and turbulence were high.

The tip switches do not rely on the hydraulics of the flow to operate; therefore, there are no foreseeable hydraulic factors which would limit the applicability of this class of driven rod sensor. Likewise, the magnetic switches for the sliding collar are not directly influenced by the hydraulics of the flow. However, the sliding collar which activates the magnetic switches is influenced by the flow. A complete evaluation of the sliding collar is presented in a preceding section. Although the sliding collar/magnetic switch configuration performed satisfactorily in the laboratory flume, it was not tested in the field. This configuration was replaced by the manual and automated sliding collar devices and was not tested in the field. The tip switch configuration also performed adequately in the laboratory, but was not tested in the field under this research. Tip or tilt switches have been tested by others (*27*), but results of that testing have not been reported.

Operating Conditions/Ranges

Temperature should have little or no influence on the effectiveness of the three sensors tested on the driven rod, except for the extreme conditions of a totally frozen shallow stream. However, temperature will be a factor in maintaining battery life for the datalogger responsible for interrogating the sensors.

Sediment transported in suspension should not adversely affect the reliability of the three sensors tested. A larger concern is the transport of large contact loads, such as gravel and cobbles. These transported sediments could severely damage any sensor exposed to the flow. Mounting the sensors in the lee of the support rod would provide some protection from direct impact.

If the driven rod is installed at or near the bed surface, floating debris should not have an adverse effect on this class of scour monitoring devices. However, submerged debris in the scour hole could inhibit the flexing of the piezoelectric film. Because the tip switches activate when the surrounding soil is removed, it is doubtful that the presence of submerged debris would adversely affect the operation of these sensors.

The durability of each individual sensor must be considered. The piezoelectric film and tip switches must be encapsulated so that they are protected from abrasion and deterioration from long exposure to the soil, water, and freeze-thaw cycles and the rod itself must be waterproof. Field tests of prototype piezoelectric sensors over a period of 4 years proved the durability of the sensors, when protected by a high-grade silicone tubing. (For additional discussion of operating conditions for a piezoelectric film device see *27* and Appendix section B-4.)

This class of devices should be reasonably secure from vandalism provided that the driven rod is installed so that the device is covered. The datalogging station must be housed in a durable, vandal-resistant enclosure.

Geotechnical Factors

Geotechnical factors will influence the methods and techniques required to install this class of devices. If the soils at the site location have a low blow count, it may be possible to drive the device into the bed without damaging the sensors. For soils which are primarily fine-grained, noncohesive materials, jetting techniques may be applicable. For stronger soils, hollow-stem augering or predrilling and driving may be necessary. Cohesive soils could also stick to the support rod. Consequently, soils with high-cohesion may inhibit the movement of the piezoelectric film and tip switches. It would be useful to conduct site-specific geotechnical investigations documenting the engineering properties of the soil before installation of this class of devices.

Datalogging and Telemetry

During laboratory testing, the piezoelectric sensors used on the driven rod were wired into the low-level alternating current (AC) input channels of a Campbell 21X datalogger. The datalogger recorded the input frequency from the piezoelectric film as it was flexed. No frequency response reflects that the sensor is buried, while any value greater than the base value indicates that the flow is buffeting the sensor. Five input channels (one for each sensor) were required for the piezoelectric sensor array as tested. However, only four were available. The lowest sensor, which was never uncovered by the scour during the laboratory tests, was left unwired to the datalogger for the tests in the outdoor flume. For an actual installation requiring more sensors, a datalogger with more AC input channels would be required for this sensor type. Fortunately, the Campbell datalogger as well as other commercially available dataloggers can be equipped with an add-on multiplexer which can extend the number of input channels.

The initial testing of the electrical signal from the prototype piezoelectric instrument indicates that the piezoelectric sensors are extremely sensitive to motion and can detect small vibrations. Although this finding makes it more difficult to discriminate between buried sensors and sensors in the free flowing water, it does allow confirmation of the condition of all the sensors installed on an instrument after installation.

Discrimination between buried and unburied piezoelectric sensors should not be an insurmountable problem. However, additional research and development of a software routine to sample and process the data from these sensors will be required. Additional raw data will need to be collected and analyzed from this prototype in order to develop the software to adequately determine the soil/water interface. It is anticipated that a combination of signal amplification, time series transformations, and tuning of the sampling frequency of these sensors will be required to consistently and accurately measure scour depths with this instrument.

For the laboratory test, the five tip switches were connected to 5 of the 16 available single-ended voltage measurement inputs on the Campbell datalogger. The five magnetic switches were connected to 5 of the 11 remaining single-ended voltage inputs on the datalogger. Excitation of all these switches with 4000 mv was produced by the excitation channels of the datalogger. Only one excitation channel was required, but one input channel per sensor is needed for these sensors. Although there were adequate input channels for the tip and magnetic switch arrays used during the near-prototype tests, actual field installations using more sensors could exceed the number of input channels available. As with the piezoelectric film, a multiplexer would be required to provide more input channels for this datalogger.

Installation

For new or replacement structures, it should be possible to install driven rod devices during construction. Installation for large perennial rivers can be accomplished while the construction coffer dam is in place and the location where the device is to be installed has been excavated.

A primary concern with the installation of the driven rod device with sensors at existing structures is designing the instrument so it can be driven or jetted into the bed in order to minimize the amount of excavation required. The laboratory device as tested in the outdoor flume was constructed so that, conceptually, as the rod was driven into the bed, the tip switches and piezoelectric film sensor would be folded into a protected recess in the support rod to allow for easy insertion of the device in the field.

It is apparent that the impact or shear forces associated with driving could be damaging to the electrical connections and sensors attached to the support rod. It may be possible to predrill a guide hole using a conventional drill rig and then drive the device into the predrilled hole. By predrilling, the driving forces could be reduced, thereby protecting the sensors from damage. However, shear forces on the sensors must be considered. Alternative installation techniques, as discussed above for the magnetic sliding collar device, would apply also to a driven rod with sensors.

Some advantages of driven rod devices with sensors are that these devices do not need to be mounted to the bridge sub- or superstructure and that these devices can be used to measure scour at sloping piers and abutments. The device may be most useful for spill-through abutments located on the floodplains. At these locations, the device can be installed in the dry and serviced by bridge maintenance personnel. Furthermore, a group of these devices could be installed on a grid in planform so that the horizontal extent of scour could be determined.

Summary Evaluation—Driven Rod Devices with Sensors

The investigations into the driven rod class of devices with various sensors indicate that this class of scour measuring devices is well suited to measuring scour at bridge piers and abutments. However, the installation methods and design of the device to withstand installation forces are important areas for further development if this class of devices is to be viable for a wide range of river types. Currently, the use of this type of device may be limited to ephemeral streams or overbank areas where these devices can be installed under dry conditions.

A significant advantage of the piezoelectric film type of sensor is that it will function during successive runoff events and will register scour and fill activity for multiple scour episodes.

Cost Analysis and Maintenance Requirements

This cost analysis of scour measuring instruments is presented to compare the costs of various instrumentation schemes. Wherever possible, actual reported costs were used. Cost information currently available includes costs associated with the installation of an Eagle DDS-1 low-cost sonic fathometer which was installed near Middleburg, NY, by the USGS and costs associated with the installation of a Data Sonics fathometer near Oneonta, NY, by the USGS. The installations of a Brisco Monitor and an Eagle Z-9500 on the South Platte River near Orchard, CO, under this project are also reported. The latter cost for a sonic system is used as a benchmark and is representative of sonic installations accomplished under this project.

Because of the spatial characteristics of the typical scour hole (see Figures 74 and 75), it may be necessary to install more than one device on a given pier or abutment to ensure that the maximum depth of scour is obtained. However, for cost-comparison purposes, the installation of a single device is considered. If several units are installed on a bridge, certain initial costs such as mobilization and traffic control would be averaged over the total installation.

Equipment Costs

In this section, the costs associated with purchasing and fabricating instruments are documented on the basis of current costs and level of development of the device. The cost analysis is presented primarily for comparison of instrumentation and, although accurate in a relative sense, should not be taken as the actual purchase price of a given instrument system. The analysis requires several assumptions so that each class of device can be compared.

The comparative cost analysis is complicated by the fact that each class of device has various capabilities. To compare each instrument on the basis of cost, it is necessary to evaluate each class of instruments assuming a basic level of functionality which, for the purposes of this report, will conform to the mandatory criteria. The basic level of functionality (BLF) will therefore be defined as the level of functionality capable of sensing the scour depth with the instrument and recording these data in digital, time-stamped form, using a datalogger, so that these data can be retrieved either manually or via a telemetering system.

Additionally, an assumed level of research and development must be adopted for the cost analysis, so that costs associated with each device can be compared. The assumed level of research and development (ALRD) will be defined as the level at which the device as designed could be fabricated in quantities less than 100 units without further research and development.

Only with these basic assumptions can reasonable comparative cost analyses be conducted. However, the costs reported for instruments which more closely match the BLF and ALRD will be more accurate than instrumentation which deviates significantly from these assumptions. In some cases, such as for instruments at the early stage of research and development (e.g., piezoelectric film devices), it will not be possible to determine a cost on the basis of the BLF and ALRD.

To compare the costs of the instruments, the actual cost of each instrument and category of equipment must be adjusted so that each device has the same functionality and capabilities. Therefore, the following assumptions were made:

1. The basic instrument will be required to measure a minimum of 3 m (10 ft) of scour.
2. Where applicable, each instrument must have a continuous power supply, which will include power from solar panels or commercial AC with a battery backup system.
3. Where applicable, each instrument must have a datalogger and enclosure. For this analysis, typical costs of commercially available dataloggers were assumed.
4. The cost estimates assume a single-device installation rather than multiple devices serviced by one datalogger.

Acknowledging that the adjustments to the actual costs can only provide an approximate cost comparison, cost data to reflect the BLF and ALRD are presented in Table 3. From this information, a preliminary evaluation of the comparative costs of each device can be made.

Once each device has been developed to the point that a basic system could be deployed, the costs for the devices evaluated in this report would range from approximately $2,500 to $8,000. The least expensive systems would be, as expected, the manual-readout magnetic sliding collar and low-cost sonic fathometer. The next least expensive system would be the automated sliding collar device. Driven rods with sensor devices are in the mid-range of cost, but a basic level of functionality has not been demonstrated for these devices. The sounding rod device represented by the patented Brisco Monitor is the most expensive instrument.

The cost comparison indicates that the Brisco Monitor will be the most expensive system if a datalogger, such as the Campbell 21X, is used to service this device. Although the

TABLE 3 Equipment Cost Assuming Basic Level of Functionality (BLF) and Assumed Level of Research and Development (ALRD)

	Approximate Equipment Costs @ BLF and ALRD for Cost Comparison							
Device Type Installation Method	Basic Instrument	Mounting Hardware	Power Supply	Cable	Datalogger	Shelter/ Enclosure	Total Equipment Costs	Remarks
Brisco (NCHRP)	5,000	600	300	N/A	2,100	200	8,200	Using third party datalogger
Sonic Fathometers Eagle DDS-1 (USGS)	500	400	300	100	2,500	200	4,000	Using existing USGS gage shelter . Operating off batteries
Eagle Z9500 (NCHRP)	500	1,000	300	Incl.	2,000	200	4,000	Continuous Power Supply Datalogger Interface
Data Sonics (USGS)	3,000	700	500	Incl.	2,000	200	6,400	Complete integrated system, system costs reduced to consider datalogging only
Magnetic Sliding Collar (Manual)	2,000	500	N/A	N/A	N/A	N/A	2,500	Basic instrument cost for ALRD
Magnetic Sliding Collar (Automated)	2,000	N/A	300	100	1,500	200	4,100	Basic instrument cost for ALRD
Driven Rod Piezoelectric	3,000	N/A	300	100	1,500	200	5,100	Estimated basic instrument cost for ALRD
Tip Switch	2,500	N/A	300	100	1,500	200	4,600	Estimated basic instrument cost for ALRD

expected equipment costs for the driven rod devices are only rough approximations on the basis of experience gained during this project, these devices may be competitive in cost to other devices evaluated in this report if they are fully developed and tested.

Installation Costs

The costs for installation of the various devices are estimated in Table 4. In this table, actual costs are presented for installation of the sonic fathometer, Brisco Monitor, and sliding collar devices by the research team. Other costs are estimated on the basis of the best available data at the time of reporting. The estimated installation cost for the Brisco Monitor assumes that a lifting crane and under-bridge worker's platform would be required.

The data in this table show that the installation costs can vary dramatically, depending on the complexity of the installation. For example, for large rivers where the installation must be conducted from the bridge deck over a perennial stream, the cost to install the sonic fathometer or sounding rod can be $5,000 to $7,000 or more. Furthermore, these costs assume that the installation on these larger bridges is reasonably straightforward. It is to be expected that the installation costs for any device could be higher than the data presented in this table.

None of the installation costs presented in this section include the costs associated with traffic control and engineering supervision. The costs also do not include final setup of the data box or enclosure or construction of any structure to house the datalogger and telemetry systems. The costs reported represent only the documented and estimated costs to install the scour monitoring hardware.

Finally, the installation costs will also depend on remoteness of the site. More remote sites will require larger expenditures for field installation crews and equipment. Because these costs will vary depending on the site, an estimate of these costs was not attempted.

Operation and Maintenance

Currently, the availability of operation and maintenance costs is limited to data from the two installations of sonic fathometers operated by the USGS. For the Data Sonics installation at Oneonta, NY, maintenance costs include an initial $500 for factory repairs of the equipment, with approximately 10 days per year for quarterly inspection and processing the data being telemetered from this equipment.

It was reported that the temperature compensation of the data from this equipment was not working properly and, therefore, the sensor might have to be repaired. The operation and maintenance for the Eagle DDS-1 at Middleburg, NY, was reported to be 15 days per year to visit the site, replace batteries for the instrument, and retrieve the data from the datalogger. At the time of this reporting, there was no information concerning operation and maintenance for the Brisco monitors installed in the New York area.

Discussion

The cost information presented in this section represents the best available data concerning costs to fabricate, purchase, install, and maintain scour monitoring devices at the time this report was prepared. The costs presented were based on actual cost information whenever hard prices were available. However, because scour measuring devices are at varying stages of research and development and have varying capabilities and functionality and because most of the devices installed in the field have been prototype instruments, the cost data presented previously should only be considered to be approximate.

APPLICATIONS

Monitoring Versus Data Acquisition

Instrumentation to measure scour at bridge piers and abutments is needed so that existing bridges susceptible to scour can be monitored. By monitoring for scour danger during a flood, these bridges could be closed, if necessary, to protect the traveling public. Scour measuring devices are also needed so that scour data can be obtained in the field to better understand the processes of scour and so that predictive equations can be refined and improved. Therefore, scour measuring devices are needed for monitoring as well as data acquisition. These two goals are achievable to varying degrees using any of the devices discussed in this report. However, the choice of which device to use and the required functionality for the device will depend on whether the device is to be installed so that scour can be monitored or whether data gathering to better understand the scour process is the primary goal.

To better understand the scour process as it occurs at bridge piers and abutments will require additional field data, including discharge, velocity, rate of scour hole development and refill, lateral size and shape of the scour hole, and other pertinent hydraulic and sediment data. Clearly, for this goal, the scour measuring device will be only one of several data acquisition devices needed for a complete understanding of the scour process. In terms of the scour measuring device itself, the device will be required to continuously measure the streambed and record time-stamped scour data with accuracies equal to or better than ± 0.3 m (± 1 ft). The data must be stored digitally, either for manual retrieval or transmission to a central computer site.

