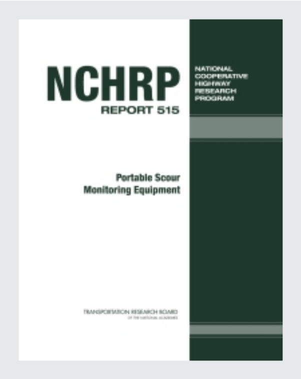

Portable Scour Monitoring Equipment

DETAILS

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP REPORT 515

Portable Scour Monitoring Equipment

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SUBJECT AREAS
Bridges, Other Structures, and Hydraulics and Hydrology • Soils, Geology, and Foundations • Maintenance

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TRANSPORTATION RESEARCH BOARD

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FOREWORD

By Timothy G. Hess
Staff Officer
Transportation Research Board

This report presents the findings of a research project undertaken to develop portable scour monitoring equipment for measuring streambed elevations at bridge foundations during flood conditions. The report provides specific fabrication and operation guidance for a portable scour monitoring device. The fabrication guidance is of sufficient detail to allow a highway agency to build a similar device. The report describes the results of detailed testing of the scour monitoring device at ten bridge sites in seven different states. This report will be of immediate interest to bridge engineers and bridge operation and maintenance personnel with responsibility for determining the safety of bridge foundations during flood events.

Scour monitoring at bridges is often necessary for protecting the traveling public during floods. Although fixed scour monitoring equipment has been developed and is readily available, it is not feasible to install fixed scour monitoring equipment on all bridges. Each year, many bridges are subjected to severe flood conditions and scour. Decisions about bridge closure are often based on streambed elevations around piers and abutments measured with portable scour monitoring equipment such as weights and echo sounders. Although existing portable monitoring equipment is adequate in some situations, many common field situations occur where existing equipment is not adequate. Common scour monitoring problems can be separated into two categories: difficult flow conditions (e.g., high velocity, air entrainment in the water column, and high sediment concentrations) and difficult site conditions (e.g., high bridges, low clearance under bridges, floating debris, and ice accumulations). These problems are common during flood events, when the need for streambed elevation information is most critical. There is a need for a portable scour monitoring device that can be used to measure streambed elevations around bridge foundations in difficult flow and site conditions during flood events. The inability to assess the safety of bridges during flood events accurately has resulted in some bridges being closed unnecessarily, causing traffic delays and increased expenses, while other bridges that should have been closed were not, resulting in increased risk to the public.

Under NCHRP Project 21-07, Ayres Associates developed a portable scour monitoring device for measuring streambed elevations and the depth of scour around bridge piers and abutments during flood events. The research team reviewed the literature to identify existing technology suitable for use in developing a scour monitoring device. Key criteria in technology selection were cost and portability. Feasible alternatives were investigated and the most promising alternative was selected for development. The research resulted in a scour monitoring device that was both portable and capable of measuring scour during actual flood events and extreme conditions. The device can be used at a wide variety of bridge geometries, including high bridges, bridges with limited clearance, and bridges with large overhangs. A comprehensive data collection software package was developed to allow immediate access to the collected data and the instantaneous plotting of channel section and scourhole bathymetry. The findings of this research will significantly enhance the capabilities of highway agencies in assessing the extent of bridge scour during flood events and making bridge closure decisions with increased confidence.

CONTENTS

PORTABLE SCOUR MONITORING EQUIPMENT

SUMMARY

Approximately 584,000 bridges in the National Bridge Inventory (NBI) are built over streams. Many of these bridges span alluvial streams that are continually adjusting their beds and banks. Many of these bridges will experience problems with scour and stream instability during their useful life. In fact, the most common cause of bridge failure is scouring of bed material from around bridge foundations during flooding.

Scour and stream instability problems have always threatened the safety of the U.S. highway system. The National Bridge Inspection Standards (NBIS) require bridge owners to maintain a bridge inspection program that includes procedures for underwater inspection. Furthermore, a national scour evaluation program as an integral part of the NBIS was established by the FHWA in 1988. As a result of the scour evaluation program, more than 26,000 bridges were classified as "scour critical" in 2002.

FHWA policy specifies that a plan of action should be developed for each bridge identified as scour critical. The two primary components of the plan of action are instructions regarding the type and frequency of inspections to be made at the bridges and a schedule for the timely design and construction of scour countermeasures. The purpose of the plan of action is to provide for the safety of the traveling public and to minimize the potential for bridge failure by prescribing site-specific actions that will be taken at the bridge to correct the scour problem.

A well-defined monitoring program is an important aspect of the plan of action and could incorporate various fixed and portable scour instrumentation devices. During the last 10 years, significant research and progress has been made with fixed instrumentation. However, fixed instrumentation is not suitable, practical, or cost-effective for all bridges. In many cases, portable monitoring during a flood is a better solution; however, not much research has been completed to improve this type of technology.

Conventional methods of portable monitoring are built on physical probing and sonar; however, both these techniques have limitations during flood events when the flow depth and/or velocity are high. As a result, critical decisions on bridge safety during floods have been hampered by the limitations of the existing equipment and its application. Without adequate scour data during flood events, some bridges have been closed unnecessarily, causing traffic delays and increased expenses, while other bridges that should have been closed were not, resulting in increased risk and liability.

The objective of this research was to improve deployment, positioning, and data collection procedures for portable scour monitoring during flood conditions. The research

concentrated on developing a truck-mounted articulated crane to position various measurement devices quickly and safely. The use of a crane for scour monitoring provided a solid platform for deployment, even under flood flow conditions, that could be instrumented to allow precise measurement of the movement of the crane. Given the availability of knuckle booms or folding cranes in the construction industry, the research was designed around modifying and instrumenting this type of articulated crane for use in scour monitoring research.

The result of the research was a fully instrumented articulated arm truck. The articulated arm truck was designed using readily available components whenever possible. These components and pieces were also designed to be a bolt-on installation, so that the articulated arm truck could be readily used for other purposes outside of the flood season. In fact, many transportation agencies already have articulated arm trucks that could be retrofitted for scour monitoring work based on the design concepts developed through this research.

A streamlined probe to position a wireless sonar was developed to allow measurement in the high-velocity conditions during a flood. Using this probe, the sonar could be positioned directly in the water nearly 30 ft (9.1 m) below the bridge deck. Once in the water, the crane could be rotated in an arc to collect data continuously upstream of the pier. The truck could also be driven across the bridge with the crane extended to collect a cross section profile quickly. A dual winch application of traditional cable suspended techniques was developed to facilitate working off higher bridges. Other deployment methods were developed to allow working off various bridge configurations, including a wireless sonar in a sounding weight and in a kneeboard deployment with a rigid frame.

Using the articulated arm truck with different sensor deployment methods allows a wide variety of bridge geometries to be monitored during flood events, including high bridges, bridges with limited clearance, and bridges with large overhangs. A comprehensive data collection software package was developed that facilitated the use of the articulated arm, providing the inspector immediate access to the data collected. Collection of position and scour data is automated, and a data file is written that allows plotting of channel section or scour hole bathymetry.

The articulated arm met most, but not all, of the criteria defined for this research. The research did not solve the measurement problems associated with debris and ice, which have been, and probably will continue to be, the nemesis of portable scour monitoring (as they are with fixed instrument monitoring). However, the articulated arm did substantially improve the ability to make measurements in high-velocity flow during flood conditions. These measurements can be completed from various bridge geometries using a truck that is affordable and maneuverable. The data collection process has been automated, and the scour data are presented in the bridge coordinate system, allowing rapid evaluation of scour criticality. Overall, the ability to make portable scour measurements during flood flow conditions has been substantially improved.

CHAPTER 1

INTRODUCTION AND RESEARCH APPROACH

PROBLEM STATEMENT

Scour monitoring can be completed by either fixed or portable instruments. Fixed instruments are those that are installed and left at the bridge and typically involve a sensor for making the scour measurement, a power supply, and a data logger. More recently, telemetry has become a common component of many fixed instrument systems. During the last 10 years, significant research and progress has been made with fixed instrumentation, through research activity, commercial development, and field installations, often completed by state transportation agencies. However, fixed instrumentation is not suitable, practical, or cost-effective for all bridges. In many cases, portable monitoring during a flood is a better solution, and yet not much research has been completed to improve this type of technology.

Physical probing has been used for many years as the primary method for portable scour monitoring by many state transportation agencies. More recently, sonar has seen increased use, in part because of the technology transfer provided through the FHWA Demonstration Project 97 (DP-97), "Scour Monitoring and Instrumentation" (*1*) and through the efforts of the U.S. Geological Survey (USGS) in supporting state scour programs. However, probing and sonar techniques both have limitations during flood events when the flow depth and/or velocity are high. Low flow monitoring during the 2-year inspection cycle with this type of technology has been effective and is used by many state transportation agencies; however, critical decisions on bridge safety during flood flow conditions have been hampered by the limitations of the existing equipment and its application. As a result, some bridges have been closed unnecessarily, causing traffic delays and increased expenses, while other bridges that should have been closed were not, resulting in increased risk and liability.

For example, during the 1994 flooding in Georgia, more than 2,100 bridges were checked during the flood and approximately 1,000 of these were closed (*2*). Many of these bridges were checked by an experienced inspection crew who had good communication during the measurements with bridge maintenance engineers, who were making closure decisions. The inspection crew used a fathometer deployed from the bridge deck, typically using a transducer mounted on a range pole. Georgia is to be commended for the prompt action, and through these efforts no lives were lost as a result of bridge failures. Yet, although the decision to close 1,000 bridges probably saved lives, it also crippled the transportation system in the flooded area (*2*). It is possible that, because of limitations of existing portable scour monitoring equipment, some bridges were closed unnecessarily, while others perhaps should have been closed to reduce the risk to the traveling public and/or to minimize structural damage to the bridge.

Another indication of the need for better portable scour monitoring technology was the widespread interest in the portable instrumentation lecture and demonstration presented during DP-97. In some cases, this might have been because portable instrumentation was perceived as a quick, low-cost entry into scour monitoring activities. However, more often it was related to a real desire to learn more about portable instrumentation and application techniques because many of the participants had faced the real-world problems presented by attempts at making portable instrument measurements during flood flow conditions.

RESEARCH OBJECTIVE

The objective of this research was to develop improvements and/or alternatives to existing portable scour monitoring equipment and techniques for measuring stream bed elevations at bridge foundations during flood conditions. The equipment and techniques developed should be operational under the following conditions:

- Flow velocities exceeding 11 fps (3.5 m/s)
- High sediment concentrations
- Floating debris
- Ice accumulation
- Limited clearance
- Pressure flow
- Overhanging or projecting bridge geometries
- Bridges with decks more than 50 ft (15 m) above the water
- Air entrainment
- Easily used and affordable by state and local bridge owners
- Transportable by pickup, van, or similar vehicle
- Accuracy of +/– 12 in. (30 cm)

RESEARCH TASKS

The research project was conducted in two phases. The first phase was designed to identify the most promising alternatives and to develop a work plan for testing under Phase II. Phase II consisted of prototype development, testing, and documentation. The specific research tasks defined to achieve the research objective were as follows:

- **Phase I**
  - — Task 1. Literature Review
  - — Task 2. Identify Alternative Technologies
  - — Task 3. Work Plan
  - — Task 4. Interim Report
- **Phase II**
  - — Task 5. Prototype Development and Limited Testing
  - — Task 6. Detailed Field Testing
  - — Task 7. User Manuals
  - — Task 8. Final Report

RESEARCH APPROACH

The purpose of Task 1 was to identify a wide range of technologies and procedures with either a direct or indirect relationship to portable scour monitoring. The next step was to sort through that information to identify the most promising technologies that should be considered as part of this research effort. This was a comprehensive analysis that considered advantages, limitations, purchase and operational costs, potential problems, and other important features or considerations.

The identification of the most promising technologies included consideration of the wide range of instrumentation capability and proficiency within different transportation agencies throughout the United States. While some states would welcome very high-technology solutions and procedures, others may prefer a simpler approach. It was considered unlikely that only one technique or procedure would be developed.

Based on the findings from Tasks 1 and 2, the work plan for the Phase II research was refined and improved to better ensure a successful research effort (Task 3). The interim report presented the results of Tasks 1, 2, and 3, and provided the basis for discussion of the Phase II work effort with the NCHRP project panel.

The objective of the Phase II research was to develop prototype devices and conduct laboratory and field testing. Development of prototype devices was necessary to provide instrumentation for the testing program, which included limited testing during development (Task 5), and then more widespread testing in cooperation with state transportation agencies across the country (Task 6). The final results of the research were documented in two reports, a users manual intended to provide enough information to replicate the preferred prototype devices (Task 7), and the final report documenting the entire research effort (Task 8).

CHAPTER 2

FINDINGS

LITERATURE SEARCH

Information Sources

The literature search was completed by investigating as many sources of potential information as possible. This included searching various computer literature databases, review of results from recent international scanning tours, assembly of relevant information obtained during the presentation of DP 97, and review of various trade publications.

A search of various computer literature data bases did not identify many references on portable scour monitoring. Databases searched included the following:

- The TRB TRIS,
- The National Science Foundation,
- The American Geophysical Union Water Resources Research,
- The American Geophysical Union Earth and Space Index,
- ASCE Publications, and
- USGS Publications.

Keywords used included instrumentation, scour, bridge scour, and scour monitoring. The most common source of literature was various bridge scour symposiums held at ASCE Water Resource Engineering Conferences from 1991 to 1998. These papers have been consolidated into a single reference, "Stream Stability and Scour at Highway Bridges" (*3*). The 1999 symposium is available through the conference proceedings.

Similarly, not much information was available from recent scanning tours. A 1998 Scanning Review of European Practice for Bridge Scour and Stream Instability Countermeasures was undertaken primarily to review and document innovative techniques used to mitigate the effects of scour and stream stability. This tour was organized under the auspices of FHWA's International Outreach Program by AASHTO through TRB. Although the focus of the tour was not scour measurement or instrumentation, results were reviewed in that context, and several contacts made in Europe were revisited, by e-mail and telephone, to identify any potential portable scour instrumentation techniques.

DP 97 was developed by the FHWA to facilitate technology transfer of instrumentation-related research to the highway industry. The objective was to promote at the state and local level the use of instrumentation, both existing and new technology, to measure and monitor scour at bridges. The demonstration project was presented over 30 times to nearly 1,000 people between 1996 and 1999. Attendees often included inspectors and others responsible for field work, including bridge scour measurements sometimes made with unique and innovative equipment developed in house. To identify and document such experience and knowledge, the course evaluation forms from the various courses were reviewed and, in selected instances, requests for additional information or documentation were made to given states.

Trade publications, such as *Ocean News* and *Sea Technology*, also have articles and advertisements for specialized hydrographic survey equipment. Although most of this technologically may not be directly applicable to scour measurements, because of size, complexity, or cost of the equipment, these magazines were reviewed for potential ideas and equipment sources.

Literature Review Findings

As described by Mueller and Landers (*4*), any portable scour measuring system includes four components:

1. An instrument for making the measurement,
2. A system for deploying the instrument(s),
3. A method to identify and record the horizontal position of the measurement, and
4. A data-storage device.

The following sections describe the results of the literature review for each of these four components.

Instrument for Making the Measurement

The results of the literature review identified a range of methods for making a scour depth measurement during a flood. In general, these methods can be classified as follows:

- Physical probing,
- Sonar,

- Geophysical, and
- Other methods.

Physical Probes. Physical probes refer to any type of device that extends the reach of the inspector, the most common being sounding poles and sounding weights (*1*). Sounding poles are long poles used to probe the bottom. Sounding weights, sometimes referred to as lead lines, are typically a torpedo-shaped weight suspended by a measurement cable. This category of device can be used from the bridge or from a boat. An engineer diver with a probe bar is another example of physical probing. Physical probes only collect discrete data (not a continuous profile) and their use can be limited by depth and velocity (e.g., during flood flow condition) or debris and/or ice accumulation. Physical probes are not affected by air entrainment or high sediment loads and can be effective in fast, shallow water.

Sonar. Sonar instruments (also called echo sounders, fathometers, and acoustic depth sounders) measure the elapsed time that an acoustic pulse takes to travel from a generating transducer to the channel bottom and back (*1*). Sonar is an acronym for **SO**und **NA**vigation and **R**anging that was developed largely during World War II. However, early sonar systems were used during World War I to find both submarines and icebergs and called ASDICs (named for the Antisubmarine Detection Investigation Committee). As technology has improved in recent years, better methods of transmitting and receiving sonar and processing the signal have developed, including the use of digital signal processing (DSP). The issues of transducer frequency (typically around 200 kHz) and beam width are important considerations in the use of sonar for scour monitoring work.

Applications of single-beam sonar range from "fish finders" to precision survey-grade hydrographic survey fathometers. This type of instrument has been widely used for bridge scour investigations, particularly the use of low-cost fish-finder type sonar instruments. Based on work completed in part for the National Scour Study, Mueller and Landers (*4*) recommended a low-cost echo sounder (preferably a paper chart, and if not, a graphical display), and a tethered kneeboard to deploy the transducer for use in bridge inspection work. Their work also included development of a prototype remote-control boat for unmanned data collection. In 1994, Schall et al. (*5*) reported on the use of a similar device based on a fish finder and several different float designs for deploying the transducer, including a pontoon-style float and a foam board.

Other types of sonar, such as side scan, multi-beam, and scanning sonar, are specialized applications of basic sonar theory. Side scan sonar transmits a specially shaped acoustic beam to either side of the support craft. These applications often deploy the transducer in a towfish, normally positioned behind and below the surface vessel. Although side scan sonar is one of the most accurate systems for imaging large areas of channel or ocean floor, most side scan systems do not provide depth information. Multi-beam systems provide a fan-shaped coverage similar to side scan, but output depths rather than images. Additionally, multi-beam systems are typically attached to the surface vessel, rather than being towed. Scanning sonar works by rotation of the transducer assembly, or sonar "head," emitting a beam while the head moves in an arc. Because the scanning is accomplished by moving the transducer, rather than towing, it can be used from a fixed, stationary position. Scanning sonar is often used as a forward-looking sonar for navigation, collision avoidance, and target delineation.

Mellor and Fisher (*6*) reported on the use of side scan sonar at tidal bridges in North Carolina. Their study found good results with 100- and 500-kHz side scan imaging of large bridges, mapping significant areas both upstream and downstream of the bridges that revealed areas of erosion, deposition, and paths of sediment transport. However, they expressed concern about collection of side scan data during storm events and commented on the laborious effort required to deploy and control the towfish.

The Sonar Scour Vision™ system was developed by American Inland Divers, Inc (AIDI) using a rotating and sweeping 675-Khz high-resolution sonar (*7*). The transducer is mounted in a relatively large hydrodynamic submersible, or "fish," that creates a downward force adequate to submerge the transducer in velocities exceeding 20 fps (6 m/s). Given the forces created, the fish must be suspended from a crane or boom truck on the bridge. From a single point of survey, the system can survey up to 325 ft (100 m) radially. Data collected along the face of the bridge can be merged into a real-time 3-dimensional image with a range of 300 ft (90 m) both upstream and downstream of the bridge.

A low-cost scanning sonar was recently developed by Interphase Technology, Inc. The Interphase Twinscope™ uses a phased array scanning technology to provide an affordable navigational sonar with the ability to look far forward and to the sides of the vessel.

Geophysical. Surface geophysical instruments are based on wave propagation and reflection measurements. A signal transmitted into the water is reflected back by interfaces between materials with different physical properties. A primary difference between sonar and geophysical techniques is that geophysical methods provide subbottom, while sonar can only "see" the water-soil interface and is not able to penetrate the sediment layer. The main differences between different geophysical techniques are the types of signals transmitted and the physical property changes that cause reflections. A seismic instrument uses acoustic signals, similar to sonar, but at a lower frequency (typically 2–16 kHz). Like sonar, seismic signals can be scattered by air bubbles and high sediment concentrations. A ground penetrating radar (GPR) instrument uses electromagnetic signals (typically 60–300 mHz), and reflections are caused by interfaces between materials with different electrical properties. In general, GPR will penetrate resistive materials and not conductive materials. Therefore, it does not work well in dense, moist clays or saltwater conditions.

A comprehensive investigation on the use of geophysical techniques in bridge scour was completed by Placzek and Haeni (*8*). In this investigation, measurements were typically taken at lower flow conditions and used to locate scour holes and areas of infilling. Results of this study demonstrated that geophysical techniques can be successfully used for bridge scour investigations. At the time of this investigation the cost and complexity of the equipment and interpretation of the data appeared to be limiting factors for widespread use and application. These issues have moderated as newer, lower-cost GPR devices with computerized data processing capabilities have been developed. However, GPR may still be limited by cost and complexity and, often, the need for borehole data and accurate bridge plan information to calibrate and interpret the results properly.

Horne (*9*) reported on the results of a GPR investigation of bridges in New York. A 300-Mhz antenna floating on the water was most successful in penetrating silty, granular material in less than 2 meters of water. The availability of soil boring and samples provided both ground truth data and, more important, information to calibrate the natural material properties, such as density and gradation, with the radar wave travel time.

A related investigation used GPR for high flow measurements by positioning the antenna above the water, which avoids the problems of placing instruments in the water at flood flow conditions (*10*). Results indicated that it was possible to estimate channel cross sectional area to within +/– 20 percent, or better; and, if the radar signal is calibrated to the specific site and time of measurement, the estimate is within +/– 10 percent.

Other. Based on the results of the literature review, two additional methods were identified that might have application to portable scour measurements. One alternative is a small underwater camera, either alone or in combination with a sensor making a scour measurement. Such cameras are typically used for video inspection of pipe systems, boreholes, water wells, and tanks. Other applications include navigation cameras for remotely operated vehicles (ROVs) working offshore. Offshore cameras are often designed for either low-light or long-range viewing. Prices for combined video and lighting units start at about $3,000. The primary complications for their use in scour monitoring include the ability to position the camera close enough to see the scour hole in highly turbid water and to maintain adequate stability in the extremely turbulent conditions that exist in or near the scourhole.

Another alternative is the potential application of a green laser as a sensor. Green lasers can operate in water up to depths of 70 ft (21 m); however, because these lasers are not yet developed as a distance-measuring device and are still proprietary to the Department of Defense, they are not currently an option. They may become viable in the future with more research and development.

System for Deploying the Instrument

The system for deploying the scour instrument is a critical component in a successful portable scour measurement system. In practical application, particularly under flood flow conditions, the inability to position the instrument properly is often the limiting factor in making a good measurement. The use of different measurement technologies from different deployment platforms can produce a wide variety of alternative measurement approaches.

Deployment methods for portable instruments can be divided into two primary categories:

- From the bridge deck and
- From the water surface.

Bridge Deck Deployment. Bridge deck deployment fell into two categories: non-floating and floating (*4*). Non-floating systems generally involved standard USGS stream-gaging equipment and procedures, including the use of various equipment cranes and sounding weights for positioning a sensor in the water. This category could also include devices that use a probe or arm with the scour measurement device attached to the end. Probes or arms include things as simple as an extendable pole or rod (such as a painter's pole) to a remotely controlled articulated arm. Hand-held probes or arms are not generally useable at flood flow conditions.

The Minnesota DOT has developed an innovative boom and sounding weight setup using a boom with a standard four-wheel drive winch for raising and lowering the sounding weight and a standard rope/wire rope counter for measuring the sounding distance. The boom, built by their maintenance shop at a very reasonable cost, is long enough to allow positioning the weight under various flow and bridge conditions.

A prototype articulated arm to position a sonar transducer was developed under an FHWA research project (*11*). An onboard computer calculated the position of the transducer based on the angle of the boom and the distance between the boom pivot and transducer. Additionally, the system could calculate the position of the boom pivot relative to a known position on the bridge deck. The system was mounted on a trailer for transport and could be used on bridge decks from 15 to 50 ft (5–15 m) above the water surface. Field testing during the 1994 floods in Georgia indicated that a truck-mounted system would provide better maneuverability and that a submersible head or the ability to raise the boom pivot was necessary to allow data collection at bridges with low clearance (i.e., less than 15 ft or 5 m).

Other sources of articulated arm technology include concrete pumper trucks and other devices built primarily for the construction industry, such as those used to handle drywall sheets and concrete block. The latter type of devices might be a lower cost, commercially available option to a custom-built articulated arm.

Another non-floating approach that might have application in scour monitoring is the use of the towed data acquisition vehicles used in the offshore industry. These tethered vehicles submerge some distance below the water surface based on a servo-control elevator. Smaller, lower cost towed vehicles are available (about $5,000), with a cargo body in the 20-in. (50-cm)-wide range that can carry several pieces of equipment. Most are equipped with onboard electronics to measure and record depth and pitch data.

Float-based systems permit measurement beneath the bridge and beside the bridge piers. Tethered floats are a low-cost approach that has been used with some success during flood flow conditions. Various float designs have been proposed and used to varying degrees for scour measurements, typically to deploy a sonar transducer. Common designs include foam boards, PVC pontoon configurations, spherical floats, water skis, and kneeboards (*1*). The size of the float is important to stability in fast-moving, turbulent water. Mueller and Landers (*4*) suggested using a conventional kneeboard with a nylon-covered Kevlar braid around the transducer cable to provide a single tether with adequate strength and abrasion resistance. They also reported good results under limited flood flow testing with a PVC style pontoon float.

Floating or non-floating systems can be also be deployed from a bridge inspection truck, an approach that is particularly useful when the bridge is high above the water. For example, bridges that are higher than 50 ft (15 m) above the water typically are not accessible from the bridge deck without using this approach.

Water Surface Deployment. Water surface deployment typically involves a manned boat; however, because of safety issues related to flood conditions, the use of unmanned vessels has been suggested. The use of manned boats generally requires adequate clearance under the bridge and nearby launch facilities. This can be a problem at flood conditions when the river stage may approach or submerge the bridge low chord and/or boat ramps may be underwater. Smaller boats may be easier to launch, but safety at high flow conditions may dictate use of a larger boat, further complicating these problems.

As an alternative to a full-sized survey boat, some companies have developed a personal watercraft completely equipped for hydrographic surveying. These systems typically include a survey grade fathometer, a survey grade global positioning system (GPS), and radio communications to transmit data to a shore computer.

When clearance is not an issue, the current and turbulence in the bridge opening may be avoided using one of the tethered floating or nonfloating methods described above from a boat positioned upstream of the bridge. For example, a pontoon or kneeboard float with a sonar transducer could be maneuvered into position from a boat holding position upstream of the bridge, thereby avoiding the current and turbulence problems at the bridge itself.

Because of the safety, launching, and clearance issues, that an unmanned or remote control boat might be a viable alternative has been suggested. A common use of unmanned vessels has been in the offshore industry where ROVs have been widely used for oceanographic research. Recent improvements in technology for electrically powered systems lead to more low-cost ROVs (LCROVs) that have been developed primarily for use in inspection and observation. LCROV prices start at about $10,000, and their application to inland operations, typically in shallow water, has been growing rapidly. Such vehicles have been used for bridge footing inspections, dam and penstock inspections, boat salvage, intake and outlet inspections, and so forth. It is unknown if any of these systems would have enough power to operate in a river at flood flow conditions.

Investigation of remote control boats for bridge scour data collection was completed by Skinner (*12*) and Mueller and Landers (*4*). Remotely controlled boats have been designed for hydrographic surveying in reservoirs, but such boats typically do not have enough power to perform well in a river, particularly at flood flow. Skinner's design objectives focused on a relatively small, portable system that could be readily deployed from the bridge deck. He concluded that a small, flat-bottom, propeller-driven boat using an electric motor, and either a tether or acceptance of a lower design velocity, might be feasible for bridge scour applications.

Mueller and Landers (*4*) developed a prototype unmanned boat using a small flat-bottom jon boat and an 8-hp outboard motor with remote controls. The boat included a wet-well to deploy instruments through the hull and was successfully tested during six flood events.

Large-scale remotely controlled power boats might be an alternative for a remotely controlled, unmanned vessel. These boats range from 3 to 5 ft (1 to 1.5 m) in length and use conventional gas engines, often a modified gas engine from a line trimmer, which might have the power to operate in a river. This style of boat was first developed in the early 1980s and has become quite popular because of its ease of operation and low maintenance. These boats are commercially available, ready-to-run, for under $1,000. Given the size of the hull, the payload should be fairly large and yet, the boat could still be deployed from the bridge deck, and the motor would be powerful enough to work at flood flow conditions. Alternatively, the engine and controls could be purchased and used on a different style hull, such as a small, flat-bottom design. This type of hull might have more payload and stability, at the expense of top speed, which is not a concern for this application.

Method to Identify and Record the Horizontal Positions of the Measurement

In order to evaluate the potential risk associated with a measured scour depth, it is necessary to know the location of the measurement, particularly relative to the bridge foundation. Location measurements can range from approximate methods, such as "3 ft (1 m) upstream of Pier 3," to precise locations based on standard land and hydrographic surveying technology. A good review of these methods as applied to portable scour measurement is provided in the DP-97 class notes (*1*) and by Mueller and Landers (*4*).

The most significant improvement in the approach to location measurement for portable scour applications may be in the use of GPS. Over the last 10 years, GPS has revolutionized the way surveyors perform geodetic and control surveys on land. GPS is a positioning system that makes use of a "constellation" of satellites orbiting the earth. Perhaps one of the greatest advantages that GPS provides over traditional land-based surveying techniques is that line-of-sight between control points is not necessary. A GPS survey can be completed between control points (even on opposite sides of a mountain) without having to traverse or even see the other point. GPS also works at night and during inclement weather, which could be a real advantage for scour monitoring during flood conditions. The most significant disadvantage of GPS is the inability to get a measurement in locations where overhead obstructions exist, such as tree canopy and, in the case of scour monitoring, bridge decks.

The use of GPS technology has similarly changed the way hydrographic surveys are performed. The rapid changes and improvements in GPS technology, along with reduced cost, make this technology increasingly viable for portable scour measurements. For example, various manufacturers have a survey-grade, waterproof GPS receiver with a built-in antenna, memory, battery, and radio. These models are typically quite compact and could be used on a boat and possibly even on a floating or non-floating deployment system to track the position of the scour measurement continuously. Data collection under a bridge deck is still restricted, but it is often possible to get some distance under the bridge before all satellite coverage is lost, particularly on bridges that are relatively high above the water. This type of technology is rapidly making most other traditional hydrographic surveying positioning methods (such as automated range-azimuth systems) obsolete.

The accuracy necessary for survey operations requires the use of differential global positioning systems (DGPS). In DGPS, two or more receivers are used: one or more receivers are set up over known points (base stations), and a remote (or rover) GPS receiver is used to locate unknown points. Any errors in the system are defined by the base stations and a differential correction is applied to the rover. Differential processing can be accomplished through an existing network of base stations operated and maintained by various governmental or private agencies. Alternatively, base stations in the survey area can be established over known points to provide the differential corrections. Given that the accuracy of the survey is a function of the rover's distance from the base stations, greater accuracy is often achieved using the latter technique.

With more widespread use of GPS, more base station networks have been established. The Coast Guard created one of the first networks of base station data along coastal areas that transmitted corrections on a marine radio frequency. More recently, a Nationwide DGPS (NDGPS) network is being developed by a seven-agency partnership under a DOT initiative to provide DGPS for public safety services. This network will extend throughout the country, not just the coastal areas. In other places, state agencies, sometimes in cooperation with universities, have established local DGPS networks.

The use of DGPS with lower cost GPS receivers, such as those developed primarily for precision farming applications, may be a viable alternative for bridge scour monitoring. This approach is capable of sub-meter accuracy. An even lower cost GPS option is the recreational variety designed for sportsmen. The accuracy of these units may limit their application; however, as technology continues to improve, these could become a viable low-cost alternative when sub-meter accuracy is not necessary. Currently, such units cost less than $500 and typically provide position information within 30 to 65 ft (10 to 20 m) accuracy. With DPGS, accuracy of 3 to 16 ft (1 to 5 m) is possible even with these low-cost GPS receivers.

Data Storage Devices

Data storage devices include hydrometeorological data loggers, laptop computers, and, more recently, Personal Digital Assistants (PDAs). Data loggers provide compact storage; however, they are generally not very user-friendly with each company typically having a unique programming language and approach.

In field applications, laptop computers are bulky and need to be ruggedized to survive the rain, dirt, and dust of a field environment. PDAs may prove useful as their capability and user-friendliness continue to improve. The advantage to these approaches is the ability to integrate data reduction software, such as plotting or topographic mapping programs, to visualize the results, often in real time while the data collection occurs.

Questionnaire

To document recent information and experience of state transportation agencies, a survey was sent by mail to every State Hydraulic Engineer. In order to keep the survey short and to ensure a higher return rate, the primary objective of the survey was simply to identify what states use portable techniques, what those techniques consist of, and what are their common problems and limitations in field application. A total of 31 surveys were returned.

The type of equipment or procedures identified included the usual probing, weighted lines, fish-finder sonar, and diving. The most common response was sonar, particularly for flood monitoring. Not surprisingly, success was considered better during routine inspection work rather than during flood monitoring.

Of the 25 general comments and observations received in Part C of the survey, 10 specifically mentioned that the equipment should be easy to deploy and use. These comments included phrases such as *easily attached to existing vehicles;*

deployed easily; operate with one person; more idiot proof; rapid deployment without traffic control; easily deployed; easy deployment; small hand-held point and shoot device; and, *Simple system that . . . can be used in high velocity flood water.* Five comments referred to the need for data logging, with phrases such as *better data recording; digital recording; downloaded to a PC; . . . keep track of the information;* and, *data logging capability.* Four also commented specifically on the need for durability with descriptors such as *more bullet-proof; durable enough . . . ; rugged and dependable;* and, *. . . take a beating.* Four commented on cost through words/phases such as *inexpensive; price . . . won't sell otherwise; cost . . . such that each district has ready access;* and, *. . . low cost.*

These conclusions are consistent with results reported by Mueller and Landers (*4*) from a similar survey effort. From their survey, they concluded the following:

- Transportation agency personnel use various techniques and equipment, including sounding weights and sonar devices.
- Most responses indicated that simplicity of operation is the most important functional characteristic.
- Other important features were portability and size, durability, cost, and the ability to provide permanent records.
- An important operational criterion was the need to limit personnel requirements and supporting equipment.
- Most respondents considered $1,000 a reasonable price per unit.

From this and other information received from the questionnaire, the researchers concluded that a bridge inspection system should do the following:

- Measure streambed elevation.
- Be easily transportable and durable.
- Operate in water velocities of at least 13 fps (4 m/s).
- Be hand deployable.
- Be operable by one or two persons (preferably one).
- Be able to measure under the bridge and along the sides of piers and abutments.
- Provide a graphical or numerical display (permanent record is optional).
- Provide depth measurement accuracy of about 1 ft (0.3 m).
- Be powered by small portable batteries.

FEASIBLE ALTERNATIVES

The objective of this research was to develop improvements and/or alternatives to existing portable scour monitoring equipment and techniques for measuring stream bed elevations at bridge foundations during flood conditions. Under flood conditions, the velocity of flow, sediment transport, and air entrainment can be high; debris loading can be a problem; and various different bridge geometries will be encountered by the inspector attempting to make these measurements. Given these conditions, which represent the actual conditions that bridge inspectors must often work under, it is unlikely that one instrument or device will meet all the desirable criteria and several different types of equipment will probably need to be developed.

Based on the literature review, various observations and findings concerning portable scour monitoring techniques can be made. In particular, the combined results and conclusions from the two survey/questionnaire efforts provide significant insight on what people in the field using portable equipment would like to have, and this defined a fairly clear mandate for the proposed research. Specifically, devices that are relatively simple to operate and deploy, provide data logging capability, and that are durable and reasonably priced, seem to be high priorities. These characteristics are consistent with low-cost and easily transportable items in the criteria list defined as part of the research objective and suggest that complex, high-technology approaches are not desirable. However, in certain cases, this may complicate meeting some of the other suggested criteria.

The following sections discuss specific findings for each component of a scour measuring system. As stated above, the four components of a portable scour measurement system are as follows:

1. An instrument for making the measurement,
2. A system for deploying the instrument(s),
3. A method to identify and record the horizontal position of the measurement, and
4. A data-storage device.

The use of different measurement technology (Item 1) from different deployment platforms (Item 2) could produce various alternative approaches. For example, it may be that the measurement technology is not dramatically new (e.g., physical probing or sonar), but the deployment techniques are improved to facilitate flood flow monitoring and application from high bridges or bridges with low clearance.

Alternatively, the measurement device might be something new or not currently used for scour monitoring deployed in a more traditional manner from the bridge deck or from a bridge inspection boat. Ideas include some of the offshore industry technology using side scan or multi-beam sonar, towfish, autonomous underwater vehicles (AUVs), and/or the use of underwater video cameras and flood lights. As will be described below, the research plan was directed more toward improving deployment techniques.

Instrument for Making the Measurement

Results from the literature review and questionnaire suggest that there are no innovative approaches currently available for measuring scour depth. The idea of an underwater camera and the application of a green laser were introduced as possible scour monitoring devices, but both have serious limitations. The conventional methods (physical probing, sonar, and geophysical), have all been used with varying degrees of success in flood monitoring work. Because of the drag forces created by high velocity and flow depth at flood flow conditions, physical probing is generally not a viable approach. Large sounding weights have been used successfully at flood flow, but this approach can be somewhat slow and tedious. The technology for this type of measurement is already well developed and there is no apparent need to research or develop this method beyond current practice.

Sonar technology, particularly single-beam methods often completed with fish-finder type devices, are widely used for scour monitoring. Although sonar has been used successfully for portable scour measurements, getting a good reading in shallow flow, high suspended sediment, and high-velocity conditions can be difficult. More complex sonar equipment, including side scan and scanning systems, have been used only on a limited basis and may be too complex and expensive for widespread use. One advantage of the more complex sonar techniques, particularly when implemented with a towfish (as used in the offshore industry), might be the ability to complete a measurement at a debris-laden pier by allowing the current to carry the towfish to the edge of, and perhaps even under, the debris pile. However, this could be a hazardous operation and could result in the loss of the towfish if it became entangled in the debris. An alternative is the low-cost scanning sonar sold by Interphase, which would reduce the economic risk of this approach, but not the hazards involved in implementing it.

Although geophysical technology continues to improve, with reduced cost and easier operation, the widespread application of these devices for scour monitoring may still be limited by cost and complexity. If the radar antenna could successfully be placed above the water surface for measurement of the channel bottom, this could be a very useful and powerful methodology.

System for Deploying the Instrument

Bridge deck deployment methods are generally well developed and include standard sounding reels, cranes, and sounding weight technology from the USGS and custom-fabricated boom devices, such as those developed by Minnesota DOT. Another option is the use of a commercially available boom (often called a non-articulating crane). These deployment approaches can be used for a direct physical probing (sounding weight measurement) or for positioning a sensor, such as a sonar transducer. A floating platform (e.g., kneeboard or pontoon float) is typically deployed directly from the boom cable and allowed to drift into position. This method generally works well, but can be more difficult on bridges that are high above the water surface or when the current is quite fast.