Any of the scour measuring devices can be used for this goal, provided the appropriate datalogging hardware and a

TABLE 4 Estimated Installation Costs for Scour Measuring Systems

Estimated Installation Costs Less Traffic Control									
Device Type	Estimated Crew Size	Estimated Days to Install	Estimated Man Days		Labor Costs (@$500/Man Day)		Special and Heavy Equip. Costs	Total ($)	Remarks
			Min	Max	Min ($)	Max ($)			
Sounding Rod									
Brisco	4	1-2	4	8	2,000	4,000	3,000	5,000 to 7,000	Crane/hoist, power drill in concrete special workers platform
Sonic Fathometers									
Eagle DDS-1 (USGS)	4	2-3	8	12	4,000	6,000	1,000	5,000 to 7,000	Hydraulic lift required 400/day x 2.5 days
Eagle Z9500 (NCHRP	4	1	4	4	2,000	2,000	500	2,500	Small front-end loader, simple installation
Data - Sonics (USGS	4	2-3	8	12	4,000	6,000	1,000	5,000 to 7,000	Hydraulic lift required
Magnetic Sliding Collar (Manual and Automated)	4	1	4	4	2,000	2,000	1,500	3,500	Hydraulic lift required
Other Driven Rod Devices									
Driven	4	1-2	4	8	2,000	4,000	1,000	3,000 to 5,000	Vibratory driver and crew/2 days
Augered	4	1-2	4	8	2,000	4,000	1,600	3,600 to 5,600	Auger - 2 days includes crew

continuous power supply are incorporated into the installation. However, the sonic fathometer and driven rod piezoelectric device stand out because they could have the ability to record the filling process as well as scour process. This would provide valuable information on the rate of scour and refill. The lateral size and shape of the scour hole could be obtained using several sonic transducers aimed at specific locations on the bed or by using multiple driven rods with piezoelectric film sensors.

If the devices are to be used solely to monitor existing bridges, the scour measuring devices could be simplified in their function for this goal. Although it might still be desirable to log and telemeter the data from a remote site, this is not necessarily required.

For scour monitoring, sonic transducers could be mounted on several bridge piers and abutments with the cable for these transducers routed to a central location on the bridge deck or streambank. During a flood, a highway crew could be dispatched with the electronics for the transducer to monitor the scour and close the bridge if necessary. Advantages to this approach are that several bridges could be instrumented with the transducers, which are relatively cheap (less than $50). Furthermore, only a few of the more expensive electronics packages would be required to be in the possession of the highway maintenance and inspection crews. This operation scheme would require a well-coordinated highway team able to respond to floods when they occur.

Warning/Monitoring Functions

Currently, the patented Brisco Monitor can be purchased with warning lights that activate once a prespecified scour depth is obtained. Consequently, this device can also be used as a monitoring device. Simpler driven rods, with sensors mounted only at those predetermined scour elevations which would pose a threat to the structural stability of the bridge, could be fabricated and installed if only scour monitoring and early warning were required. Any driven rod device could also be simplified at the datalogger with a simple series of lights denoting whether sensors at a predetermined danger level are active.

As an example, two manual-readout sliding magnetic collar devices for the New York State Thruway Authority have been configured with flashing strobes to indicate that the system has detected scour. Scour indicator flashing amber strobes were mounted above the bridge rail to be visible to passing law enforcement or Thruway personnel who are instructed to contact the appropriate maintenance supervisor. The strobe provides an effective indicator that human intervention is required.

Although only a concept, scour event-initiated automatic call could provide an effective warning of a hazardous situation. The call-out requires a switch closure or other indicator that an anomaly has occurred requiring attention. Commercially available devices can continue to place calls to several telephone numbers until one of the numbers responds. Then, the device can transmit a data string or a recorded voice message. This type of scour indicator should be easily adaptable to existing scour measurement systems design, but this has not yet been demonstrated in the field.

Abutment Installation Concepts

Most of the field installations completed under this research involved bridge pier installations of either sonar or sliding collar instruments. Pier installation concepts are well illustrated by the site-specific photographs included in Chapter 2. A low-cost sonic sounder and automated sliding collar device were installed at sloping abutments for this research. The sonic system, as installed, was only marginally successful because of accumulations of debris (see Findings, Site CO2). This section presents several alternative concepts for abutment installations.

Sonar Instruments

Installation of a sonar device on a vertical wall abutment is not significantly different from a pier installation. Generally speaking, the same mounting techniques and approaches applicable to a vertical, or nearly vertical, pier would be appropriate for a vertical wall abutment.

However, the same is not true for a sloping abutment. The abutment toe-of-slope and potential scour zone are generally not located near a structural member of the bridge to which the transducer can be attached. A mounting bracket attached from the bridge deck or superstructure vertically down to the toe-of-slope location would be susceptible to debris damage, excessive hydraulic loading, and, in many cases, impractical because of the height of the bridge off the water. The only viable application of this concept might be on low bridges using some type of "breakaway" mounting bracket that springs back into position once the debris has cleared (Figure 77). Otherwise, the only other alternative is a mounting bracket traversing the abutment slope itself to the toe-of-slope location.

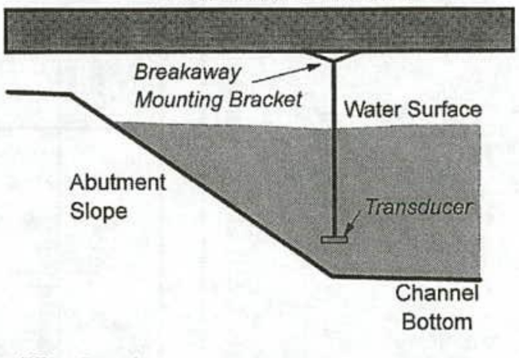


Figure 77. Breakaway mounting concept for sloping abutment installations.

Alternatives for traversing the abutment slope include variations of the "above-water-serviceable transducer housing" developed for pier applications or a structural framework to which the transducer is permanently attached. An above-water-serviceable transducer housing was adapted to many bridge pier installations for this research (see Figures 47 and 52). This same concept could be used along a sloping abutment, with the transducer positioned to "look" at an angle out of the end of the pipe (Figure 78) or through a hole in the side of the pipe (Figure 79).

Another alternative is to permanently mount the transducer to a framework secured to the abutment slope (Figure 80). This alternative does not provide the easy servicing provided by a modified above-water-serviceable housing, but does allow the transducer to be elevated somewhat, providing the transducer a better "view" of the bottom. Although this configuration is more vulnerable to damage from debris, the potential for damage is less than at a pier installation because the toe of the abutment is typically out of the main current and near the channel bottom.

Any of these alternatives traversing the abutment slope require the anchoring of the mounting hardware to the abutment slope. When concrete slope paving exists, the mounting hardware can be anchored directly to the concrete paving. When riprap protection is used, it may be adequate to grout the riprap to create a foundation or base for the mounting hardware. Alternatively, and in the case of no slope protection, it would be necessary to place a small concrete foundation to provide anchoring locations.

As noted in the findings for test site CO2, where a transducer mounting bracket with low-cost sonar was installed (see Figure 64), the instrument performed well initially; however, after several weeks of operation, the readings became intermittent. Field inspection found that grass-and-weed debris being transported in the channel had collected on the transducer and was interfering with the operation. After removing this debris, the instrument began to function properly again.

Therefore, although there was little concern about large debris, such as tree limbs and trunks, at this location, the presence of grass-and-weed debris in the channel was a problem for this type of transducer installation. Although not tested, it was concluded that one of the alternative sonar transducer-mounting schemes, consisting of a modified above-water-serviceable transducer housing, might have performed better under these circumstances.

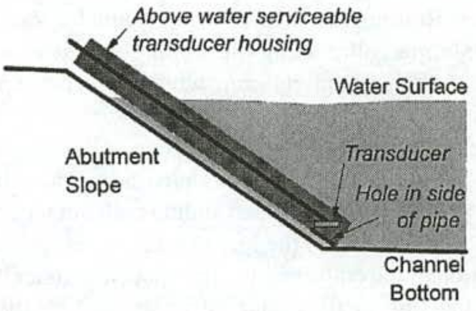


Figure 79. Side-looking transducer mount for sloping abutments.

Sliding Collar Devices

The availability of the automated sliding collar device offers additional flexibility, beyond sonar installations, for measuring or monitoring scour at abutments. As with a sonar installation on a vertical wall abutment, installation of a sliding collar device on a vertical wall abutment is not much different from a pier installation. Generally speaking, the same mounting techniques and approaches applicable to a vertical, or nearly vertical, pier would be appropriate for a vertical wall abutment. However, as with the sonar discussion above, the same is not true for a sloping abutment where the abutment toe-of-slope and the potential scour zone are generally not located near a structural member of the bridge to which the sliding collar pipe can be attached.

In particular, installation of a manual-readout sliding collar device, where the pipe for the sliding collar must extend above the water surface to the bridge deck for use in locating the collar, may not be a viable alternative for an abutment location. A pipe extending upward to the bridge deck from the toe-of-slope location would be susceptible to debris damage and excessive hydraulic loading and, in many cases, would be impractical because of the height of the bridge off

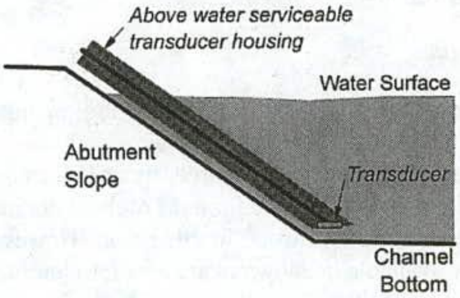


Figure 78. End-looking transducer concept for sloping abutments.

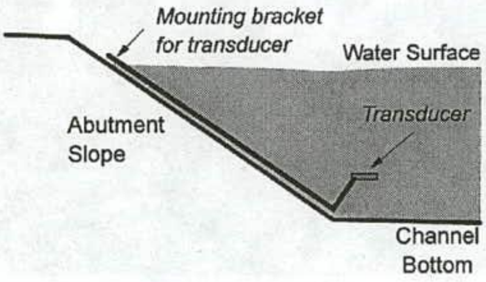


Figure 80. Transducer mounting bracket for sloping abutments.

the water. Routing the connecting conduit for the manual-readout sliding collar along the sloping abutment might be possible, but this configuration would also be exposed to hydraulic forces and debris.

However, with the automated sliding collar device, there is no need to extend a connecting pipe or conduit above the channel bottom. The automated sliding collar device replaces the pipe extending up to the bridge deck (necessary for manual location of the collar) with wires that electronically transmit the location of the collar as determined by the switch array insert. Therefore, the automated sliding collar pipe can be terminated at the channel bottom and a flexible conduit used to bring the transmission wires to the instrument shelter (Figure 81). This type of instrument is viable for abutment locations and is a great improvement over earlier versions of the instrument tested at pier locations. Most of the damage that has occurred in previous pier installations was the result of debris impact on the pipe extending above the channel bottom. The flexible conduit for the automated insert wiring can be routed off to the side or even to the downstream side of the pier or abutment to minimize the potential for debris damage. An automated sliding collar device performed well on a sloping abutment at field test site CO2 (see Figures 25 and 26), detecting about 0.5 m (1.7 ft) of scour.

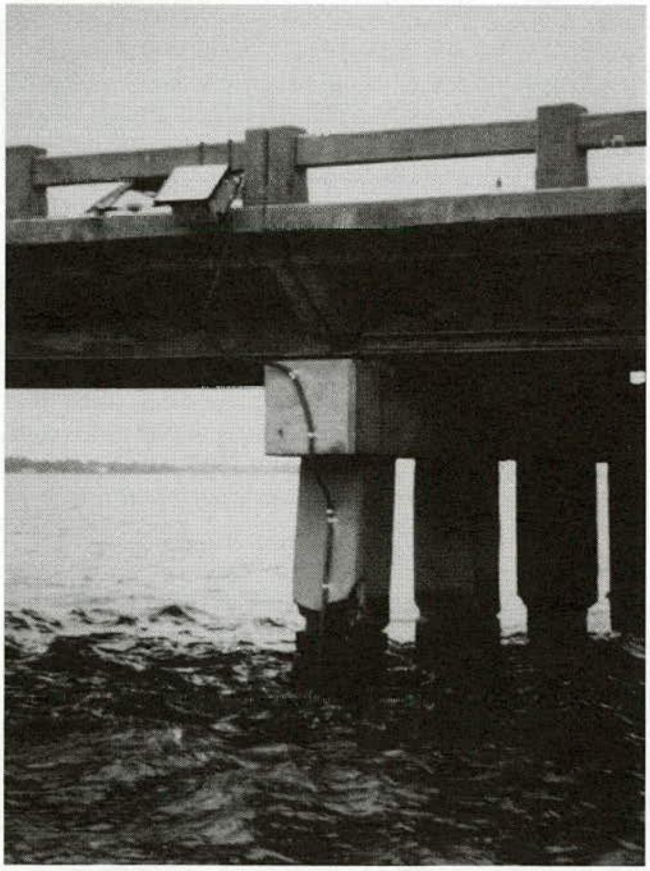


Figure 81. Nassau Sound (Site FL2) sliding collar instrument.

Wireless (Underwater) Transmission of Data

The findings in Chapter 2 include the results of a successful demonstration of the ability to transmit data that emulates the output of a scour monitoring device from an underwater location to a receiver/datalogger at a nearby location above water. The test results were favorable and it was concluded that, in the absence of interfering signals, underwater transmission of scour data should be possible, with few errors.

Given the limited nature of this demonstration, several modifications to the test apparatus could enhance overall performance. These modifications are as follows:

- **Select a more efficient antenna design.** A different internal transmitter antenna could increase overall signal strength and direct more of the transmitted power to the receiver.
- **Enhance receiver electronics.** Incorporate error checking and correction to increase reliability and reduce the effects of external signal interference.
- **Transmit multiple bursts of each record.** With this approach, the receiver compares a series of records looking for two or more in agreement. This is a proven method for reducing errors caused by interference.

With the above enhancements, the system should provide very reliable wireless communications from streambed to bridge deck.

For demonstration purposes, the experimental system described in Chapter 2 had the power on continuously. The final design operational mode would have the microcontroller normally in a powered-down "sleep" mode, waking once each hour to take a scour-level measurement. If the new measurement was a change from the previous hour, the microcontroller would activate the transmitter and report the new level to the above-water receiver. Data would be transmitted multiple times to ensure receipt. Because the transmitter uses the most power, the microcontroller would transmit operational status (scour level and battery voltage) once every 5 days or so to conserve battery life. Using state-of-the-art lithium batteries, the projected battery life would be in excess of 3 years.

Datalogging and Telemetry

Datalogging

For most classes of scour measuring or monitoring devices, existing datalogging systems are adequate to meet the needs of the sensors being used. Indeed, currently available dataloggers can be used for most of the scour measuring devices described and tested in this report. However, commercially available dataloggers are generally more sophisticated and costly than is necessary. For the low-cost sonic fathometers, commercially available dataloggers provide too many unused input channels, but data processing capabilities to adequately and efficiently filter out the nonuseable data are too limited. As noted in the findings, an interface will be required between the low-cost instrument and datalogger. Conversely, commercially available dataloggers have all the functionality required to process data from sensors used on the driven rod, but lack adequate input channels unless add-on multiplexers are used.

Remote Telemetry

Once the data have been logged in a datalogger, the telemetry of the data is relatively straightforward because the protocol for data transmission using telephone modem, radio, and satellite transmission is well established. However, additional effort will be required to define and match datalogging and telemetry capabilities to the sensors used to measure scour depth at bridge piers and abutments.

To determine a state highway agency's capability to employ telemetry in accessing bridge scour data from base locations, several states were surveyed. The survey revealed that all states apparently have at least a basic deployment of communication networking—some more robust and diverse in their technologies than others. Because not all states incorporate the same technologies, scour measurement systems must be flexible in their ability to adapt to various networking environments. Therefore, no one solution is applicable to all states.