With additional research and development, the articulated arm could solve some difficult deployment problems, but the FHWA prototype that was developed may be limited in potential application by cost and complexity. The research report for this prototype (*11*) indicated that the original plan was to develop an inexpensive, basic, and minimal system for deploying a depth sounding transducer from a pickup truck on bridges that were within 20 ft (6 m) of the high-water surface. As the project progressed, it was decided to build a larger prototype that would have greater flexibility and wider application for field testing. The resulting product was a custom-fabricated articulated arm that was never widely adopted or implemented. If a commercially available articulated crane from another industry, such as the construction materials industry, could be adapted for scour monitoring applications, a lower cost device might be possible.

A towed acquisition vehicle, similar to that used in the offshore industry might be a viable approach for positioning a sensor when the device can be controlled from a boat upstream of the bridge or possibly using a crane off the bridge deck. This idea is similar to the towfish approach often used for side-scan sonar, but could be used with other measurement approaches, including simpler sonar devices. Boat-based application would limit this approach to larger rivers with boat ramp access and bridges without clearance problems. Although this idea has merit and might allow measurement under a debris pile, this operation is considered inherently dangerous.

Water surface deployment by unmanned boats offers several advantages for flood monitoring work, including safety, access issues, and the ability to work at both low and high clearance bridges. Development of this concept will require research on boat hulls and propulsion systems.

Method to Identify and Record the Horizontal Position

The ability to measure and then record position data appears to be a high-priority criterion for any proposed system. The results of the survey/questionnaire suggested that those who have been using portable scour instruments would like the efficiency of a fully automated system. Specifically, not having to write data in a field book, as is often done with approximate methods (e.g., . . . *scour depth of 12.5 ft at a location 3 ft in front of pier 8* . . .) or trying to merge land survey based measurements of position with independent scour depth measurements that then require additional office time to merge data sets and produce a final product (such as a plot of the cross section with the bridge substructure shown or a bathymetric map). Therefore, although these approaches can be used and may be expedient for certain situations, a valuable research contribution toward improving applied practice will be developing more automated positioning technology.

The most attractive approach to automating the position measurement is to use GPS-based technology, recognizing the limitations of not being able to work directly under the bridge in most cases and trying to resolve the accuracy-versus-cost issue. The easiest way to achieve sub-meter and even centimeter accuracy is to use a survey grade GPS receiver; however, with an investment of at least $20,000 for each receiver, this approach is limited by cost and the potential risk of losing the device when working in the difficult conditions presented by flood-flow monitoring. Low-priced GPS receivers (< $7,500) can provide meter to sub-meter accuracy with differential positioning, which would be adequate for horizontal position in many cases, but certainly not for vertical. However, the scour measurement can be referenced to the water surface elevation or a reference elevation on the bridge deck, with the GPS data used only for horizontal position. Therefore, if a local DPGS signal is available (e.g., from the NDGPS network or some other source) a lower priced GPS unit on the deployment platform could be used, minimizing the cost risk while providing relatively accurate data.

For bridge deck-based deployment using cranes or booms, horizontal position can be well controlled and referenced to the abutment. Methods of locating horizontal position across the bridge that are adaptable to automated data collection include distance measuring wheels and low-cost lasers.

Data Storage Devices

Data storage devices include data loggers, laptop computers, and, more recently, PDAs. Data loggers are generally not very user-friendly; laptop computers are susceptible to damage in a field-based application; and PDAs may be too limited in capability. If local telemetry were used to transmit data from the deployment platform, the best approach might be a laptop computer, with the operator at the side of the bridge, preferably in a vehicle. In this way, the computer can be used for both data collection and data reduction, perhaps in a real-time mode, while being protected from the environment. The use of PCs is much more common than it was even 5 years ago, and most people have a comfort level and a working knowledge of their operation. In contrast, PDAs are still evolving and changing rapidly, making it more difficult to develop a system for a specialized application, such as bridge scour data collection, without it becoming quickly outdated by the next generation of devices.

PHASE II WORK PLAN

Based on the literature review and Phase I findings, a detailed work plan was developed for Phase II. The alternative technologies selected for further research, development, and testing under the Phase II work plan were as follows:

1. To document the custom-fabricated boom and winch setup developed by Minnesota DOT and any variations on that design;
2. To investigate the capabilities of the Interphase scanning sonar and its potential application to bridge scour work;
3. To research and develop an articulated arm device adequate for smaller bridges.;
4. To research the use of low-cost GPS for positioning in scour monitoring applications; and
5. To research and develop data collection software suitable for laptop computer application that facilitates data collection, analysis, and reporting.

It was recommended that off-the-shelf products be used, where possible, for each component of the above systems. This would facilitate the purchase, construction, and repair of the resulting portable scour monitoring equipment and keep the total cost reasonable. The following paragraphs summarize the Phase II objectives for each alternative.

Alternative 1—Minnesota Boom Setup

The objective of this task was to document the winch concept developed by Minnesota DOT and evaluate potential improvements to the design and/or how it is used in scour monitoring. This could include evaluating the various components used to fabricate the winch system, the mounting concepts for the winch, and the use of the winch on different types of cranes. Of interest was the application of this concept to a pickup truck, rather than a large flatbed truck.

Alternative 2—Interphase Scanning Sonar

This objective of this work was to evaluate the use of relatively low-cost Interphase scanning sonar for scour monitoring, based on limited testing under laboratory or field conditions.

Alternative 3—Articulated Arm Devices

Based on work completed by the FHWA on an articulated arm device, the objective of this work was to develop an alternative design that is smaller, less complicated, and more cost-effective. Different types of commercially available articulated arms will be investigated and methods for tracking the angular position of the arm evaluated. A prototype device will be built and tested in detail.

Alternative 4—Low-Cost GPS Positioning System

The objective of this testing was to evaluate the application of a lower cost GPS receiver for bridge scour monitoring. Field testing around a bridge will be used to establish guidelines for when and where this type of positioning will work and when it should not be considered.

Alternative 5—Data Collection Software

Efficient data collection is important in a flood monitoring situation. The objective of this work was to develop a Windows-based software to automate the data collection process. Ideally, the software would not only automate the data collection process, but also provide immediate access to the results, which could include a cross section plot or bathymetric map.

PROTOTYPE DEVELOPMENT AND LIMITED TESTING

Minnesota Boom

Original Design

Minnesota DOT developed an innovative boom and sounding weight system for scour depth measurements using a boom truck and a custom-fabricated winch setup. The use of a boom and winch to deploy a sounding weight is not a new concept and has been used extensively for stream gaging measurements for many years. More recently, various boom and winch configurations have been used for measuring scour depths at bridges. In some cases, these were custom-fabricated devices; in other cases, they were standard stream gaging boom and winches (technically called sounding reels in stream gaging work), as shown in Figure 1.

The Minnesota DOT setup was unique in that the winch was not mounted on the boom itself. This has been the traditional approach for stream gaging operations and also has been commonly used in bridge scour measurements. Instead, the winch was mounted on a frame that was attached to the truck bed (Figure 2). The winch could swivel and tilt to allow the cable to follow the movement of the articulated arm crane that

Figure 1. USGS type stream gaging crane being used for scour monitoring.

Figure 2. Minnesota DOT winch mounted on bed of truck.

Minnesota DOT was using. This particular crane was capable of extending to 40 ft (12 m).

This design allowed adding the sounding weight capability to the truck without modifying the articulated crane, which is used for other purposes when it is not being used for scour inspections. This design also facilitated installing and removing the winch, as necessary, and using the same winch setup on various trucks. Although this was a relatively simple adaptation of a standard deployment concept, it simplified building and adapting sounding reel capability on any available boom and could be readily adapted to both articulated and non-articulated (straight) booms or cranes. The following paragraphs describe the design and construction of the Minnesota DOT winch in greater detail.

To document the design of the Minnesota DOT winch, a trip was made to the DOT office in Mankato, Minnesota, where the boom was fabricated. Pictures and measurements were taken to document the device. Discussions were also held with the bridge inspection crew that developed the device to obtain suggested improvements to the design, based on experience to date. Generally, the device as built has performed quite adequately, and only minor changes to the design were suggested by the inspection crew.

The winch used was an X3 Superwinch™ (Figure 3), with the cable routed through a Hykon Reel™ wire rope length counter (Figure 4). The X3 winch has a 1.6 hp motor and 50 ft (15 m) of 7/32 inch (5.5 mm) wire rope with power in and out and freespooling capability. The rated line pull is 4,000 lbs (1,814 kgs) on a single line. The Hykon Reel is made by Hykon Manufacturing Company and can accommodate flex wire from 1/64 in (0.4 mm) to 7/8 in (22 mm) and wire rope to 1/2 in (13 mm). A guide was fabricated at the outlet of the wire rope counter to better control the cable and to direct it toward the pulley at the end of the boom. The frame for the winch and wire rope counter was custom fabricated and included a place to attach a safety chain to the truck bed.

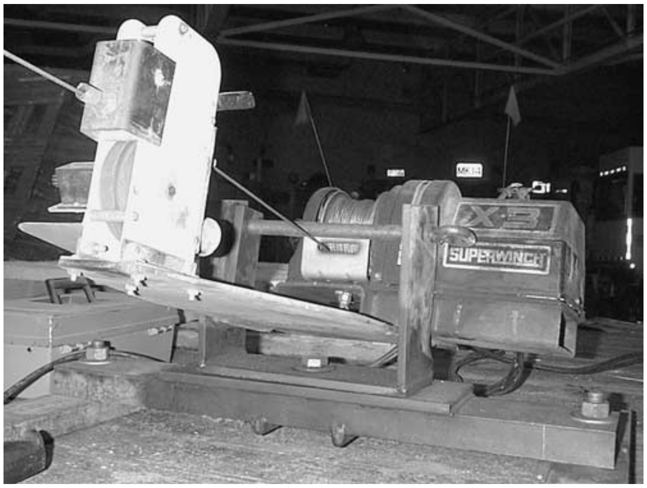

Figure 3. Close-up of Superwinch Model X-3™.

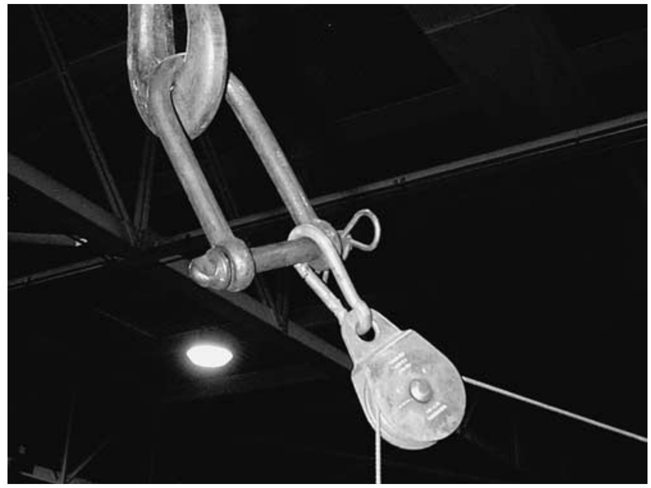

Figure 5. Pulley at end of articulated crane.

One of the suggestions for improvement by Minnesota DOT was to make sure that the frame can tilt adequately to prevent excessive rubbing of the cable through the guide, which can result in premature failure of the winch cable. The cable was routed through a pulley at the end of the crane (Figure 5). Another suggestion was to include a swivel on the pulley to prevent twisting of the cable. Figure 6 is a dimensioned drawing of the winch, as built by Minnesota DOT.

Modifications to Original Design

One of the modifications developed under this project was the use of a dual winch approach to allow more controlled operation in certain cable-suspended applications, such as when using a sonar device deployed in a floating platform. Part of the problem with floating platforms deployed by hand has been the lift on the nose created by the cable and the difficulty in controlling the position of the float. The dual winch concept eliminates the lift problem when implemented with an articulated arm that can get a cable further out in front of the float and will provide more directional control. Deployment by hand is convenient during normal flow conditions, but can be difficult under flood flow.

The concept, illustrated in Figure 7, may allow better positioning control and the ability to drift the float under the bridge, when compared to a single cable operation. A single cable suspension through the pulley on the end of the crane can still be used, similar to that in the Minnesota application, or the dual cable concept as illustrated.

Other modifications concentrated on (1) the individual components used in the design and (2) the mounting concept. In general, heavier duty components were used, both in terms of the winch and the wire rope counter, and the framework was built using heavier steel. Figure 8 shows the modified winch assembly.

More consideration also was given to balance and to providing a smooth operation as the winches follow the motion of the boom. This combined with the desire to operate two winches resulted in the post mounting concept shown in Figure 9, compared to the bed mounting concept used in the original Minnesota device. The post allows each winch to swivel independently. This feature, combined with the ability to tilt up or down, allows the winches to track the movement of the crane. The final modification related to the readout from the wire rope counter. Initially, a speedometer cable was used to relocate the mechanical readouts of the wire rope counters to the instrument box on the flatbed. Subsequently, these were replaced by pulse counters that allowed electronic readout and input to the data collection software program.

This task also included consideration of a non-articulated crane on a pickup truck, such as the one shown in Figure 10, which has a 15 ft (4.5 m) reach and sells for about $5,500.

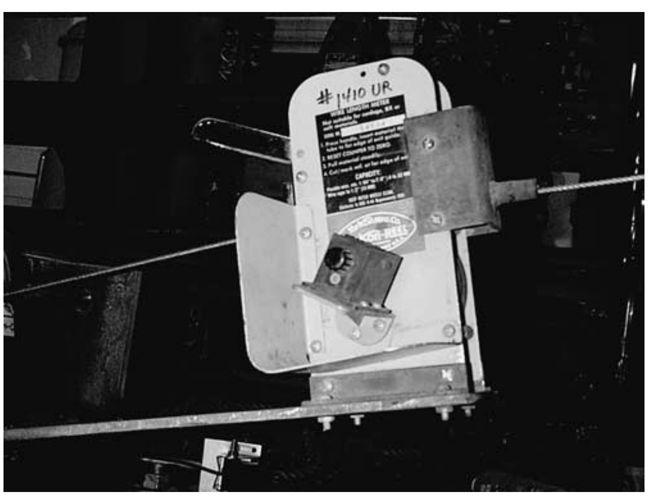

Figure 4. Close-up of Hykon—Reel™ with guide added at the outlet of the reel.

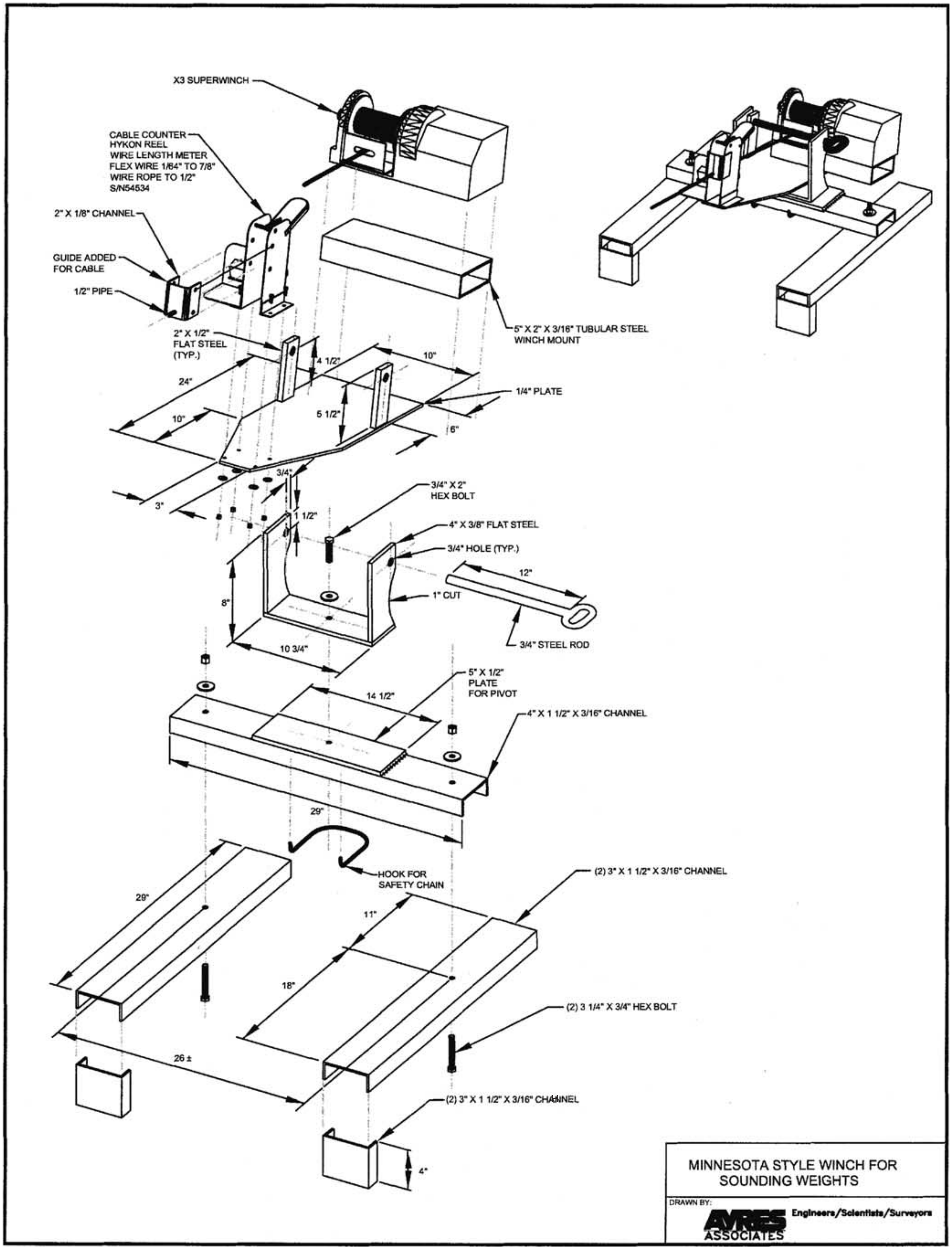

Figure 6. *Dimensioned drawing of Minnesota style winch.*

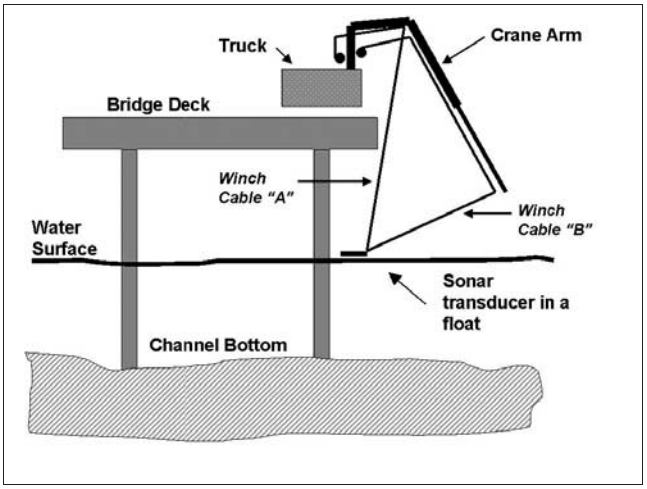

Figure 7. Two winch concept for cable suspended operations.

Given the reach of an articulated arm, and the value of handling larger sounding weights with larger winches, a smaller device on a pickup, while feasible, may not be attractive for flood monitoring applications.

Interphase Scanning Sonar

The Interphase Twinscope™ (Figure 11) is a forward-scanning sonar using a proprietary phased array acoustic technology. An acoustic array is a group of piezoelectric ceramic elements precisely sized and spaced. Each element can send and receive acoustic pulses, similar to conventional single-element depth sounders. However, when all elements in the array are sending or receiving acoustic energy at the same time, the entire array behaves like a single larger element with one important difference: the ability of the array to concentrate its acoustic energy in different directions, depending on the different phasing of the signals applied or received by each element. Depending on signal phasing, acoustic beams can be directed in an almost unlimited number of directions.

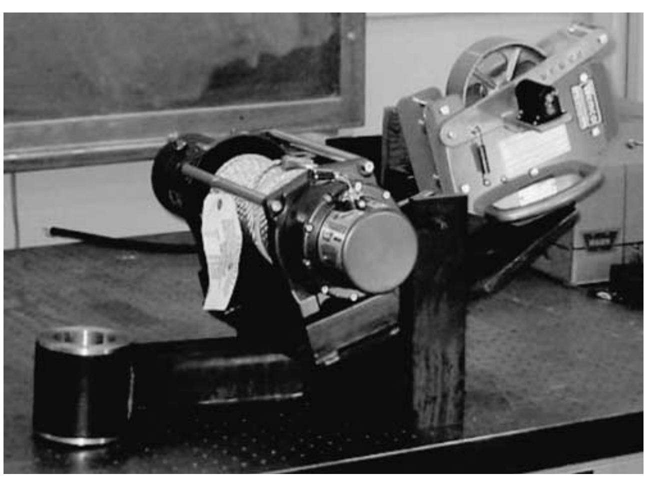

Figure 8. Modified winch design.

Figure 9. Winch system on the truck.

The Twinscope™ uses a 16-element array and can steer the acoustic beam in any of 90 different directions in either the horizontal or vertical direction. Conventional fixed-beam sonar technology would require 180 different elements to duplicate this capability, and the resulting transducer would be too large and costly for practical use. Given that the acoustic

Figure 10. Application of winch concept on a non-articulated crane.

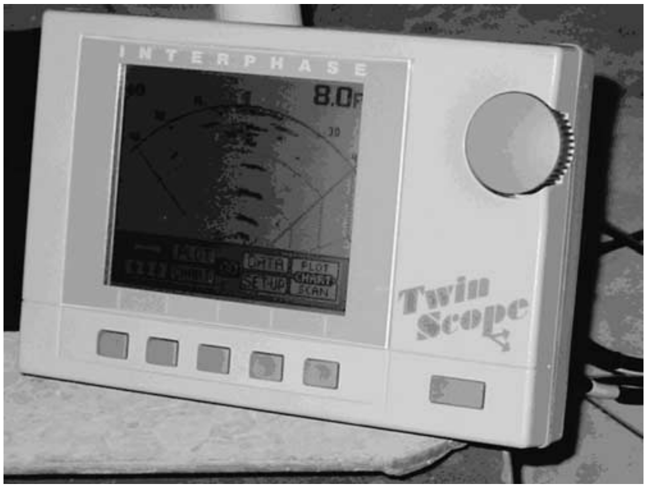

Figure 11. Interphase Twinscope™ sonar.

beam is steered electronically, with no moving parts, it can quickly scan and rescan a large area. Phased array technology also allows the user to adjust beam width, which is not possible with conventional fixed-beam sonar.

In the Twinscope™ array, 8 of the 16 elements are used to scan vertically, from straight ahead to straight under the boat, and the other 8 are used to scan forward from side-to-side. In horizontal mode, the side-to-side sweeping action of the scanning beam is up to 45 degrees on either side of the boat, angled downward at about 20 degrees. The cone angle of the Twinscope™ is approximately 12 degrees, so in vertical mode, a forward scan to 1,000 feet in front of the boat would see targets across a 210-foot width (105 feet on either side of center).

Initial testing of the Twinscope™ was conducted at the Hydraulics Laboratory at Colorado State University (CSU). The transducer was mounted in a pontoon float for testing, and positioned with an extendable pole (Figure 12). Testing was conducted at a pump station intake on the lake supplying water for some of the outdoor flumes and in the sump under the indoor laboratory. The pump station on the lake has a large platform on piles supporting the pump and its intake. However, the number of piles and cross bracing prevented getting a clearly identifiable return of a single pile on the screen. The testing in the sump adjacent to one of the pump intakes provided a clearer picture, because the transducer was seeing only the pipe for the pump intake extending down into the water, but the screen image was complicated by multiple returns from the various walls and partitions of the concrete-lined sump (Figure 13).

A field test of the Twinscope™ was conducted in Alabama. For testing purposes, a special bracket was fabricated to allow the Twinscope™ transducer to be mounted on the crane (Figure 14). Figure 15 shows the transducer positioned in the water upstream of the pile. This test was inconclusive. Based on subsequent discussions with the manufacturer, it was concluded that there must be at least 10 ft (3 m) of water for this device to work—a situation that did not exist at this bridge. No addi-

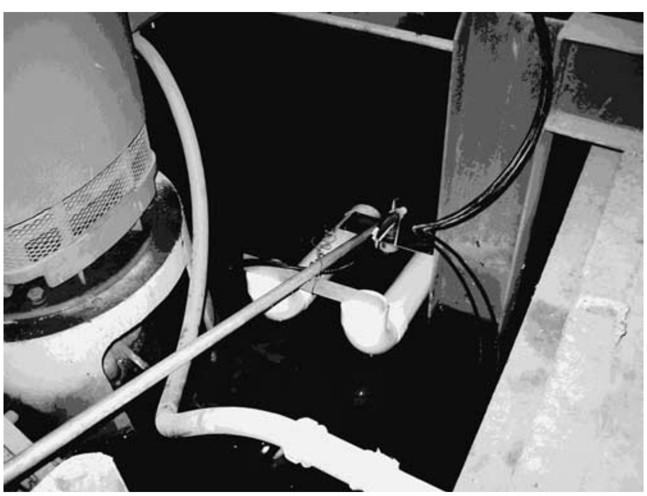

Figure 12. Pontoon float with transducer adjacent to pump intake in the CSU Hydraulics Laboratory.

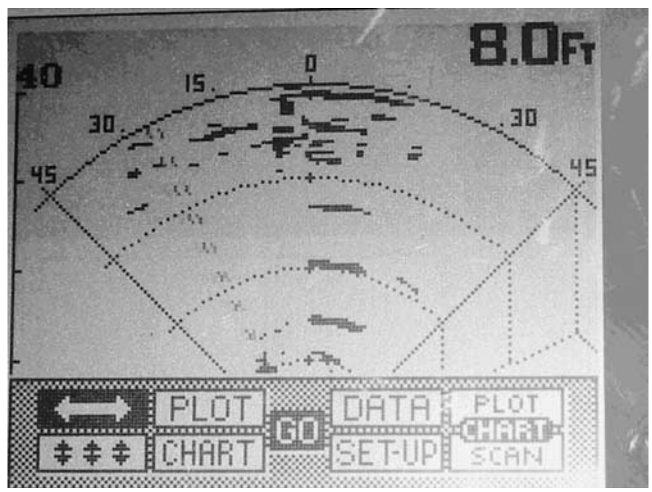

Figure 13. Horizontal scan showing multiple reflections.

Figure 14. Mounting the Twinscope™ transducer for field testing.

Figure 15. Positioning the Twinscope™ transducer upstream of a pile.

tional testing of the Twinscope™ was conducted; however, under the proper conditions, the Twinscope™ should provide a graphical perspective of conditions approaching a pier and might be a useful addition to the instruments used by a bridge inspection crew during scour monitoring.

Articulated Arm

Crane Research

Articulated arm cranes are also known as knuckle boom or folding cranes. There are various manufacturers of articulated arm cranes. The first step in the investigation of feasible alternatives for use in a scour monitoring application was to contact various dealers across the country to obtain specific design and cost information. This was accomplished through web browsing, telephone conversations, and review of literature provided by the dealers and/or manufacturers. Based on this research, four major crane manufacturers were considered: Palfinger, Effer, Jabco, and National. For each manufacturer, a specific model was selected that could be used for scour monitoring applications and preliminary cost information (2001 data) was researched. The results of that research are as follows:

- The recommended Palfinger crane was model PK 4501 C. This crane has a maximum reach of 36 ft (11.0 m) with a lifting capacity at this distance of 600 lbs. The base price for this crane is $14,500, with an installation cost of $1,800. This crane could be installed on a Ford F-450 truck or equivalent. The cost for this truck new is $31,800 plus $4,000 for a flatbed. Therefore, the total cost for this crane, new truck, flat bed, and installation would be approximately $51,000.
- The recommended Effer crane was model 28/3S. This crane has a maximum reach of 30.3 ft (9.2 m) with a lifting capacity at this distance of 650 lbs. The base price for this crane is $10,000, with an installation cost of $3,500. This crane could also be installed on a Ford F-450 truck or equivalent. The cost for this truck new is $31,800 plus $4,000 for a flatbed. Therefore, the total cost for this crane, new truck, flat bed, and installation would be approximately $49,300.
- The recommended Jabco crane was model 705/3S. This crane has a maximum reach of 32.6 ft (9.9 m) with a lifting capacity at this distance of 880 lbs. The base price for this crane is $16,000, with an installation cost of $3,500. This crane could also be installed on a Ford F-450 truck or equivalent. The cost for this truck new is $31,800 plus $4,000 for a flatbed. Therefore, the total cost for this crane, new truck, flat bed, and installation would be approximately $55,300.
- The recommended National Crane was model N-50. This crane has a maximum reach of 40 ft (12.2 m) with a lifting capacity at this distance of 700 lbs. The base price for this crane is $20,500, with an installation cost of $8,500. This crane is larger and heavier than the others and would require a slightly larger truck, such as a Ford F-500 or equivalent. The cost for this truck new is $33,700, plus $4,000 for a flatbed. The total cost for this crane, new truck, flat bed, and installation would be approximately $66,700.

Based on this information, the cost for the crane and installation, excluding the truck cost, varies from $13,500 to $29,000, with the Effer crane being the lowest and the National Crane being the highest. Although there was some difference in reach and lifting capacity, that alone did not seem to explain the wide range of cost.

When asked about the range in price, the National Crane representative suggested that the other cranes being considered were all manufactured in Europe and were not built to as stringent safety standards as cranes manufactured in the United States. The opinion of the Jabco representative was that the foreign companies have more background and experience in the design and manufacture of knuckle boom cranes. It was his observation that they have had to deal with narrow streets and limited access issues for years, where knuckle boom cranes can be particularly useful over straight arm cranes. Additionally, he indicated that many of the European cranes are made of high alloy steel and, as a result, there is less structural steel, and therefore, less cost. The additional weight of the crane, such as the National Crane, also required the use of a larger truck, as discussed above.

Crane Selected for Purchase

These issues entered into the decision for the type of crane selected for this project, with the desire to work with a smaller crane that could be mounted on a smaller truck. This criteria was to improve maneuverability, as well as to minimize lane closure and traffic control issues. Additionally, as a research project, it was important to have a dealer and manufacturer who were willing to be helpful and responsive to unique requests as it related to equipment application outside the normal range of use. Based on all these issues, a Palfinger 4501C crane was purchased (Figure 16). The final cost breakdown for the crane and truck are provided in Table 1.

Mounting the Crane on the Truck

The most common location for a crane is immediately behind the cab of the truck. An alternative location is at the back of the truck, behind the rear axle. A rear mount puts more load at the back of the truck and can cause weight distribution problems if the truck is also carrying substantial weight on the flat bed. The rear mount provides better clearance around the truck, because the cab is not in the way. For purposes of scour monitoring, with no substantial weight being transported on the truck bed, a rear mount seemed advantageous.

Based on the reach of the PK4501C crane, mounted with an offset to the center of the truck, the PK4501C has the capability to reach 21.25 ft (6.5 m) below the bridge deck when the truck is a maximum of 35 in (0.3 m) from the edge of the bridge. This reach is to the end of the crane, prior to adding any extensions for sensor mounting. Figure 17 summarizes the geometric capabilities of this crane when mounted on a Ford F-450 truck.

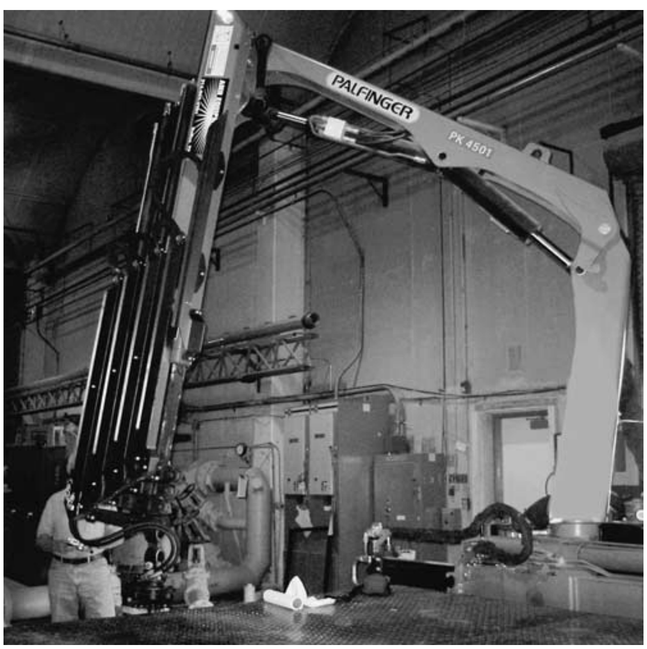

Figure 16. Palfinger PK4501C crane.

TABLE 1 Crane and truck cost information

Item	Cost ($) (excluding tax, licensing, etc.)
Palfinger 4501C Crane	14,553
Installation, including PTO pump	1,500
10-foot truck bed, installed	1,500
2001 Ford F-450	25,550
Subtotal-base cost for truck and crane	43,103
Kinshofer Hydraulic Rotator	3,600
Tool boxes, beacon lights, etc	2,000
Total Cost (estimated as of 12/31/01)	48,703

Modifications to the Rotator

The ability to provide pan and tilt operations at the end of the crane was considered a valuable feature for positioning instrumentation. Pan operation could be accommodated using a standard hydraulic rotator, often used with construction equipment on the end of a crane (Figure 18). Most rotators are designed for 360-degree, continuous rotation at a fairly high speed. Continuous rotation for scour monitoring applications was not desirable, given that the operator might accidentally tear off cables connected to transducers, and high-speed operation would complicate precise positioning and could result in possible impact damage when in close proximity to the bridge.

In the past, rotators with a 270-degree rotation were available; however, most construction operations require full rotation and the limited rotation devices are no longer available. After working with engineers at the crane manufacturer, it was concluded that the only economical solution was to use flow restrictors in the hydraulic lines to slow down the motion and to use some type of limit switch or indicator as part of the position-sensing device to control overrotation.

Standard rotators are also designed to hang from the crane on a pin connection, so that the rotator is always positioned vertically, regardless of the angle of the crane arm. Therefore, providing tilt capability required modifications and special fabrication. An additional hydraulic cylinder and custom-fabricated brackets were added to the rotator to provide the tilt action (Figure 19). The tilt was designed to provide about 35 degrees toward the bridge and about 10 degrees away from the bridge, when the crane is positioned vertically over the bridge rail. The mounting bracket for the rotator was attached to the end of the crane, which extended the reach of the crane by 1.5 ft (0.46 m).

Modifications to the Truck Flat Bed

The modifications to the truck bed included adding ladders on both sides to facilitate access, building the workstation area for the computer and instruments, and relocating the hydraulic controls to the flatbed. The hydraulic controls for an articulated crane are typically located next to the crane, allowing operator

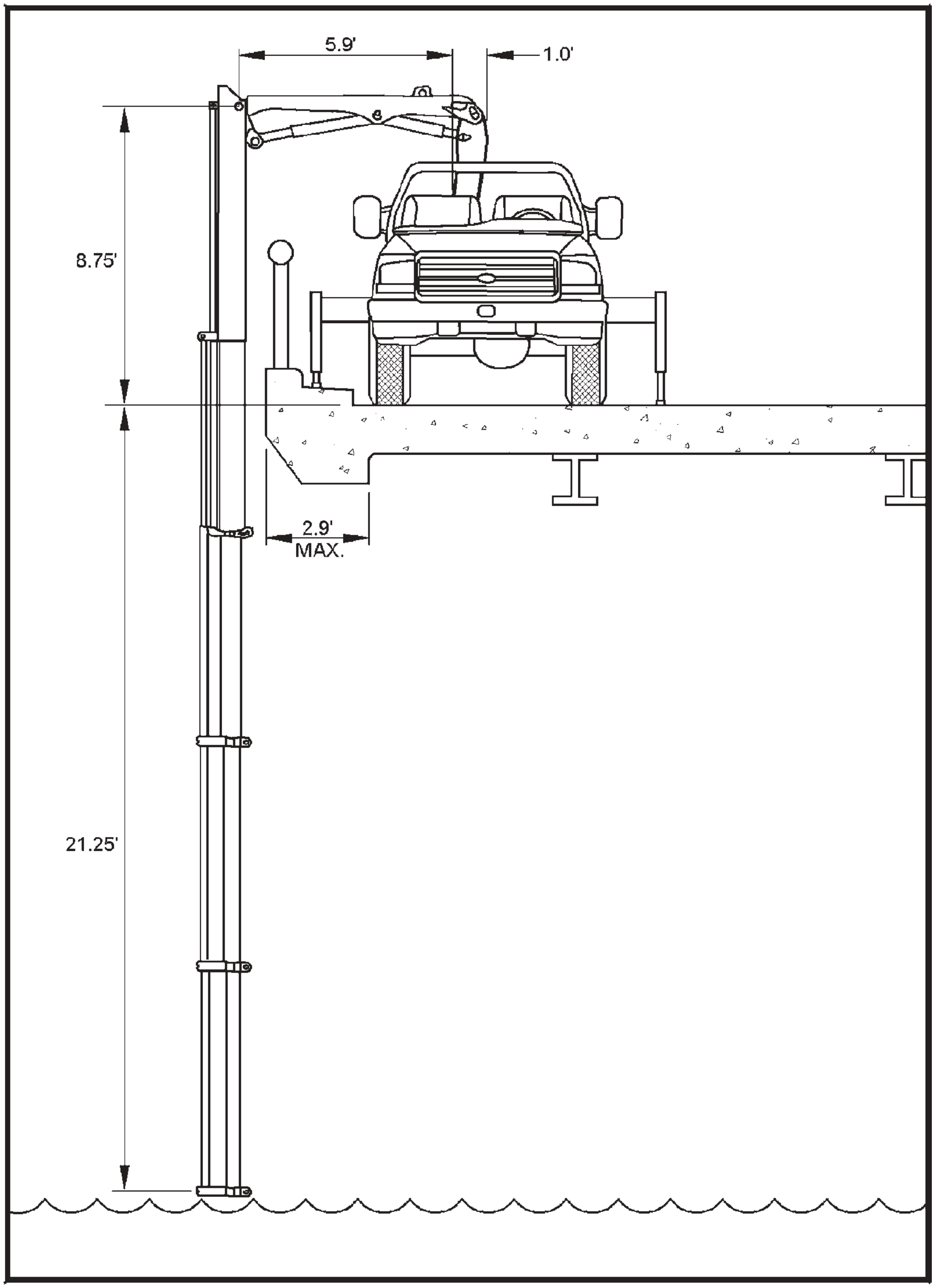

Figure 17. Reach below the bridge deck with the PK4501C crane on a Ford F-450 truck.

access while standing on the road (Figure 20). Some models, including the Palfinger 4501C, have dual controls allowing operation from either side of the truck.