Options of state-deployed telemetry that may be available for scour measurement applications include

- **Microwave Networks**. Colorado has a state-managed microwave network used by its agencies. Their microwave network carries many supervisory control and data acquisition (SCADA) applications. It also hosts entry from meteorological contractors that communicate over very high frequency (VHF) links into a network entry node. Typical entry is via landline telephone or VHF/ultra high frequency (UHF) link. Remotely located data collection sites for hydrologic or environmental measurement can transmit data several kilometers over RF radio to a receiver at a SCADA entry point. Data are sent through the SCADA system to the state's main computer system, which can then be accessed by computer terminal. Because many states have their own microwave networks and because the equipment necessary to communicate with them is readily adaptable to scour measurement systems, this telemetry option is a viable candidate for retrieving historical scour data from a site or issuing notice if scour occurs.
- **UHF/VHF Networks**. Most states employ UHF/VHF repeater-linked networks for two-way voice and data communications for state police (highway patrol) and highway maintenance. Scour measurement devices could transmit directly into these networks. Entry can be made at most repeater sites; however, many of the systems are quite busy. A "blind" transmission from a data system could cause system interruption, or the data might be lost. These networks have significant potential application because they have immediate contact with those state personnel who can investigate and take action in the event of scour. Use of these systems would require further review of a specific state's system for operating mode, priority, availability, entry locations, and traffic allocation.
- **Cellular Telephone Systems**. Cellular telephone coverage is now deployed throughout most of the country and would be an excellent option for many installations. However, the providers' relay stations are usually located on higher elevations while bridges cross streams or rivers that often follow valleys. This sometimes results in lost local coverage because of the shadowing effect that interrupts line-of-sight transmission. The cost of a cellular connection is low, but it does have continuing monthly costs. A primary advantage of cellular communications is the ability for the site to receive calls as needed and for the scour system to originate a call if scour occurs.

  A cellular telephone telemetry capability was demonstrated in 1995 at field test site CO2 in Colorado. At that site, an automated magnetic sliding collar device was configured with a cellular telephone transceiver that responded to incoming data calls. Upon command, the instrument's datalogger electronics reported collar level, battery voltages, and a date-time stamp. Scour data were retrieved at a base station approximately 64.4 km (40 mi) from the bridge.
- **Hybrid UHF/VHF/900 Mhz Networks**. Some states have hybrid networks that use 900 Mhz communications in addition to UHF/VHF. Scour measurement systems are adaptable to these networks in a manner similar to their interface with UHF/VHF networks.
- **Landline Telephone Communications**. If an existing telephone drop is in the vicinity of a bridge-located scour measurement device, a landline telephone circuit can be interfaced with an automatic dialer and modem on the scour equipment. Telephone service at a bridge site may prove difficult or costly if the cable has to be run a considerable distance.
- **Geostationary Operational Environmental Satellite (GOES)**. The U.S. Army Corps of Engineers, the USGS, and several states operate water stage, streamflow, and other environmental monitoring devices that use the GOES system to transfer data. Data are normally transmitted every 6 hours. Under special conditions, an emergency transmission is possible, if critical conditions exist. This option requires negotiating agreements with the Department of Commerce to use their backbone network.
- **Commercial Satellite Services**. Commercial satellite services are available that offer data retrieval capability. In some cases, these services offer two-way communications allowing polled data collection as well as remote

system call origination if a scour event occurs. These systems are easily installed, convenient, and use a small whip antenna that requires no aiming. The cost of data retrieval is approximately $0.01 per bit. Remote site hardware costs are on the order of $1,000.

Local Telemetry

Many bridges have high traffic volume or are without safe access to pier-mounted scour measurement systems. This problem was encountered at several of the Texas DOT sites where instruments were installed under FHWA DP97 (see Findings, Chapter 2). These bridges could be equipped with local telemetry that will allow access to the scour data from a safe location off the bridge. Current technology provides several options that satisfy this requirement. The most viable of the available options are hard-wired cabling and radio frequency. Hard-wire technology has the following capabilities:

- Line extenders for RS-232 can be used to extend the normal 15.2-m (50-ft) RS-232 limitation to over 304.8 m (1,000 ft).
- Short-haul modems, using twisted-pair cable, can transfer data up to 1.6 km (1 mi).
- RS-485 interfaces, using twisted-pair cable, communicate over distances greater than 1.6 km (1 mi).

Radio frequency technology has the following capabilities:

- Commercially available RF transceivers are easily interfaced with scour measurement systems and can transfer data over distances of several kilometers into a base station or state-maintained communications network.
- Spread spectrum modems are now available that provide data communications over line-of-sight transmission. Spread spectrum is in the 900 to 928 Mhz range and uses a "frequency-hopping" technique to provide data communication that is both secure and reliable. It is designed to connect computers and other peripheral devices between rooms in the same building and between adjacent buildings without the use of cabling. Most spread spectrum systems offer distances of about 609.6 m (2,000 ft) line-of-sight. New models now available can provide distances of several kilometers, but at greater expense.

Ground Truth Instrumentation

Ground truthing is an independent measurement or confirmation of data collected by a given instrument or device. In order to evaluate the accuracy and limitations of the fixed instruments developed by this research effort, ground truthing was an integral part of field testing and data collection. The initial ground truth effort was based on standard USGS stream-gaging equipment and procedures. Stream-gaging involves measuring the depth and velocity across the channel, from which both a cross section can be developed and the discharge can be computed. The depth and cross-sectional data were directly applicable to evaluating the fixed instrument performance, and the velocity and discharge data were useful in interpreting channel cross-section and scour conditions.

Standard stream-gaging equipment includes a current meter positioned in the flow by either a rod ("wading rod") or a suspended cable with a weight ("sounding weight"). At test sites such as Sites NM1 and NM2 on the Rio Grande and Sites CO1 and CO2 on the South Platte River, only a suspended cable approach was feasible for positioning the current meter. The cable winch ("sounding reel") for raising and lowering the current meter is typically either mounted on a portable dolly that is rolled across the bridge or installed on a truck-mounted crane device and the truck is driven across the bridge. For ground truth measurements, a truck-mounted boom with a Price AA current meter, model B-56 sounding reel, and 22.8-kg (50-lb) sounding weight were used. Figure 82 illustrates this equipment in use at test Site NM2.

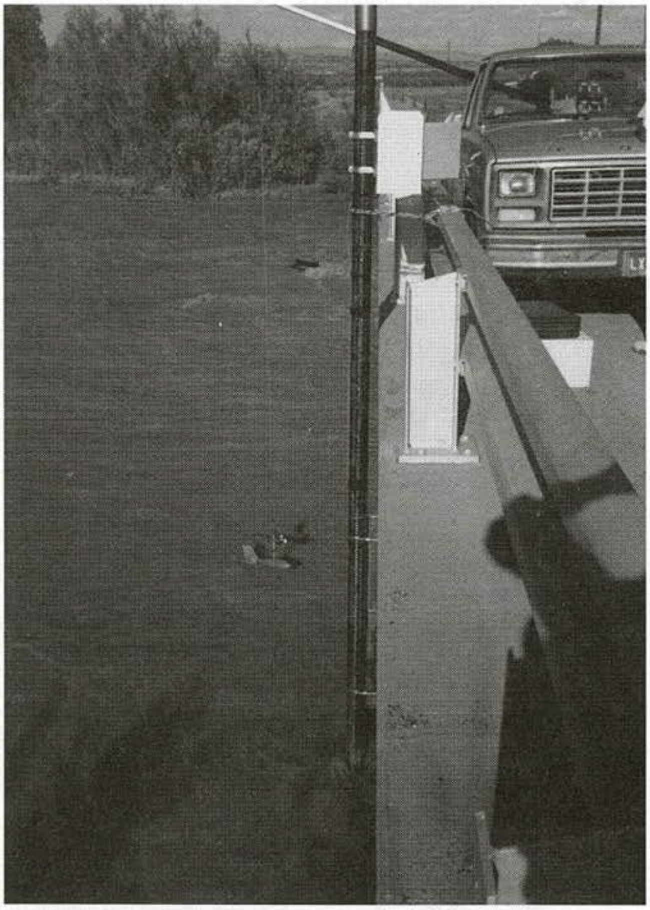


Figure 82. Stream-gaging and ground truth measurements at the San Antonio bridge (Site NM2).

TABLE 5 Applicability of Scour Measuring Devices for Pier and Abutment Geometry

Device Type	Piers			Abutments		Remarks/Warrants
	Spread Footing	Sloping Column	Vertical Column	Vertical	Spill-Through	
Sounding Rod	No	Possible	Yes	Yes	Difficult	Installation difficult on sloping piers or abutments >15°
Manual Sliding Collar	Yes	Possible	Yes	Yes	Difficult	Best application to low bridges and shallow water <4.6 m (15 feet)
Automated Sliding Collar	Yes	Possible	Yes	Yes	Yes	
Low-Cost Sonic Fathometer	Possible	Yes	Yes	Yes	Possible	Transducer mounting angle should be limited to no more than 15°
Driven Rod with Piezoelectric Sensors	Yes	Possible	Yes	Yes	Possible	Performance in field and datalogging not proven

With this equipment, several ground truth visits were made to the New Mexico and Colorado test sites during runoff season, and valuable data and insight on instrument performance were collected. However, in an effort to maximize the ground truth activities, several low-cost, portable sonar units that could be handheld over the bridge rail to provide additional ground truth during weekly visits were developed.

These low-cost portable instruments proved to be a valuable adjunct to this research and more general bridge inspection requirements. An overview of low-cost portable sonic sounding instruments that can be used for ground truth of field instrument installations or more general scour inspections is provided in Appendix C. Ground truth operations should be included as an integral part of the ongoing operation and maintenance of any fixed instrument installation.

Application Warrants

The evaluations of scour instrument applicability presented in this chapter can be summarized with a set of guidelines or warrants relative to bridge substructure conditions and flow or geomorphic characteristics. Tables 5 and 6 summarize application warrants for instruments tested during this research. Because a tabular presentation is of necessity simplified, reference to the findings of Chapter 2 and the instrument-specific evaluation of this chapter is also suggested.

Bridge Pier and Abutment Geometry

From the evaluations presented earlier in this chapter, it is clear that no single device is applicable to all bridge pier and abutment geometries. However, most bridge geometries can

TABLE 6 Applicability of Scour Measuring Devices for Flow and Geomorphic Conditions

Device Type	Streambed Characteristics			Flow Characteristics			Remarks/ Warrants
	Sand Bed	Cobble Boulder	Silt/Clay Cohesive	Perennial	Ephemeral	Tidal	
Sounding Rod	No	Yes	Yes	Yes	Yes	No	Poor performance experienced on sand-bed streams. Corrosion or marine growth may be a problem at tidal sites.
Manual Sliding Collar	Yes	Large bed material may preclude installation	Cohesive bed material may inhibit driving	Yes	Yes	Yes	Excellent for shallow water <4.6 m (<15 feet). Ice and debris may pose problems. May require predrilling in coarse- or cohesive-bed streams.
Automated Sliding Collar	Yes	Large bed material may preclude installation	Cohesive bed material may inhibit driving	Yes	Yes	Yes	May require predrilling in coarse- or cohesive-bed streams. May require diver support in deeper water.
Low-Cost Sonic Fathometer	Yes	Yes	Yes	Yes	Yes	Yes	Ice and debris pose significant problems.
Driven Rod with Piezoelectric Sensors	Yes	Large bed material may preclude installation	Cohesive bed material may inhibit driving	Unknown	Yes	Unknown	May require predrilling in coarse- or cohesive-bed streams. Drilling or driving over water may be a problem.

be accommodated with one of the scour measuring devices evaluated and tested in this study. Table 5 presents warrants for installation of each of the devices tested solely on the basis of the bridge pier and abutment geometry.

This table shows that all instruments tested are adaptable in some degree to vertical piers and abutments. Sloping piers and spill-through abutments present difficulties for most instrument configurations. Driven rod instruments, such as the automated sliding collar or piezoelectric film device, not fastened to the substructure can be used on sloping piers and abutments. However, the piezoelectric sensor driven rod has had only limited field testing. Adapting scour instrumentation to a large spread footing or pile cap configuration also presents challenges. A sounding rod should not be installed through the footing and there is an operational limit on sonic fathometers when attempting to mount the transducer at a high angle so that the sonar does not reflect off the footing or pile cap.

Flow and Geomorphic Conditions

Each class of scour measuring instrument will not be applicable to all flow and geomorphic conditions. The applicability of each class of sensors to these conditions is presented in Table 6. Although some of these limitations stem from the capabilities of the device itself, some pertain to whether the device is installable given the geomorphic and flow conditions.

Sounding rods have not performed well in sandbed streams, although the addition of a large baseplate to the sounding rod could help correct the problem. No data could be found regarding fixed sounding rod installations at a tidal site, but it is expected that a combination of corrosion and marine organism growth could restrict free movement of the rod.

All devices using a driven rod configuration will have limitations imposed by bed and substrate characteristics. Predrilling, jetting, or augering may permit installation under a wide range of conditions (see Chapter 2, Driven Rod Installation Techniques), but these techniques may be expensive and could be difficult over water. The connecting conduit required by the manual-readout sliding collar device is vulnerable to ice and debris impact, but the instrument proved surprisingly durable at field test sites with significant debris.

Low-cost sonic fathometers are applicable to a wide range of streambed characteristics and flow and geomorphic conditions, but ice and debris in the stream can quickly render a sonic fathometer inoperable. Strategies such as placing the fathometer close to the streambed may reduce, but will not eliminate, the vulnerability of this instrument to ice and debris.

CHAPTER 4

CONCLUSIONS AND SUGGESTED RESEARCH

CONCLUSIONS

Background—The Bridge Scour Evaluation Program

On March 10, 1995, at about 9:00 p.m., the southbound and northbound bridges on Interstate 5 over Arroyo Pasajero in California collapsed during a large flood. Four vehicles plunged into the creek, resulting in seven deaths. Scour played a significant role in the collapse. The Arroyo Pasajero tragedy is only the latest in a series of bridge failures that have highlighted the national problem of bridge scour. The catastrophic failure of the Schoharie Creek bridge on the New York Thruway in April 1987, which cost 10 lives, focused attention in the United States on the bridge scour problem; and the subsequent failure of the U.S. 51 bridge over the Hatchie River in April 1989, which cost eight lives, broadened the concern to stream stability problems, as well. The damages and economic costs of the Mississippi River floods in 1993 and floods in Georgia in 1994 underscored the vulnerability of the nation's transportation system to bridge scour and stream instability.

Following the catastrophic failure of the Schoharie Creek bridge, the FHWA established a national scour evaluation program. The 1989 revision of the National Bridge Inspection Standards (NBIS) requires an inspection program that includes procedures for underwater inspection. Results of each bridge inspection are documented according to the guidelines provided in the "Recording and Coding Guide for Structure Inventory and Appraisal of the Nation's Bridges" (*47*), more commonly referred to as the "Coding Guide." The FHWA also issued a Technical Advisory (TA) that provides guidance on the development and implementation of procedures for evaluating bridge scour. The TA indicates that every bridge over a waterway, whether existing or under design, should be evaluated for scour in order to determine prudent measures to be taken for its protection (*48*).

Existing bridges found to be scour-critical, either from field observations or results of the analytical scour evaluation, require development of a plan of action. The plan of action should include instructions regarding the type and frequency of inspections, particularly as it may relate to the need to close a bridge, if necessary, and a schedule for the timely design and construction of scour countermeasures. Initial scour-susceptibility screening was completed for the most part by October 1992. FHWA established January 1997 as the completion date for scour evaluations of all existing bridges identified as scour-susceptible.

The scour evaluation program has identified, to date, more than 10,000 scour-critical bridges and almost 100,000 bridges with unknown foundations. An unknown foundation rating means that after office and field reviews, it was uncertain what the structural foundation condition was or what pile lengths were for pile-supported foundations. Consequently, for 22 percent of the bridges over water in the United States, an in-depth scour evaluation cannot be completed. An additional 132,000 bridges that were screened (assessed) as scour-susceptible have not been evaluated.

There are many scour-vulnerable bridges in the United States. With limited time and funding available, the scour-critical bridges cannot be immediately repaired or replaced and the scour-susceptible bridges cannot be immediately evaluated. Moreover, the unknown foundation bridges will require monitoring for the foreseeable future. The two instruments developed under this research, a low-cost sonic system and either a manual-readout or automated magnetic sliding collar device, have been tested extensively and are fully field-deployable. Use of these instruments as scour monitoring countermeasures will provide state highway agencies with an essential element of their plans of action for many scour-critical, scour-susceptible, or unknown foundation bridges.

Thus, the two scour measuring devices developed by this research will allow monitoring of scour-critical bridges so that countermeasures can be taken before the problem becomes severe or will provide a possible long-term alternative countermeasure for scour in some circumstances. These actions will increase the safety of the traveling public and will reduce the costs of bridge inspection, operation, and maintenance. The results of this research will be of immediate value to state highway agencies, authorities, county and city roadway and street departments, and private bridge owners. In addition, several states have undertaken or will initiate cooperative scour research programs. Instrumentation to measure maximum scour depths at bridge piers and abutments will provide invaluable support to such cooperative research efforts.

Scour Measuring and Monitoring Instruments

The basic objective of this research was to develop, test, and evaluate instrumentation that would be both technically and economically feasible for use in monitoring maximum scour depth at bridge piers and abutments. The scour monitoring devices were required to meet a set of mandatory criteria as follows:

- 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, and
- Operability during storm and flood conditions.

Additional desirable criteria for the instrumentation were also established.

It was apparent from initial laboratory and field evaluations that no *single* methodology or instrument for measuring scour at bridge piers and abutments can be used to solve the scour measuring problems for *all* situations encountered in the field. Considering the wide range of operating conditions necessary, environmental hazards such as debris and ice, and the variety of stream types and bridge geometries encountered in the field, it was obvious that several instrument systems using different approaches to detecting scour would be required.

This research accomplished its basic objective. Various scour measuring and monitoring methods were tested in the laboratory and in the field, including sounding rods, driven rod devices, sonic fathometers, and buried devices. Two instrument systems, a low-cost above-water-serviceable sonic fathometer and magnetic sliding collar device using a driven rod approach showed significant promise after laboratory testing and limited field testing. As a result, the field testing phase of the project concentrated on installing and testing these two instrument systems under a wide range of bridge substructure geometry, flow, and geomorphic conditions. **Both instrument systems met all of the mandatory criteria and most of the desirable criteria established for this project.**

These instruments were tested at riverine bridge sites in Colorado and New Mexico and tidal sites in Florida. Through wider deployment relationships with state DOTs in Minnesota and Michigan, sliding collar devices were tested at streams with ice and debris hazards. With the support of an FHWA Demonstration Project on scour instrumentation (DP97), additional installations of low-cost sonic systems and sliding collar devices were completed by Texas DOT on sediment-laden, debris-prone streams in southeastern Texas, and by the USGS in New York and Oregon. In addition to providing diversity in the field test sites, the installations by the state DOTs proved that both instrument systems can be installed and maintained with equipment and technical skills normally available to District-level DOT maintenance and inspection personnel. Moreover, the participation of District-level personnel in the installation of these devices revealed a high degree of interest and a significant level of resourcefulness to install and maintain such equipment.

The installation, operations, and fabrication manuals for the low-cost sonic system and magnetic sliding collar devices (*NCHRP Reports 397A* and *397B*) provide complete instrument documentation, including specifications and assembly drawings. That information, together with the findings, appraisal, and applications information of this final report, provide a potential user of a scour measuring or monitoring device complete guidance on selection, installation, operation, maintenance, and if desired, fabrication of two effective systems, one of which could meet the need for a fixed scour instrument at most sites in the field.

The lack of field data on scour has required researchers investigating bridge scour and those developing analytical tools to predict scour to rely on laboratory data, usually collected from scale models. However, problems in scaling sediment sizes and erosional processes limit the value of laboratory data acquired from scale models and such data cannot provide reliable confirmation of analytical procedures. Therefore, there is a real and immediate need for field measurement of scour and erosional processes at bridge crossings. The development by this research project of two reliable, cost-effective devices for measurement of maximum scour will support efforts to acquire and expand a field database on scour that will be of great value in development of reliable analytical procedures for scour prediction. Such data will be welcomed by researchers worldwide.

A third instrument, a driven rod device with piezoelectric film sensors, was tested in the laboratory and received very limited field testing under this research. This instrument was given a lower development priority than either the low-cost sonar or sliding collar devices, primarily because of its inherent complexity and anticipated difficulty in relating sensor output to scour status. The instrument shows promise and, unlike the sliding collar class of devices, would be able to track the development of a scour hole and subsequent refill over an unlimited number of scour cycles. This instrument systems warrants further research.

Of the devices tested extensively in the field, the low-cost sonar system and the manual-readout sliding collar device are both vulnerable to ice and debris; however, both proved to be surprisingly resistant to damage from debris or ice impact at field test sites. The sonic system can be rendered inoperative by the accumulation of debris, and presumably ice, between the transducer face and streambed. The manual-readout sliding collar requires an extension conduit, generally up the front face of a pier, which can be susceptible to debris or ice impact damage, unless the extension can be firmly anchored to a substructure element. From this perspective, the automated sliding collar device (or the driven rod with piezoelectric film sensors) has the distinct advantage of having a configuration that places most of the device below the streambed and, therefore, is not vulnerable to ice or debris. The connecting cable from the device to a datalogger on the bridge deck can be routed through a buried conduit and up the *downstream* face of a bridge pier or abutment where it is much less vulnerable to damage. This research also demonstrated the feasibility of wireless transmission of scour data from an instrument module under water at or just above the streambed to a receiver on a bridge deck. For both the automated sliding collar or the driven rod with piezoelectric film sensors, this would further reduce system susceptibility to ice or debris damage.

SUGGESTIONS FOR FURTHER RESEARCH

Although this research produced two reliable, field-deployable scour measuring and monitoring instruments, there are four areas in which further research and development activities would extend the results of this effort or provide enhanced capabilities to measure or monitor scour in the field. Each area is discussed, briefly, below.

Piezoelectric Sensor Driven Rod Device

In establishing priorities for the implementation phases of this research, a decision was made to concentrate efforts on development of two relatively simple instruments that could be brought to a field-deployable level quickly. Research on a third device, a driven rod with piezoelectric film sensors was given a secondary priority and only limited field testing was completed on this instrument. On the basis of this testing, however, the device shows promise and warrants additional research and development.

Limited laboratory and field testing have established the functionality of a driven rod with piezoelectric film sensors in relation to the mandatory criteria for scour instrumentation. Independent testing of a prototype device by the USGS indicates that the instrument performed and survived under conditions that might have destroyed any other device (see Appendix section B-4). In logging and interpreting data from the piezoelectric film sensors, their unexpected sensitivity to vibration from sources other than the hydrodynamics of the flow (e.g., truck traffic on the bridge) create a need to screen the sensor signals. Data interpretation may require a level of operator training not required by simpler devices, but the ability to track the scour and refill process and the relative invulnerability of this instrument to debris and ice could provide a substantial payoff. Further research for a piezoelectric film device should concentrate on

- Data screening techniques to discriminate between signals from buried and unburied sensors,
- Field tests of sensor reliability and durability,
- Field testing and development of jetting and driving techniques that minimize shear and impact forces on the piezoelectric film sensors,
- Development of user-friendly data interpretation protocols, and
- Further testing of piezoelectric film encasement materials and techniques.

Local and Remote Telemetry of Scour Data

This project demonstrated the feasibility of remote telemetry of scour data from an instrument installed at a bridge in the field to a base station more than 64 km (40 mi) away. The range of options to transmit scour data from a bridge site to a remote base station is surveyed in Chapter 3. There remains a need to implement telemetry of scour data using the techniques most commonly available to highway agencies and to provide guidance on the necessary interface between the scour datalogger and the various telemetry options.

Because many bridges have high traffic volume or are without safe access to a pier-mounted scour monitor, a local telemetry capability could be desirable. Current technology offers both hard-wired and radio-frequency options for local telemetry (see Chapter 3). Hard-wired local telemetry could use RS-232 line extenders, short-haul modems, or an RS-485 interface with ranges of about 300 m (1,000 ft) to 1.6 km (1 mi). Radio frequency technology includes RF transceivers (for distances of several kilometers) and spread spectrum modems with a transmission distance of about 600 m (2,000 ft) line of sight. Application of these technologies for local telemetry is routine, but none of these techniques was investigated during this research.

Underwater transmission of scour data from an instrument positioned near the streambed to a receiver on or near a bridge deck could reduce the vulnerability of driven rod or buried scour instruments to debris and ice by eliminating the physical link between the instrument and the bridge. The feasibility of underwater transmission of scour data was demonstrated during this research (see Chapter 3), but because of the limited nature of that demonstration, additional research and development would be required to perfect equipment and operational techniques. The following modification or enhancements should be investigated:

- Select a more efficient antenna design,
- Enhance receiver electronics to incorporate error checking and correction to reduce the effects of external signal interference, and
- Develop techniques for transmission of multiple bursts of each data record with error checking.

Warning/Monitoring Functions

The addition of an early warning capability to the monitoring function for scour instruments could provide additional safeguards for the traveling public. A flashing strobe indicator has been developed outside this research project and implemented on two manual-readout magnetic sliding collar instruments. Additional applicable technology would include scour-event initiated auto calling.

Technology Transfer

For state highway agencies to make maximum effective use of the findings of this report and the installation, operation, and fabrication manuals which accompany it, a dedicated program of technology transfer will be necessary. To this end, the FHWA has developed and implemented a Demonstration Project on scour instrumentation (DP97). This demonstration project provides, in a lecture and hands-on workshop format, the instruction necessary to select and install various fixed scour instruments, including the low-cost sonic system and sliding collar devices developed under this research. This critical effort should continue.

In addition to this report, *NCHRP Reports 397A* and *397B* and DP97 provide some guidance on selecting an appropriate instrument for a given set of bridge foundation, flow, and geomorphic characteristics. Additional effort is warranted to expand this guidance, and, considering the principles of river engineering, provide further guidance on selecting a location on the bridge with the highest probability of detecting the most serious scour threat when only a few instruments can be justified for a given site.

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APPENDIX A

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APPENDIX B

SUPPORTING LABORATORY AND FIELD TEST DATA

B-1: DESCRIPTION OF LABORATORY APPARATUS

Recirculating Flume

Scale model instruments/devices were tested in an existing indoor recirculating steel flume at Colorado State University (CSU). The flume, 61 m (200 ft) in length, 2.4 m (8 ft) in width and 1.2 m (4 ft) in depth, can be adjusted to vary the slope from 0 to nearly 3 percent. The flume has a discharge capacity of approximately 3 m^3/s (100 cfs). Velocities can exceed 3 m/s (10 fps).

The interior of the indoor flume was segmented into three sections: (1) a flow development section, (2) a test section, and (3) a tailwater control/material recovery section. The flow development section extended from the flume headbox and diffuser downstream approximately 30.5 m (100 ft). The test section abutted the flow development section and extended downstream approximately 18.3 m (60 ft). A model pier was installed in the test section simulating placement into a stream channel of erodible material. The remaining 12.2 m (40 ft) of the flume served as a bed material recovery basin and tailwater control. The flume slope was set at approximately 0.5 percent.

The pier used in the indoor flume was a 1:15 (model: prototype) Froude scale model of the pre-failure pier of the New York State Thruway bridge over Schoharie Creek. The model pier is 1,671 mm (65.8 in.) long and 384 mm (15.1 in.) wide; the footing thickness is 102 mm (4 in.); and the pier height is 810 mm (31.9 in.) as illustrated in Figure B-1 (also see Figure 1, Chapter 2). The pier was mounted so that the base of the footing was elevated approximately 0.3 m (1 ft) above the flume bottom. The pier was situated parallel to the flume walls and flow.

The bed material was composed of two noncohesive sands with median grain sizes of approximately 2.3 mm (0.09 in.) and 4.0 mm (0.16 in.). Both bed materials have a coefficient of uniformity of approximately 1.9. The bed materials were loosely placed in the flume to an elevation of 203 mm (8 in.) above the top of the footing.

A circular rod was used to simulate pier scour monitoring devices such as driven and sounding rods. A circular steel rod, 1,422 mm (56 in.) long and 19.6 mm (0.77 in.) in diameter, was used in all the tests.

Outdoor Fixed Geometry Flume

A concrete flume was used for all outdoor, near-prototype tests of scour monitoring devices. The flume is 54.9 m (180 ft) long, 6.1 m (20 ft) wide, and 2.4 to 4.0 m (8 to 13 ft) deep as shown in Figure B-2. The flume was modified so that the upper 6.1 m (20 ft) served as an inlet basin for energy dissipation and wave suppression. A headwall was constructed and served as the inlet to the approach channel. The throat of the test section was 3.7 m (12 ft) wide to provide a concentrated flow through the test section. The channel extended approximately 22.9 m (75 ft) downstream of the headwall.

The channel was segmented into three sections: (*1*) an entrance and flow development section, (*2*) a test section, and (*3*) a tailwater control section. The entrance and flow development section extended from the headwall and diffuser downstream approximately 9 m (30 ft). The diffuser was composed of 51-×51-mm (2-×2-in.) material constructed in a 0.6-×0.6-m (2-×2-ft) grid covered with 12.7-mm (0.5-in.) wire mesh. The test section extended downstream approximately 6.1 m (20 ft). The model pier was installed into the test section simulating placement into a stream channel of erodible material. The remaining 7.6 m (25 ft) of the channel served as the tailwater control. The bed material was leveled horizontally. The water surface was controlled with stop logs at the channel outlet.

Water was supplied to the facility from Horsetooth Reservoir through an existing pipe network. A 914-mm (36-in.) butterfly valve located just upstream of the flume served to control inflow to the inlet basin. A sonic flowmeter was used to determine the inlet discharge with accuracy of ±3 percent. Water temperature varied from 10°C to 12.2°C (50°F to 54°F).

The model was a 1:4 (model: prototype) scale model similar to the pre-failure pier of the New York State Thruway bridge over Schoharie Creek. The model pier was 2.1 m (7 ft) long, 0.46 m (1.5 ft) wide, and 1.5 m (5 ft) high and the footing was 24 m (8 ft) long, 0.61 m (2 ft) wide and 0.3 m (1 ft) thick. The model (near-prototype) pier is illustrated in Chapter 2 (Figure 2). The pier was mounted in the channel on 0.61 m (2 ft) high simulated piles as shown in Figure B-3. The pier was situated parallel to the channel sidewalls.

The bed material was composed of a noncohesive sand-pea gravel with median grain size of approximately 3.15 mm (0.12 in.). The bed material was placed in the channel to an elevation of 1.2 m (4 ft) above the concrete floor and 0.3 m (1 ft) above the top of the footing.

During each test, localized velocities were measured using a Marsh-McBirney magnetic flowmeter. The meter was periodically calibrated throughout the experiment program. Water surface elevations were monitored using staff gages placed up- and downstream of the pier. A point gage was used to contour the bed near the pier before and after each test. The

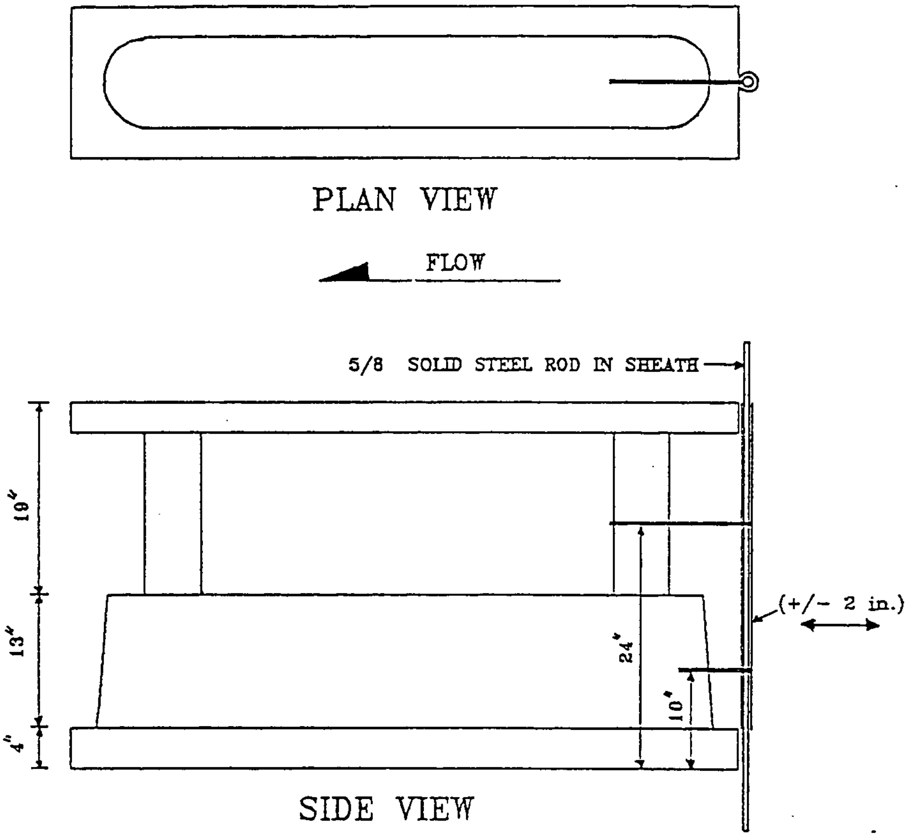

Figure B-1. Plan and profile of model pier.