After reviewing the truck and crane operation, it was concluded that it would be better to relocate the controls from the standard location for reasons of safety and to provide better visibility of river conditions for the operator. To reach over the side of the bridge, it will be necessary to position the truck as close to the edge of the bridge as possible, which may restrict access for the operator on the bridge side of the vehicle. Access from the opposite side, when the crane is equipped with dual controls, would still be feasible, but visibility to the water sur-

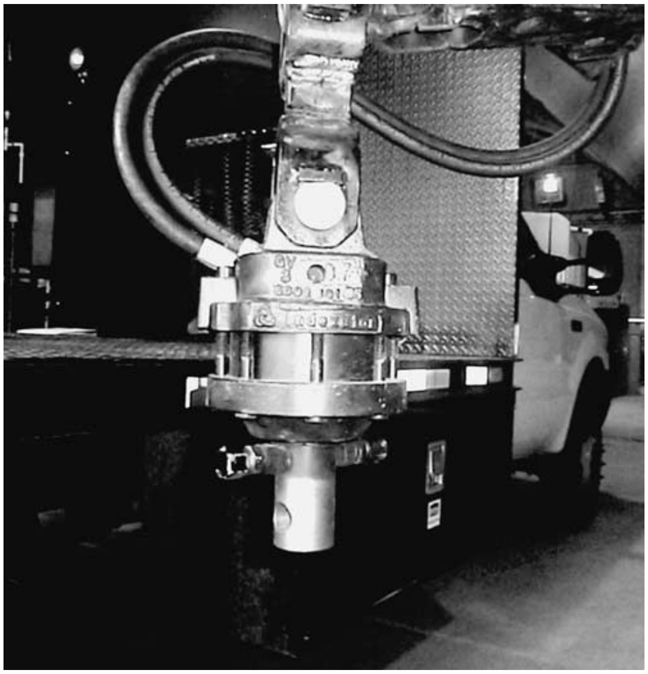

Figure 18. Standard rotator (prior to modifications to allow tilt).

face would be limited from that location and roadside safety would be a concern.

Moving the control valves up onto the flatbed eliminated the access and safety issues related to operation from the road surface and greatly improved the visibility to the water surface for the operator. The controls were moved to a position at the back of the flatbed, a workstation was fabricated on the flatbed to provide a shelter for the computer, and a seat was installed on the bed (Figure 21).

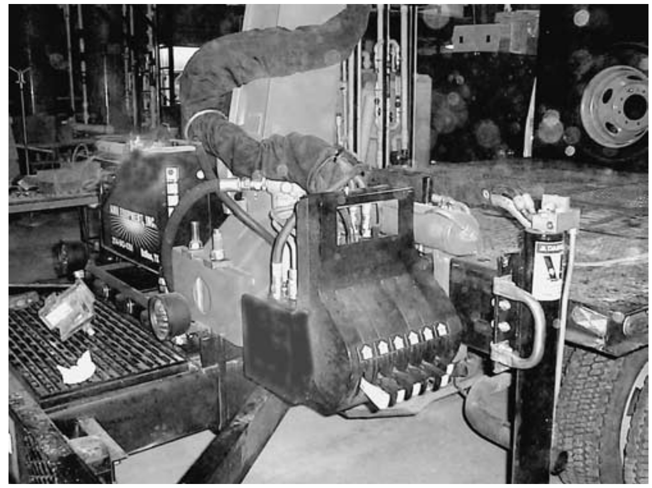

Figure 20. Hydraulic controls in typical location allowing operation from roadway.

Tracking the Position of the Crane

Various sensors were installed on the truck and crane to allow geometric calculation of the position of the end of the rotator. An articulated crane provides a very stable platform to deploy scour measurement devices, but does not provide any positioning information without the addition of other sensors to track the movement of the crane. Therefore, a critical part of the articulated crane research was to develop a methodology to track the location of the end of the crane in a real-time mode as the crane was being operated. It was also necessary to define the position of the truck on the bridge deck.

Initially, 10-turn potentiometers with various gearing arrangements were used to measure the azimuth of the crane

Figure 19. Rotator after modifications to provide tilt capability.

Figure 21. Instrument shelter for computer and relocated hydraulic controls.

and the rotator. However, these were not as robust as needed, and alternative methods were investigated. Subsequently, the potentiometer for the azimuth measurement was replaced with a 50 in. (125 cm) linear environmentally sealed draw wire. The draw wire was routed around a 15-in. (38-cm)-diameter circular plate mounted near the base of the crane (Figure 22). The draw wire was permanently mounted to a bracket on the truck bed and a groove on the edge of the plate kept the draw wire in place as the crane rotated. This solution was not feasible for the rotator, and no other alternatives were identified. Therefore, the 10-turn potentiometer was retained.

Tilt meters were used to measure the deflection angle of the crane arm and the rotator arm. The tilt meter for the crane arm was mounted inside the instrument box attached to the end of the crane (Figure 23). The tilt meter for the rotator arm was attached directly to the support bracket fabricated to allow tilting the rotator (as described above). A 400 in. (10 m) environmentally sealed draw wire was used to measure the linear extension of the arm (Figure 24).

Tilt data for the crane and rotator, the azimuth of the rotator, and the linear extension of the arm are transmitted by a wireless modem from an instrument box at the end of the crane that also transmits sonar data. The data are pre-processed with a Campbell CR10 data logger prior to transmission to the computer on the truck (Figure 23).

An acoustic stage sensor was used to measure the distance to the water surface (Figure 25). A second CR10 mounted in the instrument shelter on the truck bed was used to process truck data, which included the azimuth of the crane, winch data, the distance to the water surface, and the distance traveled across the bridge deck.

A computer with two serial ports was used to process the data from each data logger, sent as serial data strings. Knowing the rotation of the crane and the rotator, the deflection angles of the crane arm and rotator, and the extension of the crane arm allowed geometrically calculating the position in space of the end of the rotator relative to the center pivot of the crane where it was mounted to the truck bed.

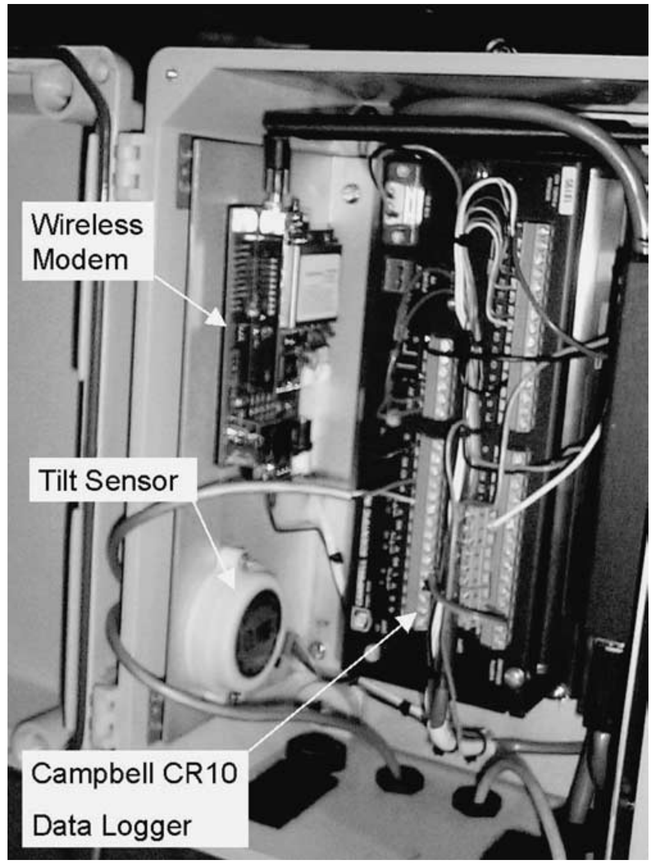

Figure 23. Tiltmeter installed in the instrument box at the end of the crane.

Figure 22. Attachment for crane azimuth measurement using draw wire.

Tracking the Position of the Truck on the Bridge Deck

Tracking the position of the truck on the bridge deck was the last piece of information necessary to locate the scour mea-

Figure 24. Draw wire used to measure linear extension of crane.

Figure 25. Acoustic stage sensor used to measure distance to the water surface.

surements accurately. Initially, the use of low-cost GPS was considered, but that approach was not found to be feasible (see below). Given that the truck would always be positioned as close to the curbline or barrier rail as possible, and given that the bearing of the bridge is a known quantity, the only real location information necessary was the distance the truck had been driven across the bridge, and the elevation of the truck. The elevation of the truck could be established from the elevation of the bridge deck, as given on bridge plans, and the height of the truck bed above the bridge deck. Therefore, the primary field measurement necessary to locate the truck was simply the distance the truck had traveled across the bridge deck.

Various methods were considered to establish the distance traveled. To be useful, the measurement device had to be accurate, simple to use, and able to output a serial data string. Laser measuring devices were considered because of their high accuracy and simplicity. However, because the laser must hit a target at the end of the bridge, there was concern about reflecting off the wrong target and the potential difficulties of getting a measurement when the bridge had a horizontal or vertical curve.

Electronic distance meters are available for installation on vehicles used for various highway survey projects (e.g., measure guard rails, pole or sign signing, and estimate pavement areas). For example, the Nitestar™ system computes the distance traveled by attaching to the speed sensor in the vehicle's transmission. This device has a calibration feature that can be used to account for change in tire size because of wear and under or over inflation of tires and is accurate to 30 cm over 1.6 km (1 ft per mile). It has RS-232 output capabilities that allow it to record data into a computer, which can be viewed by Nitestar software or by user-defined software. The cost of this unit with the appropriate installation kit was approximately $700 dollars.

Based on simplicity, cost, and accuracy, this system was purchased and installed on the truck. However, this meter caused a fault in the truck anti-lock braking system and was also found to be difficult to interface with the data collection program being developed. Therefore, it was replaced with a standard surveying measuring wheel attached to the back of the truck (Figure 26). The only limitation of standard survey wheels is that they use a mechanical counter and do not have any electronic output capability. To provide a serial data string, pulse counters were added to the wheel to register electronically the distance traveled.

Scour Measurement Devices

As developed, the instrumented, articulated crane could be used to position various scour measurement devices, both directly from the end of the crane and from cable-suspended methods using the winches. Sonar could be deployed off the end of the crane, or as a cable-suspended operation, while direct probing was possible off the end of the crane.

To provide sonar measurement capability, a sonar instrument with all the electronics built into the transducer head was selected (Figure 27). The sonar outputs a serial data string of depth and temperature that was connected to the Campbell CR10 data logger and transmitted by the wireless modem (as shown in Figure 23). This eliminated having to route any electronic cables for the sonar from the water surface to the bridge deck.

Given the desire to operate at flood conditions with high velocities, a streamlined probe was built to position the sonar transducer directly in the water using the articulated arm. The probe was fabricated from a section of helicopter blade and proved to be very stable when placed in high-velocity flow during field trials. The streamlined probe eliminated the vortex shedding problems of a simple cylinder-shaped rod exposed to high-velocity flow.

Figure 26. Surveyors wheel mounted to rear bumper of truck.

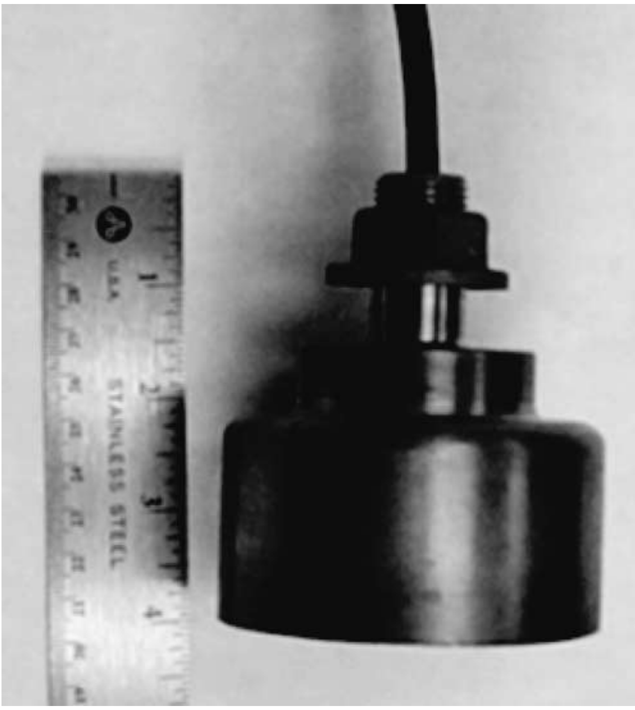

Figure 27. Sonar transducer with all electronics built into the transducer head.

The initial design for the streamlined probe had a rigid mount to the rotator, requiring the operator to turn the rotator as the crane angle changed, in order to keep the fin aligned with the current (Figure 28). This design was modified to allow the fin to swivel and track the current on its own; however, the axis of rotation was too far back on the fin and it would not track the current in low-velocity situations. A third version was built with the rotation point moved forward, as well as being built with a longer extension that provide more reach with the crane arm and less chance of submerging the rotator and instrument box at the end of the crane (Figure 29). The length of the extension was 80 in (2 m). Given the distance

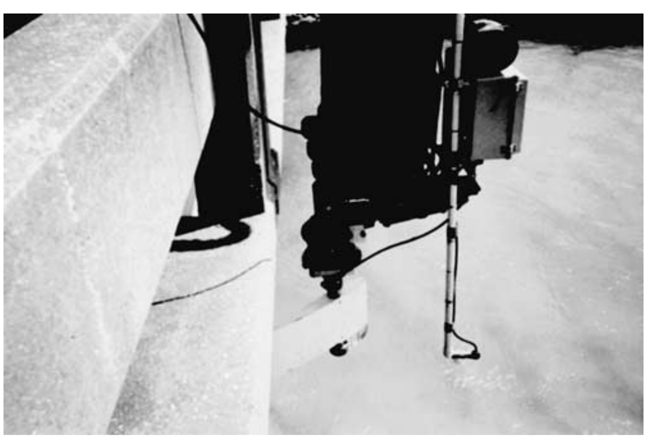

Figure 28. Streamlined probe.

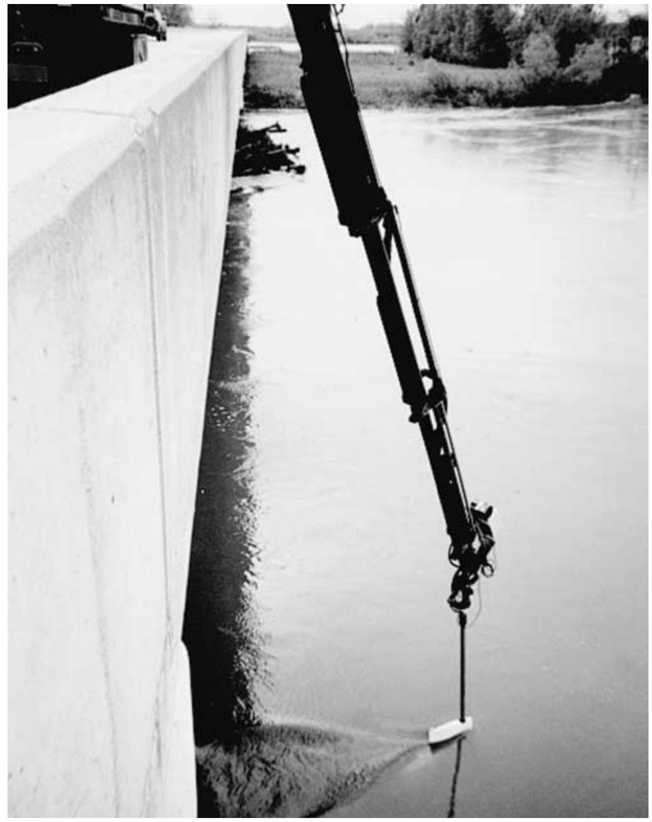

Figure 29. Modified streamlined probe with swivel capability and longer extension.

the crane could reach below the bridge deck (21.25 ft or 6.5 m) and the length of the rotator mounting bracket (1.5 ft or 0.46 m), the crane could reach nearly 30 ft (9.1 m) below the bridge deck for a sonar measurement.

To provide physical probing capability, an extendable rod was fabricated. The rod extensions were built with 125 mm stainless steel, Schedule 80 pipe in 1.5 m lengths, allowing a total length up to 4.5 m. Threaded unions allow individual sections to be connected to create the longer extensions. Using the articulated crane for physical probing is most appropriate in a gravel/cobble bed or to evaluate riprap conditions, because the strength of the crane hydraulics makes it difficult to know exactly when a soft channel bottom is reached.

Cable-suspended operations were possible using the two Minnesota-style winches described above. Using a single- or dual-winch approach, traditional sounding weight measurements can be made. The dual-winch approach reduces the size of the weight necessary, because the winch running through the end of the crane can be used to limit the movement under the bridge deck. Although the weight is not a concern, given the ability of the crane and the winches to handle very large weight, it does allow better control over the position of the sounding weight.

A kneeboard with a wireless sonar was also developed that could be deployed from either a rigid framework attached to the rotator or as a cable-suspended operation. The sonar with the electronics built into the transducer was used and a small PVC enclosure fabricated for the kneeboard to hold the battery and wireless modem (Figure 30). Several versions of the framework for deployment off the end of the crane were fabricated, with the version shown in Figure 30 working the best. It was difficult at times to get the kneeboard positioned on the water surface, but, once in place, it could be readily moved forward and backward under the bridge, and, within limits, side to side using the rotator (Figure 31). This arrangement facilitated measurements under the bridge deck when direct measurement with the arm, or cable suspended weights, was not possible. An accurate location of the sonar measurement could be calculated knowing the position of the end of the rotator, the length of the framework, the distance to the water surface, and the angle of the rotator.

Figure 31. Kneeboard positioned under the bridge.

Cable-suspended operations with a sonar installed in a sounding weight were also tested. A 4 ft (1.2 m) hanger bar for the sounding weight was built with a PVC pipe enclosure to house the battery and wireless modem at the top (Figure 32). This eliminated routing the sonar cable from the water surface up to the bridge deck and greatly enhanced cable-suspended operations using a sonar device. A standard 75-lb sounding weight was used, with a hole machined in the bottom for the transducer. Standard sounding weights are designed with a flat bottom so they will sit upright without rolling. Under high-velocity flow, this can create a separation zone off the bottom that might adversely affect the sonar measurement. Therefore, the transducer was not mounted flush with the flat bottom, but allowed to protrude and a shim was fabricated to transition the flow more smoothly off the nose of the sounding weight (Figure 33).

Figure 30. Kneeboard with wireless sonar being deployed with a rigid frame.

High-Load Casters

Data collection with the crane extended was desirable for measuring a channel cross section. Many under bridge inspection trucks have counterweights and/or high-load castors to

Figure 32. Sounding weight with wireless sonar.

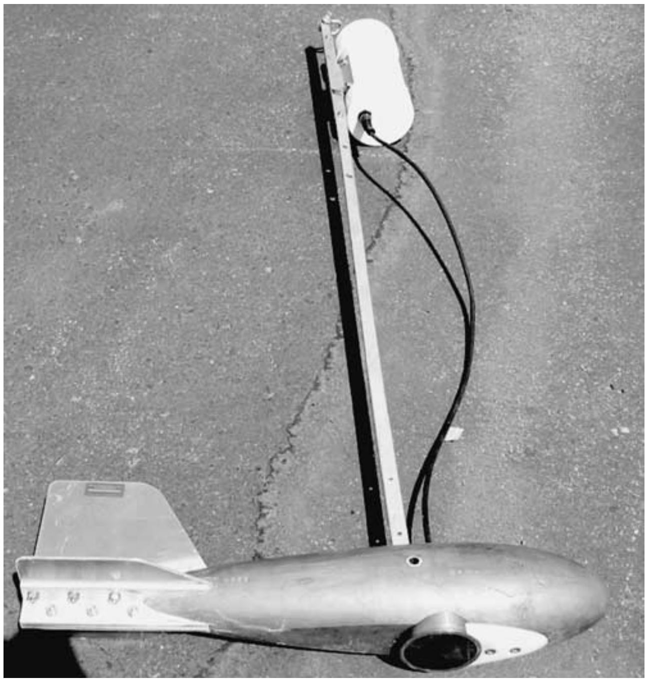

Figure 33. Sonar mounted in bottom of sounding weight with shim to transition flow off the nose.

allow truck movement when the crane arm is extended. To permit this type of operation with this crane, high-load casters were fabricated and installed on the outriggers. The castors worked well, but the lateral loading during transit was straining the outriggers. This problem was initially solved by building heavy-duty turnbuckles to create a strut between the truck frame and the caster (Figure 34). This created a very rigid support system, but the turnbuckle had to be removed to raise the outrigger, and the castor needed to be removed for transit given the clearance to roadway. This was not a difficult operation, but was time-consuming; during a flood situation, the time to mobilize and deploy prior to making measurements can be critical.

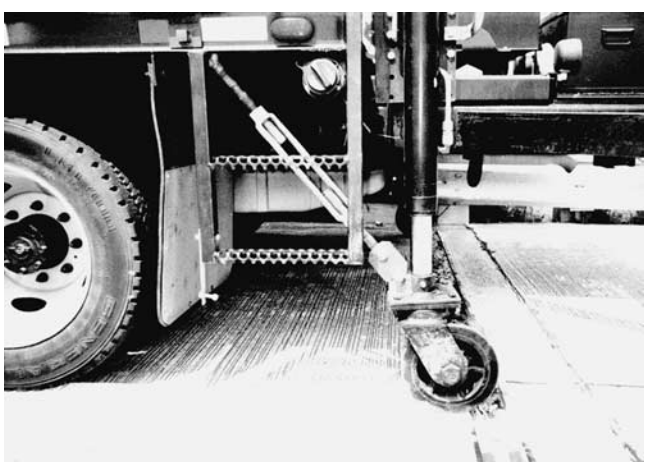

Figure 34. Turnbuckle to stabilize the hydraulic jacks for the crane.

Figure 35. Final design for castor system.

Therefore, an alternative design was developed based on an arm that could be lowered under the outrigger foot pad. The wheel was permanently attached to the arm, with the arm providing the lateral support necessary after the outrigger was lowered onto the castor (Figure 35). This design was not quite as rigid as the turnbuckle approach, because the outrigger could move around slightly on the plate, depending on how high the truck was raised, but the method worked and was very quick to set up.

Low-Cost GPS

Available GPS Receivers

Research on low-cost GPS receivers was completed to evaluate their ability to provide position information for the truck and/or other related scour measurement technologies. Although GPS technology can provide accurate position information and has been used in scour measurement applications, its high cost and lack of ease of use limits its widespread application. For example, GPS receivers used for land surveying applications are very accurate, but cost $20,000 or more and require specialized training.

Therefore, the objective of this task was to research current GPS products that could provide sub-meter accuracy and were affordable and easy to use. The testing was not intended to be comprehensive, covering all available manufacturers and models, but rather was limited to a small sample of available products that could give an idea of the capability of receivers in the $5,000 to $8,000 range. Units in this price range are typically used for precision farming, forestry, or utility-related geographic information system (GIS) applications, when the accuracy of a survey grade system is not necessary. This grade of GPS receiver can typically provide meter or sub-meter accuracy using a differential correction signal from a satellite or beacon receiver.

The simplicity of the GPS system was important, given that inspection and/or maintenance crews might not have GPS experience. To be valuable in a flood response context, the GPS system must also be able to report a real-time position on site and not require post-processing of the GPS data to get correct coordinates.

Lower cost GPS systems range from basic handheld receivers using a WAAS (Wide Area Augmentation System) correction only, to more advance receivers using a satellite or beacon correction. Systems using WAAS are easy to operate and cost-effective, but cannot achieve the sub-meter accuracy. Typical examples of the variety of lower cost GPS receivers on the market in 2001 were as follows:

- The Garmin GPSMAP 176™ is typical of low-cost, recreational style GPS receivers. It is a 12-channel WAAS-enabled GPS receiver under $200. This receiver has a display screen on which built-in base maps of the United States can be viewed. Data (NEMA String) can be output to a computer by way of an RS232 cable. This receiver is cost-effective, but is unable to give a high degree of accuracy. Using the WAAS system as a differential correction, an accuracy of 3 to 5 meters is attainable, and when the receiver is operating autonomously, an accuracy of approximately 15 meters can be obtained. This receiver was not considered for testing and is identified only to provide insight on the capabilities and limitations of very low-cost differentially corrected GPS.
- The Trimble Pathfinder Pro XRS™ is a 12-channel, differential beacon and satellite receiver. This receiver can receive a WAAS signal, Coast Guard (USCG) beacon, and OmniStar™ signals. The Pathfinder Pro XRS™ receiver is equipped with multipath rejection technology in the antenna to remove multipath signals in reflective environments. When using the Omni star or Coast Guard beacon, submeter accuracy can be achieved. Data can be output onto a Trimble data logger or PC using Trimble™ or other software to record data. The cost of this receiver without any additional add-on software is approximately $5,500.
- The Starlink Invicta 210S™ is a 10-channel GPS receiver that can receive differential correction from USCG, Canadian, or IALA beacon signals. Satellite differential correction is also available using the OmniStar™ subscription-based service. This system is designed to be mounted out of the way with no setup required to collect data. A front display provides the user with access to menu screens for configuring the receiver and/or viewing satellite performance. When the power is turned on, the receiver broadcasts the position via a NEMA string in WGS-84 geographic coordinates. A laptop and user-defined software are required to view or save position data. No post-process data are collected. Accuracy with either the USCG beacon or OmniStar™ system would be 1 meter or less. This system costs approximately $4,500.
- The Leica GS 5+™ is a compact receiver/antenna combination where the receiver is housed inside the antenna casing. The unit consists of a 10 cm by 15 cm receiver/antenna with a power and data cable. Once the power is turned on to the receiver, a NEMA string is output to the data collector in the WGS-84 datum. This system was mainly designed with GIS in mind and a GIS software package and data logger is an available option. The GS 5+™ includes a 12-channel GPS receiver and a 2-channel USCG beacon receiver that will provide accuracy of 1 to 2 meters. This unit sells for about $2,500.
- The Leica GS50™ is the next step in the Leica™ line of GPS receivers. This receiver can receive either beacon or satellite differential corrections with an accuracy of 1 meter or less. The GS 50™ receiver can collect and store post-process data which, when processed, will increase the accuracy slightly. This system is operated using a Leica™ data logger which enables it to change parameters, monitor performance, or store data. The antenna has built-in multipath mitigation and carrier phase smoothing. A data string can also be output to a laptop using in-house software. Cost of the receiver and data logger are approximately $9,500.

Test Plan

The receivers tested were the Trimble Pathfinder Pro XR and the Leica GS 50. The Leica GPS system was available on loan from a local survey supplier. The Trimble system was demonstrated by a Trimble representative. The differential correction signal for each receiver was a Coast Guard beacon located in Whitney, Nebraska, about 400 kilometers (250 miles) away. Representatives from both companies indicated that the accuracy would be about 30 centimeters better if the receiver was close to the beacon signal. They also indicated that correction using a satellite system (e.g., OmniStar) would provide comparable results.

A testing grid was set up on a local bridge to test the accuracy and repeatability of these two GPS systems. Temporary control points were marked on the bridge deck and in the channel (Figure 36). Some points in the channel were located where trees, the bridge deck, and high channel banks created less-than-ideal conditions. The objective was to see if the low-cost receivers could overcome these obstructions and how long it would take to get a fixed solution.

Accurate coordinates for all points in the test grid were established using a survey grade GPS system and available permanent bench marks on the bridge (Table 2). The control survey was also based on a nearby National Geodetic Survey control point, in the Geographic Coordinate System, NAD 83. A Larimer County control point located approximately one-quarter of a mile from the bridge was checked to verify the accuracy of the control survey.

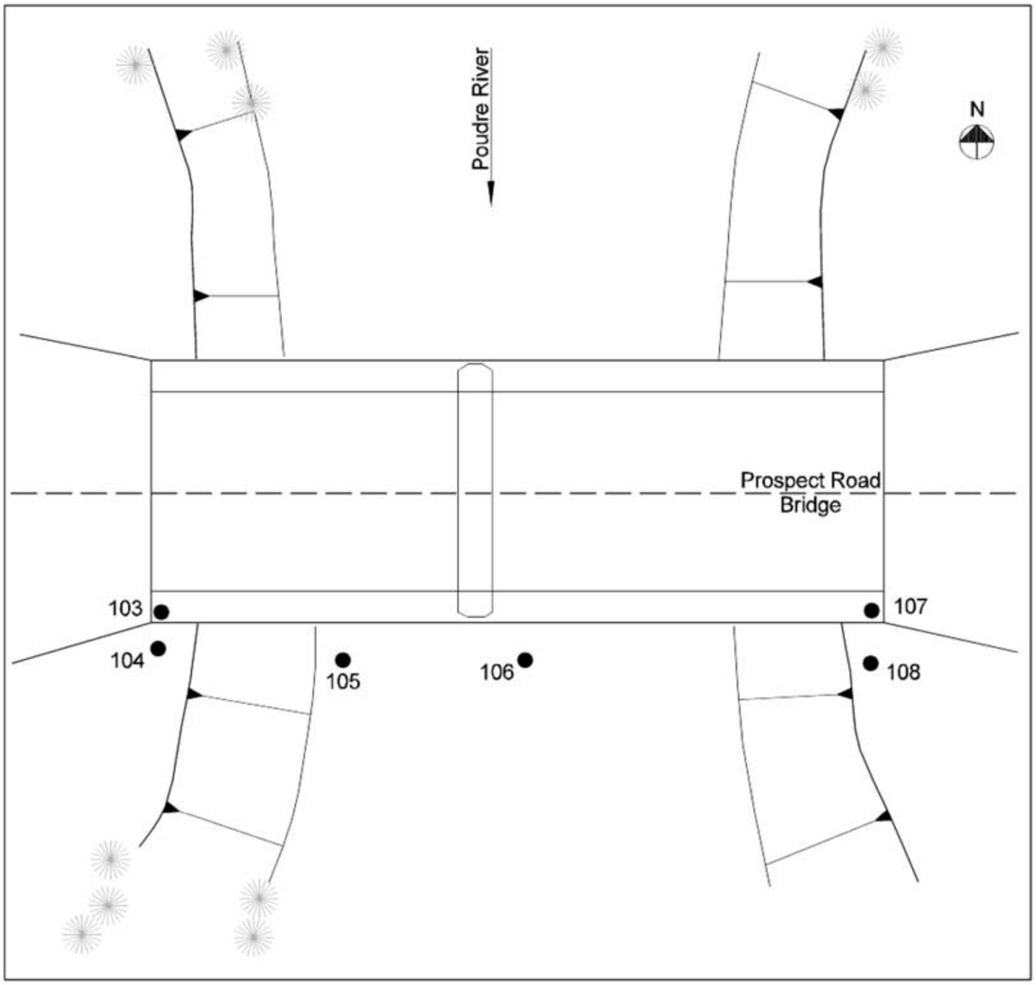

Figure 36. Control grid for GPS testing.

Each temporary control point was then revisited using the Leica GS50 and the Trimble Pathfinder XR system. The GS50 was available twice, allowing measurements on two different days with this system. Therefore, the test plan allowed testing different equipment at different locations on different days. The potential differences from one day to the next were a concern, given that satellite coverage may be less than ideal on one day or even at different times of a given day. Although the GPS satellite constellation is described as being in geosynchronous orbit, suggesting that the satellite coverage should not change with time, there are issues related to the time of measurement.

GPS satellite orbits consist of 24 satellites that orbit the earth twice in a 24-hour period. The satellites orbit the earth in six orbital planes with four satellites in each plane. Although their orbit is described as geosynchronous, it is not exactly geosynchronous and there are times of the day when satellite coverage for a given area is better than for other times of the

TABLE 2 Control network

Pt. Number	Pt. Description	Northing (m)	Easting (m)	Elevation (m)
101	NE Corner of Bridge	441901.28	954463.60	1496.6
102	NW Corner of Bridge	441901.96	954395.69	1496.6
103	SW Corner of Bridge	441879.11	954395.49	1496.5
104	SW Rebar	441878.44	954396.30	1496.6
105	Painted Rock	441876.96	954403.95	1493.7
106	Rebar in Channel	441873.22	954422.49	1491.3
107	SE Corner of Bridge	441878.44	954463.40	1496.6
108	Painted Rock	441872.27	954454.03	1493.2
162	County Control Point	441859.73	955474.99	1490.7

day. Satellite almanacs are available to view the satellite orbits and plan what times of day will have the best coverage in a given area. For instance, Figure 37 from an almanac program shows the view of the Northern Colorado sky at 12:00 p.m., during which 12 satellites are in view. Figure 38 shows the same view of the sky, but at 4:00 p.m. when only 5 satellites are visible. Because of this, most GPS surveyors in northern Colorado avoid working late in the afternoon when the coverage is not optimal.

Note that when the horizon is clear of obstructions, the GPS receiver will be able to see enough satellites to get an accurate solution at all times of the day, but the solution may be more accurate or faster when more satellites are in view. When working around bridges, problems can occur during low satellite count when part of the sky is blocked off by vegetation or the bridge structure, causing the GPS receiver to lose sight of key satellites that are part of the real-time solution. A quality real-time solution takes a minimum of four satellites to compute an accurate coordinate. If enough satellites are not visible to the receiver, the surveyor would have to wait until the satellite orbit has changed to include enough satellites that are unobstructed. Another factor that affects the ability of the GPS receiver to get a quality real-time solution is the location of the satellites in the sky. Satellites that are orbiting low on the horizon or directly above the receiver usually cannot be used in calculating a solution. Satellite location is important when obstructions are present and has an effect on the GPS solution.

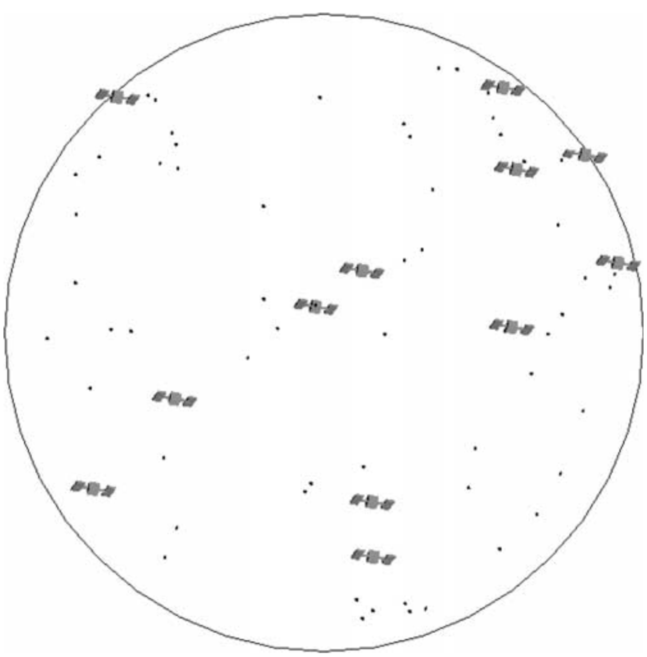

Figure 37. Satellites available at 12:00 p.m. as viewed looking up at the satellite orbits from Fort Collins, Colorado.

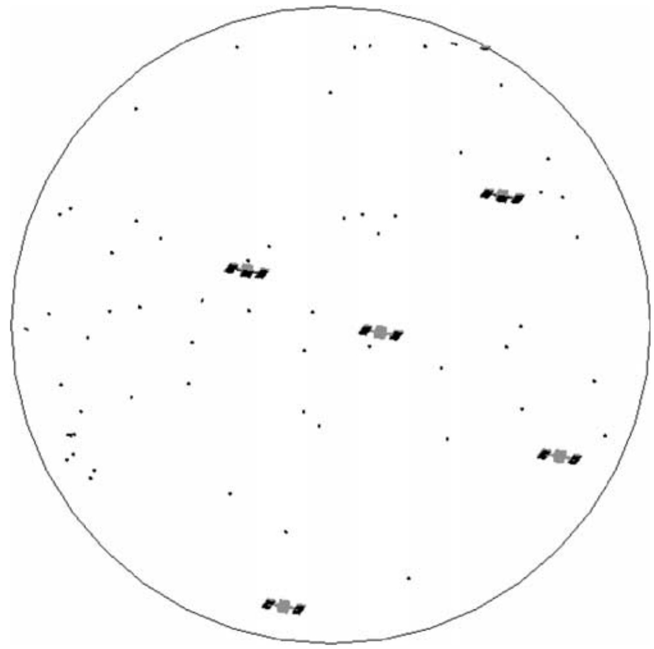

Figure 38. Satellites available at 4:00 p.m. as viewed looking up at the satellite orbits from Fort Collins, Colorado.

Test Results

Test results are shown in Tables 3 and 4. The measured horizontal value was typically within 3 feet (1 meter) of the control survey coordinate. Figure 39 shows the scatter of the measured data around the control point. The vertical elevations, as expected, were not as accurate. Repeatability of the horizontal result was a problem when the measurements collected during different tests were compared. The error between identical points taken during different tests was as high as 10 feet (3 meters).

Careful review of the plotted points in Figure 39 indicates that satellite coverage was not the cause of the observed errors. The best satellite coverage and the most available satellites occurred during the Leica Test #2, but these results are not significantly different from those of Leica Test #1, or the Trimble test, both of which occurred at a time of day when the satellite coverage was marginal.

The influence of the bridge and/or tree cover was also not significant in the accuracy or repeatability of the measurements. Points 103 and 107 were on the bridge deck with little overhead interference, yet results at these points were not significantly better than points influenced by the bridge (Points 105 and 106) or tree conditions (Points 104 or 108). The most noticeable effect of the bridge and tree cover, as well as time of day, was a longer solution time to arrive at a coordinate when conditions were not optimal. Therefore, these results suggest that a lower-cost, sub-meter-grade GPS receiver, as commonly

TABLE 3a Leica Test #1: September 26, 2001, 3:00 p.m.

Pt. Number	Pt. Description	Northing (m)	Easting (m)	Elevation (m)
103	SW Corner of Bridge	441879.11	954395.13	1480.5
*103-a	SW Corner of Bridge	441877.76	954395.30	1482.1
*103-b	SW Corner of Bridge	441878.22	954395.36	1482.1
104	SW Rebar	441878.40	954396.15	1480.5
105	Painted Rock	441875.78	954403.21	1477.8
106	Rebar in Channel	441875.88	954421.76	1475.7
107	SE Corner of Bridge	441877.95	954463.36	1480.3
*107-a	SE Corner of Bridge	441880.11	954461.22	1481.2
*107-b	SE Corner of Bridge	441877.12	954462.75	1482.7
*107-c	SE Corner of Bridge	441877.25	954462.78	1481.9
*107-d	SE Corner of Bridge	441877.52	954462.96	1482.1
108	Painted Rock	441871.24	954453.47	1479.0
*For comparison, the same point was revisited approximately 10 minutes later.				

TABLE 3b Leica Test #2: October 2, 2001, 10:00 a.m.