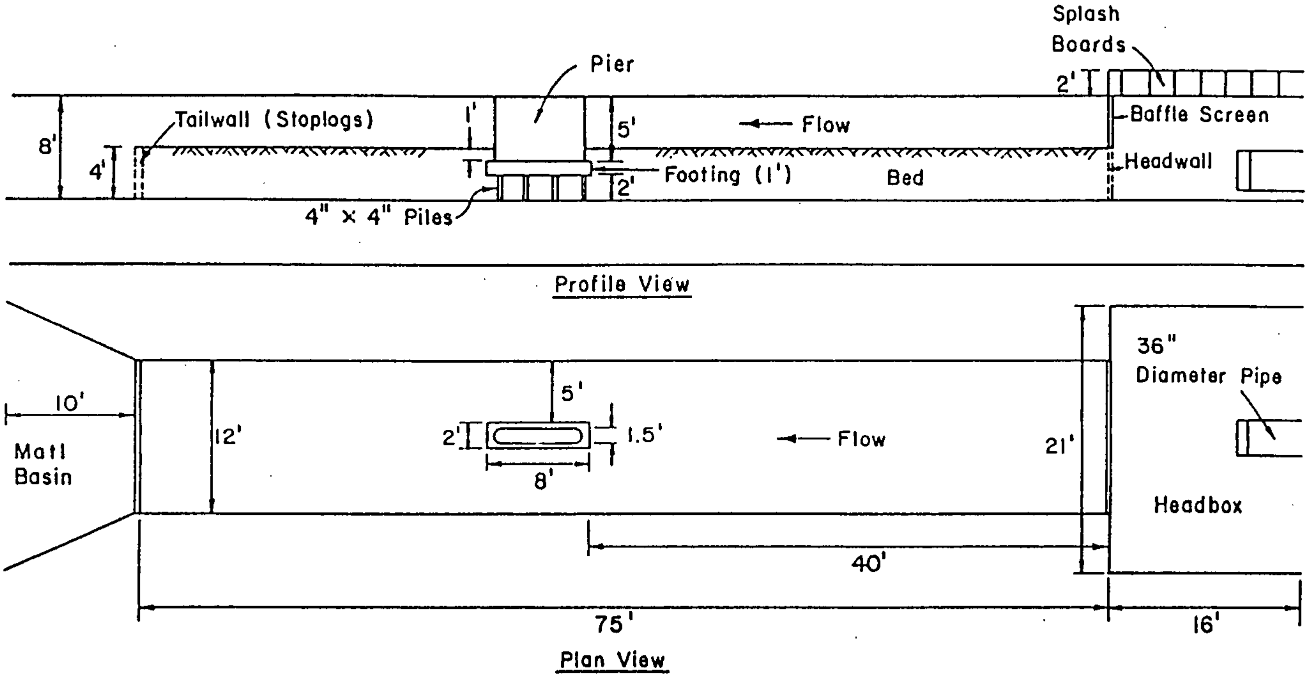

Figure B-2. Schematic of outdoor testing facility.

Figure B-3. Simulated pier support piles.

point gauge was accurate to within 0.003 m (±0.01 ft). Photographic and videotape documentation were recorded before, during, and after each test.

B-2: DESCRIPTION OF FIELD TEST SITES

Colorado

CO1 South Platte River—Highway 144 Near Orchard, Colorado

This bridge site was selected to serve as the local field test site for bridge pier installation of a Brisco Monitor, low-cost sonic instrument system, and prototype installation of a piezoelectric film driven/buried rod device. The bridge is on State Highway 144 near the town of Orchard, CO, (see Figure B-4). The site was selected because of the characteristics of the South Platte River which include significant heavy debris, potential for ice, variable flow, and sand- bed material.

As shown in Figure B-5, the bridge is an old wood structure, approximately 122 m (400 ft) long, with wooden stringers and pile bents. Replacement circular steel piles have been retrofitted as "crutch piles" to support the bridge—many of the original wood piles have deteriorated and broken.

The South Platte River is a perennial, sand-bed channel on the plains east of the Colorado Front Range. The drainage area upstream of the study site is approximately 34,200 km^2 (13,200 mi^2). Although perennial, the river tends to peak in the spring with the snowmelt. Spring rainstorms along the Front Range tend to augment the flow in the river, and the flow can be classified as perennial, but flashy. Furthermore, spring rainstorms tend to dislodge and transport large trees, branches, and other organic debris. Although flows are typically low in the winter, ice conditions are possible. A gaging station, operated and maintained by the USGS (USGS gage number 06758500) is approximately 9.7 km (6 mi) downstream from the bridge site.

CO2: South Platte River—Highway 37 Near Kersey, Colorado

Site CO2 (see Figure B-4) is on the South Platte River about 40 km (25 mi) upstream of Site CO1. Hydrologic, hydraulic, and geomorphic conditions are quite similar (see above). An overview of the Kersey site is shown in Figure B-6.

The left (north) abutment at this site was selected for field test of instrument installation on a paved sloping abutment. The left abutment has a 1:2 sloping slab paving and has experienced scour in the past. Riprap rubble toe protection has been added as a scour countermeasure. This combination of geometric factors, coupled with the flow and geomorphic characteristics of the river provided a challenging site for the research team to test abutment installation techniques and instrument performance under adverse conditions.

New Mexico

NM1 and NM2—Rio Grande, New Mexico

NM1 U.S. 60 near Bernardo (Bridge No. 8580). The Bernardo crossing (NM1, Figure B-7) is in a rural area and classified as a minor arterial (Figure B-8). The bridge is a steel-pile-supported structure relatively low to the water (Figure B-9). Guide banks facilitate flow through the bridge opening, which occurs in a single channel. The bridge has two traffic lanes with a narrow shoulder or emergency lane along each side. The ADT loading in 1988 was 630, but occurs at highway speeds [>80 km/h (>50 mph)] and includes truck traffic. Instrument installation was facilitated by the relatively small diameter, round piers, and limited bridge overhang. A USGS stream gage is just downstream of the bridge.

NM2 U.S. 380 near San Antonio (Bridge No. 3499). The San Antonio crossing (NM2, Figure B-7) is in a rural area and classified as a principal arterial (Figure B-10). The bridge is a steel-pile-supported structure relatively low to the water (Figure B-11). The channel is relatively confined and appears relatively deep. The bridge has two traffic lanes with a narrow shoulder or emergency lane along each side. The ADT loading in 1989 was 1416, but occurs at highway speeds [>80 km/h (>50 mph)] and includes truck traffic. Instrument installation was facilitated by the relatively small diameter, round piers, and limited bridge overhang.

New Mexico Field Site Characteristics

Several possible riverine field test sites were identified in New Mexico. Most of these sites offered year-round operation, anticipated cooperation from local agencies, and rela-

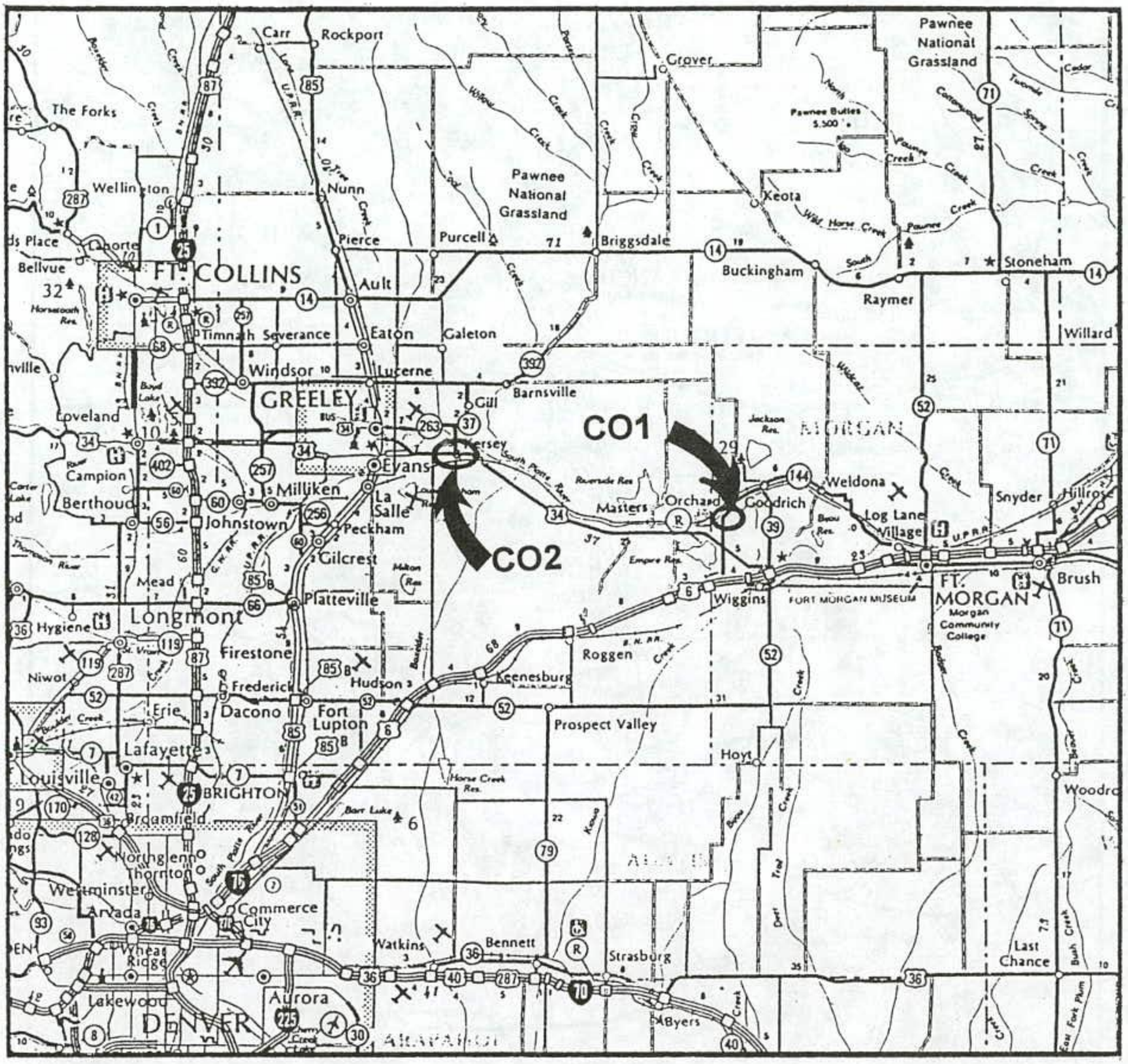

Figure B-4. South Platte River test sites-Highway 144 near Orchard, Colorado (CO1) and Kersey bridge (CO2).

Figure B-5. Photo of Orchard bridge (Site CO1). Flow is left to right.

Figure B-6. Overview of Kersey bridge (Site CO2)-looking downstream.

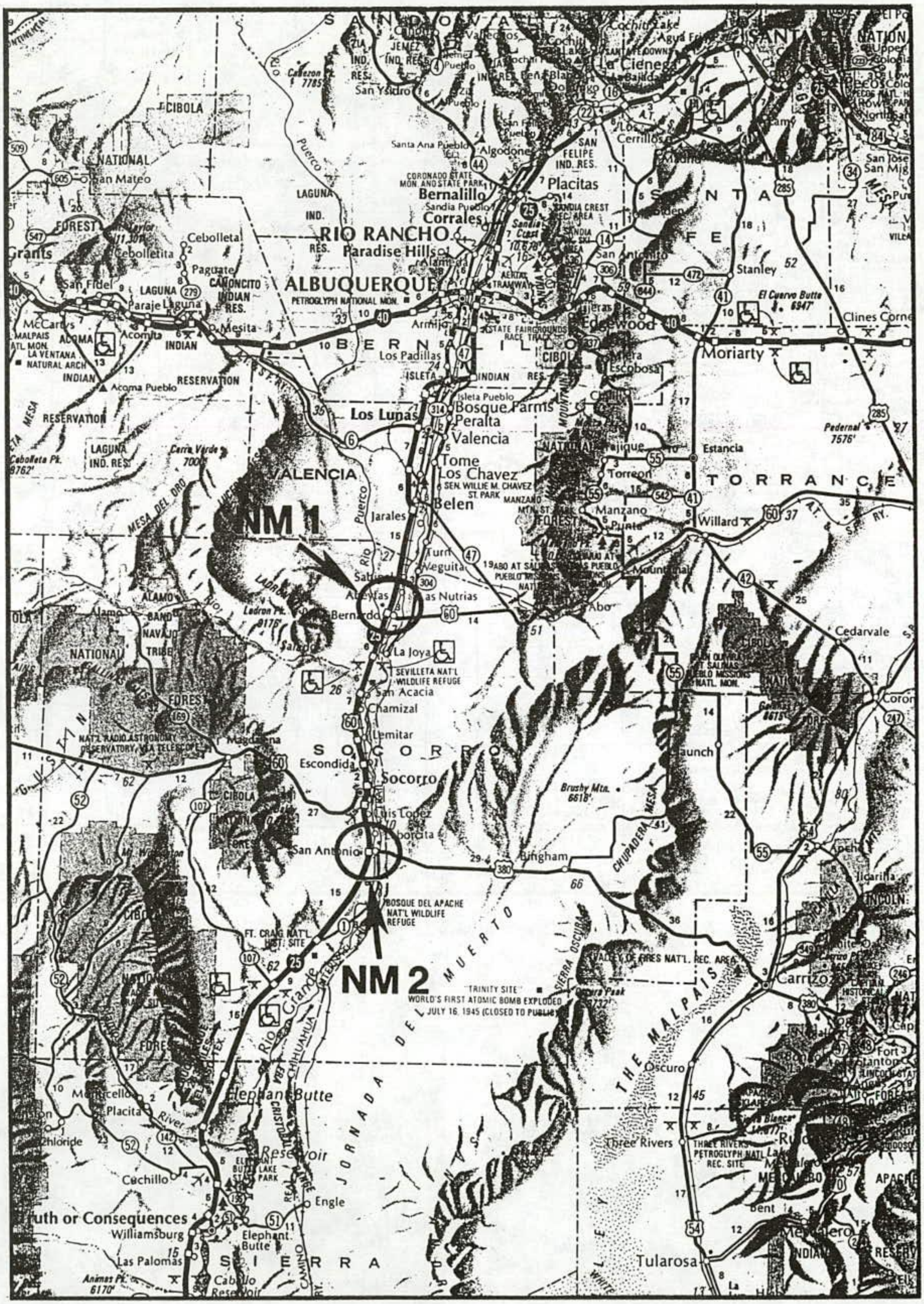

Figure B-7. Rio Grande bridge test sites in New Mexico.

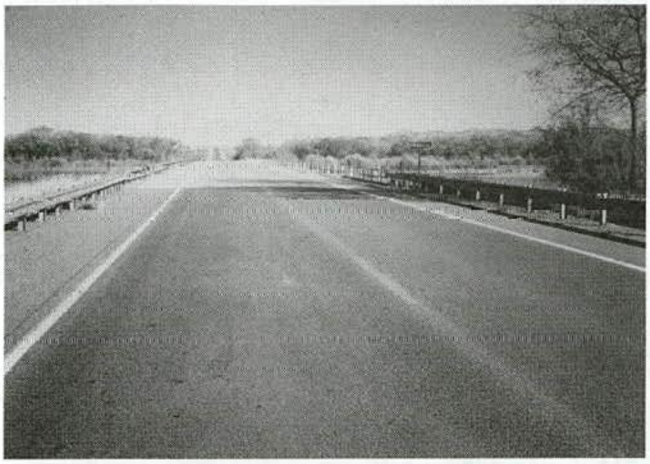

Figure B-8. Bernardo bridge deck (NM1).

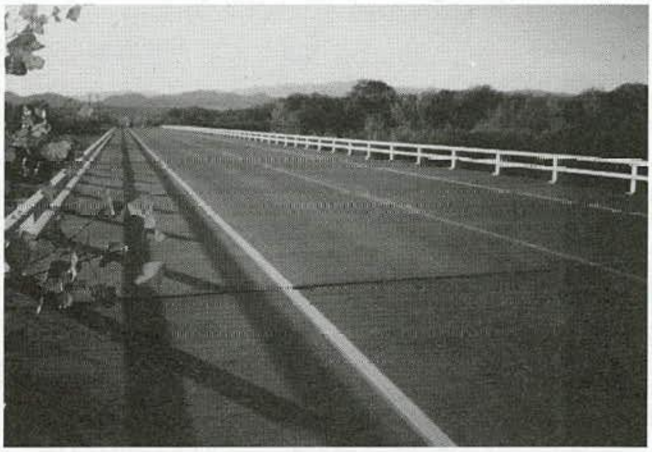

Figure B-10. San Antonio bridge piers (NM2).

tively easy coordination for the research team. Factors considered in site selection included runoff, debris potential, turbidity, sediment load, anticipated scour conditions, available supporting data, bridge geometry as related to instrument installation, safety, and costs.

Runoff in the Bernardo to San Antonio reach of the Rio Grande has been completely regulated by Cochiti Dam since November 1973, and there are literally hundreds of diversions for irrigation. Major diversions influencing flow south of Albuquerque include the Rio Grande Conveyance Channel, Isleta Diversion Dam, and San Acacia Diversion Dam. The Conveyance Channel, which replaced the San Francisco Riverside drain, is the largest project and began controlled diversions in October 1952. The original design called for the Conveyance Channel to carry flows up to about 57 m³/s (2,000 cfs); however, the actual diversion capacity is limited to about 42 m³/s (1,500 cfs) because of groundwater and irrigation return flows that enter the conveyance channel. Because of downstream limitations at Elephant Butte Reservoir, the Conveyance Channel has not been operated since 1985 and probably will not be used soon. Therefore, while some water may be lost from the main channel of the Rio Grande, referred to as the Rio Grande Floodway in USGS water supply records, it was anticipated that adequate water would remain in the Rio Grande (floodway) to allow testing of scour instrumentation.

To illustrate the range of flows that might occur, the streamflow data for USGS gaging station number 08332010, Rio Grande Floodway near Bernardo, were analyzed. An average annual hydrograph for the period since closure of Cochiti Dam was developed by averaging daily flow records for water years 1975–1990 (1974 was not used in order to reduce the effects of reservoir filling on the averaging process). Additionally, on the basis of annual flow volume, a wet and dry year were defined. Figure B-12 illustrates these hydrographs and indicates that in a wet year, flows as high as 170 m³/s (6,000 cfs) could occur, while a dry year would be limited to less than 28 m³/s (1,000 cfs).

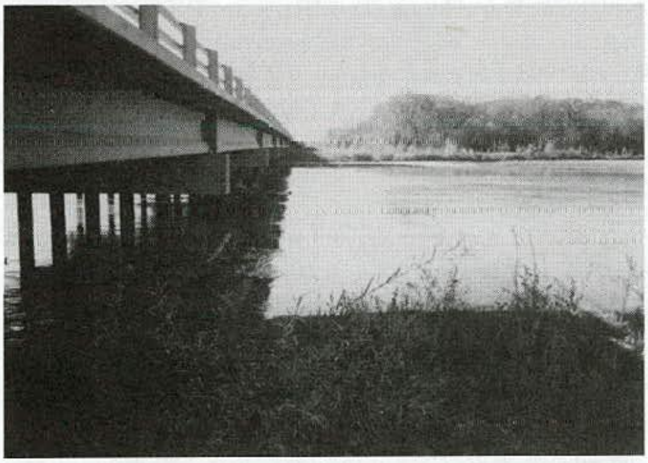

Figure B-9. Bernardo bridge piers (NM1).

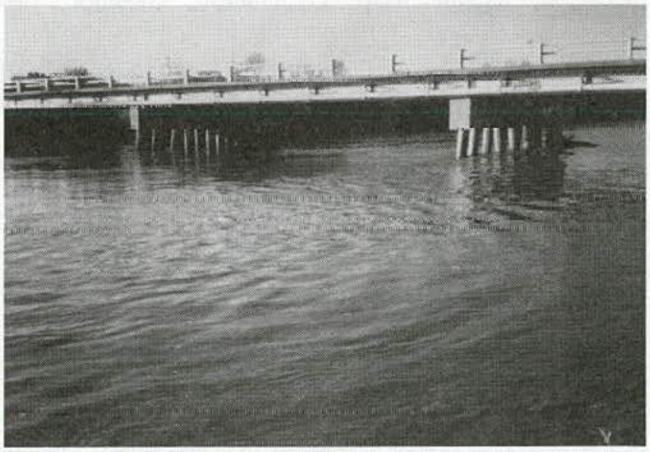

Figure B-11. San Antonio bridge piers (NM2).

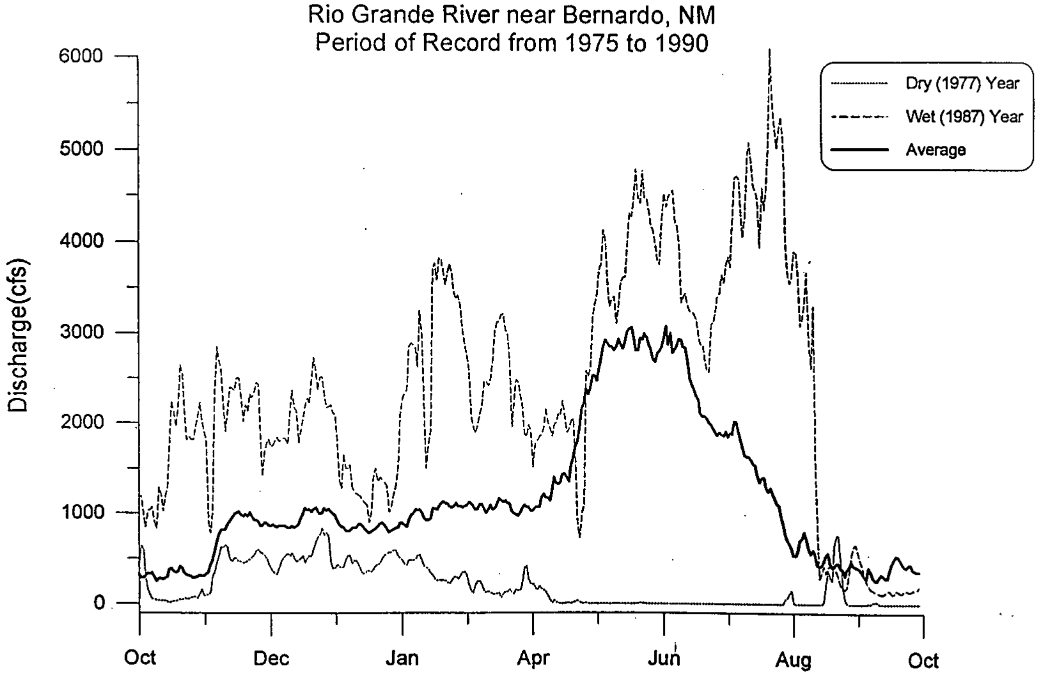

Figure B-12. Rio Grande dry year, wet year, and average annual hydrographs.

Average annual conditions indicate a peak of about 99 m³/s (3,500 cfs).

U.S. Bureau of Reclamation (USBR) personnel have studied the river near the San Antonio bridge site (U.S. 380) and have various data available, including time-sequenced cross-sectional data. The USBR has observed that as discharge increases from 11 to 170 m³/s (400 to 6,000 cfs) and back, the water surface only changes about 152 mm (6 in.), suggesting that major scour and refilling is occurring. The San Antonio bridge was selected because it was likely that some scour would occur even in a low runoff year. Given the angled leading pier and scour-fill cycle, this bridge was considered an ideal candidate for a sonar installation. The round piers would facilitate instrument mounting. The only drawback to this site was traffic moving at highway speeds—although the ADT level was relatively low, work zone safety was important. It was noted that the channel in this reach is well-confined, creating a relatively deep narrow cross section at the bridge. In fact, the cross section in this reach is more like a perennial stream in the midwest than an arid region channel, where cross sections are typically wide and shallow. In addition, all bridges on the Rio Grande experience debris accumulation, and the San Antonio bridge is downstream from the confluence of the Rio Puerco and Rio Grande. The Rio Puerco has experienced some of the highest sediment concentration ever recorded on a river in the United States. These conditions, heavy debris load and high sediment concentration, would severely test a sonic device at this site.

The Bernardo bridge (NM1) was selected in part because of proximity to the San Antonio site and to an established USGS gaging station. The round piers vertically placed provided easy installation for a magnetic sliding collar device. As with the San Antonio site, traffic moves at highway speeds—although the ADT level is low, work zone safety at this site was again important. While the Bernardo site is more typical of an arid region stream, flow is still carried though the bridge in a single channel and provided greater potential for scour at the instrumented pier.

Formal coordination was initiated with the New Mexico State Highway and Transportation Department (NMSHTD) and Districts 1 and 3 for permission to use the Rio Grande bridges at San Antonio and Bernardo. Permission to use these bridges as test sites was received from NMSHTD in March 1993, and research team members visited District 3 in Albuquerque and conducted a final reconnaissance of the bridges to obtain final data and measurements for mounting hardware. A representative from District 1 met them on site at the San Antonio bridge. Detailed plan sheets were obtained for both bridges, and traffic control requirements were discussed with both Districts. The use of a snooper truck from NMSHTD during installation and participation of District personnel at both sites was also discussed. A visit to the U.S. Army Corps of Engineers in Albuquerque revealed that snowpack in the Rio Grande basin was 180 percent of normal and the Corps anticipated a high runoff and substantial releases from Cochiti Dam [193 km (120 mi) upstream of the bridge sites] in the May to June period.

Florida

FL1—Johns Pass Tidal Inlet Near St. Petersburg, Florida

The Johns Pass bridge in FDOT District 7 was selected for installation of a sonar device and has been designated Site FL1. The Johns Pass bridge connects Treasure Island and Madeira Beach on the Gulf Coast near St. Petersburg, FL (Figure B-13). Johns Pass is a natural tidal inlet connecting the Gulf of Mexico with Boca Ciega Bay, a shallow estuary approximately 16 km (10 mi) long and 3 km (2 mi) wide. The four-lane Johns Pass bridge, built in 1971, is a drawbridge with two large bascule piers and ten intermediate bents (Figure B-14).

As early as 1976, severe scour was found in the vicinity of the bridge and, by 1984, the tips of three piles were exposed. The piles were originally driven 6.1 m (20 ft) into the bed, indicating an average annual scour of about 0.5 m (1.5 ft).

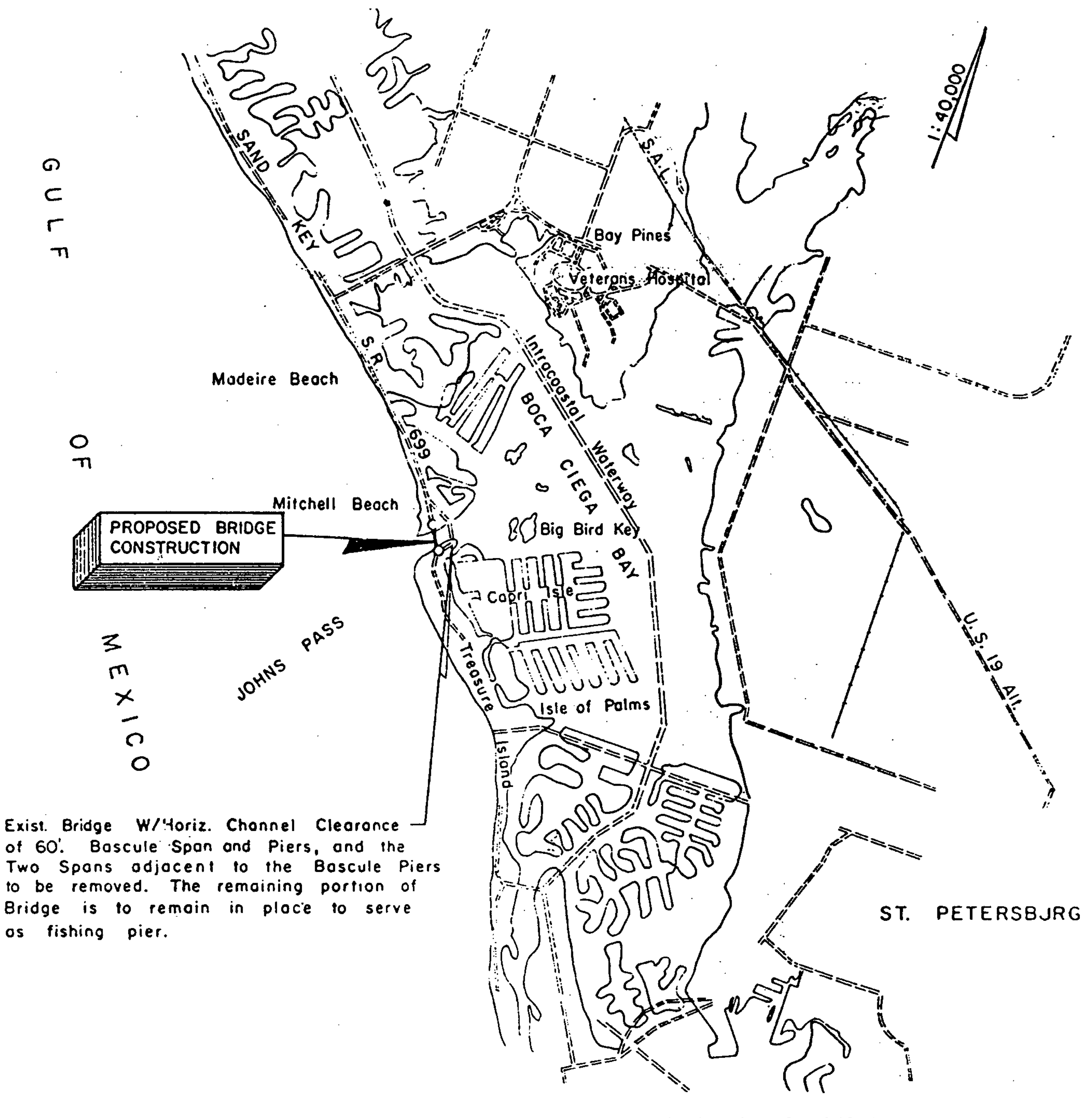

Figure B-13. Location map for site FL1—Johns Pass bridge (from FDOT bridge plans dated 1971).

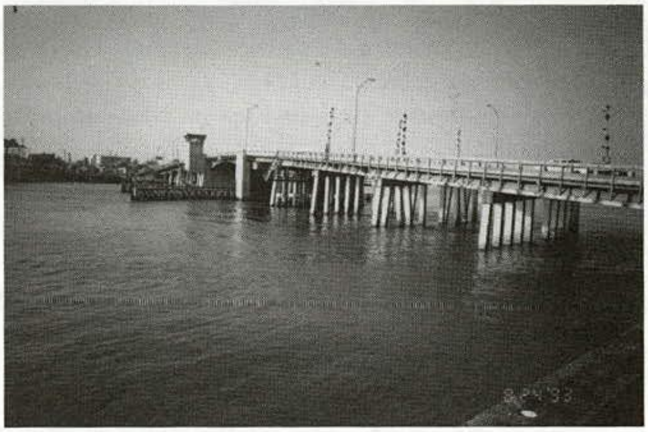

Figure B-14. Johns Pass bridge near St. Petersburg, Florida (Site FL1).