Pt. Number	Pt. Description	Northing (m)	Easting (m)	Elevation (m)
103	SW Corner of Bridge	441879.99	954396.03	1482.0
103-a	SW Corner of Bridge	441879.93	954395.75	1483.1
103-b	SW Corner of Bridge	441879.75	954395.72	1482.6
104	SW Rebar	441879.20	954396.18	1482.8
105	Painted Rock	441877.95	954404.41	1478.9
106	Rebar in Channel	441874.56	954422.33	1476.9
107	SE Corner of Bridge	441879.26	954463.51	1482.0
107-a	SE Corner of Bridge	441878.89	954463.51	1483.1
107-b	SE Corner of Bridge	441878.98	954463.48	1483.0
108	Painted Rock	441873.25	954454.15	1479.2
162	County Control Point	441860.18	955475.69	1472.7
*For comparison, the same point was revisited approximately 10 minutes later.				

used in precision farming, forestry, or utility-related work, cannot provide the level of accuracy and repeatability needed for scour-related measurements.

Data Collection Software

Extensive effort was put into creating a software package to automate the data collection process with the articulated arm. Data collection and processing occurred with a laptop computer equipped with two serial ports, one for the boom data and one for the truck data, as sent by the two Campbell CR10 data loggers.

Different programs were required, depending on the deployment method. The programs were written in Visual Basic and all had the same general Windows™ layout. The primary difference was the different geometric calculations necessary for position, depending on which deployment method and sensors were being used.

Four programs were created: one for direct sonar measurements with the articulated arm, one for use with the kneeboard deployed on a rigid frame, one for direct probing, and one for cable-suspended operations. All programs produce an x,y,z data file that can be read by CAESAR (Cataloging and Expert Evaluation of Scour Risk and River Stability) or any other program such as AutoCad or Microstation. The x dimension defined the vertical direction, including the measured scour depth. The y dimension was the distance out from the bridge, and the z dimension was the location along the bridge deck.

TABLE 4 Trimble #1: October 5, 2001, 3:00 p.m.

Pt. Number	Pt. Description	Northing (m)	Easting (m)	Elevation (m)
103	SW Corner of Bridge	441879.31	954395.54	
*103-a	SW Corner of Bridge	441881.15	954395.27	
*103-b	SW Corner of Bridge	441880.29	954395.22	
104	SW Rebar	441878.97	954396.85	
105	Painted Rock	441879.20	954403.81	
106	Rebar in Channel	441874.39	954422.83	
107	SE Corner of Bridge	441878.66	954463.20	
*107-a	SE Corner of Bridge	441878.75	954463.92	
*107-b	SE Corner of Bridge	441879.85	954463.64	
*For comparison, the same point was revisited approximately 10 minutes later.				

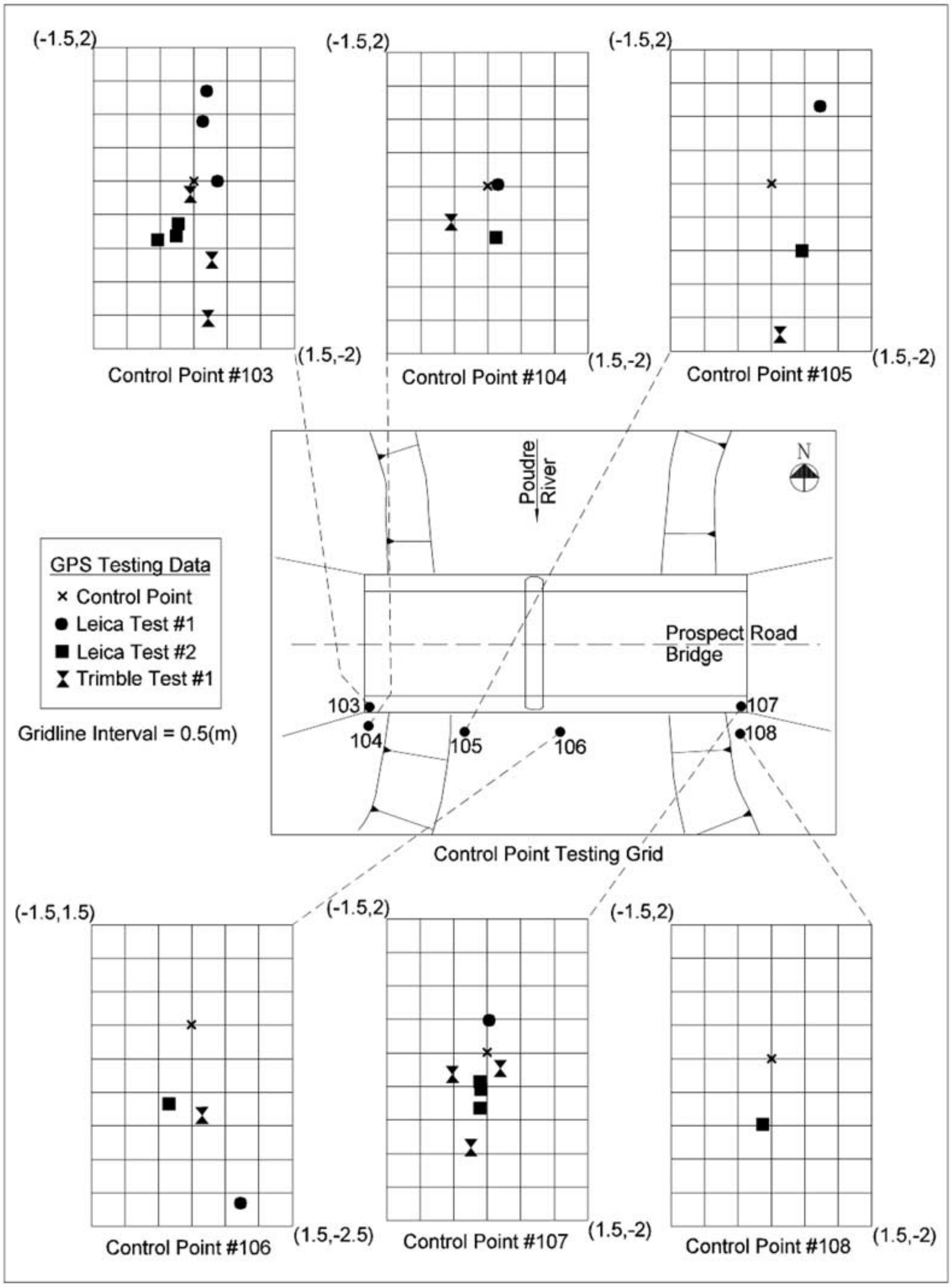

Figure 39. Error in the measured data at each control point.

The program for direct sonar measurements and the one for the kneeboard deployment on a rigid frame were fully developed and tested. The program for direct probing and the one for cable-suspended operations were prototype versions, with only limited field testing.

The sensors on the truck define position data relative to the rotational pivot of the crane. This coordinate system was defined as the "truck" coordinate system. Within the software, these coordinates were converted to "bridge" coordinates, as defined by the profile line for the bridge. The profile line is a station-elevation line on the bridge plans, typically along the centerline of the bridge deck. This same datum is also used for other dimensions on the plans, such as pier locations and pile tip elevations. Providing the scour measurement results in bridge coordinates, facilitates rapid review and evaluation of bridge integrity, and was considered an important aspect of software development.

To convert the truck coordinate data to bridge coordinates required inputting the profile line into the program before beginning data collection. The program was designed to allow this to occur before arriving at the bridge, or it could be done after setting up on the bridge. It was also necessary to measure the horizontal and vertical offsets of the truck relative to the profile line. A chisel mark on the rear bumper of the truck was used as the point of reference, and both the distance from the pavement to that mark, and the horizontal distance from the profile line were measured and entered into the program. The vertical offset was manually corrected for the cross slope of the pavement (typically 2 percent) when entering that distance. With this information, the computer program automatically calculated and reported results in bridge coordinates.

The software for sonar measurements with the crane allows point measurements or continuous recording as the crane is either driven across the bridge or, with the truck in a stationary position, sweeping the crane in an arc. The x,y,z data collected by sweeping the articulated arm with the truck in a stationary position can be used to develop bathymetric plots using standard contouring programs. Cross-section data collected while driving the truck across the bridge can be plotted in any x-y plotting program. The program also included a calibration menu that allows calibrating all sensors, to compensate for any drift or changes in zero that might have occurred either in transit or from environmental or use factors.

Limited graphical presentation of the data is provided during data collection. A schematic of the crane provides a visual reference of the crane geometry for the operator. A running plot of bed elevation versus time facilitates monitoring the scour depth measurements.

DETAILED FIELD TESTING

Objective

The objective of detailed field testing was to evaluate the performance of the articulated arm truck at various sites, representing a range of bridge and site conditions with the assistance and/or cooperation of at least two local or state transportation agencies. The purpose of this testing was to validate the performance of the prototype devices and/or procedures under real-world conditions, as implemented by highway personnel.

Ideally, detailed testing would occur during flood conditions to evaluate the performance of the articulated arm relative to the 12 criteria established as part of the research objective. In particular, this included a range of bridge conditions (e.g., high bridge decks and limited clearance) and flow conditions (e.g., high velocity and sediment concentrations, floating debris, ice, pressure flow, and air entrainment).

Selecting Field Test Sites

Locating field test sites was predicated on finding states willing to provide cooperation. This required more than just permission from the bridge owners to be on site, because there were also issues related to traffic control, assistance in locating suitable test sites that met at least some of the defined criteria, and providing bridge plans and scour history related to the structure. Willing participants were located primarily through personal contact with states known to have an interest in scour-related issues.

A complicating factor in designing the field testing program was the record drought conditions throughout much of the country in 2002. Figure 40 illustrates areas below normal moisture at the end of April 2002, when the selection and scheduling of test sites was underway. This map is based on 7-day averages at given USGS gaging stations and provides a better indication of longer-term streamflow than either real-time or daily streamflow data. Only stations with at least 30 years of record are used, and the dots represent comparisons of the 7-day average to percentiles of historical weekly streamflow for the given week. The dots range from conditions depicting below normal streamflow (lightest colored dots) to extreme hydrologic drought (darkest colored dots).

The below normal moisture conditions eliminated many states from consideration, even when there was a willingness to cooperate. For example, as indicated in Figure 40, most of the eastern and southern states were not good candidates, as was also the case for many of the snowmelt-driven states throughout the west.

Initially, seven states were identified as possible candidates for detailed testing under Task 6 (i.e., Colorado, Nevada, California, Idaho, Alabama, Indiana, and Missouri). These states represented a wide range of flow conditions, from snowmelt-driven rivers, to rainfall-based floods, to tidally influenced rivers and bays. Colorado, Nevada, California, and Idaho provided opportunities for snowmelt-driven rivers, possibly with some ice flow conditions. Alabama provided oppor-

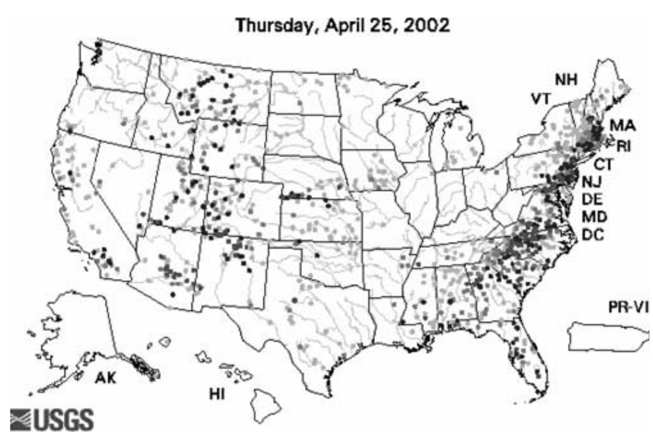

Figure 40. Locations of below normal streamflow at the end of April 2002.

tunities for tidally influenced conditions along the Gulf coast and rainfall-driven runoff in more inland areas. Indiana and Missouri provided rainfall-driven flooding, with good possibility for high debris and suspended sediment loading.

After identifying possible states, the next objective was trying to schedule site visits. The window of opportunity was relatively short, given that the prime time for either rainfall- or snowmelt-driven flooding in the identified states was during late spring to early summer (i.e., April through June). In order to schedule as many visits as possible, it was decided to make the initial site visits in the south and work north and west as weather conditions warmed up. Therefore, the first scheduled trip was to Alabama, however, based on a desire to map conditions around a scour-critical pier that had just been riprapped, prior to high flow occurring, several early season trips were also made to a bridge in western Colorado.

Beyond general planning with each state, trips were not tightly scheduled in the hope that when flooding began, a trip could be made on relatively short notice. Flow conditions in each state were tracked by regular phone calls to each state hydraulic engineer and by tracking reported conditions using the NRCS Snotel network and the USGS streamgage network.

Unfortunately, as time passed, the drought conditions only worsened. In many of the snowmelt-driven basins, low runoff occurred even when snowpack levels were near normal. Discussions with NRCS hydrologists indicated that this trend was occurring because of overall low moisture conditions and, therefore, much of the snowmelt was being absorbed into the ground. Furthermore, what runoff made it to the channels was typically being stored in reservoirs given water management issues related to the drought. In particular, this occurred in Nevada, where the Truckee River peaked at a very low value about 30 days before the long-term average peak flow historically occurred. This also occurred in rivers draining the western side of the Sierras and in southern and eastern Idaho in the Snake River basin.

In many of the precipitation-driven states, there were no sustained storms producing widespread flooding conditions. Small, localized storms were occurring that generally kept moisture and flow conditions from being in a drought category, but the overall runoff conditions were low and certainly not the flood-type conditions desirable for Task 6 testing. Ultimately, only Missouri and Indiana had any flooding of significance.

Despite these conditions, adequate testing was completed to verify the performance and operation of the equipment. High-velocity conditions were found in western Colorado, not because of flood flow but simply because of higher channel gradient. Major flooding occurred in southern Indiana, and significant high water was found in Missouri. Other testing provided the opportunity to try the equipment on various bridge geometries and conditions, even though severe flow conditions were not encountered.

Table 5 summarizes the locations and dates of field testing that were completed. Table 6 summarizes the runoff conditions at the test sites, relative to the research criteria established for the project (as discussed in Chapter 1). Velocity conditions were estimated by timing floating debris passing under the bridge or, in a few select locations, by actual current meter measurements. Sediment concentrations were not measured, but were estimated from nearby gage data. No ice or debris conditions existed at any of the locations where data were collected. Air entrainment conditions were based on a qualitative assessment of flow conditions and turbulence in the region of the measurements. Table 7 summarizes the geometric conditions at the test sites, relative to the research criteria. No pressure flow conditions were encountered, and the lowest clearance was 9 ft (2.7 m); but the articulated arm would have worked under conditions of little or no clearance (i.e., pressure flow), given the positioning capability of the arm. Similarly, no high bridges were tested, given that the most interest was in the capability of the articulated arm with the streamlined sonar probe, and generally bridges where this setup could be tested were selected. High bridges (more than 50 ft or 15 m) could have been measured using the winch system on the truck, which was tested on a bridge in Indiana.

Field Testing Results

Information in the following paragraphs summarizes the field testing completed and the major findings at each location. Additional discussion on the field test results for each location is provided in Appendix B.

TABLE 5 Locations and dates of detailed field testing

State	River	Bridge	Date
Colorado	Colorado River	I-70 near Debeque	March 14 & 26, 2002
Alabama	Heron Bay	State Highway 193	April 3, 2002
	Chickasaw Creek	State Highway 213	April 3, 2002
	Little Lagoon Pass	State Highway 180	April 4, 2002
Minnesota	Minnesota River	State Trunk Highway 93	May 13, 2002
Wisconsin	Wisconsin River	State Trunk Highway 80	May 14, 2002
Missouri	Grand River	U.S. Highway 24	May 17, 2002
Indiana	White River	State Highway 61	May 22, 2002
Idaho	Snake River	Ferry Butte	June 4, 2002
		Shelley	June 4, 2002

TABLE 6 Runoff conditions at field test sites relative to the established research criteria

River	Discharge (cfs)	Velocity (fps)	Conc (ppm)	Debris?	Ice?	Air Entrainment
Colorado River at I-70	1,500 cfs at USGS Gage 09095500 (8 mi downstream)	11	<2000	No	No	Medium
Heron Bay at SH 193	NA	<3	<100	No	No	Low
Chickasaw Creek at SH 213	NA	<3	<100	No	No	Low
Little Lagoon Pass at SH 180	NA	3	<100	No	No	Low
Minnesota River at STH93	7,460 cfs at USGS Gage 05330000 (20 mi upstream)	<3	<500	No	No	Low
Wisconsin River At STH80	22,900 cfs at USGS Gage 05407000 (located at bridge)	<3	<200	No	No	Medium
Grand River At US24	18,600 cfs at USGS Gage 06902000 (25 mi upstream)	6.5	<1000	No	No	Medium
White River At SH61	90,000 cfs at USGS Gage 03374000 (located at bridge)	5	<1000	No	No	Medium
Snake River At Ferry Butte	2,890 cfs at USGS Gage 13069500 (located at bridge)	<3	<500	No	No	Low
Snake River At Shelley	6,820 cfs at USGS Gage 1306000 (located at bridge)	<3	<500	No	No	Low

TABLE 7 Geometric conditions at bridge

River	Clearance (ft)	Pressure Flow ?	Overhang or Projecting Geometry	Height Above Water (ft)
Colorado River at I-70	20	No	Projecting riprap pile around pier	15.5
Heron Bay at SH 193	19	No	Projecting Piles (battered piles)	16
Chickasaw Creek at SH 213	9	No	Projecting Piles (battered piles)	6
Little Lagoon Pass at SH 180	18	No	Projecting Piles (battered piles)	15
Minnesota River at STH93	20	No	Deck Overhang (hammerhead pier on piles)	15
Wisconsin River At STH80	14	No	Slight Overhang (hammerhead pier on spread footing)	9
Grand River At US24	14	No	Deck Overhang (piles)	9
White River At SH61	20	No	Deck Overhang (hammerhead pier on piles)	15
Snake River At Ferry Butte	16	No	Projecting Pier on spread footing	12
Snake River At Shelley	20	No	Projecting Pier on spread footing	16

Colorado I-70 Bridge

The I-70 Bridge across the Colorado River in DeBeque Canyon has been rated scour critical based on observed conditions (Item 113, Rating 2). The bridge was designed for a 50-year discharge of 32,000 (900 m^3/s). The channel bed material is primarily gravels and cobbles. The upstream channel bend has migrated, creating a skewed alignment into the bridge opening and a large scour hole at Pier 2 that extends through the bridge opening to the downstream side. Prior to extensive riprap placement in mid-March 2002, a 20 ft (6.1 m) scour hole had developed, exposing about 10 ft (3.0 m) of pile.

Figure 41 shows the bridge from the upstream side, with Pier 2 on the right side where the articulated arm truck is parked. Flow conditions between Pier 2 and the right abutment are shown in Figure 42. At about mid span, the velocities were 11 fps (3.3 m/s), and the flow depth was about 6 ft (1.8 m). Data were collected on the downstream side by positioning the truck to the right of the pier where the scour hole had been and sweeping multiple arcs (Figure 43).

The Colorado testing was the only test site that provided high-velocity conditions, and the articulated arm proved to be quite stable. This site also provided an early opportunity to test various components of the truck and articulated arm system. This testing resulted in refinement in the data collection program and incorporation of filters on the wireless data to minimize radio interference problems.

Alabama Bridges

Three bridges were visited in the Mobile, Alabama, area over a 2-day period. These bridges were all in tidal, or tidally influenced, channels and were selected to investigate the use of the truck in this type of environment. This also provided an opportunity for additional early runoff season testing prior to the start of more rainfall-driven runoff events in other parts of the country. This area had received rain during the week prior to the trip, and more showers were forecast during the site visit, but, unfortunately, no additional rain occurred. The trip was timed to coincide with predicted strong tidal conditions, but that too was moderated by unexpected offshore winds. Therefore, flow conditions were not as strong as expected, but the testing was still valuable because it provided the opportunity to use the equipment and identify necessary changes and improvements early in the testing program.

Figure 41. Interstate 70 bridge across DeBeque Canyon.

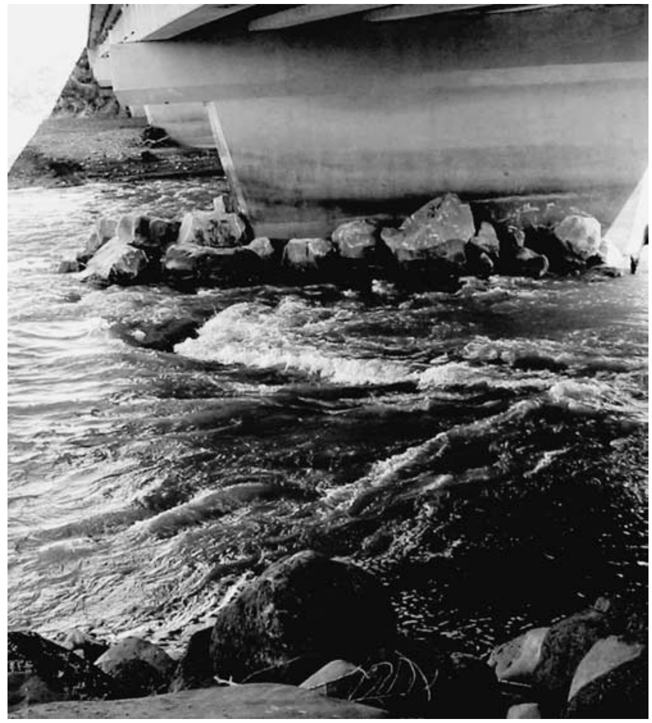

Figure 42. Flow conditions between the right abutment and Pier 2.

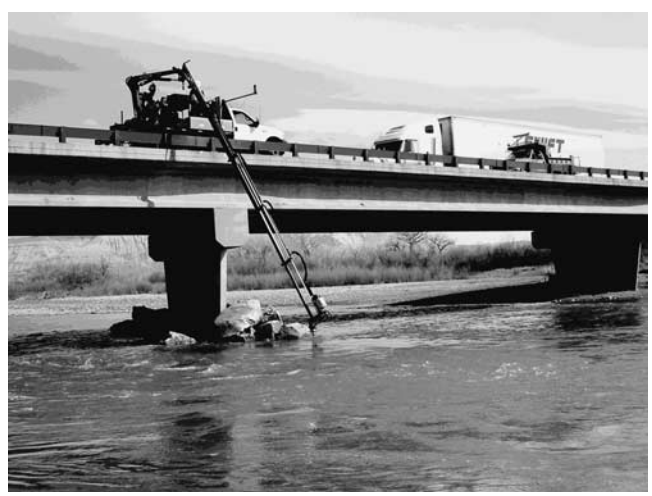

Figure 43. Using the crane to sweep arcs on downstream side of Colorado River bridge.

All three bridges were similar in design, with two lanes and a pile foundation (Figure 44). The bridges at Little Lagoon Pass and Chickasaw Creek did not have shoulders and required traffic control which was provided by the Alabama DOT. Heron Bay had a shoulder with adequate room for the truck (Figure 45). The Alabama bridges provided the first opportunity to test the 5 ft (1.5 m) extension on the end of the articulated arm and the ability of the fin to swivel freely and track the current on its own. This was also the first field test of a cross-section measurement by driving the truck with the castors down. Based on these tests, the streamlined probe was redesigned, and an improved method of mounting the castor was developed.

Figure 44. Little Lagoon Pass bridge.

Figure 45. Truck position on the Heron Bay bridge, Highway 193 near Daulphin Island.

Minnesota Trunk Highway 93 Bridge

Minnesota Trunk Highway 93 (TH93) crosses the Minnesota River near LeSueur, Minnesota. The bridge has five spans on four piers on a pile foundation. At the time of the inspection, runoff was low and there were no known scour problems. Figure 46 shows the approach conditions to the bridge, and Figure 47 shows the truck in position to measure conditions at Pier 1. This site allowed testing of the new extension for the sonar stabilizer with the pivot point further forward on the blade and the new castor system for cross-section measurements.

Figure 46. Upstream conditions at Minnesota TH93 across the Minnesota River.

Figure 47. Truck positioned at Pier 1, Minnesota TH93.

Wisconsin State Highway 80

Wisconsin STH 80 crosses the Wisconsin River near Muscoda, Wisconsin. The bridge has nine spans on eight hammerhead piers supported by spread footings. The bridge has had scour problems at Pier 1, which is in an eddy along the left bank creating reverse-flow conditions at the pier. Figure 48 shows conditions at Pier 1 on the upstream side of the bridge as arc measurements were being made. This bridge provided the first opportunity to test the kneeboard on a rigid frame (Figure 49). Knowing the location of the end of the crane, the angle of the rotator, the length of the frame, and the distance to the water surface, the position of the kneeboard could be calculated as it was moved under the bridge. During testing, the framework was damaged, leading to a revised design.

Missouri U.S. Highway 24

U.S. Highway 24 crosses the Grand River near Brunswick, Missouri. The bridge has seven spans on six piers, two of which have been protected with gabion baskets in response to scour problems. Missouri had received significant rainfall in the week prior to the inspection, but most of the smaller drainages had already peaked. The Grand River watershed is large and flow conditions at this bridge were still quite high at the time of inspection, with velocities around 7.0 fps (2.1 mps). Figure 50 shows the truck position on the bridge to collect data at Pier 5, and Figure 51 shows the sonar in the water.

Figure 48. Arc measurements on the upstream side of Wisconsin STH80, pier 1.

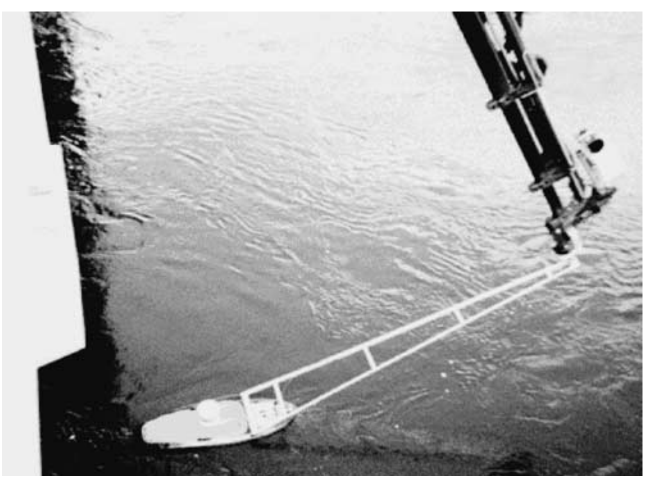

Figure 49. Kneeboard in the water before being pushed under Wisconsin STH80 bridge.

Indiana State Route 61

Indiana S.R. 61 crosses the White River southeast of Vincennes, Indiana. The bridge has five spans on piers with pile caps with steel H piles driven to approximate refusal. At the time of inspection, the river was at flood stage and the southern part of the state was experiencing the wettest May on record. Figure 52 shows the bridge and the flood stage conditions. The bridge has not had any major scour problems, but has had a large sand bar in the bridge opening that had been contracted for removal. In addition to potential pier scour during the recent high flows, the Indiana DOT was particularly interested to see if the sand bar was still present.

Testing at this bridge provided the opportunity to work at flood stage with relatively high velocities (about 7 fps or 2.1 mps). The bridge had large grate inlets that required positioning the truck away from the barrier for a cross-section measurement. This had not been tried before, but worked well because the crane could still be articulated into position. The wireless sonar in the sounding weight was also tested at this bridge (Figure 53) and was found to track the current and remain in a steady position, which had been a problem with earlier versions of the modified sounding weight.

Idaho Bridges

Two bridges on the Snake River were visited near Blackfoot, Idaho. The drought conditions limited runoff in the state, particularly in eastern Idaho, however, these bridges have had

Figure 50. Truck in position at U.S. 24, Missouri.

Figure 51. *Arc measurement at pier 5, U.S. 24.*

scour problems in the past and were of interest to the Idaho DOT. Additionally, they were going to install A-jacks™ as a countermeasure later in the year and were interested in having a pre-construction survey. The bridge design for the Ferry Butte Bridge, south of Blackfoot, and the West Shelley Bridge, north of Blackfoot, were similar, with four spans on spread

Figure 52. *Indiana SR61 at flood stage.*

Figure 53. Sounding weight with a wireless sonar being tested in Indiana.

footing piers. The deck width was 33 ft (10.0 m) with no shoulder, requiring a lane closure for traffic control that was provided by Bingham County. Figure 54 shows the bridge at Ferry Butte.

Arc measurements were made at the upstream side of the piers at both bridges, supplemented by kneeboard measurements at Ferry Butte and a cross section at West Shelley. High-velocity and turbulent conditions existed near the piers (Figure 55), but the crane and the streamlined probe were quite stable. These bridges allowed testing an improved kneeboard (Figure 56), as well as running the castors through sand and gravel that had collected along the curbline.

Reduction of Data from Field Tests

As described above, various data were collected at each bridge using different deployment methods from various locations on the bridge deck. During each measurement, bed conditions could be monitored on the computer, either as a scrolling graph of bed conditions or in tabular format. How-

Figure 54. Ferry Butte bridge across the Snake River, Idaho.

Figure 55. High-velocity conditions near the pier at West Shelley, Idaho.

ever, once a measurement was completed, the computer software also produced an archived x,y,z data file in bridge coordinates. This data file could be used by various plotting and/or contouring programs to provide a detailed graphical representation of the data.

Figure 57 shows data collected at the upstream side Indiana State Route 61 over the White River. The data were reduced in Microstation™, but any similar program would produce comparable results. The basic bridge geometry was included, using information provided on the bridge plans. At this location, both arc measurements in front of the piers and a cross section measurement were taken. Similar graphs for all other bridges visited are included in Appendix B.

Figure 56. Kneeboard with revised frame.

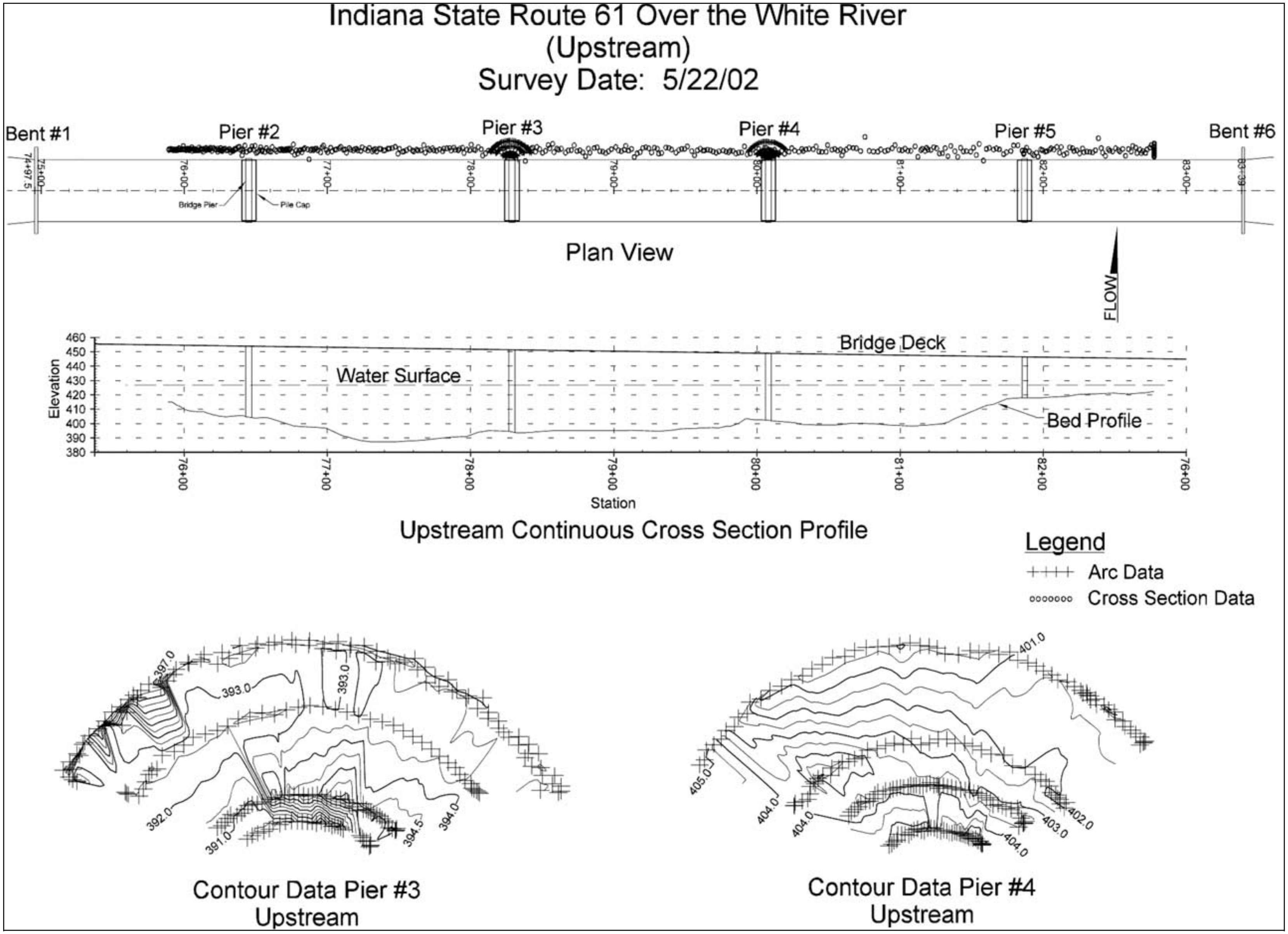

Figure 57. Typical results obtained with the articulated arm.

CHAPTER 3

INTERPRETATION, APPRAISAL, AND APPLICATIONS

INTRODUCTION

This chapter presents interpretation, appraisal and applications for the portable scour monitoring instruments tested under this project. Although all aspects of the research completed are discussed, Chapter 3 concentrates on the articulated arm truck. Application of this device should improve the ability of inspectors to make portable scour measurements during flood conditions, when such measurements can be difficult because of flow conditions.

INTERPRETATION AND APPRAISAL

The primary product of the research was the articulated arm truck, which also included a modified Minnesota-style winch system and data collection software. A detailed analysis and evaluation of this integrated device, particularly as they relate to the objectives of the research, are presented below. Prior to that discussion, a general evaluation and appraisal of the secondary components of the research, specifically the Interphase Scanning Sonar and the low-cost GPS systems, are presented.

Interphase Scanning Sonar

The Interphase Scanning Sonar was included in the research plan to evaluate its potential application as a scour monitoring device. The expectation was that it could provide a relatively low-cost method to get a three-dimensional perspective on conditions at a pier. The design of the test program only allocated a small effort for this task; hence, the testing should not be considered comprehensive. Furthermore, none of the field sites visited provided ideal testing conditions. One of the findings was that this instrument requires at least 10 ft (3 m) of water, which given the drought conditions did not exist at many of the bridges visited. The testing did not include evaluation in high-velocity, suspended sediment, or air entrainment conditions.

Based on the limited testing completed, this instrument could be a valuable addition to the "toolbox" of devices used for scour monitoring. Field testing was completed with the articulated arm, and laboratory testing had the transducer mounted in a pontoon-style float for deployment. Given the cables necessary from the display to the transducer, the cable length would constrain its use to bridges relatively close to the water. Any type of float deployment with a tether would create the typical cable management problems encountered with deployment of any cabled instrument. The instrument has no data storage capability and no way to output the data, so the inspector would have to make notes on conditions displayed on the monitor. Reasonable pictures of the display monitor were possible using a digital camera and such pictures could be part of the documentation record.

Therefore, although the instrument is thought to have limited application and would not be considered the primary sensor for scour monitoring during floods, it does have value and should be considered as a useful tool to include in a comprehensive portable instrumentation package.

Low-Cost GPS

Low-cost GPS was included in the research plan to evaluate the application of this technology for positioning scour instrumentation. Potential applications include locating the inspection truck on the bridge deck, directly tracking the location of the end of the articulated crane, and/or locating a boat being used either as a manned or unmanned monitoring vessel. A limitation of GPS application in scour monitoring has been cost, so this task was designed to evaluate a specific class of GPS receivers in the $5,000 to $8,000 range.

The design of the Phase II test program only allocated a small effort for this task; hence the testing should not be considered comprehensive. The test program included only two GPS receivers, although the design of the test program was reasonably complete and comprehensive. The results of the testing found that this class of GPS receivers is not currently capable of providing the accuracy defined by the objectives of this research (1 ft or 30 cm).

These results limit the application of GPS positioning, using this grade of equipment, with the articulated arm or in other scour measurement applications. Scour hole geometry is often confined to a relatively small area around a pier or abutment, and the ability to map the scour hole or to compare measurements on successive measurements requires higher accuracy and more consistent performance than these units can provide. A higher-priced GPS receiver could be used and/or a local base station could be setup on the bridge itself, but cost and ease of use issues limit these approaches as they relate to scour monitoring applications.

However, as with many new technologies, GPS equipment continues to improve while costs decrease. Therefore, although the results obtained under this testing were not positive, future improvements in equipment and technology may provide the necessary accuracy at a reasonable cost.

Articulated Arm Truck

After completion of Phase I, the development of an articulated arm for deployment of scour instrumentation became the primary focus of the research and most of the Phase II research was dedicated to this task. The objective was to develop a mechanical arm that could be used for deploying various scour monitoring sensors. Given the availability of knuckle booms or folding cranes in the construction industry, the research was designed around modifying and instrumenting this type of articulated crane for use in scour monitoring research.

The use of a crane for scour monitoring was expected to provide a solid platform for deployment, even under flood flow conditions, that could be instrumented to allow precise measurement of the movement of the crane. Unlike the cranes commonly used in the construction industry, which are designed to handle large weight but with limited extension, the crane necessary for scour monitoring needed the ability to reach long distances, without having to manage much weight or force.

Ultimately, the selected crane with the hydrodynamic extension for the sonar could reach directly into the water nearly 30 ft (9.1 m) below the bridge deck. Working off higher bridges required cable suspension methods, provided by the Minnesota-style winch included in the Phase II research. Modified deployment methods were developed to allow working off of various bridge configurations, including the wireless sonar in a sounding weight and in a kneeboard deployment with a rigid frame. A comprehensive data collection software package was developed that facilitated the use of the articulated arm, providing the inspector with immediate access to the data collected.

The following paragraphs discuss the evaluation and appraisal of the articulated arm, as developed under this research, relative to the defined research objectives. As defined in Chapter 1, the equipment and techniques developed under the research should be operational under the following conditions:

- Flow velocities exceeding 11 fps (3.5 m/s);
- High sediment concentrations;
- Floating debris;
- Ice accumulation;
- Limited clearance;
- Pressure flow;
- Overhanging or projecting bridge geometries;
- Bridges with decks more than 50 ft (15 m) above the water;
- Air entrainment;
- Easily used and affordable by state and local bridge owners;
- Transportable by pickup, van, or similar vehicle; and
- Accuracy of +/− 12 in. (30 cm).