Substrate around the bridge is a hardpan montmorillonite clay that typically would be considered erosion resistant; however, the channel bottom is colonized with a high density of mollusks that burrow into the substrate and promote disintegration and erosion of the surface layer of this very cohesive material. This factor combined with relatively high velocities that inhibit sand deposition from littoral drift, have resulted in ongoing erosion. In the early 1980s, to stabilize the bridge, FDOT installed crutch pilings on four of the intermediate bents and placed riprap on the bascule piers (Figure B-15).

A site reconnaissance of the Johns Pass bridge was conducted in November 1993 and the research team met with both FDOT engineering and dive inspection staff to discuss the scour problem at the bridge. This meeting resulted in a recommended location for instrument installation, and final coordination arrangements were discussed. As-built drawings were provided and the District agreed to provide personnel and equipment to support the installation of the device.

FL2—Nassau Sound Near Jacksonville, Florida

The Nassau Sound Highway 105 bridge crosses the mouth of the Nassau River on the Atlantic coast north of Jacksonville, FL. This site, designated FL2 (see Figures B-16 and B-17), is a very active tidal estuary which has a sand bed and has experienced scour problems in the past. FDOT District 2 has installed crutch piling at several bents near the south bridge abutment as a scour countermeasure (Figure B-18).

A site reconnaissance indicated that this low-level bridge over an active tidal waterway would provide an excellent site to test a sliding collar instrument in a tidal environment.

B-3: TEMPERATURE COMPENSATION FOR LOW-COST SONAR FATHOMETER

Limited laboratory investigations were completed to evaluate the effects of water temperature on low-cost sonar devices. The initial investigation was performed in a 3-m (10-ft) high, vertical Plexiglas water column. Readings with the sonic sounders were recorded and compared to actual depths ranging from 1.9 to 1.4 m (6.25 to 4.75 ft), with overwater temperatures ranging from 36°C to 6°C (96°F to 42°F). Results of this investigation indicated that depth was overestimated by as much as 0.15 m (0.5 ft) at colder temperatures. Based on these results, it was concluded that temperature correction may be required when using low-cost sonar devices in the field.

Review of the initial laboratory study suggested that the experimental design may not have been adequate to fully understand the effects of temperature in actual field applications of low-cost sonar instruments used in bridge scour measurement. In particular, evaluation of larger flow depths was considered necessary. This question was addressed in detail through a comprehensive evaluation of the theoretical aspects of the speed of sound in water and a limited field investigation.

Theoretical Investigations

The speed of sound in any medium is

$$c = \sqrt{K / \rho} \qquad (B.1)$$

where

c = Speed of sound
K = Bulk modulus of elasticity
ρ = Density

Both the bulk modulus of elasticity and density are a function of temperature, and the density of water is further variable with suspended or dissolved solids content.

Applying Equation B.1 for freshwater over a range of 0°C to 100°C (32°F to 212°F) defines the range of the speed of sound in freshwater (Figure B-19). As indicated by Figure B-19, the range is about 1,402 to 1,524 m/s (4,600 to 5,000 fps), with the maximum value occurring at about 49°C (120°F). However, for application to bridge scour measurement in open-channel flow conditions, the maximum practical range of interest is from 0°C to 38°C (32°F to 100°F). Considering this range only, and increasing the graphic scale resolution, provides additional insight on the changes in the speed of sound in conditions typical of bridge scour measurement (Figure B-20). Over any given 5.5°C (10°F) temperature change, the change in the speed of sound ranges from about 6 to 21 m/s (20 to 70 fps).

Most low-cost sonar units cannot be calibrated for potential changes in the speed of sound, but rather, assume a single value for a specific temperature (typically around 16°C [60°F]). Furthermore, even survey grade instruments can only be calibrated for average conditions in a given vertical, because measuring and correcting for actual variations at

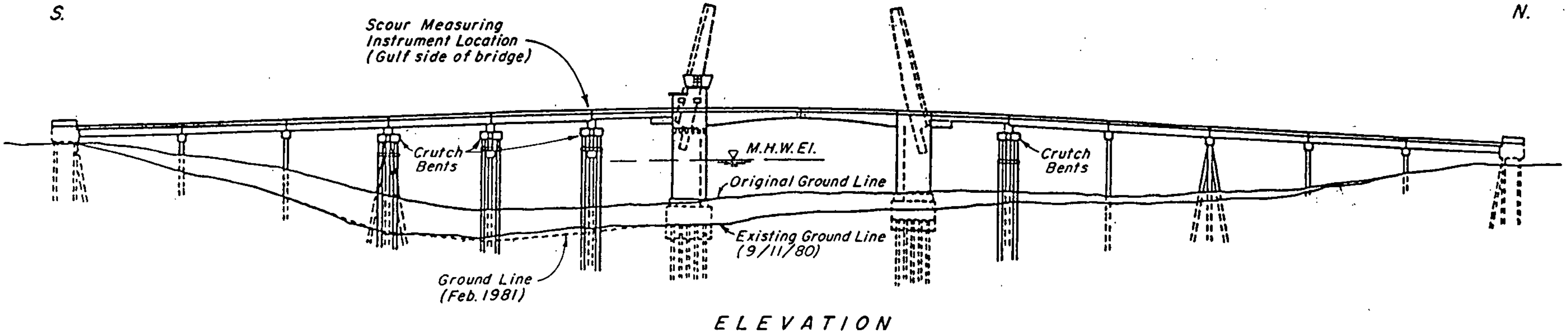

Figure B-15. Johns Pass bridge crutch bents and scour (Site FL1).

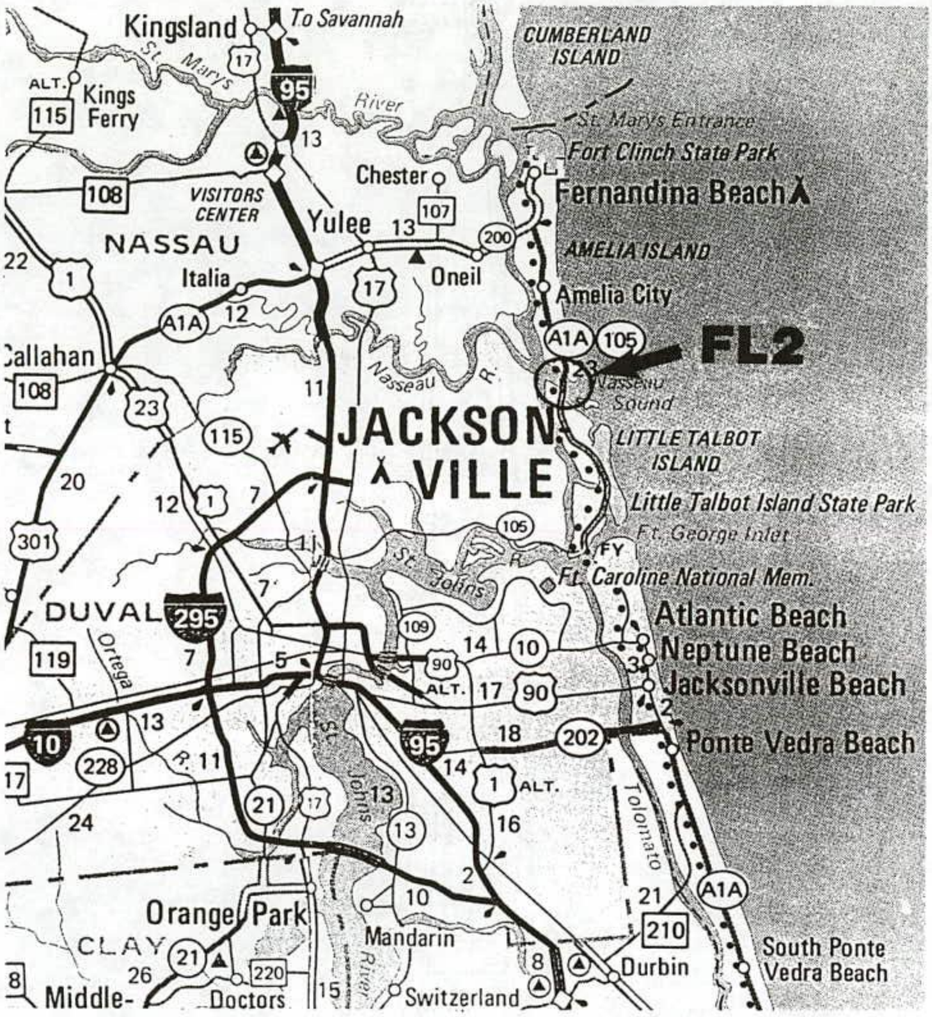

Figure B-16. Location map—Nassau Sound Bridge (Site FL2).

each depth interval is difficult. For the Lowrance fish-finder type units used in much of this research, the speed of sound is assumed to be 1,463 m/s (4,800 fps) (pers. comm., Lowrance Electronics 1993) with no adjustment or calibration possible. This value is about the average value over a temperature range of 0°C to 38°C (32°F to 100°F) and is representative of freshwater water at about 16°C (60°F) (Figure B-20).

Figure B-21 illustrates the error introduced over a range of flow depths when the actual speed of sound deviates from the assumed 1,463 m/s (4,800 fps). This figure was constructed by computing the travel time for a given flow depth and speed of sound from

$$t = (2*d)/c \tag{B.2}$$

where

t = total travel time
d = flow depth
c = speed of sound

The travel time error was then computed for differences between the actual speed of sound and the assumed speed of sound 1,463 m/s (4,800 fps). The error in the travel time was then converted to the error in depth reading based on the assumed speed of sound. A negative deviation of –46 m/s (–150 fps) (i.e., actual speed of sound of 1,417 m/s (4,650 fps)) represents water nearly at freezing, while a positive deviation of 38 m/s (125 fps) (i.e., actual speed of sound of 1,501 m/s [4,925 fps]) represents water at about 27°C (80°F) (Figure B-20). Therefore, the results presented in Figure B-21 represent a realistic range of water temperature conditions that might be encountered in bridge scour measurements when the temperature deviates from an assumed value of about 16°C (60°F) (where the speed of sound is about 1,463 m/s [4,800 fps]).

These results indicate that when the water temperature is near freezing, the maximum flow depth that can be measured without exceeding an error of +0.3 m (+1 ft) is about 9.1 m (30 ft). Similarly, when the water is quite warm (near 27°C [80°F]), the maximum flow depth that can be mea-

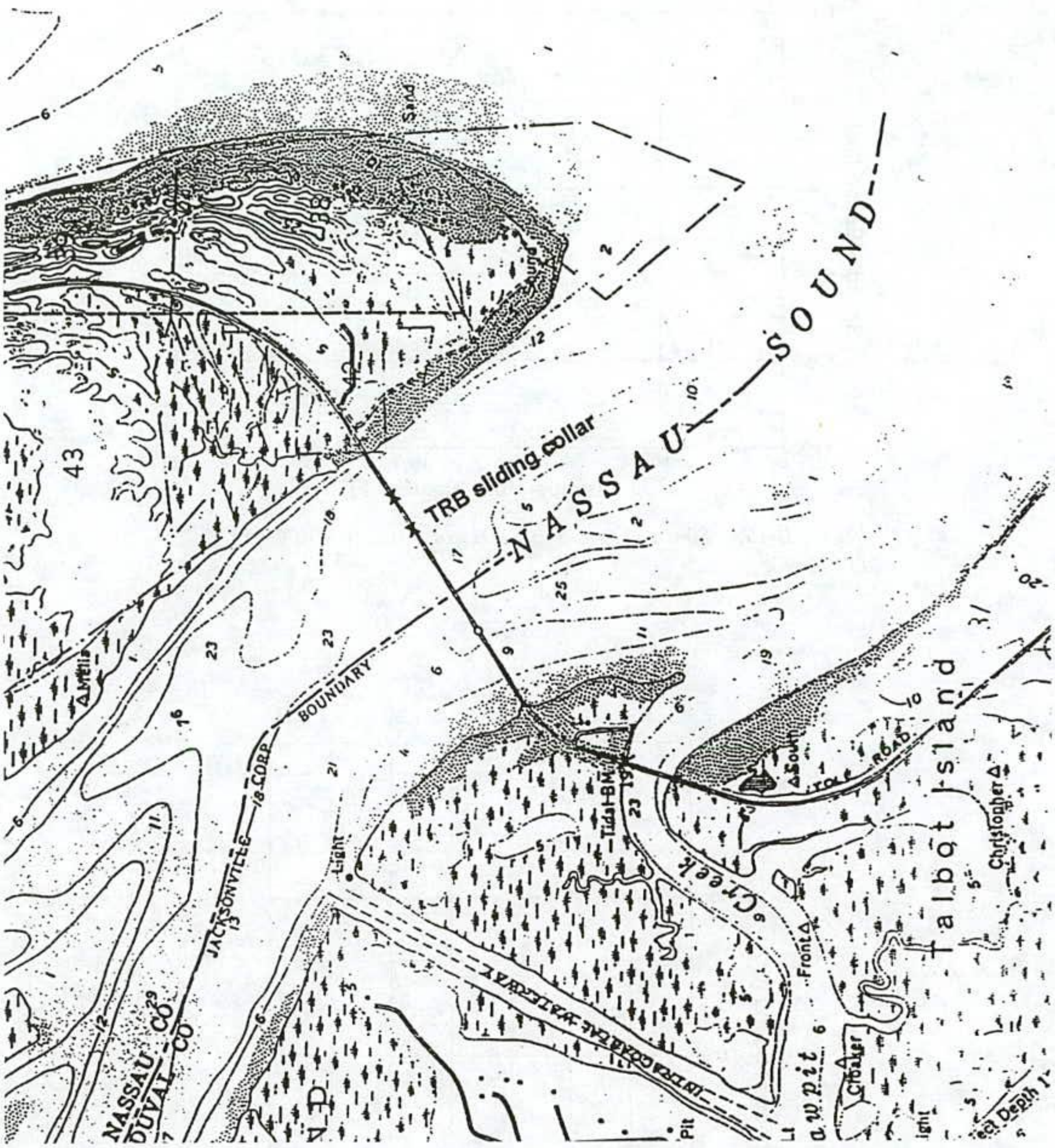

Figure B-17. Nassau Sound bridge (Site FL2) showing location of instrument.

Figure B-18. South abutment , Nassau Sound bridge looking to the north.

sured without exceeding an error of –0.3 m (–1 ft) is about 12 m (40 ft).

The effect of density on the speed of sound also raises concerns about the accuracy and the use of a low-cost sonar unit in a seawater environment. As with freshwater, the density of seawater is a function of temperature; however, seawater density is also a function of salinity. Fortunately, most seawater falls in a narrow range of salinity (typically in the range of 3.3 to 3.5 percent) with a representative value of 3.4 percent often assumed (*B-2*). Figure B-22 compares the speed of sound in seawater (3.4 percent salinity) with freshwater and indicates that the speed of sound is typically about 18 m/s (60 fps) lower at any given temperature. Furthermore, the assumed speed of sound for a low-cost sonar unit (1,463 m/s [4,800 fps]) occurs at about 21°C (70°F) in seawater, rather than the approximate 16°C (60°F) in fresh water.

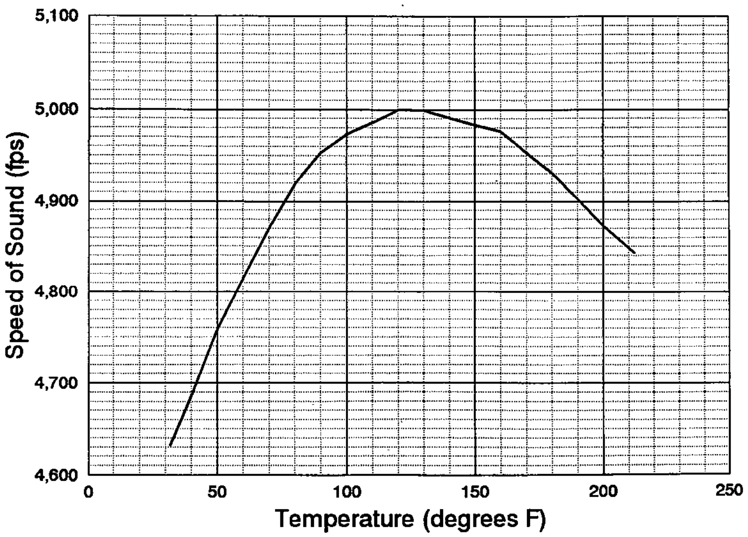

Figure B-19. Speed of sound in fresh water 0°C to 100°C (32°F to 212°F).

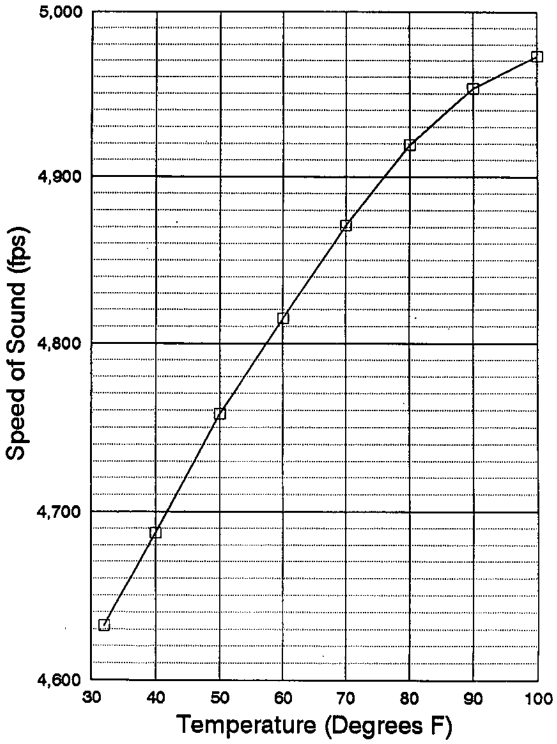

Figure B-20. Speed of sound in fresh water 0°C to 38°C (32°F to 100°F).

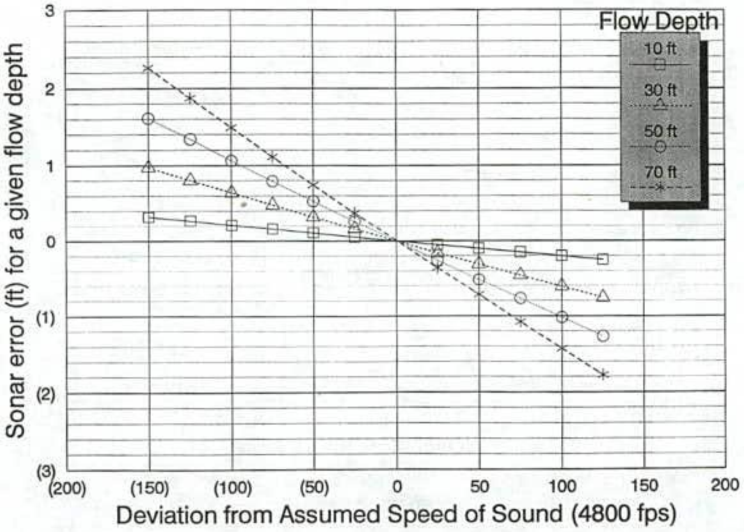

Figure B-21. Sonar error for given flow depths when speed of sound deviates from 1,463 m/s (4,800 fps).

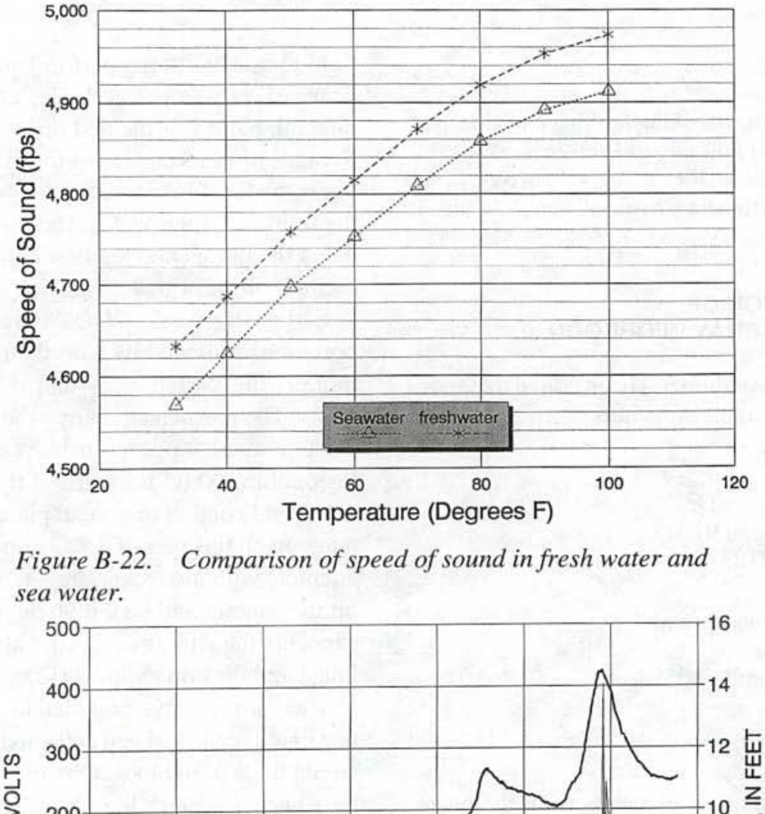

Figure B-22. Comparison of speed of sound in fresh water and sea water.

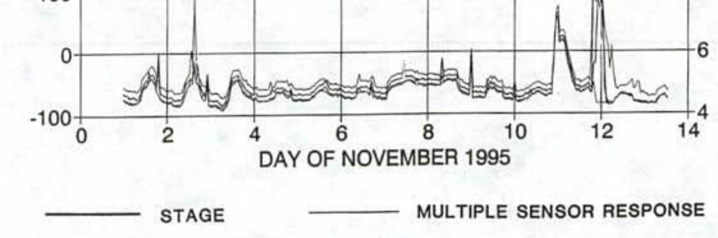

Figure B-23. Piezoelectric driven-rod array data for Sandy River, near Troutdale, OR.

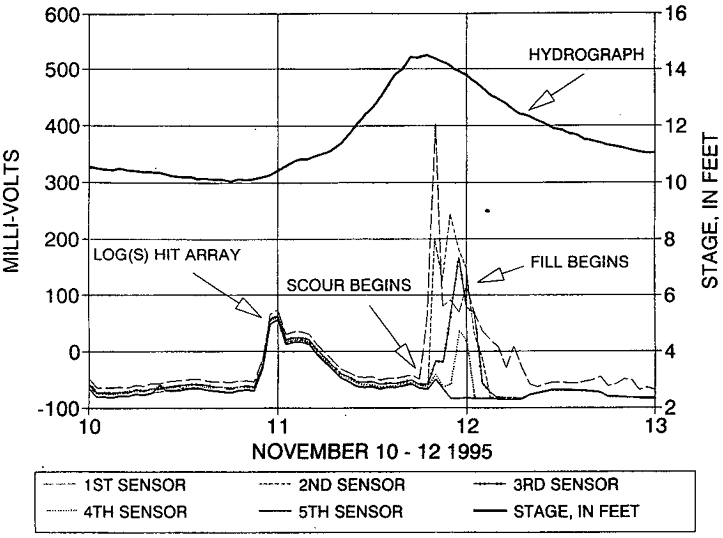

Figure B-24. Data from piezoelectric, driven-rod array located at the Sandy River, near Troutdale, OR.

REFERENCES

B-1. Olsen, R.M., 1973. "Essentials of Engineering Fluid Mechanics," Third Edition, Intext Educational Publishers, New York.

B-2. Fischer, H.B., List, E.J., Koh, R.C.Y., 1979. Imberger, J., and Brooks, N., "Mixing in Inland Coastal Waters," Academic Press, New York.

B-4: USGS INSTALLATION OF PIEZOELECTRIC ARRAY IN OREGON

(Note: The enclosed memorandum has been edited to present only conclusions relevant to this Appendix.)

FROM: Milo Crumrine
18200 S. Clear Acres Dr.
Oregon City, Oregon 97045
Phone: 503-631-2183

TO: ETI Instruments Incorporated
1317 Webster Ave.
Fort Collins, Colorado 80524

DATE: November 28, 1995

Enclosed are two plots that show results from the piezoelectric driven-rod array at Sandy River near Troutdale, OR. I am pleased with the performance of this array. This high-water event was not very big, about a 3-year reoccurrence interval, but it was the first major high-water we have had in a couple of years and it was the first storm of the year. As you know the first high-water of the year carries more debris than the following high-water. The high-water changed the channel at the bridge and really scoured out the streambed in the vicinity of the bridge.

Earlier this week, ODOT (Oregon Department of Transportation) provided us with their divers so we could determine if the switch array and the piezoelectric array were intact. The piezoelectric array took some major hits, you can see one at 11:00 p.m. on November 10th, from logs. The logs, some 100 ft long and 3–4 ft in diameter, really bent the 1-in. rigid conduit in several places. There were several logs hung up on this pier - ODOT removed the logs, after several attempts with a wrecker, they rented a log skidder. One log hit the conduit and bent it 90 degrees, breaking the pipe and exposing the wire inside. After all the abuse, the wire stayed intact and the array still works.

These arrays have provided us with good scour data. Data that could not have been collected by any other means. Sonar would have been blocked by the logs, a sliding collar would have been part of the log-jam after the first hit, and hand measurements by any method would have been suicidal.

APPENDIX C

PORTABLE SONIC SOUNDERS FOR GROUND TRUTH

The initial "portable sonar" unit developed for ground truthing activities at the Rio Grande test sites in New Mexico (NM1 and NM2) was a Lowrance LMS-200 graphic sonar mounted in a toolbox with a small sealed gel-cell battery to allow portability. The battery could be recharged in a vehicle by plugging into the cigarette lighter or at the office by plugging in a built-in trickle charger. Transducer selection was influenced by flow conditions, including high velocities, turbulence, and sediment transport. A small torpedo weight was made with an 8° disk-style transducer as an integral part of the streamlined torpedo body; however, as constructed, there was not enough weight to hold horizontal position in velocities greater than about 0.9 m/s (3 fps). During high-flow conditions, the velocities throughout much of the cross section at both bridges (NM1 and NM2) exceeded this amount and an alternate system was required.

Because the Rio Grande test bridges were not high off the water, an extendible painter's pole (up to 7.3 m [24 ft]) was used successfully with the transducer attached to the bottom of the pole. In high velocities the drag on the transducer was significant which limited how deep into the water the transducer could be placed. Results indicated that only a narrow cone transducer (8°) would function in the high sediment concentrations typical of the Rio Grande, particularly at low-flow depths (less than 0.9 to 1.2 m [3 to 4 ft], down to a minimum of about 457 mm [18 in.]). This was attributed to the more concentrated energy of the narrow cone and the smaller areal coverage limiting the scatter of the sound wave by suspended sediment. Note that the ability to operate in sediment-laden water is also a function of the sonar output power. The LMS-200 is a relatively high power unit at 75 watts RMS and has advanced signal processing capabilities to assist in discriminating noise.

Although the "tool box" instrument facilitated ground truthing during frequent site visits, its size and weight still made it cumbersome for one person to operate. Using a small dash-mount style sonar with digital readout only, a more portable instrument was developed. The instrument selected for use was an Interphase model DG-1 with a narrow cone transducer. The low current drain of this sonar (less than 0.3 A) allowed powering it by a smaller battery source. To minimize the overall size of the instrument, conventional hobby remote control (RC) battery packs were used with a 1,500 milliamp hours. These ni-cad battery packs are readily available and can be quickly recharged (15 min each) using an RC battery charger that plugs into a cigarette lighter or household current. Two 7.2-volt battery packs wired in series provided the proper voltage to operate the sonar. The sonar and battery packs were mounted in a PVC pipe not much bigger than a flashlight (76-mm [3-in.] diameter, 254-mm [10-in.] long) and equipped with a neck strap to allow a one-person operation (see Figure C-1). The transducer was again mounted to a 4.9-m (16-ft) painter's pole.

One limitation of this instrument was its low power (35 watts) and lack of more sophisticated signal processing capability. Consequently, it did not work well in sediment-laden flows and had a minimum depth capability of 10.7 m (35 ft). Further testing of this instrument found that the instrument functioned well in tidal water, where there may be significant turbidity, but relatively little suspended sediment. Figure C-2 shows this device being used on a bridge with a 7.3-m (24-ft) painter's pole supporting the transducer. Testing and evaluation of a higher powered (approximately 75 watts), yet relatively small sonar unit proved equally effective and provided a device that is lightweight and portable, yet functional in sediment-laden, riverine conditions.

The need for ground truth at larger bridges typical of tidal waterways led to the development of a pontoon-type float built of PVC pipe sections to position the transducer (Figure C-3). A 0.9- to 1.8-m (3- to 6-ft) painter's pole with a hook on the end was used to maneuver the cable over the side of the bridge and position the float. This device performed well

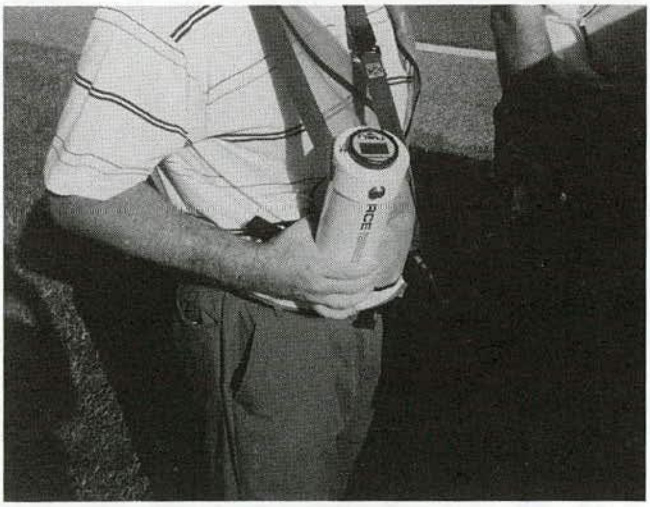

Figure C-1. Digital readout unit for ultra low-cost sonic sounder.

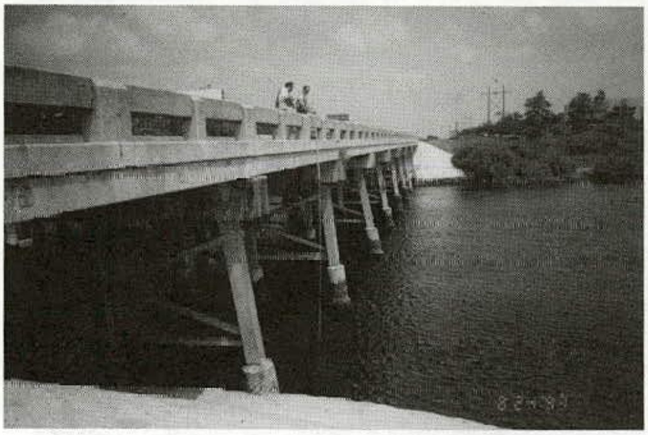

Figure C-2. Transducer on 2.4- to 7.3-m (8- to 24-ft) extendable pole used for sounding during FDOT scour evaluations (Anlote River, Highway 19, Pinellas County, FL).

Figure C-3. Float-mounted sonic transducer sounding in 14.6 m (48 ft) of water, Johns Pass bridge near Clearwater, FL.

in tidal water conditions, up to moderate velocities (e.g., 0.9 m/s [3 fps]), and was effective on bridges as high as 15.2 m (50 ft) off the water when a standard transducer extension cable was used. Although this device worked well in tidal flows, because of the relatively small size of the float, there could be problems in high-velocity riverine flows if significant wave disturbance existed. Alternate float/weight arrangements could be developed for ground truthing in high-velocity flows when an extendible pole support is not feasible.

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Abbreviations used without definitions in TRB publications:

AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ITE	Institute of Transportation Engineers
NCHRP	National Cooperative Highway Research Program
NCTRP	National Cooperative Transit Research and Development Program
NHTSA	National Highway Traffic Safety Administration
SAE	Society of Automotive Engineers
TCRP	Transit Cooperative Research Program
TRB	Transportation Research Board
U.S. DOT	U.S. Department of Transportation

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