High-Velocity Conditions

To be applicable in flood conditions, the articulated arm needed to deploy sensors in high-velocity flow conditions. At the conclusion of Phase I, one of the stated research needs was to develop a hydrodynamic probe that could be used with the crane, given the concern for vortex shedding that might occur with a simple rod-shaped probe. This resulted in the use of a section of helicopter blade that could swivel to follow the current no matter how the crane was positioned when deploying the wireless sonar. The Colorado site provided the opportunity to test the articulated arm in such conditions. The arm proved to be very stable in the fast, turbulent current under this bridge. The combination of a strong, stable mechanical arm and a streamlined probe provided very successful results in high-velocity conditions.

High Sediment Conditions

Flood conditions often produce large suspended sediment loading, which can complicate measurements with some sensors, particularly sonar. High flow conditions were encountered in Indiana and Missouri, with what could be described as typical flood-level suspended sediment conditions for these regions. No gage data were available to quantify the suspended sediment loading, and yet, given that the rivers were at flood stage and data were successfully collected, it is reasonable to conclude that the equipment can perform in higher sediment conditions typical of a midcontinent river at flood stage. Extreme suspended sediment conditions, such as might exist in a sand bed channel in the southwest, were not encountered during field testing and it is unknown whether or not the equipment would have worked under these conditions.

Part of the success in high sediment conditions is minimizing other factors that can complicate a sonar measurement, including separation zones and high air entrainment. The streamlined probe that was developed minimized these effects by reducing turbulence induced by the probe and streamlining the flow over the transducer. The streamlined probe also positioned the transducer about 12 in. (30 cm) under water for the measurement, which eliminates surface interference issues typical of a floating deployment where the transducer is skimming the surface.

Floating Debris

The accumulation of floating debris is a common problem on the upstream side of a bridge. Trees, logs, and branches are trapped by the piers and gradually build out to create a potentially large debris jam. This debris not only complicates the measurement process, but can also increase the scour that occurs. The use of the articulated arm could increase the opportunity for success under these conditions when it is possible to position the end of the crane upstream of the debris pile and point the sonar under the debris. However, debris piles often have substantial depth, sometimes accumulating down to the channel bed, that would limit success even if the crane could be positioned at the upstream edge of the debris pile. Additionally, as the tilt angle increases, the strength of the sonar return signal gets weaker and any angled measurement would need to be corrected to vertical.

Alternatively, the physical probe that was developed, consisting of a 2 in. (5 cm) stainless steel pipe, might be forced through a debris pile using the crane hydraulics. However, once through the debris, the same crane hydraulics would make it difficult to detect the channel bottom. Without developing some type of sensor at the end of the physical probe to detect the channel bottom, this is not a practical solution.

Therefore, debris has been and continues to be a serious problem complicating scour measurements. The articulated arm may improve the potential for a successful measurement in a few cases, but overall, the research completed has not resolved this problem.

Ice Accumulation

Ice accumulation creates problems similar to debris accumulation by creating a physical obstacle to measurement and potentially increasing the scour that occurs. Similar to the conclusions stated in the debris discussion, the research completed has not resolved this problem.

Limited Clearance

Limited clearance conditions often exist during floods because of high stage conditions. This reduces the clearance under the bridge, which can complicate scour measurements. For example, the original articulated crane developed by FHWA had difficulty working in limited clearance situations because the crane could not be articulated into a position that would allow a measurement without submersing the boom. The crane developed under this research can be articulated such that direct measurements can be made from a water level just below the bridge deck downward to about 30 ft (9 m).

Pressure Flow

When flow is so high that the low-chord of the bridge is underwater, the use of floating deployments is virtually eliminated. However, under these conditions, the crane is still feasible and within certain physical limits could be articulated into position under water. Another concern is that under pressure flow, the velocity is typically accelerated from free surface conditions, and more turbulence exists. Although these conditions were not tested, the overall stability of the articulated crane and the strength of the crane hydraulics would facilitate making measurements in such adverse flow conditions.

Overhanging Bridge Geometry

Overhanging bridge geometry is a common problem, and many of the bridges tested during this research had such conditions. In fact, the only bridges that did not have any type of overhang were in Idaho. The bridges in Alabama had a slight overhang, but also had a battered pile such that the crane was at the correct location when the arm was vertical over the rail. However, most of the other bridges were hammerhead designs with significant deck overhang.

With the ability to tilt the rotator, the crane could be articulated slightly to allow some positioning under the bridge deck. However, this ability is limited; and, without an alternate solution, such bridge geometries would continue to create measurement difficulties. This led to the development of a rigid frame for the kneeboard. The framework allowed pushing the kneeboard under the bridge deck up to 10 ft (3 m) and was attached to the rotator to allow a side-to-side movement under the bridge.

Field testing found that it could be difficult to get the kneeboard positioned on the water and ready to push under the bridge. The original version of the framework was aluminum and was bent during testing in Wisconsin. A second version was made of steel and, although stronger, was still difficult to get into position. One of the problems with a kneeboard on a rigid frame was the tendency for the kneeboard to submarine when a side edge caught a wave. Once on the water, the kneeboard provided good data at overhanging bridge geometries, but this measurement was considerably more problematic than a direct measurement with the streamlined probe.

High Bridges

High bridges, where the water surface is well below the bridge deck, can create difficult measuring situations. Not only is the height of the bridge an issue, but at such locations there can often be significant wind blowing through the bridge opening. The limit of the articulated crane under a direct measurement is 30 ft (9 m), and therefore, high bridges typically require a cable-suspended approach.

The Minnesota-style winch was built and added to the articulated arm truck to allow measurement on high bridges. The development of the two-winch concept on a post mounting (Figure 9) provided more versatility in the measurement approach. Problems of a single-winch deployment are the drift under the bridge and the effects of wind on the cable or the deployment platform. The original Minnesota application used an articulated crane, with the pulley at the end of the crane, allowing an extension up river to 40 ft (12 m). This minimized some of the drift issues; however, the dual-winch approach allows a second cable and better control of the location of the deployment platform, as illustrated in Figure 7.

With any cable-suspended operation, particularly on high bridges, the ability to track the position of the sensor accurately is lost. Therefore, the positional accuracy will always be better with the direct measurements made with the streamlined probe or the physical probe.

Air Entrainment

The problems with air entrainment are particularly significant when making sonar measurements. Similar to high suspended sediment conditions, high air entrainment can complicate a sonar measurement. The streamlined probe that was developed minimized these effects by reducing turbulence induced by the probe and streamlining the flow over the transducer.

The streamlined probe also positioned the transducer about 12 in. (30 cm) under water for the measurement, which eliminates surface interference issues typical of a floating deployment where the transducer is skimming the surface. Therefore, although no testing was completed in conditions with excessive air entrainment, the streamlined probe deployment of the sonar should provide the best opportunity for success when using sonar in high air entrainment conditions.

Easily Used and Affordable

To facilitate future implementation and use, the cost of any device developed under this research was important. The products from this research needed to be affordable by state and local transportation agencies to better ensure widespread application of the research results. For example, based in part on cost and the specialized training necessary, many states only have one underbridge inspection truck. This vehicle and its crew are often on the road year round and are scheduled so far in advance that they have little or no flexibility for breakdown or complications. By analogy, if the cost of scour monitoring technology was so high that states could only afford one or two devices, they might not be able to respond adequately to, or cover, widespread flood conditions.

One way to control cost is to use commercially available, "off-the-shelf" products whenever possible and thereby avoid special fabrication requirements. Therefore, the articulated arm truck was designed using readily available components whenever possible. These components and pieces were also designed to be a bolt-on installation, so that the articulated arm truck could be readily used for other purposes outside of the flood season. In fact, many transportation agencies already have articulated arm trucks that could be retrofitted for scour monitoring work based on the design concepts developed through this research.

The smaller truck chassis used in the research did minimize the cost of the vehicle itself, however, a larger truck also offers advantages. The F-450 used in the research was not large enough to handle even the lightweight crane selected without hydraulic stabilizers. This lead to development of the castor system to allow driving the truck with the crane deployed for measuring cross sections. As an alternative, a larger truck chassis might be able to handle the lightweight crane selected for the research without the outriggers and the additional cost and complication of the castor system.

The cost of the truck and crane were about $50,000 prior to adding instrumentation. Allowing $25,000 for instrumentation and fabrication, the total cost for the scour monitoring truck is about $75,000. Discussion of cost with the states visited during the testing program suggested that a cost in this range for a scour monitoring inspection vehicle was not viewed as prohibitive.

To make the system easy to use, a comprehensive software package was developed to collect the data. The program was written in Visual Basic to provide an easy-to-use Windows-style environment, and the menus and layout of the program were designed to provide an intuitive operating process. The data are reported in station-elevation format to allow immediate comparison of the results with information on the bridge plans.

The sensors selected for monitoring the position of the truck and crane movement were fairly simple, robust, and easy to replace. The only exception is the sensor setup to measure the angle of the rotator at the end of the crane. The computer program was designed with a calibration menu to allow easy zeroing of any new sensor, should one need to be replaced. However, as with any automated system that relies heavily on sensors, data loggers, and computers, the system does require an aptitude for electronics and computers and would require some training for users to be able to understand and operate the system.

Easily Transportable

The articulated arm truck was designed around the smallest truck chassis possible, so as to control cost, provide maneuverability, and minimize the traffic control requirements. The latter issues are important when operating in a flood response mode, because the inspection crew needs to collect data as efficiently as possible and get to as many bridges as it can in a short time. An F-450 truck chassis is not much bigger than a full-sized pickup, and therefore, the articulated arm truck as developed was easily transportable and maneuverable.

Accuracy

The desired accuracy of the measurement was +/−12 in. (30 cm). Most sonar devices meet this criterion, and so as it relates to the articulated arm truck, this criterion was more critical for the positioning system. After concluding that GPS was not a viable approach for positioning (either for the truck or the end of the crane), an alternate method was developed. This method was based on a surveyor's wheel for position of the truck and several tilt sensors and draw wires for the angle and extension, respectively, of the crane.

Individually, the accuracy of each sensor is much better than the required accuracy. The combined accuracy of the entire system, including the software calculations to reduce the data, was verified by ground truthing with a grid on the pavement. Using the grid, the crane was moved from one point to the next and the output from the computer was compared with the known coordinates. The results of this test found the measurements to be well within +/−3 inches.

Ultimately, what controlled the accuracy of the system was probably the deflection in the crane. At full extension and in high flow conditions, some deflection was observed in the crane. Additionally, movement of the crane, either during an arc measurement or while driving across the bridge deck when making a cross-section measurement, caused some measurements to be in error by more than +/−12 inches. During the Idaho measurements, considerable variation was noted in the y-direction (streamwise direction) during a cross-section measurement. This resulted from driving the truck too fast and developing some bounce in the crane that caused the tilt sensors to overreact. Therefore, the conclusion is that the articulated arm truck can provide the desired accuracy, however, these limits may be exceeded if proper and careful application procedures are not followed.

Research Criteria Summary

Based on all of the above information, Table 8 summarizes how well the articulated arm satisfied the research criteria. The articulated arm met most, but not all, of the criteria defined for this research. The research did not solve the measurement problems associated with debris and ice, which have been and probably will continue to be the nemesis of portable scour monitoring (as is the case with fixed instrument monitoring). However, the articulated arm did improve the ability to make measurements in high-velocity flow during flood conditions substantially. These measurements can be completed from various bridge geometries (limited clearance, overhanging geometry, and high bridges) using a truck that is affordable and maneuverable. The data collection process has been automated, and the scour data are presented in the bridge coordinate system, thereby allowing rapid evaluation of scour criticality. Overall, the ability to make portable scour measurements during flood flow conditions has been substantially improved.

APPLICATIONS

Scour Monitoring Concepts

Approximately 584,000 bridges in the National Bridge Inventory (NBI) are built over streams. Many of these bridges span alluvial streams that are continually adjusting their beds and banks. Many of these bridges will experience problems with scour and stream instability during their useful lives. In fact, the most common cause of bridge failure is scouring of bed material from around bridge foundations during flooding (*13*). The magnitude of scour and stream instability problems is demonstrated by annual flood damage repair costs of approximately $50 million for highways on the Federal-aid system (*14*).

Scour and stream instability problems have always threatened the safety of the U.S. highway system. The National Bridge Inspection Standards (NBIS) requires bridge owners to maintain a bridge inspection program (23 CFR 650, Subpart C) that includes procedures for underwater inspection. A national scour evaluation program as an integral part of the NBIS was established in 1988 by FHWA Technical Advisory T5140.20, which was superseded in 1991 by Technical Advisory T5140.23.

Technical Advisory T 5140.23 specifies that a plan of action should be developed for each bridge identified as scour criti-

TABLE 8 Summary of success in meeting the research criteria by the articulated arm*

Research Objectives	Articulated Arm Device
1. Flow velocities > 3.5 m/s	Excellent
2. High sediment concentrations	Fair
3. Floating debris	Poor
4. Ice accumulation	Poor
5. Limited clearance	Good
6. Pressure flow	Good
7. Overhanging geometries	Good
8. Higher than 15 m	Fair
9. Air entrainment	Good
10. Easily used and affordable	Excellent
11. Transportable by pickup, van or similar	Excellent
12. Accuracy to 30 cm	Good

*Including Minnesota-style winch and other deployment methods developed cal in Item 113 of the NBIS. The two primary components of the plan of action are (1) instructions regarding the type and frequency of inspections to be made at the bridges and (2) a schedule for the timely design and construction of scour countermeasures. A scour countermeasure is something incorporated into a highway-stream crossing to monitor, control, inhibit, change, delay, or minimize stream instability or scour problems. The primary categories of countermeasures are hydraulic, structural, and monitoring (*15*).

Hydraulic countermeasures are designed primarily to modify the stream flow or resist erosive forces. Examples of hydraulic countermeasures include the installation of river training structures and the placement of riprap at piers or abutments. Structural countermeasures usually involve modification of the bridge substructure to increase bridge stability. Typical structural countermeasures are underpinning and pier modification.

The purpose of the plan of action is to provide for the safety of the traveling public and to minimize the potential for bridge failure by prescribing site-specific actions that will be taken at the bridge to correct the scour problem. A defined monitoring program is an important aspect of the plan of action and can incorporate various fixed and portable scour instrumentation devices. A properly designed scour monitoring program includes two primary components (*15*):

1. The frequency and type of measurements to facilitate early identification of potential scour problems, and
2. Specific instructions describing precisely what must be done if a bridge is at risk because of scour.

In summary, any bridge categorized as scour critical should have a plan of action describing what will be done to correct the scour-related deficiency. The plan of action details the countermeasures that will be implemented to correct the scour problem, which could include the use of instrumentation as part of a monitoring plan. The monitoring plan may be a short-term countermeasure, implemented while the design and construction of hydraulic and/or structural countermeasures occurs, or it alone may be the selected long-term countermeasure. Note that when monitoring is selected, without other structural or hydraulic countermeasures, the bridge retains its scour critical rating because monitoring alone does not fix the scour problem.

As of 2002, scour evaluations have been completed for about 93 percent of the bridges in the NBI. Based on these scour evaluations, approximately 26,000 bridges were rated as scour critical. Having completed, or nearly completed, the scour evaluation process, many states are now considering the plan of action requirements for their scour-critical bridges. Given that a monitoring program could be an integral part of the plan of action for many of these 26,000 scour-critical bridges, the potential application of scour instrumentation in the near future is tremendous as states begin to address the question of scour-critical bridges.

Application of the Articulated Arm Truck

The type and frequency of inspection work called for in the plan of action can vary dramatically depending on the severity of the scour problem and the risk involved to the traveling public. For example, a bridge rated scour critical by calculations, but which has relatively deep piles in an erosion-resistant material and has been in place for many years with no sign of scour, might be adequately addressed through the regular inspection cycle and after major flood events. Alternatively, a bridge found to be scour critical by inspection, such as during an underwater inspection that finds a substantial scour hole undermining the foundation, would obviously be a greater concern and would require a more aggressive inspection plan.

In either case, the application of portable scour monitoring devices during and after a flood, such as the articulated arm truck developed under this research, could be a key element of a scour monitoring program developed as part of the plan of action for a scour-critical bridge. The articulated arm truck provides a stable platform for deploying various scour instruments. The size of the truck and the automated data collection system facilitate flood measurements by allowing detailed data to be collected in a short time.

During field testing, some state inspectors questioned the complexity of the truck, as compared with their conventional approach using a lead line measurement from fixed locations across the bridge. The lead line approach is simple and can provide fast results without the complexity of the articulated arm. However, it is important to recognize the complications presented by flood flow conditions, as highlighted by the 12 criteria that the research addressed. The conditions described were typical of large flood events, such as might be produced during the 100-year storm. The application of conventional methods in use by many bridge inspectors would be extremely difficult under such severe conditions.

Another difference between the truck and more conventional methods in widespread use is the large amount of data that can be collected with the truck in a relatively short time. Conventional methods generally produce point measurements at defined locations across the bridge, which under many conditions may be adequate to evaluate scour criticality. Although the truck can provide the same data, its real benefit and value occurs when more data are necessary or desirable to define the scour problem, and these data must be collected under the adverse conditions of an extreme flood event. For example, positioning the truck at a pier and sweeping arcs with the crane can provide enough points to map the approach conditions and scour hole itself. Once in position on the bridge, this measurement can typically be completed in 15 minutes or less and can be done equally well during low flow or at flood flow conditions. The truck can also provide continuous cross section in the time its takes to drive across the bridge at a slow speed (typically 10 to 20 minutes). This allows identification of problems between piers that might be missed by simple point measurements at the centerline of each pier.

Therefore, it is important to recognize that the articulated arm truck was designed for a specific application, that being flood flow conditions, and it may not be the best tool for all situations. At lower flow conditions, or when fewer data can adequately address the problem, other methods may be preferable. With the number of sensors, the data loggers, and the computer data collection methods, the truck is a more complicated device than most conventional scour monitoring methods. Proper use of the articulated arm truck will require some training and a certain aptitude to operate and maintain.

Therefore, the integration of the articulated arm truck into a state scour inspection program might be based on a single truck and a crew specifically trained in its use. In larger states, or states with more scour-critical bridges to monitor during and after floods, several trucks and trained crews might be necessary. These same crews might also be doing 2-year inspections or lower flood event monitoring with more conventional methods; but, when a big flood occurs, they are the only ones who are trained and ready to operate the truck. Ultimately, once trained and comfortable with the truck, these same crews might find using the system for more regularly occurring bridge inspections and surveys would be beneficial.

As with all scour monitoring methods, the truck has advantages and limitations. Recognizing and remembering what these are will facilitate successful application of the articulated arm truck in a scour monitoring program. The articulated arm truck should be viewed as another tool in the inspector's toolbox for scour monitoring and, for any given job, the right tool or combination of tools must be applied.

CHAPTER 4

CONCLUSIONS AND SUGGESTED RESEARCH

CONCLUSIONS

This research resulted in improved deployment, positioning, and data collection procedures for portable scour monitoring work. These improvements will facilitate data collection under adverse conditions and will allow more successful monitoring at a wide range of bridges under flood flow conditions. The research was conducted recognizing the need to provide solutions that are easily used and affordable by state and local bridge owners.

The research completed did not include work directed toward new measurement technology, but concentrated on improved deployment methods. The proposed solution, as developed in the articulated arm truck, did not meet all the identified criteria defined for this research. In particular, the research did not solve the measurement problems with debris and ice. However, the research did solve some difficult implementation problems and provided improvement over current practice in flood flow monitoring. The resulting product will be beneficial to bridge inspectors and should greatly improve their ability to get reasonable results under adverse conditions.

SUGGESTIONS FOR FURTHER RESEARCH

Although this research produced a reliable, fully functional articulated arm device, improvements could be made to the device, and other areas of research and development would further improve the ability to make flood flow measurements.

Physical Probing Attachment

A physical probe was fabricated from Schedule 80 stainless steel pipe that could be used for point measurements of scour hole conditions. Knowing the location of the end of the crane, these point measurements could be completed with accurate positioning. The primary limitation of the probe was that it could be used only in gravel/cobble beds or around piers with riprap, because the strength of the crane hydraulics would drive the probe into the bed in softer materials. Given this concern, a sensor at the end of the physical probe would be beneficial to help identify the water sediment interface. Such a sensor might be as simple as a pressure switch; however, alternative solutions that do not require wires or cables would be preferable.

Rigid Frame Deployment of a Kneeboard

Further research and development on the kneeboard concept deployed on a rigid frame would be valuable. As developed, the kneeboard on a rigid frame was able to facilitate data collection on bridges with projecting decks and/or large overhangs. However, there were deployment issues related to getting the kneeboard on the water surface and maintaining a stable platform for measurement. The conclusion was that a rigid frame deployment of a kneeboard was viable, but an alternative floating platform might work better.

A kneeboard works well on a tether, and the larger surface area is necessary under those conditions to keep the board upright. However, on a rigid frame it is not necessary to have as much flotation, and a different board or floating system might work better. One idea is a pontoon-style system with a stabilizing fin between the pontoons that locates the transducer under water 6 to 12 inches and also provides directional stability. Alternatively, the transducer could simply be mounted on a rigid, horizontal frame submerged under water without flotation.

Angular Measurement of Rotator

The rotator at the end of the crane was included to provide the ability to rotate a sensor deployed at the end of the crane. The angle of rotation was measured with a 10-turn potentiometer. Mounting this sensor on the rotator required significant fabrication, and the 10-turn potentiometer was not as robust or durable as the other sensors included to monitor crane position.

An improved sensor arrangement for measuring the position of the rotator would be desirable if the concept of a kneeboard on a rigid frame is pursued further. The rigid frame deployment of the kneeboard was ultimately the only application that required rotational ability. For example, rotational ability was not necessary for the streamlined probe concept, after it was modified to allow it to rotate and track the current on its own. It was also not necessary for any of the cable-suspended operations. The tilt ability at the end of the crane (as provided with the additional hydraulics that were added to the crane) was a desirable and necessary improvement. However, the additional capability to rotate and to measure that rotation added significant cost and complexity to the crane. Therefore, without additional research and development to make the kneeboard concept more functional, the crane design and construction could be simplified by eliminating the rotator and its measurement.

Alternative Positioning Systems

The calculation of the location of the end of the crane was based on assorted tilt and displacement sensors, along with a surveyor's wheel to locate the truck on the bridge deck. This system worked well. With the exception of the rotator measurement, as discussed above, the sensors selected were fairly simple and robust. The computer software was designed to complete all the geometric calculations necessary to define crane location, without any direct operator involvement.

However, this approach did create a system of multiple components that required a certain electronic aptitude to operate and maintain. A simpler positioning system involving fewer components, such as the low-cost GPS concept explored during the research, might be preferable if the required accuracy was possible. Therefore, as GPS technology continues to improve, an alternate positioning system based on GPS might be possible. Another approach could involve proximity sensors located on the bridge a fixed distance ahead and behind the truck to track the movement of the crane arm. Additional research might identify other methods as well, with the intent being to reduce the number of sensors and calculations necessary to track the movement of the crane arm.

Additional Software Development

Extensive effort was put into creating a software package to automate the data collection process with the articulated arm. However, this work concentrated on direct sonar measurement with the streamlined probe and the kneeboard deployment on a rigid framework. These programs were fully developed and field-tested and are believed to be fairly robust software packages.

The cable-suspended program and the physical probing did not receive the same level of development and testing. They were developed to a prototype level, but did not receive the same degree of field testing as the other programs. Developing fully functional software that is thoroughly de-bugged is a time-consuming process that requires extensive testing. Additional testing and development of these two pieces of software would provide greater confidence in their operation and use.

Remote Control Boat

The use of an unmanned, remote control boat offers several advantages for flood monitoring, including safety, access issues, measurement anywhere around or under the bridge, and the ability to work at both low- and high-clearance bridges. Previous research has been completed on the use of remote control boats for scour and stream gaging work, involving the use of both gas and electric propulsion systems. Ultimately, the hull and the propulsion system should be designed around the payload that must be carried, and, using the wireless sonar developed as part of this project, the payload requirements would be relatively small. Other areas of concern include developing a boat durable enough to survive the potential rough water, debris, and difficult operational conditions. This would require ruggedized servos and controllers mounted in waterproof compartments.

The use of an unmanned remote control boat for scour monitoring was identified during the literature review in Phase I. Although this concept was not pursued as part of this research project, it is still a viable concept that should be investigated further.

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APPENDIX A

USERS MANUAL

CONTENTS

CHAPTER **1**

SYSTEM DESCRIPTION

DESCRIPTION

The articulated arm truck described in this document was the result of research conducted under NCHRP Project 21-07, *Development of Portable Scour Monitoring Equipment.* The research concentrated on developing a truck-mounted articulated crane to quickly and safely position various measurement devices. The use of a crane for scour monitoring provided a solid platform for deployment, even under flood flow conditions, that could be instrumented to allow precise measurement of the movement of the crane. *NCHRP Report 515* provides detailed findings from this research project and the interpretation and appraisal of information developed from detailed field testing.

The articulated arm truck was designed using readily available components whenever possible. These components and pieces were also designed to be a bolt-on installation, so that the articulated arm truck could be readily used for other purposes outside of the flood season. In fact, many transportation agencies already have articulated arm trucks that could be retrofitted for scour monitoring work based on the design concepts developed through this research.

The articulated arm truck can be used in various ways to collect scour data. Once in the water, the crane can be rotated in an arc to collect sonar data on a continuous basis upstream of the pier. The truck can also be driven across the bridge with the crane extended to collect a cross-section profile quickly. Traditional cable-suspended techniques can be used with the crane when working off higher bridges. Figure A1 illustrates the application of the articulated arm truck on a bridge during a scour measurement.

The articulated arm truck provides improved deployment, positioning and data collection procedures for portable scour monitoring work, particularly under adverse conditions. These measurements can be completed from a variety of bridge geometries (e.g., limited clearance, overhanging geometry, and high bridges) using a truck that is affordable and maneuverable. The data collection process is automated, and the scour data are presented in the bridge coordinate system, thereby allowing rapid evaluation of scour criticality. Overall, the ability to make portable scour measurements during flood flow conditions has been substantially improved through development of the articulated arm truck.

MAJOR COMPONENTS

The articulated arm truck consists of four major components: a truck with an articulated arm crane; instrumentation to monitor the position of the crane in space; instrumentation to measure scour depth; and, computer software to collect, process, and present the results.

The articulated arm truck consists of a standard knuckle boom or folding crane typical of the construction industry. The crane was mounted on a Ford F-450 truck chassis. Various tool boxes and storage compartments were added to the flatbed truck to store instrumentation used to collect data.

In order to evaluate the potential risk associated with a measured scour depth, it is necessary to know the location of the measurement, particularly relative to the bridge foundation. Therefore, various sensors are used to track the movement of the articulated arm in space, so that the location of the end of the crane is always known.

Scour measurements are completed based on both sonar and physical probing methods. Sonar methods were developed around a new, wireless sonar that eliminates the need for any cables from the transducer to the bridge deck. Physical probing methods were based on a simple rod at the end of the crane, the location of which is known in space by the sensors used to track crane movement.

Comprehensive data collection software programs were developed to facilitate the use of the articulated arm, providing the inspector with immediate access to the data collected. Collection of position and scour data is automated, and a data file is written that allows subsequent plotting of the channel section or scour hole bathymetry.

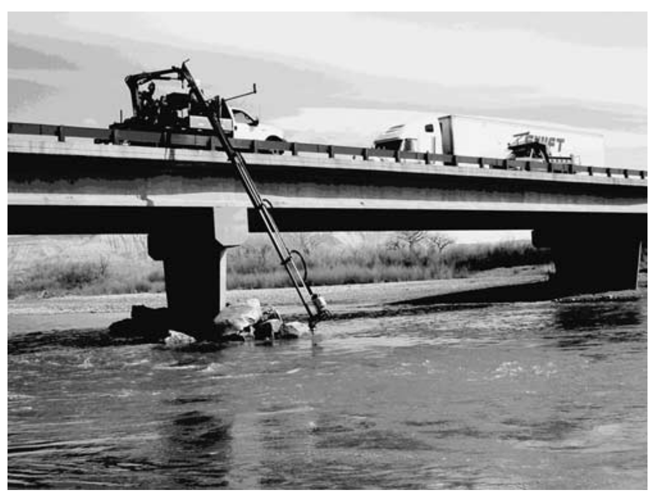


Figure A1. Articulated arm truck making a scour measurement.

CHAPTER 2

FABRICATION

INTRODUCTION

The articulated arm truck was designed around readily available parts and components to facilitate design, operation, and maintenance, and to control cost. However, some special fabrication and machine shop work was necessary, and the sensors and instrumentation required custom design and construction.

The purpose of this chapter is to provide detailed information on the components used and the fabrication required to develop the articulated arm truck that resulted from NCHRP Project 21-07. Adequate information is provided to allow a competent shop to build a similar articulated arm truck. To facilitate building the truck, a list of suppliers used is provided in Appendix A, although similar products would also be available from other sources. Given that much of the fabrication and construction is specific to the truck and crane selected, some of the information and details provided would need to be adapted for the specific equipment selected or available for use.

CRANE AND TRUCK

Crane Selection

The cranes commonly used in the construction industry typically are designed to handle large weight but with limited extension. In contrast, for scour monitoring the crane needed to reach long distances, without having to manage much weight or force. It was also desirable to work with a smaller crane that could be mounted on a smaller truck. These criteria were developed in part to improve maneuverability and in part to minimize lane closure and traffic control issues.

For research and development, a Palfinger PK4501C crane was used (Figure A2). This crane has a 600 lb (270 kg) lift at 36 ft (11 m) and was small enough to be mounted on a Ford F-450 truck chassis. A larger crane with more lift would be acceptable, as long as it also had a long reach. The long reach is necessary to be able to work off of higher bridges. Based on the reach of the PK4501C crane, mounted with an offset to the center of the truck, the PK4501C can reach 21.25 ft (6.5 m) below the bridge deck when the truck is a maximum of 35 in (0.3 m) from the edge of the bridge. This reach is to the end of the crane, prior to adding any extensions for sensor mounting. Figure A3 summarizes the geometric capabilities of this crane when mounted on a Ford F-450 truck. Cranes with similar capabilities are also available from other manufacturers.

Crane Mounting Location

The most common location for a crane is immediately behind the cab of the truck. An alternative location is at the back of the truck, behind the rear axle. A rear mount puts more load at the back of the truck and can cause weight distribution problems if the truck is also carrying substantial weight on the flat bed. The advantage of the rear mount is the better clearance around the truck, because the cab is not in the way. For purposes of scour monitoring, with no substantial weight being transported on the truck bed, a rear mount seemed advantageous (Figure A4). However, mounting behind the cab would be acceptable, particularly if that location is more desirable for other lifting operations that the truck might be used for when not being used for scour monitoring.

High-Load Castors

Data collection with the crane extended was desirable for measuring a channel cross section. Many under-bridge inspection trucks have counterweights and/or high-load castors to allow truck movement when the crane arm is extended. To permit this type of operation with this crane, a castor design was developed based on an arm that could be lowered under the outrigger foot pad. The castor was a 10 in. (25.4 cm) urethane wheel with a 4,200 lb capacity at 6 mph. The wheel was permanently attached to the arm, with the arm providing the lateral support necessary after the outrigger was lowered onto the castor. When not in use, the arm was raised and bolted to the truck frame, and a safety chain was attached. Figure A5 shows the castor system and its dimensions.

The smaller truck chassis used in the research did minimize the cost of the vehicle itself, however, a larger truck also offers advantages. The F-450 used in the research was not large enough to handle even the lightweight crane selected without hydraulic stabilizers. As an alternative, a larger truck chassis might be able to handle the lightweight crane selected for the research without the outriggers and the additional cost and complication of the castor system.

Modifications to the Rotator

The ability to provide pan and tilt operations at the end of the crane was considered a valuable feature for positioning instrumentation. Pan operation could be accommodated using

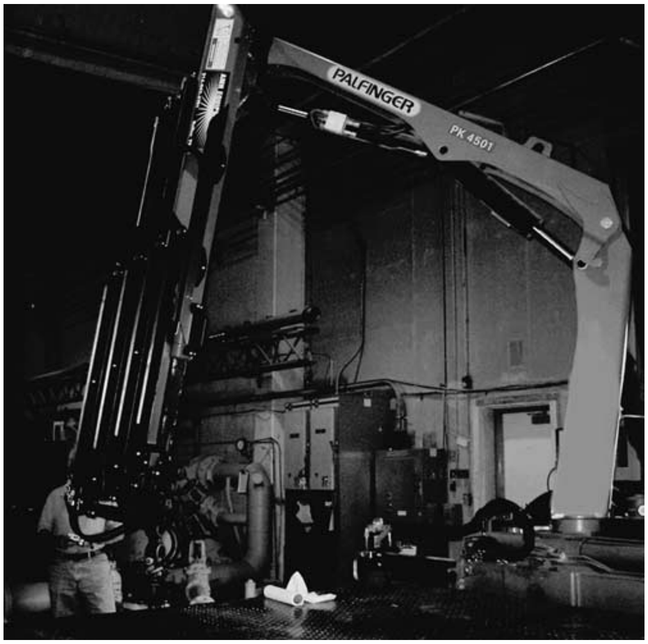


Figure A2. Palfinger PK4501C Crane.

a standard hydraulic rotator, often used with construction equipment on the end of a crane. The rotator used was a Kinshofer Liftall Model KM 04 F (Figure A6).

Most rotators are designed for 360-degree, continuous rotation at a fairly high speed. Continuous rotation for scour monitoring applications was not desirable, given that the operator might accidentally tear off cables connected to transducers, and high-speed operation would complicate precise positioning and could result in possible impact damage when in close proximity to the bridge. To solve this problem, flow restrictors were used in the hydraulic lines to slow the motion. The movement of the rotator was tracked with a 10-turn potentiometer, with a readout on the computer software to prevent overrotation.

Mounting the 10-turn potentiometer to the rotator, without drilling into the rotator housing, required fabricating a special mounting bracket. The bracket was made of aluminum and designed as a compression fitting around the perimeter of the rotator. The potentiometer was mounted in this bracket and measured rotation by a sprocket attached to the shaft of the rotator (Figure A7).

Standard rotators are also designed to hang from the crane on a pin connection, so that the rotator is always positioned vertically, regardless of the angle of the crane arm. Therefore, providing tilt capability required modifications and special fabrication. An additional hydraulic cylinder and custom-fabricated brackets were added to the rotator to provide the tilt action (Figure 7). The tilt was designed to provide about 35 degrees toward the bridge and about 10 degrees away from the bridge, when the crane is positioned vertically over the bridge rail. The mounting bracket for the rotator was attached to the end of the crane, which extended the reach of the crane by 1.5 ft (0.46 m).

Modifications to the Truck Flat Bed

The modifications to the truck bed included adding ladders on both sides to facilitate access, adding toolboxes and storage compartments, building the workstation area for the computer and instruments, and relocating the hydraulic controls to the flatbed. Figure A8 shows the tool boxes and sizes that were added to both sides of the truck. These boxes provided ample storage room for all the equipment and sensors necessary.

The hydraulic controls for an articulated crane typically are located next to the crane, thereby allowing operator access while standing on the road. Some models, including the Palfinger PK4501C, have dual controls allowing operation from either side of the truck. These controls were removed and relocated to the flatbed to improve safety and to provide better visibility of river conditions for the operator. The controls were moved to a position at the back of the flatbed, a workstation was fabricated on the flatbed to provide a shelter for the computer, and a seat was installed on the bed (Figure A9).

Other equipment added included safety equipment. A dual-bulb yellow warning light was installed at the top-center of the truck rack behind the cab (i.e., Code 3 Inc., 420 Beacon Warning Light SAE W397W5-1 98). A second single-bulb warning light was installed on a post on the back left (driver's side) of the truck bed (i.e., Whelen Strobe Model 2012 series). A large 12-volt battery was installed in a steel box at the back of the truck, with a with a battery isolator to allow recharging from the engine alternator. This battery was used to power a 1000-watt invertor (i.e., Vector Model VEC049) in the instrument shelter and the winches used for cable-suspended work.

INSTRUMENTATION TO MONITOR CRANE POSITION

Various sensors were installed on the truck and crane to allow geometric calculation of the position of the end of the rotator. An articulated crane provides a very stable platform to deploy scour measurement devices, but it does not provide any positioning information without the addition of other sensors to track the movement of the crane. The sensors used included various devices to measure tilt angles and linear displacement.

Sensors were required both at the end of the crane and on the truck itself, requiring two instrument boxes. The instrument boxes contain the power supplies, electronics necessary to operate each sensor, and a data logger to receive sensor data. An instrument box mounted at the end of the crane was used for the crane-end sensors and was designed to be removable for transit. The instrument shelter mounted on the bed of the truck, designed to hold the computer, was used for the sensors on the truck itself.

Crane Rotation

The rotation of the crane was measured with a 50 in. (125 cm) linear environmentally sealed draw wire (i.e., Unimeasure

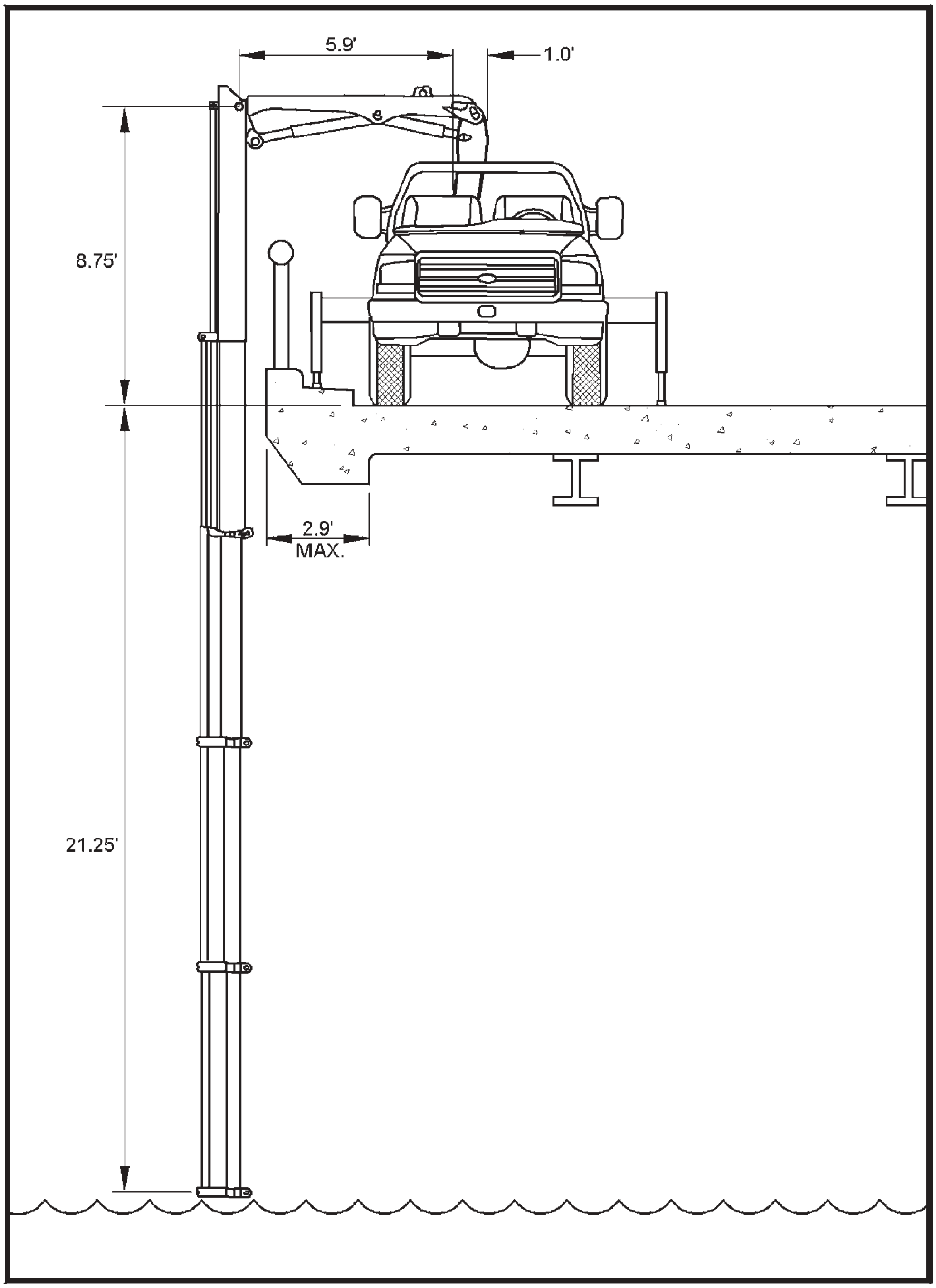


Figure A3. Reach below the bridge deck with the PK4501C crane on a Ford F-450 truck.

Inc., Model HX-P510-50-E3). The draw wire was routed around a 15-in (38-cm)-diameter circular plate mounted near the base of the crane (Figure A10). The circular plate was made from ultra-high-molecular-weight (UHMW) polyethylene. The draw wire housing was permanently mounted to a bracket on the truck bed, and a groove on the edge of the plate kept the draw wire in place as the crane rotated.

Crane Deflection Angle and Extension

Tilt meters were used to measure the deflection angle of the crane arm and the rotator arm (i.e., Cline Labs, Inc., Electronic Clinometer). The tilt meter for the crane arm was mounted inside the instrument box attached to the end of the crane (Figure A11). The tilt meter for the rotator arm was

Figure A4. PK4501C crane mounted on the back of a F450 truck.

attached directly to the support bracket fabricated to allow tilting the rotator (as described above).

A 400 in (10 m) environmentally sealed draw wire (i.e., UniMeasure Inc., Model HX-P510-400-E1) was used to measure the linear extension of the arm. The draw wire was mounted to the instrument box at the end of the crane and attached to a fixed mount near the top of the crane by a lightweight chain (Figure A12).

Tilt data for the crane and rotator, the azimuth of the rotator, and the linear extension of the arm were transmitted by a MaxStream radio modem from an instrument box at the end of the crane that also transmits sonar data. The data were preprocessed with a Campbell CR10 data logger prior to transmission to the computer on the truck (Figure A11).

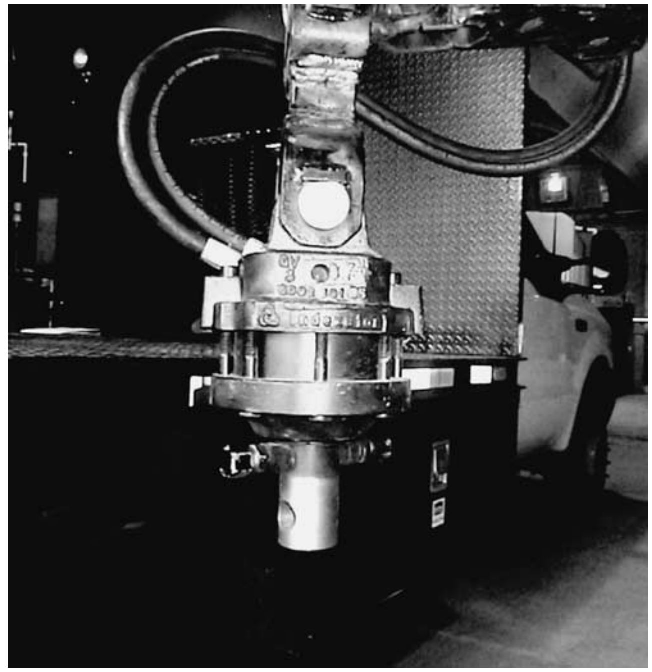


Figure A6. Standard rotator (prior to modifications to allow tilt).

Tracking the Position of the Truck on the Bridge Deck

Tracking the position of the truck on the bridge deck was the last piece of geometric information necessary to locate the scour measurements accurately. Given that the truck would always be positioned as close to the curb line or barrier rail as possible, and given that the bearing of the bridge is a known quantity, the only real location information necessary was the distance the truck had been driven across the bridge and the elevation of the truck. The elevation of the truck could be established from the elevation of the bridge deck, as given on bridge plans, and the height of the truck bed above the bridge deck.

Therefore, the primary field measurement necessary to locate the truck was simply the distance the truck had traveled across the bridge deck. This was accomplished with a standard survey measuring wheel attached to the back of the truck (Figure A13). Pulse counters were added to the wheel and connected to the Campbell CR10 data logger to register the distance traveled electronically.

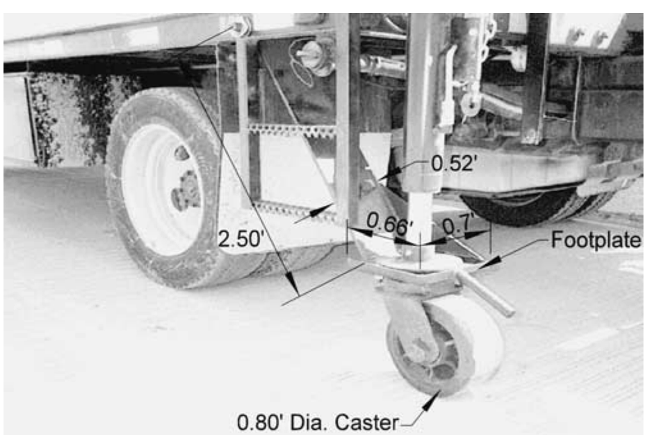


Figure A5. Castor system.

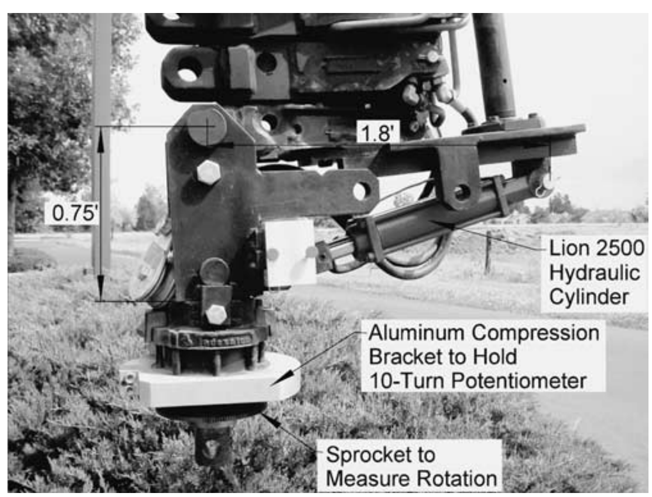


Figure A7. Rotator after modifications to provide tilt.

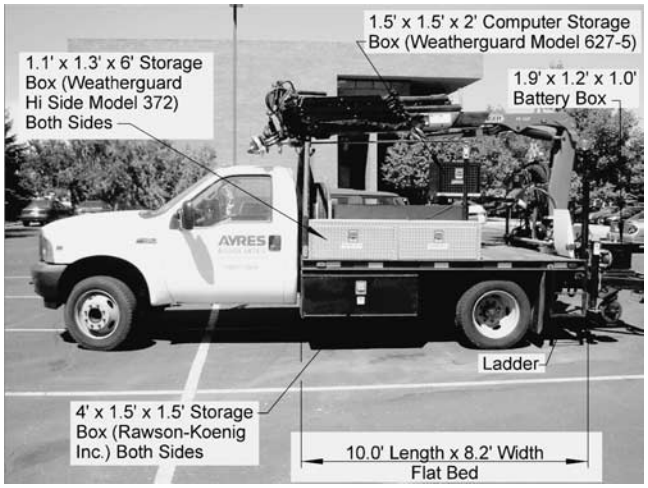


Figure A8. Truck bed and toolbox dimensions.

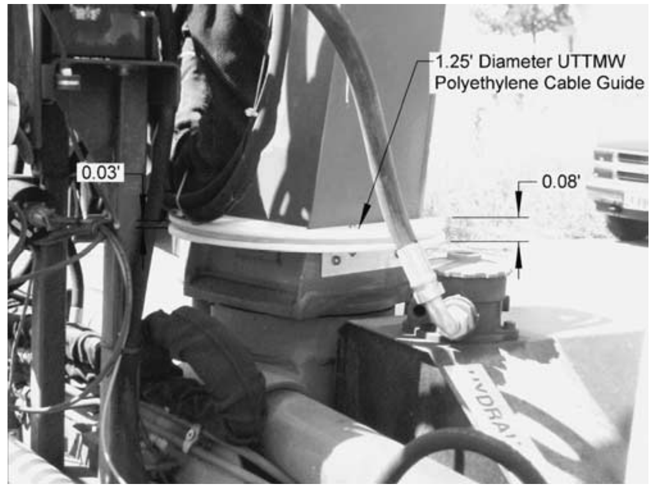


Figure A10. Draw wire attachment to base of crane.

Water Surface Elevation

An acoustic stage sensor (i.e., STI Automation Sensors, Inc., Model U550-PV-CP-3N-ARR2-AK-H2) was used to measure the distance to the water surface (Figure A14). The stage sensor was mounted on an extendable arm to allow it to be positioned beyond the bridge rail with a clear view of the water.

Position Calculation

The Campbell CR10 data logger at the end of the crane collected the tilt data for the crane and rotator, the azimuth of the rotator, and the linear extension of the arm. These data were transmitted by the wireless radio modem to the computer on the bed of the truck. A second Campbell CR10 data logger at the computer workstation on the truck collected the data on crane rotation, distance traveled, and water surface elevation. Figure A15 shows the inside of the computer workstation with the wireless modem receiving data from the end of the crane, the Campbell data logger for the truck data, the voltage convertor for the acoustic stage sensor, and the DC-AC invertor.

A laptop computer would be placed on the foam inside the instrument box for data collection and processing. The computer must have two serial ports to process the information from each data logger, sent as serial data strings. A PCMCIA serial card was used to provide the second serial port. Geo-

Figure A9. Instrument shelter for computer and relocated hydraulic controls.

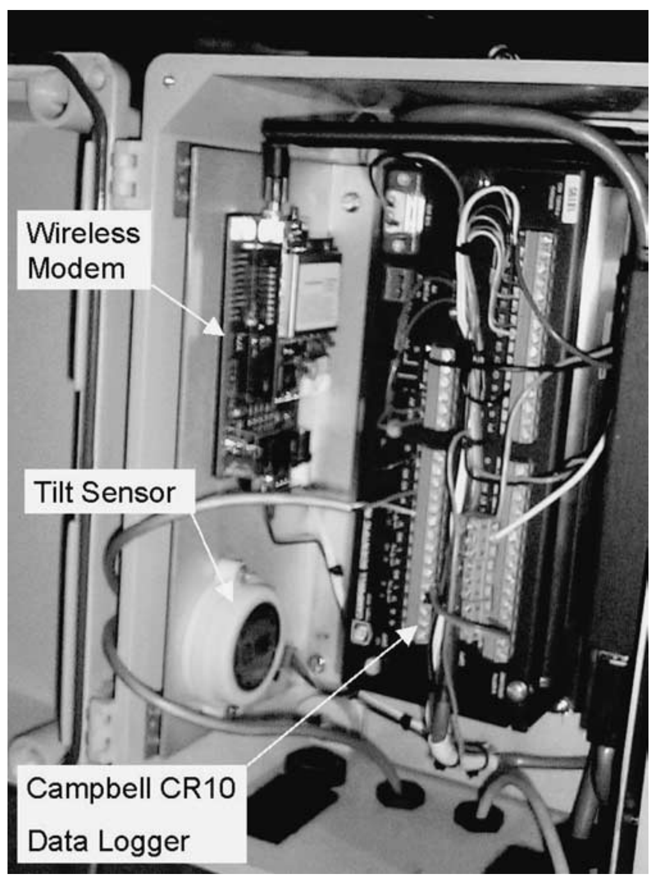


Figure A11. Instrument box at the end of the crane.

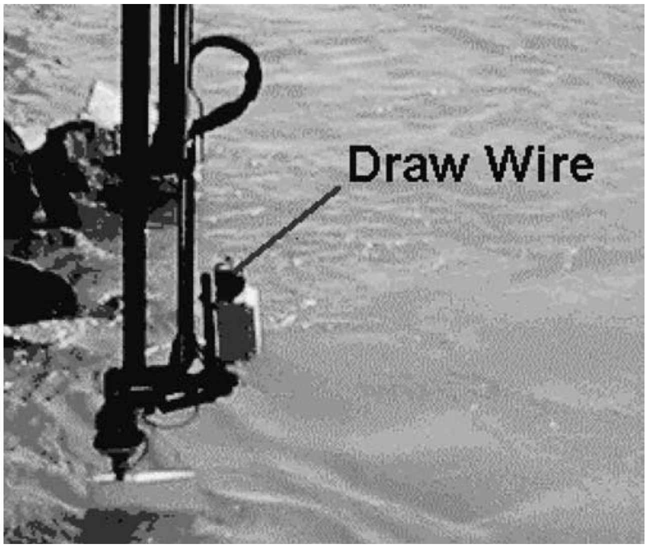


Figure A12. Draw wire to measure the extension of the crane.

Figure A13. Surveyor's wheel attached to back of truck.

Figure A14. Acoustic stage sensor.

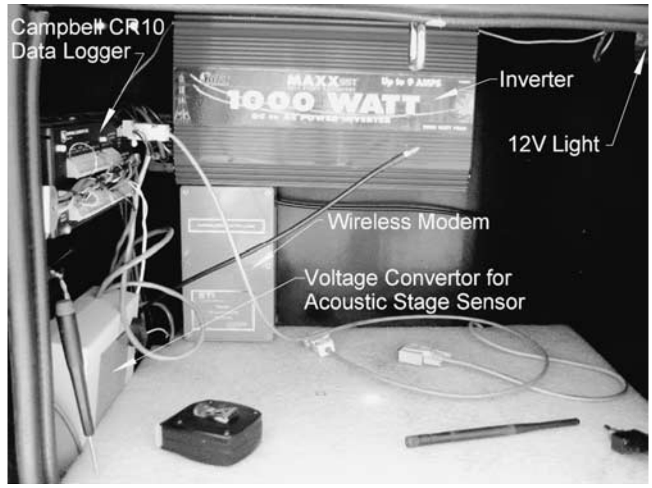


Figure A15. Inside view of instrument shelter on truck bed.

metric calculation of the position of the crane was predicated on keeping the top arm of the crane horizontal, because this provided the reference point for all calculations. Knowing the rotation of the crane and the rotator, the deflection angle of the vertical arm of the crane, the deflection angle of the rotator, and the extension of the crane arm allowed calculation of the position of the end of the rotator relative to the center pivot of the crane where it mounted to the truck bed. With the truck position defined on the bridge deck, the location of the crane in space could be completely described.

SCOUR MEASUREMENT DEVICES

As developed, the instrumented, articulated crane could be used to position various scour measurement devices, both directly from the end of the crane and from cable-suspended methods using the winches. Sonar could be deployed from the end of the crane or as a cable-suspended operation, while direct probing was possible off the end of the crane.

Streamlined Sonar Probe

To provide sonar measurement capability, a sonar instrument with embedded microelectronics was selected (Figure A16). With the transducer element and signal processor in the transducer head, a separate readout device was not necessary. The signal from the depth transducer was processed inside the sensor and directly output as a serial data string of depth and temperature. The serial data output of the sonar was connected to the same Campbell CR10 data logger used at the end of the crane to collect position information. Given that information from this data logger was transmitted by the wireless modem (as shown in Figure A11), this eliminated having to route any electronic cables for the sonar from the water surface to the bridge deck. The sonar used was manufactured by Airmar Technology, Inc., and was an 8-degree, 200-kHz transducer.

Given the desire to operate at flood conditions with high velocities, a streamlined probe was built to position the sonar

Figure A16. Sonar transducer with all electronics built into the transducer head.

transducer directly in the water using the articulated arm. The probe was fabricated from a section of helicopter blade (Figure A17) and proved to be very stable when placed in high-velocity flow during field trials. The streamlined probe eliminated the vortex shedding problems of a simple cylinder-shaped rod exposed to high-velocity flow. Helicopter blades are generally available from helicopter service companies who must routinely replace the blades or blades are available as a result of damage to a portion of the blade during use. Although various sizes and shapes are used on helicopters, the actual dimensions used when fabricating a sonar probe are not critical. For example, the blade used for research was 1.75 ft (0.53 m) long; however, any given helicopter blade would perform in a similar manner by improving the flow streamlines around the sonar transducer.

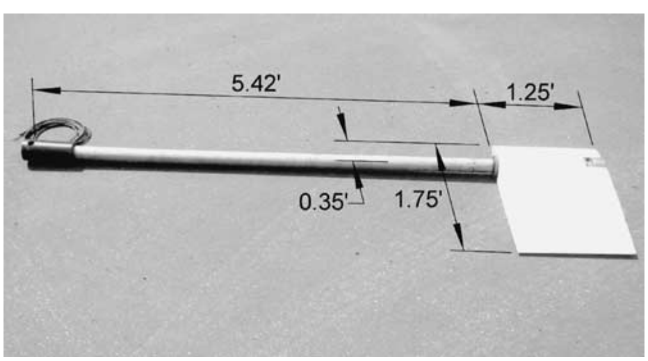


Figure A17. Streamlined sonar probe.

The fin on the streamlined probe could freely rotate, which allowed the fin to follow the current, no matter what horizontal angle the crane was positioned in. The fin was attached to an 80 in. (2 m) by 2 in. (125 mm) Schedule 80 stainless steel pipe. Given the distance the crane could reach below the bridge deck (21.25 ft or 6.5 m) and the length of the rotator mounting bracket (1.5 ft or 0.46 m), the crane could reach nearly 30 ft (9.1 m) below the bridge deck for a sonar measurement.

Physical Probing

To provide physical probing capability, an extendable rod was fabricated. The rod extensions were built with 2 in (125 mm) stainless steel, Schedule 80 pipe in 5 ft (1.5 m) lengths, allowing a total length up to 15 ft (4.5 m). Threaded unions were machined to allow individual sections to be screwed together to create the longer extensions. Using the articulated crane for physical probing is most appropriate in a gravel/cobble bed or to evaluate riprap conditions, given that the strength of the crane hydraulics makes it difficult to know exactly when the channel bottom is reached.

Kneeboard on Rigid Frame

A kneeboard with a wireless sonar was also developed that could be deployed from either a rigid framework attached to the rotator or as a cable-suspended operation. The sonar with the electronics built into the transducer was used, and a small enclosure was fabricated (from 6-in. PVC pipe) for the kneeboard to hold the battery and radio modem (Figure A18). It was difficult at times to get the kneeboard positioned on the water surface, but, once in place, it could be readily moved forward and backward under the bridge, and, within limits, side to side using the rotator. This arrangement facilitated measurements under the bridge deck when direct measurement with the arm or cable-suspended weights was not possible. An accurate location of the sonar measurement could be calculated knowing the position of the end of the rotator, the length of the kneeboard framework, the distance to the water surface, and the angle of the rotator.

Cable-Suspended Operations

Winch System

Minnesota DOT developed an innovative boom and sounding weight system for scour depth measurements using a boom truck and a custom-fabricated winch setup. What was unique about the Minnesota DOT setup is that the winch was not mounted on the boom itself, which is the traditional approach for stream gaging. Instead, the winch was mounted on a frame attached to the truck bed (Figure A19). The winch could swivel and tilt to allow the cable to follow the movement of the articulated arm crane that Minnesota DOT was using.

This design allowed the sounding weight capability to be added to the truck without modifying the articulated crane,

Figure A18. Kneeboard with wireless sonar (note PVC instrument enclosure where transducer and radio modem are located).

which is used for other purposes when it is not being used for scour inspections. It also facilitated installing and removing the winch, as necessary, and using the same winch setup on various trucks.

Figure A19. Minnesota style winch.

Building on this concept, a dual-winch approach was developed to allow more controlled operation in certain cable-suspended applications, such as when using a sonar deployed in a floating platform. Part of the problem with floating platforms deployed by hand or with a single winch has been the lift on the nose created by the cable and the difficulty in controlling the position of the float. The dual-winch concept eliminates the lift problem when implemented with an articulated arm that can get a cable further front of the float and will provide more directional control.

The concept, illustrated in Figure A20, allows better positioning control and the ability to drift the float under the bridge, when compared with a single-cable operation. A single-cable suspension through the pulley on the end of the crane can still be used, similar to the Minnesota application, or the dual-cable concept as illustrated.

The winches used were Warn Model M6000, a medium-duty, compact winch with a rated line pull of 6000 lb (Warn Part Number 45880). The winch has a 4.8-hp motor and 80 ft (15 m) of 5/16 inch (8 mm) wire rope with power in and out and freespooling capability. The winch cable was replaced with standard stream gaging sounding reel cable, which is smaller and more flexible. The cable was routed through a Wemco Model 700 wire rope meter to measure the cable length played out. The mechanical readouts of the wire rope counters were replaced by pulse counters that allowed electronic readout and input to the data collection software program.

The winch and wire rope meter were mounted on a tilting bracket with a collar for a post mounting (Figure A21). The post was mounted vertically at the back of the truck. The collars slide over the post with brass washers and spacers so each winch setup can rotate freely (Figure A22). With the ability to rotate and the tilt up and down, the winches could track any movement of the crane.

Sounding Weight

Using a single- or dual-winch approach, traditional sounding weight measurements can be made. The dual-winch approach

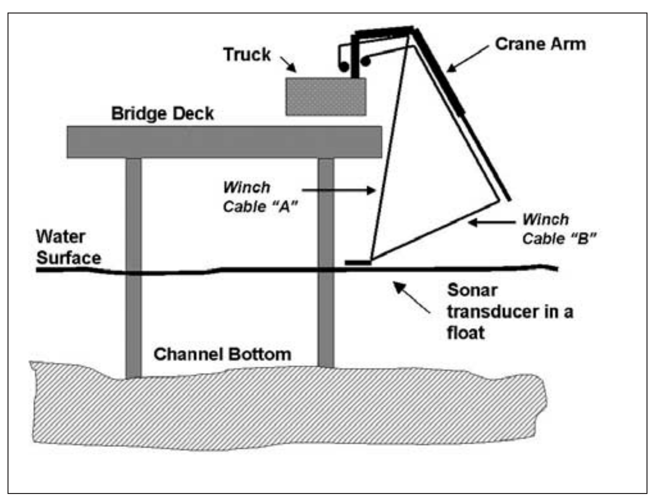


Figure A20. Dual winch concept.

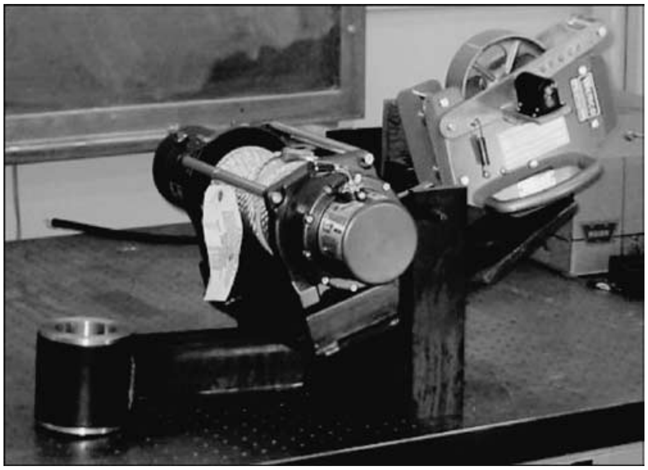


Figure A21. Winch and wire rope counter on mounting bracket.

reduces the size of the weight necessary, given that the winch running through the end of the crane can be used to limit the movement under the bridge deck. Although the weight is not a concern, given the ability of the crane and the winches to handle very large weight, it does allow better control over the position of the sounding weight.

Sounding Weight with Sonar

Cable-suspended operations are also possible with a wireless sonar installed in a sounding weight. A 4 ft (1.2 m) hanger bar for the sounding weight was built with a 4 in (10 cm) PVC pipe enclosure to house the battery and wireless modem at the top (Figure A23). This eliminated the need to route the sonar cable from the water surface up to the bridge deck and greatly enhanced cable-suspended operations using a sonar device. A standard 75-lb sounding weight was used, with a hole

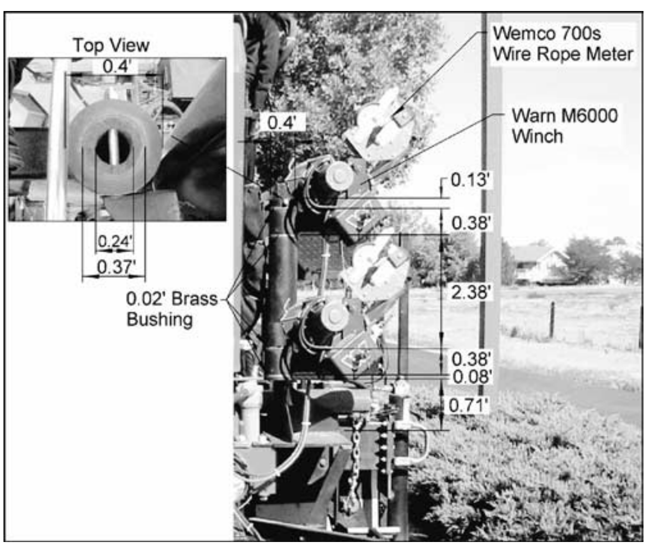


Figure A22. Post mounting design for dual winches.

Figure A23. Wireless sonar in a sounding weight.

machined in the bottom for the transducer. The mounting hole for the transducer was placed just ahead and as close as possible, to the bolt hole for the hanger bar, in order to maintain sounding weight balance.

Standard sounding weights are designed with a flat bottom so they will sit upright without rolling. Under high-velocity flow, this can create a separation zone off the bottom that may adversely affect sonar measurement. Therefore, the transducer was not mounted flush with the flat bottom, but allowed to protrude and a shim was fabricated to transition the flow more smoothly off the nose of the sounding weight (Figure A24).

Figure A24. Shim on bottom of sounding weight.

CHAPTER 3

APPLICATION GUIDELINES

FHWA SCOUR MONITORING GUIDANCE

Approximately 584,000 bridges in the National Bridge Inventory (NBI) are built over streams. Many of these bridges span alluvial streams that are continually adjusting their beds and banks. Many of these bridges will experience problems with scour and stream instability during their useful lives.

Scour and stream instability problems have always threatened the safety of the U.S. highway system. The National Bridge Inspection Standards (NBIS) require bridge owners to maintain a bridge inspection program (23 CFR 650, Subpart C) that includes procedures for underwater inspection. A national scour evaluation program as an integral part of the NBIS was established in 1988 by FHWA Technical Advisory T5140.20, superseded in 1991 by Technical Advisory T5140.23.

Technical Advisory T5140.23 specifies that a plan of action should be developed for each bridge identified as scour critical in Item 113 of the NBIS. The two primary components of the plan of action are instructions regarding the type and frequency of inspections to be made at the bridges and a schedule for the timely design and construction of scour countermeasures.

The purpose of the plan of action is to provide for the safety of the traveling public and to minimize the potential for bridge failure by prescribing site-specific actions that will be taken at the bridge to correct the scour problem. The inspection requirements in a plan of action typically will include recommendations for scour monitoring during and after floods.

APPLICATION OF THE ARTICULATED ARM TRUCK

General

The type and frequency of inspection work called for in the plan of action can vary dramatically depending on the severity of the scour problem and the risk involved to the traveling public. For example, a bridge rated scour critical by calculations, but having relatively deep piles in an erosion-resistant material and having been in place for many years with no sign of scour, might be adequately addressed through the regular inspection cycle and after major flood events. Alternatively, a bridge found to be scour critical by inspection (e.g., during an underwater inspection that finds a substantial scour hole undermining the foundation) would be of greater concern and would require a more aggressive inspection plan.

In either case, the application of portable scour monitoring devices, such as the articulated arm truck, during and after a flood, could be a key element of a scour monitoring program developed as part of the plan of action for a scour-critical bridge. The articulated arm truck provides a stable platform for deploying various scour instruments. The size of the truck and the automated data collection system facilitate flood measurements by allowing detailed data to be collected in a short time.

The articulated arm truck is not a replacement for conventional scour monitoring methods, but is a supplement to those methods, designed specifically for work under adverse flood conditions. One of the most common conventional scour monitoring methods is the use of a lead line measurement from fixed locations across the bridge. The lead line approach is simple and can provide fast results without the complexity of the articulated arm.

However, a lead-line measurement is extremely difficult under the severe conditions encountered during a major flood event. High-velocity flow alone can make a lead line measurement infeasible, or at best, very difficult and inaccurate.

Another difference between the truck and conventional methods in widespread use is the large amount of data that can be collected with the truck in a relatively short time. Conventional methods generally only produce point measurements at defined locations across the bridge, which may or may not be adequate to evaluate scour criticality.

Although the truck can provide the same data, its real benefit and value occurs when more data are necessary or desirable to define the scour problem and such data must be collected under the adverse conditions of an extreme flood event. Using the articulated arm truck is somewhat analogous to completing a hydrographic survey, where a large amount of data is collected and used to create a bathymetric map. Working from the bridge deck, the truck can provide numerous data points that can be used for various contouring and mapping work products.

Therefore, it is important to recognize that the articulated arm truck was designed for a specific application, that being flood flow conditions, and it may not be the best tool for all situations. At lower flow conditions, or when fewer data can adequately address the problem, other methods may be preferable. With the number of sensors, the data loggers, and the computer data collection methods, the truck is a more complicated device than most conventional scour monitoring methods.

Proper use of the articulated arm truck will require training and a certain aptitude to operate and maintain.

Therefore, the integration of the articulated arm truck into a state scour inspection program might be based on a single truck and a crew specifically trained in its use. In larger states, or states with more scour-critical bridges to monitor during and after floods, several trucks and trained crews might be necessary. These same crews might also be doing 2-year inspections or lower flood event monitoring with more conventional methods, but when a big flood occurs, they are the only ones who are trained and ready to operate the truck.

Similar to all scour monitoring methods, the truck has advantages and limitations. Recognizing and remembering what these are will facilitate successful application of the articulated arm truck in a scour monitoring program. The articulated arm truck should be viewed as another tool in the inspectors' toolbox for scour monitoring, and for any given job, the right tool or combination of tools must be applied.

Advantages of the Articulated Arm Truck

High-Velocity Flow

A major advantage of the articulated arm truck is the ability to make measurements in high-velocity flow. When the water surface is within 30 ft (9.1 m) of the bridge deck, the streamlined sonar probe can be directly inserted into the water, providing a very stable measurement with very reliable positioning data. This measurement has been completed in velocities in excess of 10 fps, and, based on those results, even higher velocities could be measured. The combination of a strong, stable mechanical arm and a streamlined probe provided very successful results in high-velocity conditions.

High-Sediment and Air Entrainment Conditions

Flood conditions often produce large suspended sediment loading, which can complicate measurements with some sensors, particularly sonar. Part of the success in high-sediment conditions is minimizing other factors that can complicate a sonar measurement, including separation zones and high air entrainment. The streamlined probe that was developed minimized these effects by reducing turbulence induced by the probe and streamlining the flow over the transducer. The streamlined probe also positioned the transducer about 12 in. (30 cm) under water for the measurement, which eliminated those surface interference issues typical of a floating deployment where the transducer is skimming the surface.

Limited Clearance

Limited clearance conditions often exist during floods because of high stage conditions. This reduces the clearance under the bridge, which can complicate scour measurements. The crane can be articulated such that direct measurements can be made from a water level just below the bridge deck down to about 30 ft (9.1 m).

Pressure Flow

When flow is so high that the low-chord of the bridge is underwater, the use of floating deployments for pier scour measurement is virtually eliminated. However, under these conditions, the crane is still feasible and, within certain physical limits, could be articulated into position underwater. Another concern is that, under pressure flow, the velocity is typically accelerated from free surface conditions, and more turbulence exists. The overall stability of the articulated crane and the strength of the crane hydraulics would facilitate making measurements in such adverse flow conditions.

Overhanging Bridge Geometry

Overhanging bridge geometry often complicates scour measurement. With the ability to tilt the rotator, the crane could be articulated slightly to allow some positioning under the bridge deck. Greater ability to work under the bridge is available through the rigid frame deployment of the kneeboard. The framework allows pushing the kneeboard under the bridge deck up to 10 ft (3 m) and can be rotated side-to-side with the rotator. Field testing revealed that it can be difficult to get the kneeboard positioned on the water and ready to push under the bridge. Therefore, although the use of the framework is somewhat problematic and is more difficult to use than a direct sonar measurement with the streamlined probe, this deployment method works and does allow data collection under the bridge.

High Bridges

High bridges where the water surface is well below the bridge deck can create difficult measuring situations. Not only is the height of the bridge an issue, but at such locations there can often be significant wind blowing through the bridge opening. The limit of the articulated crane under a direct measurement is 30 ft (9.1 m); therefore, high bridges typically require a cable-suspended approach. The dual-winch concept on a post mounting provides versatility in the measurement approach. One of the problems of a single-winch deployment is the drift under the bridge and/or the effects of wind on the cable or the deployment platform. The dual-winch approach allows a second cable and better control of the location of the deployment platform. With any cable-suspended operation, particularly on high bridges, the ability to track the position of the sensor accurately is lost. Therefore, the positional accuracy will always be better with the direct measurements made with the streamlined probe or the physical probe.

Easily Used and Affordable

Although the articulated arm truck is a specialized measurement device, it was designed to be affordable and relatively ease to use and maintain. The truck was designed around commercially available, “off-the-shelf” products, whenever possible, to avoid special fabrication requirements. These components and pieces were also designed to be a bolt-on installation, so that the articulated arm truck could be readily used for other purposes outside of the flood season. The combined cost of the truck and crane was about $50,000 prior to adding instrumentation. Allowing $25,000 for instrumentation and fabrication, the total cost for the scour monitoring truck is about $75,000.

The Windows-based data collection software program makes the system relatively easy to use. The data are reported in station-elevation format to allow immediate comparison of the results with information on the bridge plans.

Easily Transportable

The articulated arm truck was designed around the smallest truck chassis possible, in part to control cost and in part to provide maneuverability and to minimize the traffic control requirements. The latter issues are important when operating in a flood-response mode, given that the inspection crew needs to collect data as efficiently as possible and get to as many bridges as they can in a short time. An F-450 truck chassis is not much bigger than a full-sized pickup, and, therefore, the articulated arm truck as developed was easily transportable and maneuverable.

Accuracy

The desired accuracy of a scour measurement is typically +/−12 in. (30 cm). Most sonar devices meet this criterion, and so as it relates to the articulated arm truck, this criterion was more critical for the positioning system. Individually, the accuracy of each sensor is much better than the required accuracy. The combined accuracy of the entire system, including the software calculations to reduce the data, was well within +/−12 in (30 cm). Ultimately, what controls the accuracy of the system is the deflection in the crane. At full extension and in high-flow conditions, some bending was observed in the crane arm. Additionally, bouncing of the crane, either during an arc measurement or while driving across the bridge deck when making a cross-section measurement, caused some measurements to be in error by more than +/−12 inches. Therefore, although the articulated arm truck can provide the desired accuracy, these limits may be exceeded if proper and careful application procedures are not followed.

Limitations of the Articulated Arm Truck

Floating Debris

The accumulation of floating debris is a common problem on the upstream side of a bridge. Trees, logs, and branches are trapped by the piers and gradually may create a large debris jam. Such debris complicate the measurement process and also can increase the scour that occurs. The use of the articulated arm could increase the opportunity for success under these conditions when it is possible to position the end of the crane upstream of the debris pile and point the sonar under the debris. However, debris accumulations often have substantial depth, sometimes accumulating down to the channel bed; this would limit success even if the crane could be positioned at the upstream edge of the debris pile.

Alternatively, the physical probe that was developed, consisting of a 2-in. (5-cm) stainless steel pipe, might be forced through a debris pile using the crane hydraulics. However, once through the debris, the same crane hydraulics would make it difficult to detect the channel bottom. Without developing some type of sensor at the end of the physical probe to detect the channel bottom, this is not a practical solution.

Therefore, debris continue to be a serious problem complicating scour measurements. The articulated arm may improve the potential for a successful measurement in a few cases, but overall, this problem has not been resolved.

Ice Accumulation

Ice accumulation creates problems similar to those of debris accumulation by creating a physical obstacle to measurement and by potentially increasing the scour that occurs. Similar to the conclusions stated in the debris discussion, the articulated arm truck has not resolved this problem.

System Complexity

The sensors selected for monitoring the position of the truck and crane movement were fairly simple, robust, and easy to replace. The computer program was designed with a calibration menu to allow easy zeroing of any new sensor, should one need to be replaced. However, as with any automated system that relies heavily on sensors, data loggers, and computers, the system requires that operators have an aptitude for electronics and computers and some training so as to be able to operate and maintain the system.

CHAPTER 4

OPERATIONAL GUIDELINES

DATA COLLECTION

Software Programs

Extensive effort was put into creating a software package to automate the data collection process with the articulated arm. Data collection and processing occurred with a laptop computer equipped with two serial ports: one for the boom data and one for the truck data, as sent by the two Campbell CR10 data loggers.

Different programs were required depending on the deployment method. The programs were written in Visual Basic and all had the same general Windows™ layout. The primary difference was the different geometric calculations necessary for position, depending on which deployment method and sensors were being used.

Four programs were created: one for direct sonar measurements with the articulated arm; one for use with the kneeboard deployed on a rigid frame; one for direct probing; and one for cable-suspended operations. All programs produce an x,y,z data file that can read by CAESAR (Cataloging and Expert Evaluation of Scour Risk and River Stability) or any other program such as AutoCad or Microstation when contouring capability is desired. The x dimension defined the vertical direction, including the measured scour depth. The y dimension was the distance out from the bridge, and the z dimension was the location along the bridge deck.

Coordinate System

The sensors on the truck define position data relative to the rotational pivot of the crane. This coordinate system was defined as the “truck” coordinate system. Within the software, these coordinates were converted to “bridge” coordinates, as defined by the profile line for the bridge. The profile line is a station-elevation line on the bridge plans, typically along the centerline of the bridge deck. This same information is also used for other dimensions on the plans, such as pier locations and pile tip elevations. Providing the scour measurement results in bridge coordinates facilitates rapid review and evaluation of bridge integrity and was considered an important aspect of software development.

To convert from truck coordinates to bridge coordinates required inputting the profile line into the program before beginning data collection. The program was designed to allow this to occur before arriving at the bridge or it could be done after setting up on the bridge. It was also necessary to measure the horizontal and vertical offsets of the truck relative to the profile line. A chisel mark on the rear bumper of the truck was used as the point of reference, and both the distance from the pavement to that mark and the horizontal distance from the profile line were measured and entered into the program. The vertical offset was manually corrected for the cross slope of the pavement (typically 2 percent) when entering that distance. With this information, the computer program automatically calculated and reported results in bridge coordinates.

Methods of Data Collection

The software for sonar measurements with the crane allows point measurements or continuous recording. Continuous recording can occur as the crane is either driven across the bridge or with the truck in a stationary position and sweeping the crane in an arc. The crane sensors are measuring once per second, and so the amount of data collected in a continuous mode depends on how fast the truck is moving during a cross-section measurement or how fast the crane is swept in an arc-based measurement.

Physical Probing

Physical probing with the stainless steel pipe attached to the rotator provides point x,y,z data. The method works best to locate the profile of riprap that might be place around a pier or in a gravel/cobble bed. Otherwise, the crane hydraulics limit accurate definition of the water/sediment interface. Given the positional information available on the crane, this method provides very accurate point data and data points can be collected in a short time.

Cross-Section Measurement

When driving a cross section, the truck needs to move slowly for safety reasons and to avoid bouncing the crane, which causes erroneous readings from the tilt sensors. This may require feathering the clutch on a manual transmission. The truck should be positioned to avoid running the wheels or the castors over any bridge grates, which might bounce the crane and/or result in breaking the grate. The driver needs to maintain a straight line, which may require observers walking ahead and/or behind the truck. An observer should also be watching the river for floating debris and to make sure that the sonar does not lift out of the water or go too deep with changes in roadway profile. Cross-section data collected while driving the truck across the bridge can be plotted in any x-y plotting program. Multiple passes can be driven to collect several lines of data that could be used to map a larger upstream approach area.

Sweeping Arc Measurement

Similarly, when sweeping arcs with the crane from a stationary location, the crane operator needs to swing the crane slowly. The usual pattern is to start with the crane at a right angle and swing a short arc immediately in front of the pier, with each successive arc getting larger and collecting data farther in front of the pier. The data collected during this measurement can all be written to one file, pausing the data collection as the crane is re-positioned for the next arc. The resulting x,y,z data collected by sweeping multiple arcs with the truck in a stationary position can be used to develop detailed bathymetric plots of the scour hole and approach conditions.

Kneeboard Measurement

Collecting data with the kneeboard on a rigid frame provides additional point measurements under the bridge that can be used alone or in combination with other data to map additional area. Once the kneeboard is in position, the crane can be used to pull it forward or backward, and the rotator can be used to swing small arcs side-to-side. During all these motions, the position of the kneeboard is being calculated and, at the end of the measurement, an x,y,z data file is written.

Cable-Suspended Measurement

Cable-suspended methods can be used with a traditional sounding weight, the modified sounding weight with the sonar, or a cable-suspended version of the kneeboard. The cable displacement is measured by a pulse counter and recorded by the computer program. Using any cable-suspended method limits the positional data and would be used primarily to locate a potential problem quickly, but not to provide enough data to map the potential problem in any detail.

Typical Results

Figure A25 illustrates typical results available with the articulated arm truck. At this bridge a cross section was taken, and arc measurements at two piers were completed, all on the upstream side of the bridge. The x,y,z data collected from these measurements along with bridge plan information were used in Microstation to create the plots shown in Figure 25. The top drawing shows the limits of the cross-section data collected, and the arcs that were taken at Piers 3 and 4. The middle part of the figure shows the cross section plotted, and at the bottom of the figure are the contour plots developed for each pier.

TYPICAL SEQUENCE OF EVENTS TO COLLECT DATA

The most common and perhaps the best application of the articulated arm truck is to collect data with the streamlined sonar probe. This provides the best positional data and the most rapid data collection. It can be used for cross-section–or arc-based measurements under both low-flow and flood flow conditions. As an illustration of the setup and data collection procedures when using the articulated arm truck, the following paragraphs describe the typical sequence of events that would occur when collecting such data.

Before driving onto the bridge:

1. Mount the instrument box at the end of the crane. Do not install the battery yet.
2. Connect the chain for the draw wire measuring crane extension.
3. Connect the wire from the rotator tilt sensor to the instrument box CR10.
4. With the truck engine running, engage the PTO in the cab to power the crane hydraulics. Leave the truck running with the parking brake set.
5. Remove the bolt holding the crane in place during transport and, with the crane hydraulics, lift the crane off the transport block. Rotate slightly to position the crane over the center of the cab. Extend the crane out over the cab and lower down to the pavement in front of the truck to facilitate attaching the streamlined sonar probe. This operation can be done without placing the outriggers on the ground, provided the crane is kept over the center of the truck and not rotated side-to-side. NEVER ROTATE THE CRANE SIDE-TO-SIDE WITHOUT THE OUTRIGGERS ON THE GROUND.
6. Bolt on the streamlined sonar probe to the end of the rotator on the instrument box.
7. Connect the sonar cable to the terminal block connector.
8. Install the battery in the instrument box. The crane-end system, including all sensors, the CR10 data logger, and the modem, is now active and transmitting

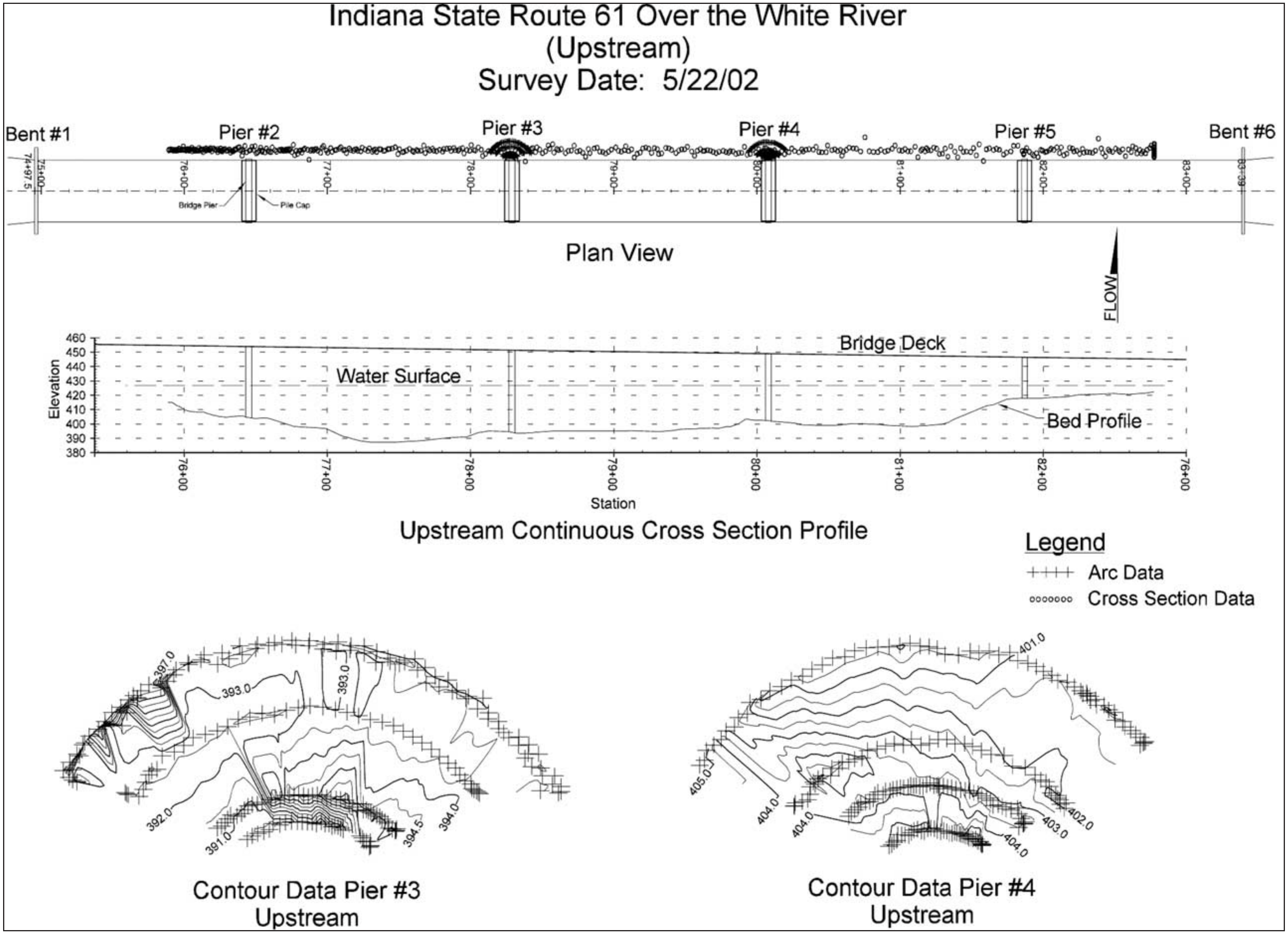


Figure A25. Typical results obtained with the articulated arm.

data (i.e., sonar, tilt angles and crane extension) once per second.

9. Install the surveyor's wheel on the back of the truck. Place in the up position (wheel not on the roadway), and pin the wheel to prevent freewheeling.
10. Install the acoustic stage sensor in the mounting bracket and connect the wire harness. Do not extend out off the side of the truck until positioned on the bridge.
11. Place the computer in the instrument shelter, plug in the power supply to the invertor, and turn on the invertor.
12. Connect the wireless modem to one serial port on the computer, and the truck CR10 to the other serial port.
13. Turn on the power switch controlling the wireless modem and the power convertor for the acoustic stage sensor.
14. Boot-up the computer and execute the data collection program.
15. If the station-elevation file for the profile line has not been created, do this before pulling onto the bridge deck. The profile line is a reference line on the bridge plans, typically along the centerline of the bridge.
16. Raise the end of the crane and fully retract the crane to position it over the cab. It does not need to be put back in the transport block.
17. The truck is now ready to drive onto the bridge. Make sure appropriate traffic control is in place.
18. Drive the truck to the starting station, positioned as close to the curb line or barrier rail as possible.
19. Extend the acoustic stage sensor over the bridge rail. Make sure it is far enough out for a clear shot of the water surface.
20. Lower the outriggers. For a cross-section measurement, the outriggers should be lowered onto the castors. For a stationary measurement at a given pier, the castors do not need to be used.
21. Level the truck bed using a bubble level.
22. Extend the crane out over the bridge rail, and articulate into a 90-degree position.
23. Re-level the truck bed and then position the crane top arm in a horizontal position. This arm must be maintained in a horizontal position for all measurements.
24. Measure the vertical distance from the pavement to the chisel mark, and the horizontal distance from the profile line (typically the centerline) shown on the bridge plans. Enter this information in the program. Account for the cross slope drop from the profile line to the chisel mark when entering the vertical offset.
25. Lower the sonar into the water.
26. Check the program and make sure all sensors are responding.
27. Data collection can now begin.

Collect data:

28. If a cross section measurement is being completed, articulate the crane to the desired location and lower the survey wheel. Click the start button on the program and drive slowly across the bridge. Monitor the position of the sonar in the water, and raise or lower the crane as necessary with the changes in the roadway profile. The position of the crane is being tracked continuously, and the program will compensate for any changes in crane position necessary as the cross section is being driven.
29. If the truck is positioned at a pier and the crane will be used to sweep arcs in front of the pier, rotate the crane until the arm bumps the side of the bridge. Click the start button and slowly rotate the crane until you bump the other side. Pause the program, reposition the crane, click the start button, and sweep a second arc back the other direction. Continue the process sweeping multiple arcs until all data have been collected.
30. Monitor the crane position graphic and the scour depth graphic as data are being collected to watch for any anomalies.
31. After all data collection is complete, for either the cross section or the multiple arcs, click the finish button to write a permanent data file with the x,y,z data in bridge coordinates.

CHAPTER 5

TROUBLESHOOTING, MAINTENANCE, AND SERVICING

TROUBLESHOOTING

Problem

When the data collection program is started, no data appear from the data box at the end of the crane.

Solution

1. Make sure the power switch in the instrument box is on.
2. Check the serial port connection on the computer, and make sure the communications protocol is correct.
3. Check the battery voltage in the instrument box at the end of the crane. If the voltage is low (i.e., less than 11 volts), replace the battery with a charged battery.
4. Close the data collection program and reboot the computer.
5. If data are still not appearing, exit the program and use MS Windows Hyperlink™ to see if data are being sent and received.

Problem

When the data collection program is started, no data appear from the truck-based sensors.

Solution

1. Make sure the power switch in the instrument box is on.
2. Check the serial port connection on the computer, and make sure the communications protocol is correct.
3. Close the data collection program and reboot the computer.
4. If data are still not appearing, exit the program and use MS Windows Hyperlink™ to see if data are being sent and received.

Problem

Data are being transmitted, but the raw angle and/or distance data appear in error.

Solution

1. Use an inclining bubble level to determine angles and check against the program results.
2. If there are discrepancies, set the crane in the calibration position. The calibration position is when the crane is fully retracted and articulated at a right angle over the bridge deck.
3. Check the truck bed and crane top arm to ensure they are still level.
4. Check the crane and rotator angles with an inclining bubble level. The crane should be set at 90 degrees, and the rotator arm should be parallel to the crane (180 degrees).
5. Run the calibration program.

MAINTENANCE AND SERVICING

Maintenance and servicing relate primarily to the truck and crane. Standard maintenance for the truck and the specific manufacturer recommendations for the crane should be followed.

The instrumentation for the positioning and depth require minimal maintenance; servicing a broken sensor typically would involve replacing the defective sensor with new one. Typically, the cost of the sensors is small, and there are no user-serviceable parts.

CHAPTER 6

ENHANCEMENTS

Although the articulated arm truck is fully functional, improvements could be made to the device. Sensor-related improvements include work on both the kneeboard and physical probe concepts. Work is needed on the rigid frame version of the kneeboard to improve the deployment and stability of the device. A sensor at the end of the physical probe would be beneficial to help identify the water sediment interface when working in softer bed materials.

The calculation of the location of the end of the crane based on assorted tilt and displacement sensors, along with a surveyor's wheel to locate the truck on the bridge deck. This system worked well, but created a system of multiple components that required a certain electronic aptitude to operate and maintain. A simpler positioning system involving fewer components would be preferable, if the required accuracy can be maintained. For example, as GPS technology continues to become more cost-effective and user-friendly, an alternate positioning system based on GPS may be feasible.

APPENDIX B

FIELD TESTING RESULTS

Colorado Field Testing

The I-70 bridge across the Colorado River in DeBeque Canyon has three piers on pile caps with 12 H-piles under each pile cap. The total width is 40.5 ft (12.3 m) consisting of two 12 ft (3.7 m) driving lanes, a 10 ft (3.0 m) shoulder on the right, a 4 ft (1.2 m) shoulder on the left and curb sections with Type 3 bridge rail (15 inches (0.4 m) wide). The first site visit to this bridge was made during the week of March 8 as the temporary road into the channel was being built for placing additional riprap. Some riprap had been placed previously by end dumping from the bridge, but Colorado DOT was unable to fill the scour hole completely. Therefore, they were building a rock road into the channel to allow more direct placement of rock.

Data collection was attempted during this first trip using the crane system, but the computer kept locking up. This may have been caused by a cell phone tower just upstream of the bridge scrambling some of the data during wireless transmission from the end of the crane. The software was subsequently modified to filter for bad data, and on a return trip during the last week of March, data were collected on both the upstream and downstream sides of the bridge from Pier 2 to the right abutment (defined looking downstream). Colorado DOT provided traffic control during both trips.

Data was collected on the downstream side by positioning the bridge to the right of the pier where the scour hole had been and sweeping multiple arcs (Figure B1). Data were collected on the upstream side with the truck positioned at the centerline of Pier 2 and about midway between Pier 2 and the abutment (Figure B2). Figure B3 shows the articulated arm being lowered into position. The instrument shelter with the computer and other instrumentation is shown in Figure B4, as is one of the two post-mounted winches. The instrument box at the end of the crane is being wired for operation in Figure B5. Figure B6 shows one of the two winches being used to suspend the sounding weight, and the Marsh-McBirney velocity sensor on a 50-lb (24-kg) weight is shown in Figure B7.

Based on the data collected, a plot of the bathymetry was developed for the area upstream and downstream of Pier 2 (Figure B8). CDOT was interested in the riprap placement, because it had to be done underwater in high-velocity conditions. Based on the bathymetry, the scour hole was filled with rock.

Alabama Bridges

Three bridges were visited in the Mobile, Alabama, area. The Heron Bay Bridge, a five-span bridge on State Highway 193 leading to Dauphin Island, is scour critical based on calculations. The bridge is a two-lane structure with wide-enough shoulders to park the truck without additional traffic control (Figure B9). Cones and signs carried on the truck were used, and an Alabama DOT vehicle was parked on the approach with its lights flashing. Figure B10 shows a measurement being made by sweeping the crane in an arc movement in front of the pier. Multiple arcs were taken to completely map the area approaching the pier from the Gulf side.

The Chickasaw Bridge is a four-span structure taking State Highway 213 across Chickasaw Creek in northwest Mobile. This bridge is tidally influenced and was rated scour critical based on calculations. There were no shoulders and data collection required a lane closure, provided by Alabama DOT. Figure B11 shows the sonar in place to begin a measurement at a pier. Figure B12 shows the positioning of the stabilizers, with one on the deck and one on the curb.

The Little Lagoon Pass Bridge is a six-span bridge on State Highway 180 near Gulf Shores, Alabama. The bridge is in a constricted tidal inlet that historically has had significant sediment movement and relatively high velocities because of the constriction created by the seawalls. The bridge has had some scour problems because of the velocities, while the entire bridge reach in the inlet area has had sediment deposition problems, requiring dredging. Alabama DOT had expected relatively high tidal velocities at this bridge, but after several hours of waiting on the bridge for the cross over point between low and high tide, when the velocities would be highest, measurements found the maximum velocities on this day to be about 3 fps (0.9 m/s). Velocity measurements were made with a Marsh-McBirney current meter attached to the end of the crane (Figure B13). For this bridge, the extension was taken off the sonar to allow mounting the current meter as shown. The velocities and stream power were high enough to create ripples and some dune movement of the bed but no significant scour at the piers.

Figures B14a through c provide plots of the data collected at these bridges.

Minnesota Trunk Highway 93 Bridge

Minnesota Trunk Highway 93 (TH93) crosses the Minnesota River near LeSueur, Minnesota. The bridge has five spans on four piers on a pile foundation. The total width is 46 ft, 2 in. (14.1 m) consisting of two 12 ft (3.7 m) driving lanes, two 9 ft, 5in (2.9 m) shoulders and an 18 in. (0.46 m) barrier railing.

Given the drought conditions in Minnesota, the bridge was visited primarily to demonstrate the equipment to Minnesota DOT and to complete initial testing of components that had been modified since the Alabama trip. This included the new

Figure B1. Crane on downstream side of bridge near scour hole.

extension for the sonar stabilizer with the pivot point further forward on the blade and the new castor system for cross-section measurements. At the time of the inspection, runoff was low and there were no known scour problems. The inspection was completed on May 13, 2002, and included arc measurements at Pier 1 and a cross section on the upstream side of the bridge. Minnesota DOT provided traffic control.

Figure B15 shows the truck in position to measure conditions at Pier 1. The new stabilizer blade performed well and was able to track the current, even given low-velocity conditions. Figure B16 shows the improved castor system used to allow truck movement with the crane deployed. This system was not quite as rigid as the original turnbuckle design, but was much easier to deploy. The turnbuckle system took about 30 minutes to set up, while the new system, with the castor on an arm that can swing in place under the outrigger before it is

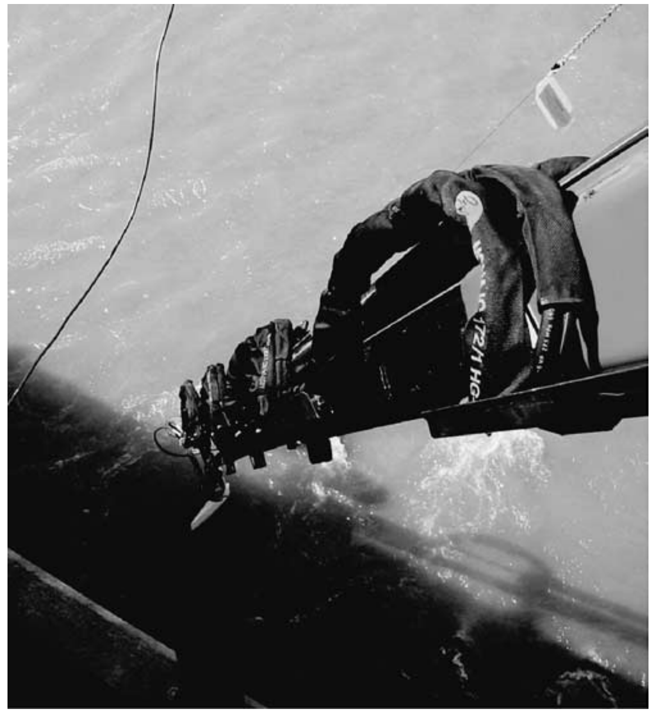


Figure B3. Looking down the articulated arm as the sonar is being positioned in the water.

lowered, takes only minutes to deploy. Figure B17 shows the truck ready for a cross-section measurement, with the castors in place and the surveyor's wheel on the ground.

Figure B18 plots the data collected at these bridges.

Wisconsin State Highway 80

Wisconsin STH 80 crosses the Wisconsin River near Muscoda, Wisconsin. The bridge has nine spans on eight

Figure B2. Using the articulated arm to sweep arc's on the upstream side of bridge.

Figure B4. Collecting data.

Figure B5. Instrument box on end of crane.

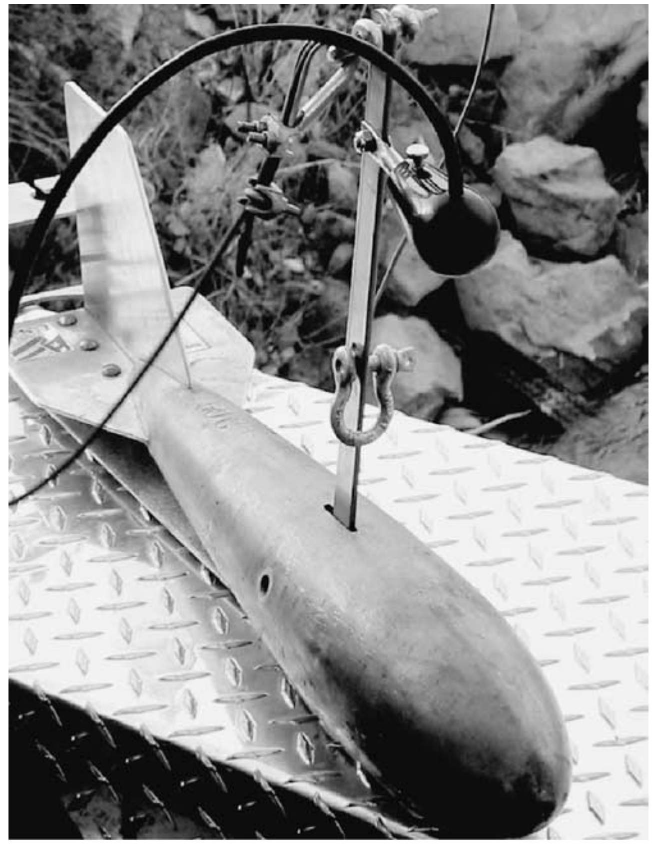


Figure B7. Marsh-McBirney velocity sensor on a 50 lb sounding weight.

hammerhead piers supported by spread footings. The total width is 42 ft (12.8 m), consisting of two 12 ft (3.7 m) driving lanes, two 6 ft (1.8 m) shoulders, and 18 in. (0.46 m) parapets.

The bridge has had scour problems at Pier 1, which is in an eddy along the left bank creating reverse-flow conditions at the pier. The inspection was completed on May 14, 2002, and included arc measurements at Pier 1, a cross section from Piers 1 to 3, and kneeboard measurements to get further under the bridge deck at Pier 1. Wisconsin DOT provided traffic control.

Figure B19 shows the sonar in the water on the upstream side of Pier 1. Note the orientation of the stabilizing fin in Figure 20, which indicates the reverse-flow condition at this pier. Figures B20 through B22 illustrate the deployment of the kneeboard on a rigid frame to get under the bridge. The frame was made of aluminum and connected to the rotator on the end of the crane. Knowing the location of the end of the crane, the angle of the rotator, the length of the frame, and the distance to the water surface, personnel can calculate the position of the kneeboard as it is moved under the bridge.

During this field trial, as the kneeboard was being swept side-to-side under the bridge with the hydraulic rotator, the frame was bent as the flow line between the main flow and the reverse flow was crossed. A software problem was also discovered in the position calculation for this method during this test. A stiffer, simple frame was designed after this event and the software was revised, prior to additional testing in Idaho (see below).

Figure B23 plots the data collected at these bridges.

Figure B6. Using a single winch to position sounding weight with Marsh-McBirney.

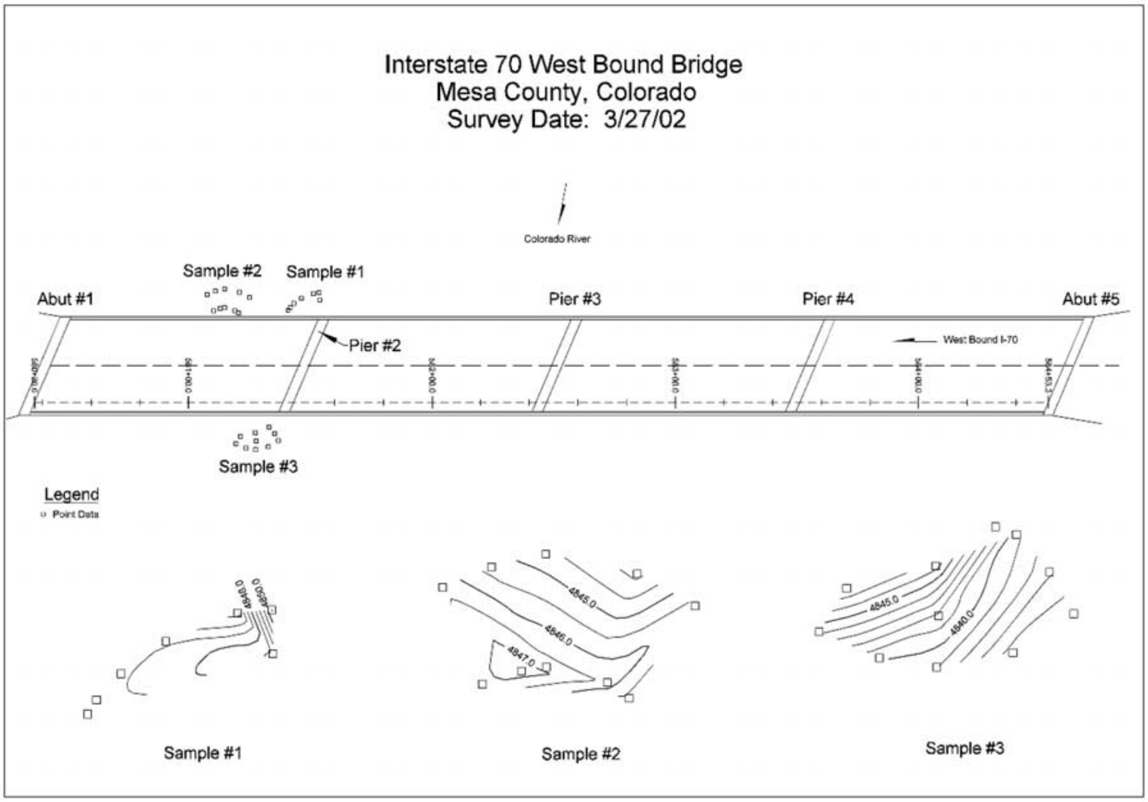


Figure B8. Colorado I-70 results.

Figure B9. Heron Bay bridge, Highway 193 near Daulphin Island.

Figure B10. Making an arc measurement on the Gulf side of the bridge.

Missouri U.S. Highway 24

U.S. Highway 24 crosses the Grand River near Brunswick, Missouri. The bridge has seven spans on six piers, two of which have been protected with gabion baskets because of scour problems. The bridge is about 47 ft (14.3 m) wide, with two 12 ft (3.7 m) lanes, two 10 ft (3.0 m) shoulders and 18 in (0.46 m) barrier rails.

The inspection was completed on May 17, 2002. Missouri had received significant rainfall in the week prior to the inspection, but most of the smaller drainages had already peaked. After visiting several bridges around the Macon area that were on smaller drainages and finding little flow in the channels, this bridge was selected to evaluate the performance of the gabion baskets during and after a large flow event. The Grand River

Figure B11. Crane in position at the Chickasaw Bridge.

watershed is large, and flow conditions were still quite high at the time of inspection, with velocities around 7.0 fps (2.1 m/s). Based on the time available and a large debris snag at Pier 6, measurements were completed only at Pier 5.

Figure B24 shows the approach conditions to the bridge. Figure B25 illustrates an arc measurement at full extension. Figure B26 plots the data collected at these bridges.

Indiana State Route 61

Indiana S.R. 61 crosses the White River southeast of Vincennes, Indiana. The bridge has five spans on piers with pile caps with steel H piles driven to approximate refusal. The bridge was designed for a 100-year flow of 114,810 cfs (3,250 m^3/s). At the time of inspection, May 22, 2002, the river was at flood stage, and the southern part of the state was experiencing the wettest May on record.

The bridge has not had any major scour problems, but had a large sand bar in the bridge opening that had been contracted for removal. In addition to potential pier scour during the recent high flows, Indiana DOT was particularly interested in seeing if the sand bar was still present and asked that the research team survey both the upstream and downstream sides of the bridge.

Figure B27 depicts the bridge deck, which was 48 ft, 4 in. (14.7 m) wide, with 12 ft (3.7 m) lanes, 10 ft, 8 in. (3.2 m) shoulders, and 18 in. (0.46 m) concrete barrier wall. Traffic control was provided by Indiana DOT. Figure B28 illustrates conditions on the upstream side of the bridge.

Figure B29 shows the cross-section measurement being taken on the upstream side, and Figure B30 shows the sonar in the water as the measurement is being made. The truck had to be positioned away from the concrete barrier to avoid running the castors over the drainage inlets (Figure B31). However, this did not create a problem as the arm was articulated into an acceptable position for the cross section. Figure B32 shows an arc measurement on the downstream side of the bridge. Note the wake indicating the strength of the current, which was flowing about 6.8 fps (2.1 mps).

The wireless sonar mounted in a 75 lb (34 kg) sounding weight was tested at this bridge. The sounding weight was suspended by a 4 ft (1.2 m) hanger bar with the electronics (wireless modem) enclosed at the top of the hanger bar (Figure B33). The sonar is embedded in the bottom of the sounding weight, with a small wedge to better transition flow over the transducer face (Figure B34). This was necessary given that most sounding weights are not streamlined on the bottom, but are designed with a flat bottom so they are stable when set on the ground for rigging current meters. The flat-bottom design could create a separation zone off the nose of the sounding weight, which would not be an issue for current meter applications but was a concern when mounting a sonar transducer in the bottom of the weight.

Figure B35 plots the data collected at these bridges.

(*text continues on page B-9*)

Figure B12. Positioning the stabilizer on the curb line.

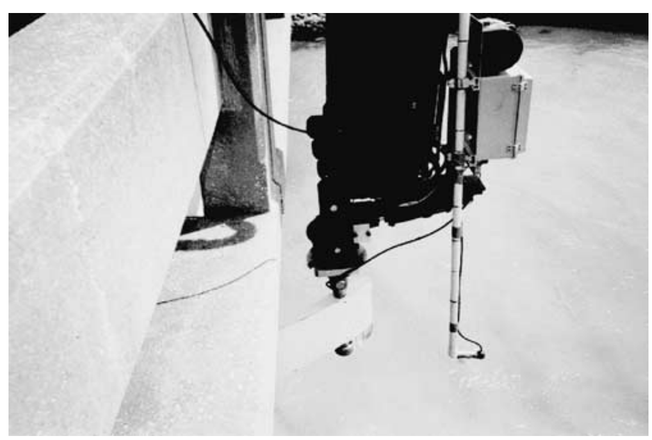


Figure B13. Marsh-McBirney current meter mounted on the crane upstream of the sonar.

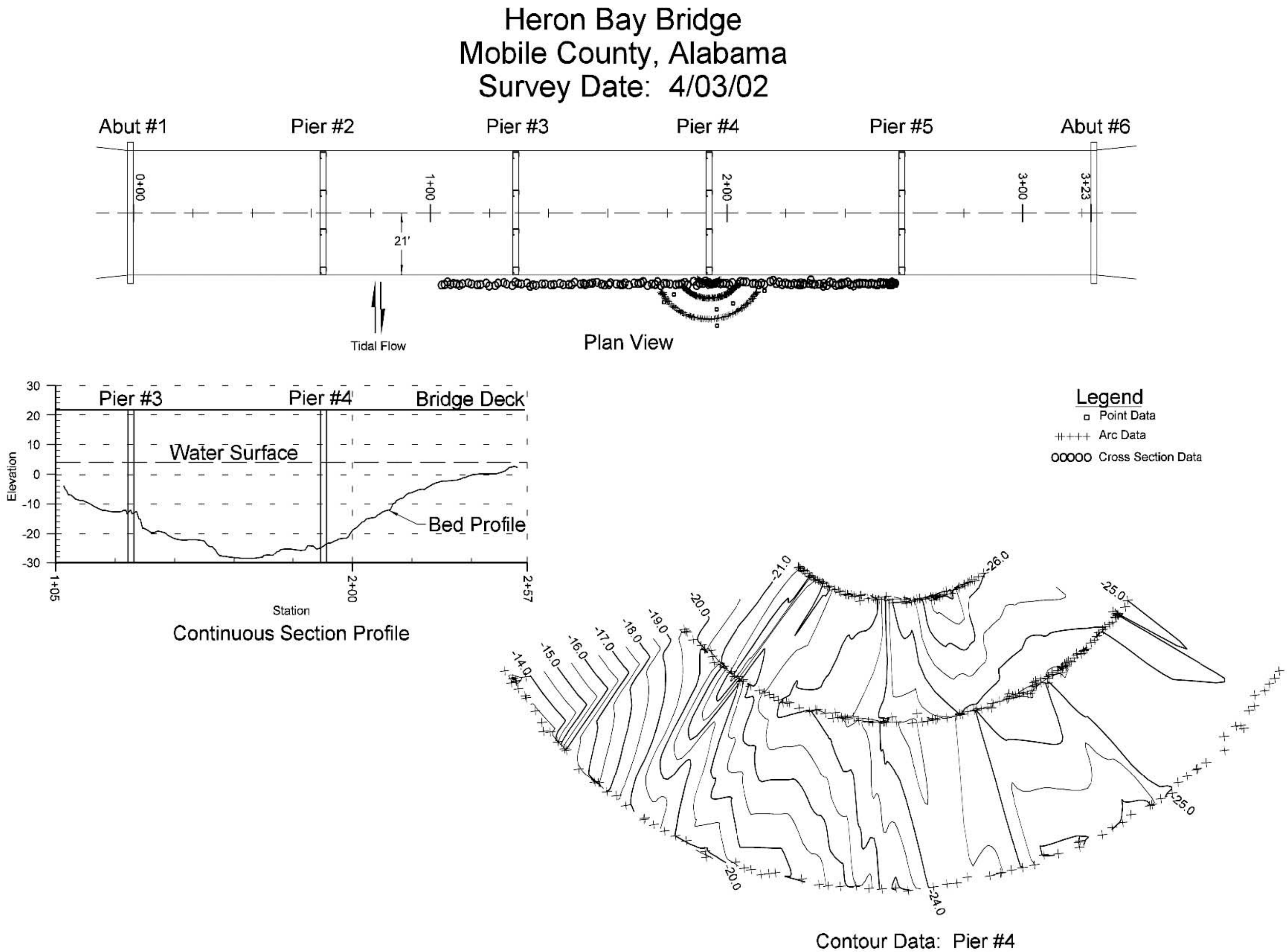


Figure B14a. Heron Bay results.

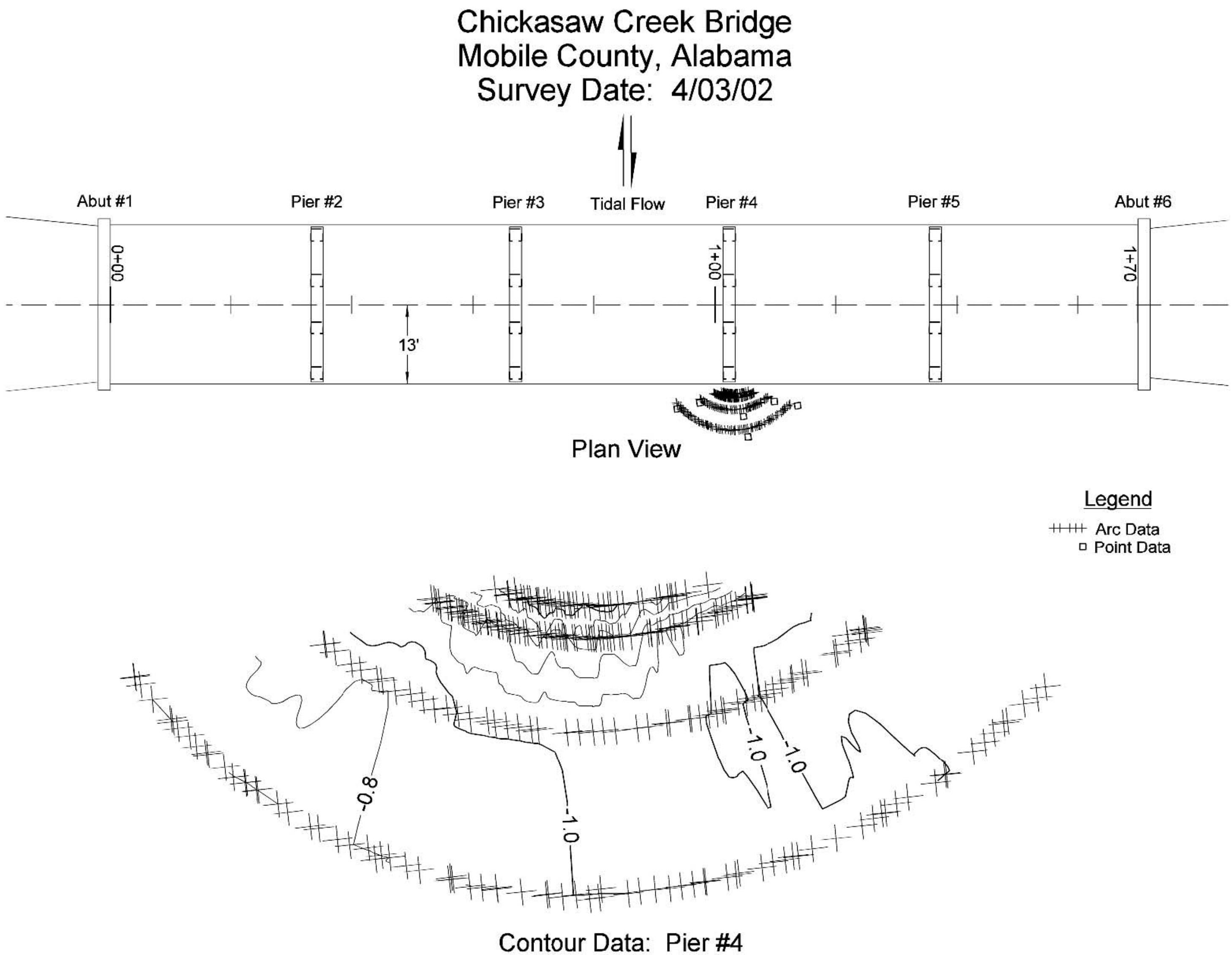


Figure B14b. Chickasaw Creek results.

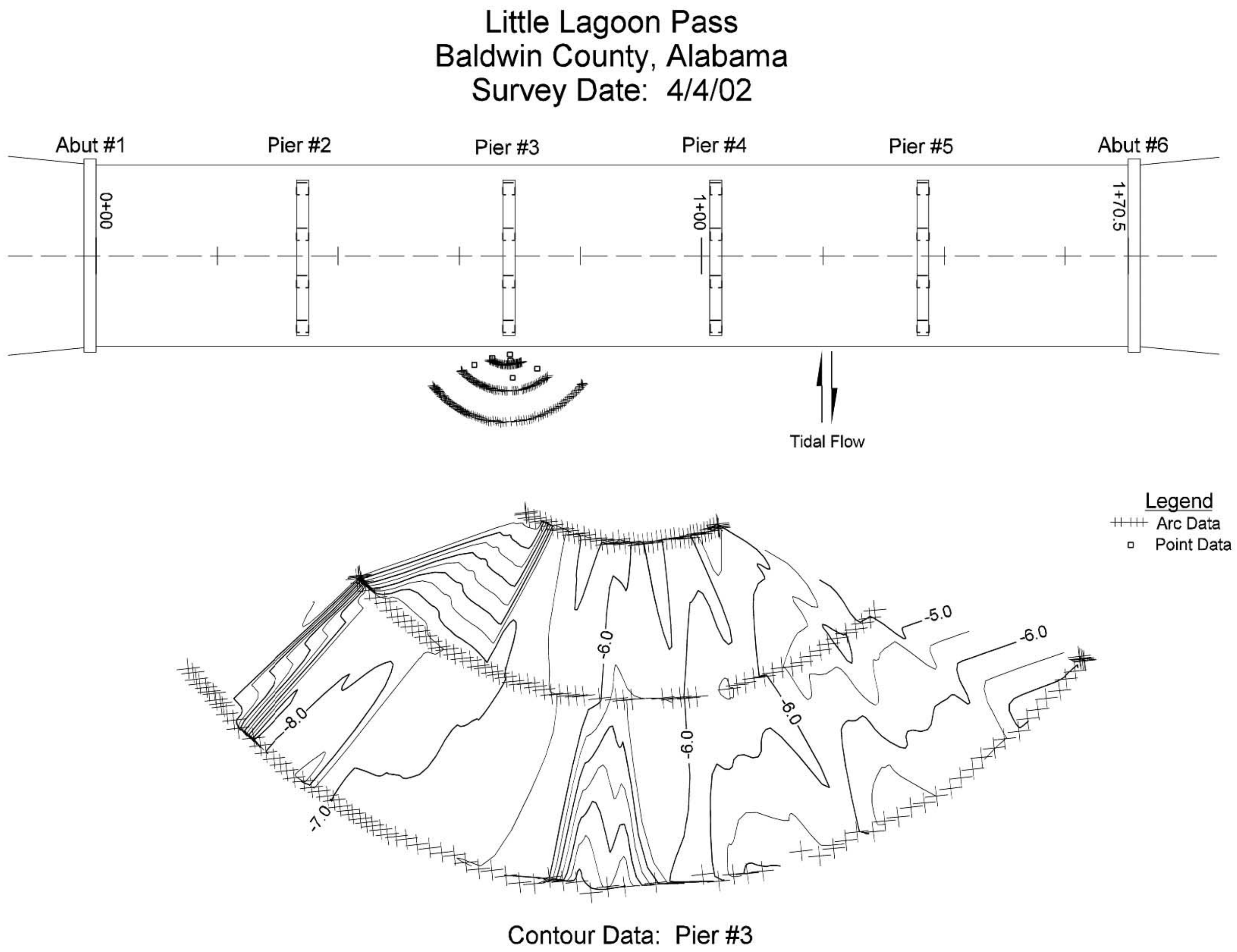


Figure B14c. Little Lagoon Pass results.

Figure B15. Making measurements at Pier 1.

Figure B16. Close-up of stabilizer sitting on castor.

Figure B17. Cross section measurement with castors deployed and survey wheel in place to measure distance traveled.

Idaho Bridges

Two bridges on the Snake River were visited near Blackfoot, Idaho. The drought conditions limited runoff in the state, particularly in eastern Idaho; however, these bridges have had scour problems in the past and were of interest to Idaho DOT. Additionally, they were going to install A-jacks™ as a countermeasure later in the year and were interested in having a survey prior to construction. Both the Ferry Butte Bridge, south of Blackfoot, and the West Shelley Bridge, north of Blackfoot, were visited on June 4, 2002.

The bridge design for both structures is similar, with four spans on spread footing piers. The deck width was 33 ft (10.1 m) with no shoulder, requiring a lane closure for traffic control that was provided by Bingham County. Arc measurements were made at the upstream side of the piers at both bridges, supplemented by kneeboard measurements at Ferry Butte and a cross section at West Shelley.

Given narrow bridges with no shoulder, placement of the truck on the bridge deck at these bridges (Figure B36) was similar to the Chickasaw Bridge in Alabama. Figure B37 shows an arc measurement in process on the upstream side.

After problems with the kneeboard frame in Wisconsin, a revised frame was developed. The revised frame was made of steel (the original was aluminum) and was more rigid and also allowed the kneeboard to swivel, similar to the concept used on the sonar stabilizing fin. The frame was tested at the Ferry Butte Bridge and worked better than the original design, but the kneeboard/frame was still somewhat difficult to get initially placed in the flow and then pushed under the bridge. Figure B38 shows the kneeboard along side the pier wall at the bridge. The software revisions made after the Wisconsin bridge to calculate the position of the kneeboard did correct the position problems that existed.

Figure B39 shows an arc measurement near a pier at the West Shelley Bridge. Even at low flow, the local velocity and turbulence near the piers were significant. An accumulation of gravel and sand along the curb line on this bridge was a concern in terms of the castors during the cross-section measurement, but the neoprene wheels rolled through this material with no problems (Figure B40).

Figure B41 plots the data collected at these bridges.

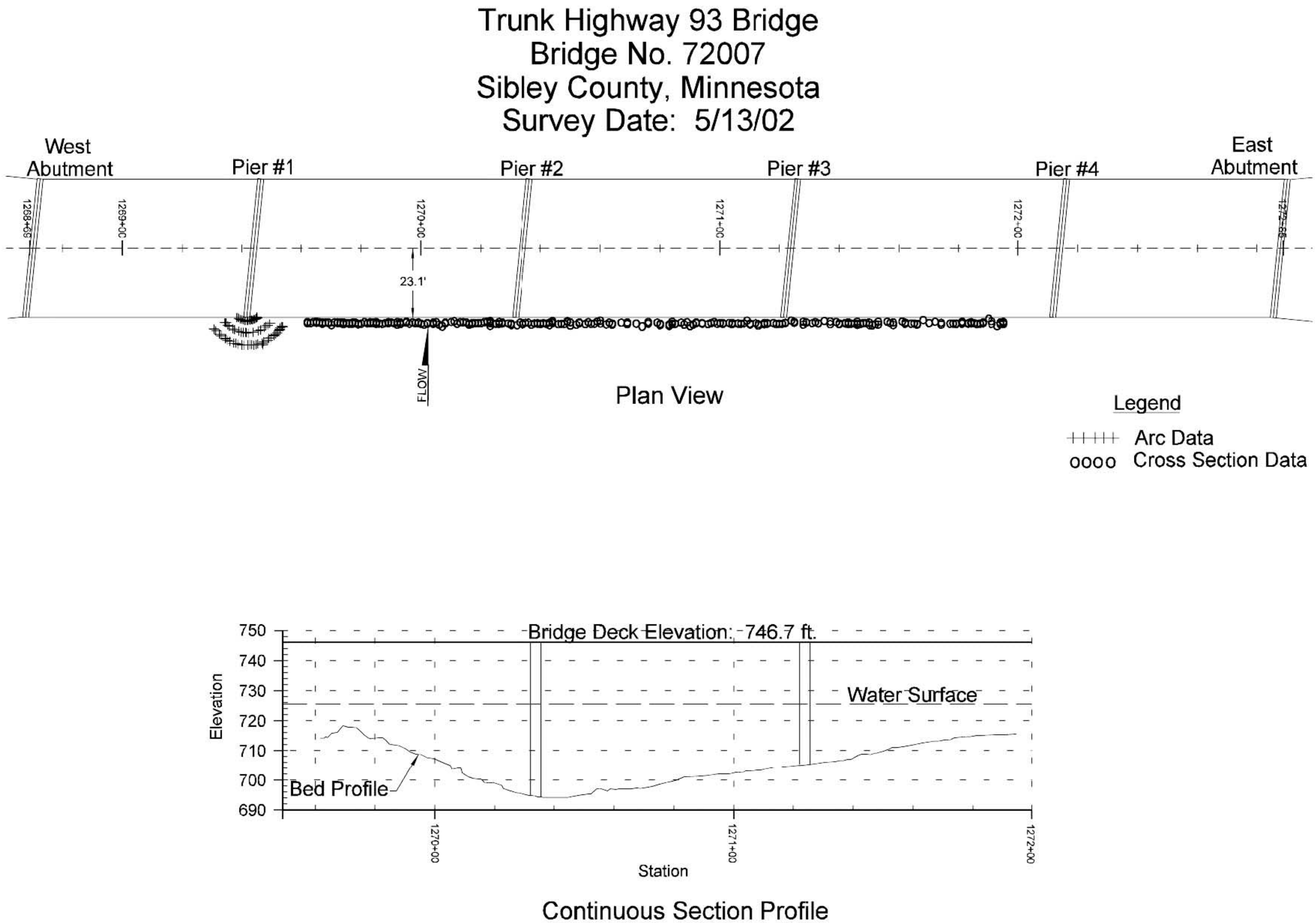
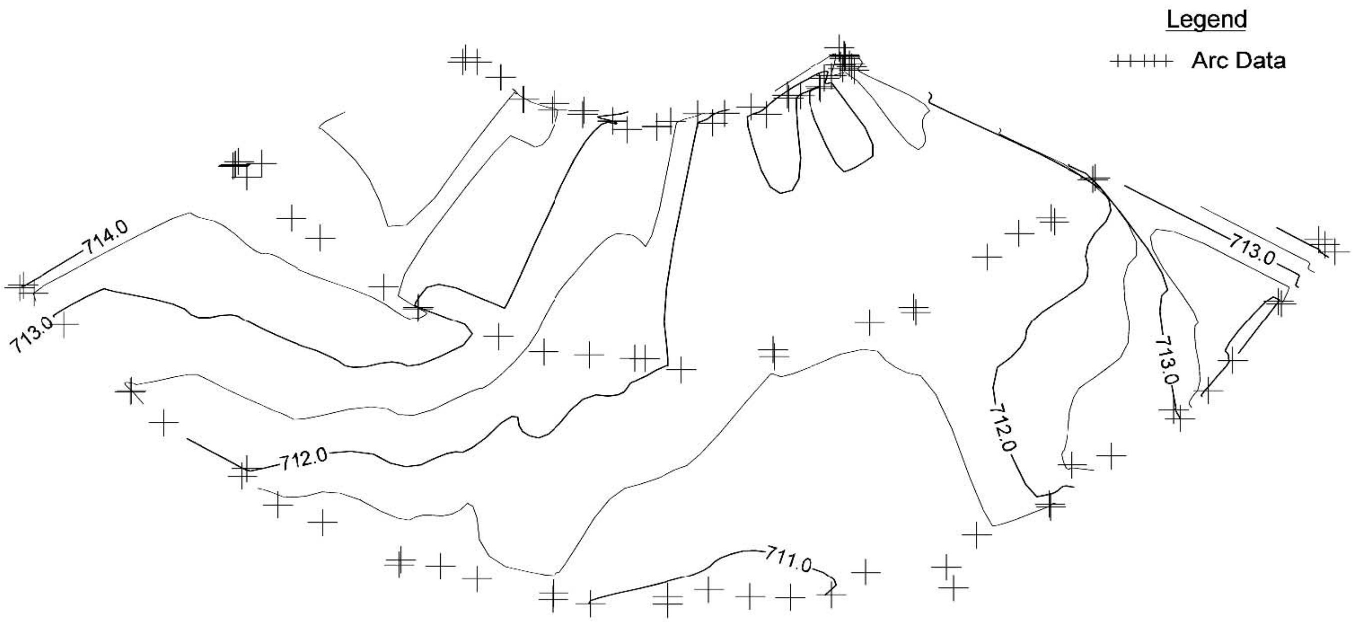


Figure B18a. Minnesota Trunk Highway 93 cross section results.

Trunk Highway 93 Bridge
Bridge No. 72007
Sibley County, Minnesota
Survey Date: 5/13/02



Contour Data: Pier #1

Figure B18b. Minnesota Trunk Highway 93 pier 1 results.

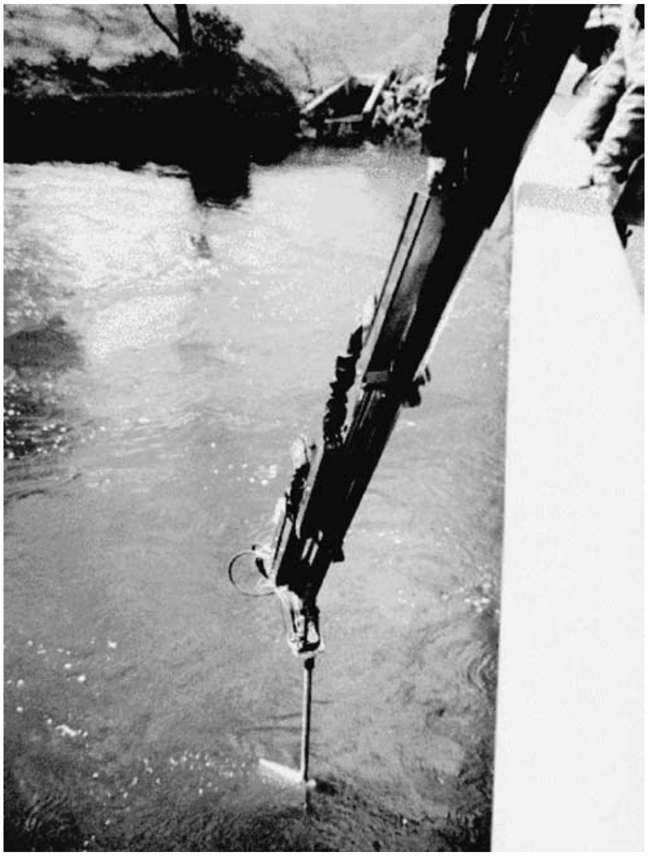


Figure B19. Arc measurement on the upstream side of Wisconsin STH80.

Figure B21. Deploying the kneeboard.

Figure B20. Kneeboard on a rigid frame.

Figure B22. Kneeboard under the bridge.

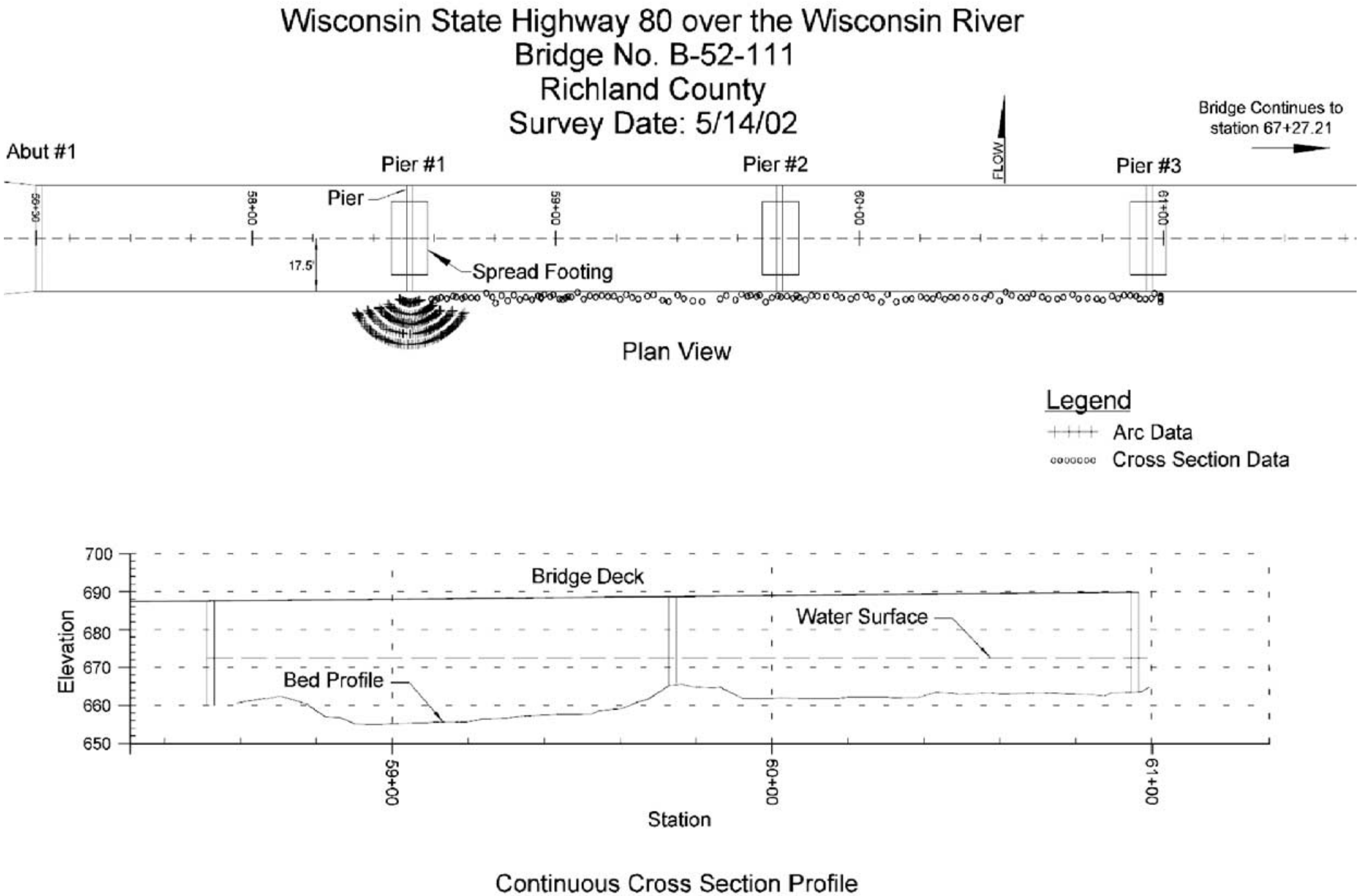


Figure B23a. Wisconsin State Highway 80 cross section results.

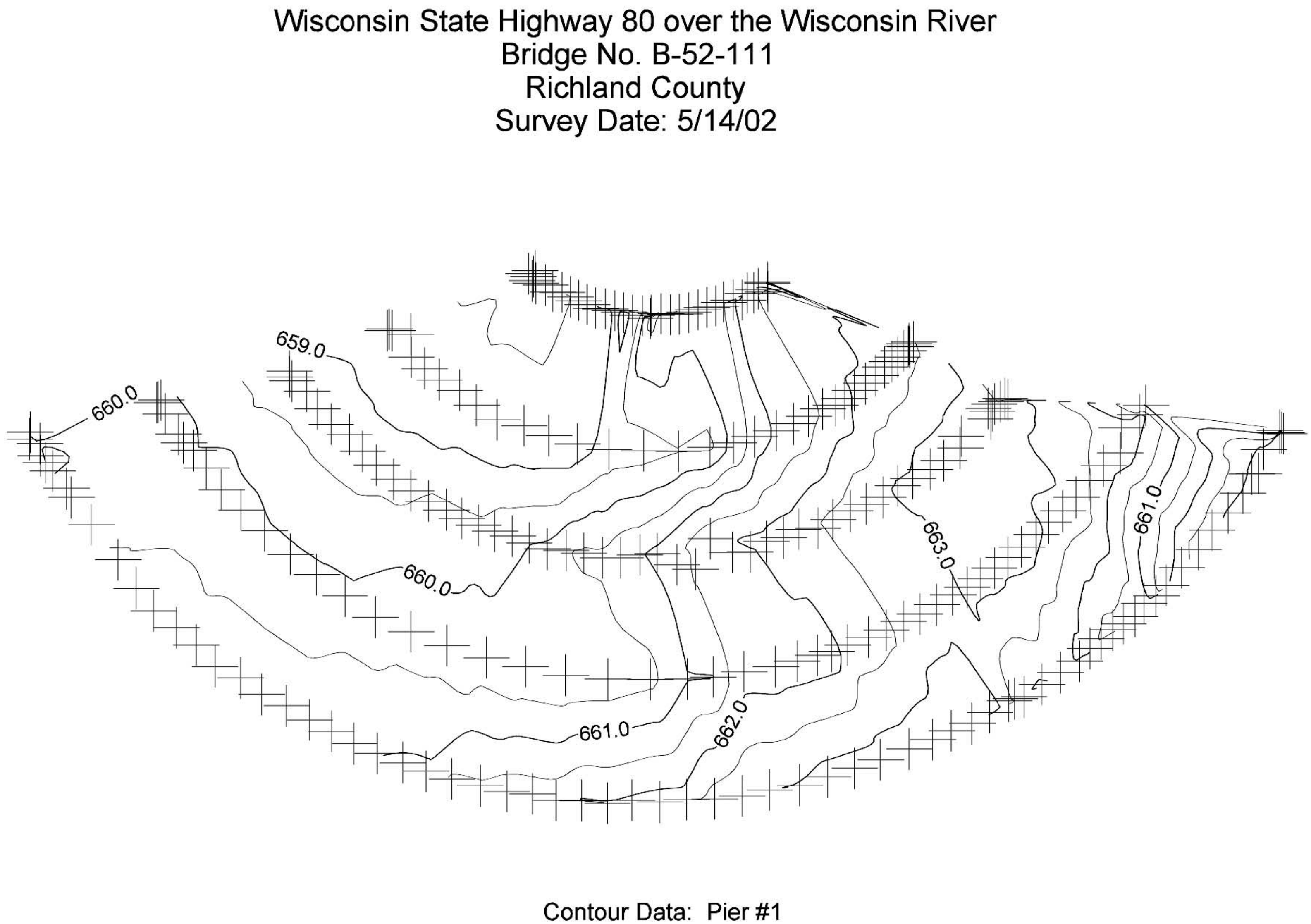


Figure B23b.   Wisconsin State Highway 80 pier 1 results.

Figure B24. Approach conditions at U.S. 24, Missouri

Figure B25. Arc measurement at full extension.

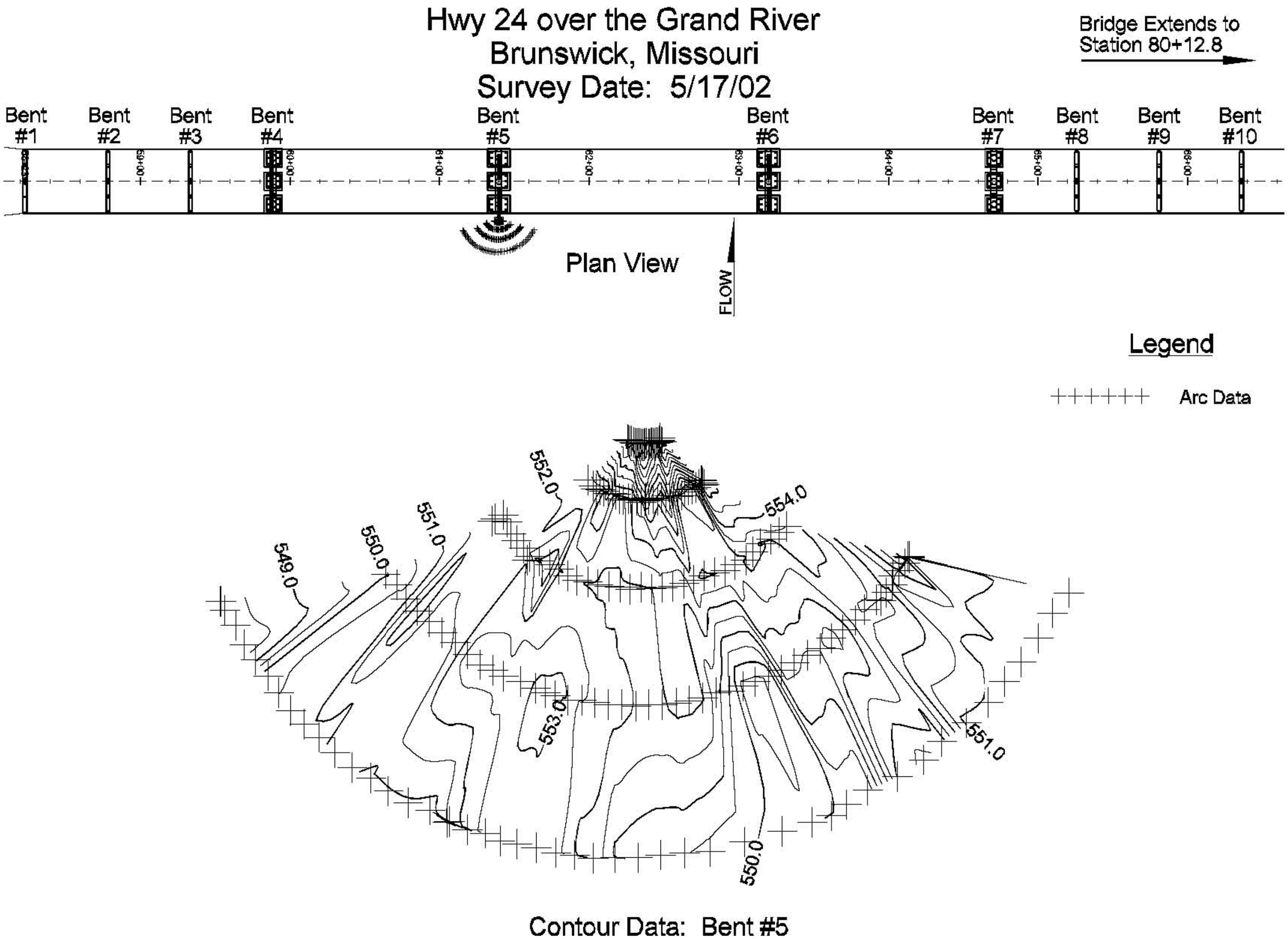


Figure B26. Missouri Highway 24 results.

Figure B27. SR 61 crossing the White River in Indiana.

Figure B29. Measuring a cross section at SR 61.

Figure B28. Upstream conditions at S 61.

Figure B30. Sonar in the water as the truck is moving across the bridge during a cross section measurement.

Figure B31. Truck positioned to clear grate during cross section measurement.

Figure B33. Sounding weight with sonar.

Figure B32. Arc measurement on downstream side.

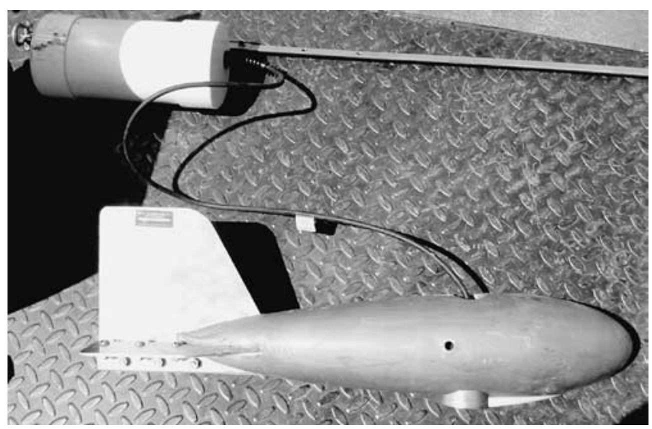


Figure B34. Close up of sounding weight showing wedge on leading edge of sonar.

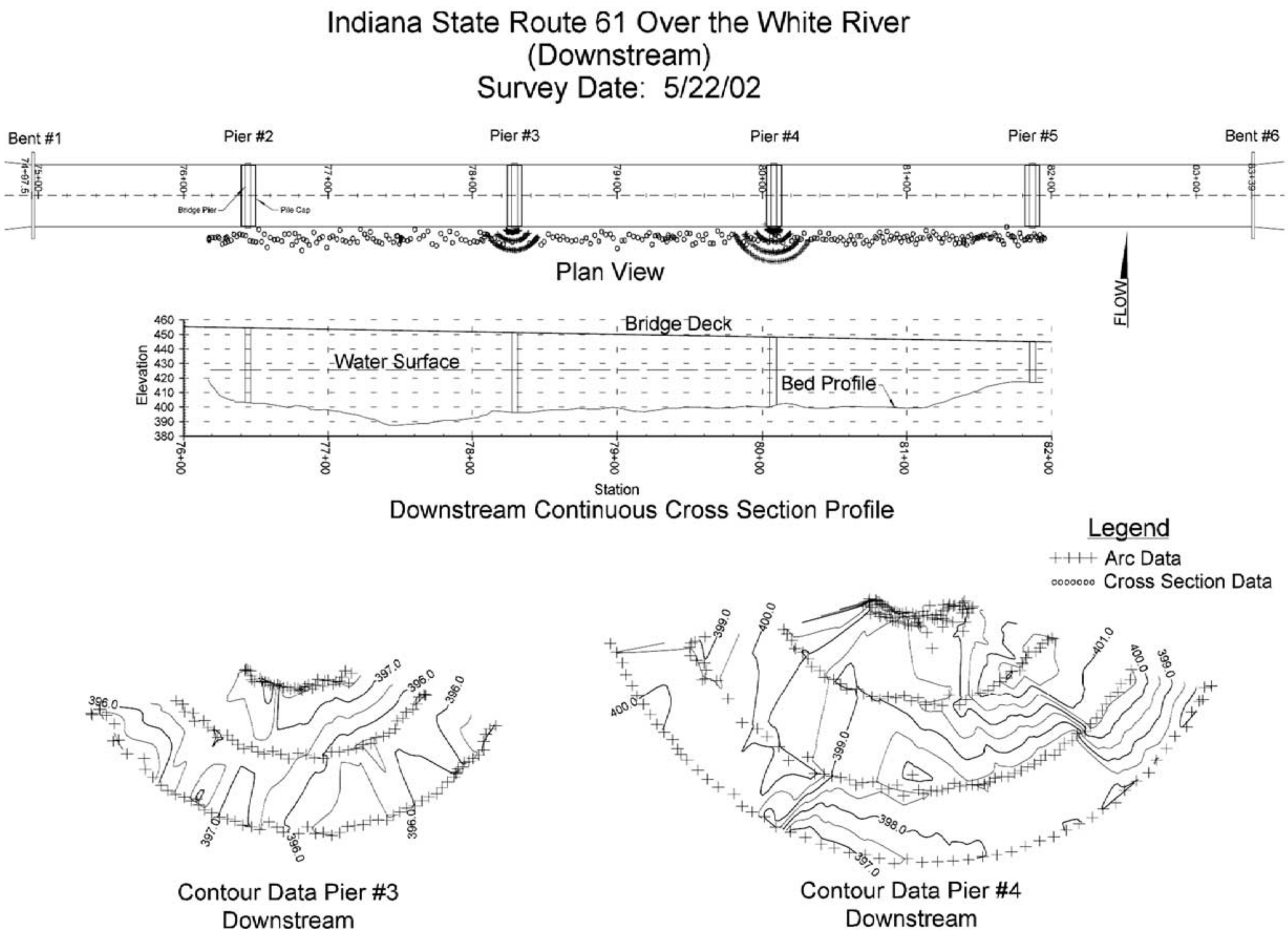


Figure B35. Indiana State Route 61 downstream side results.

Figure B36. Truck placement at Ferry Butte.

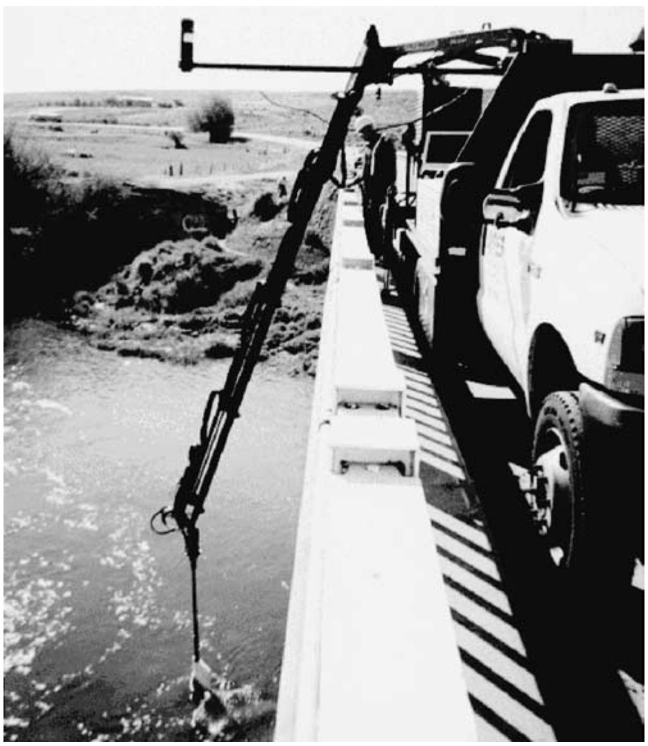


Figure B37. Arc measurement on upstream side.

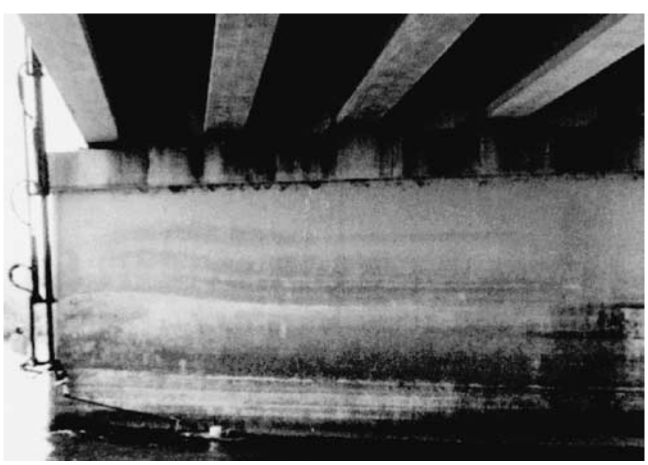


Figure B38. Kneeboard under bridge at Ferry Butte.

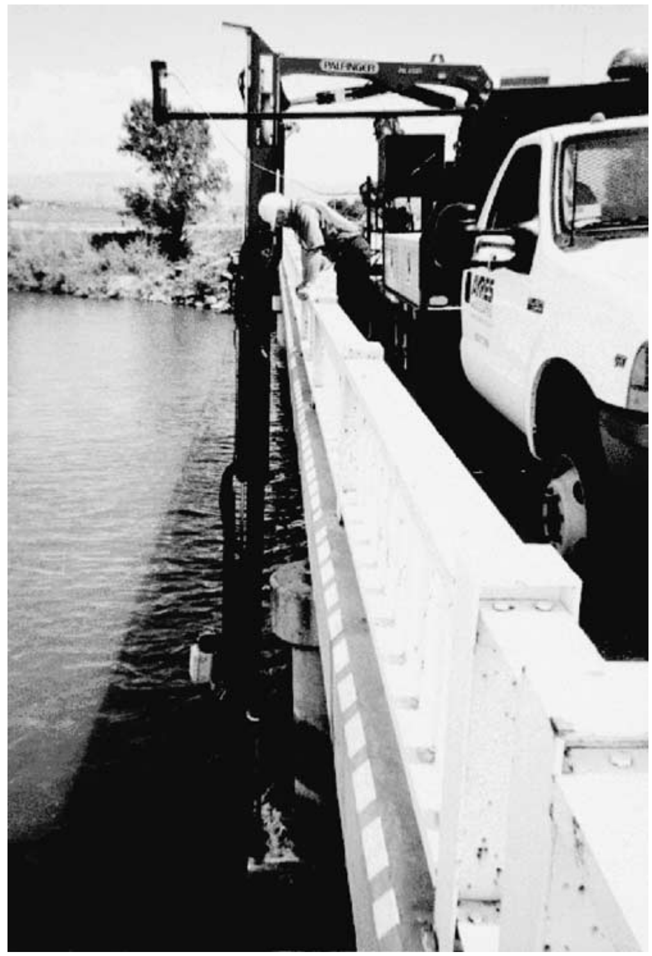


Figure B39. Arc measurement upstream at West Shelley.

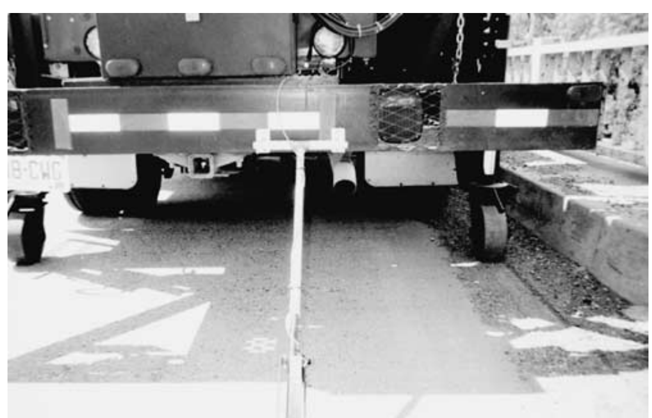


Figure B40. Castor movement through sand and gravel deposited along curbline.

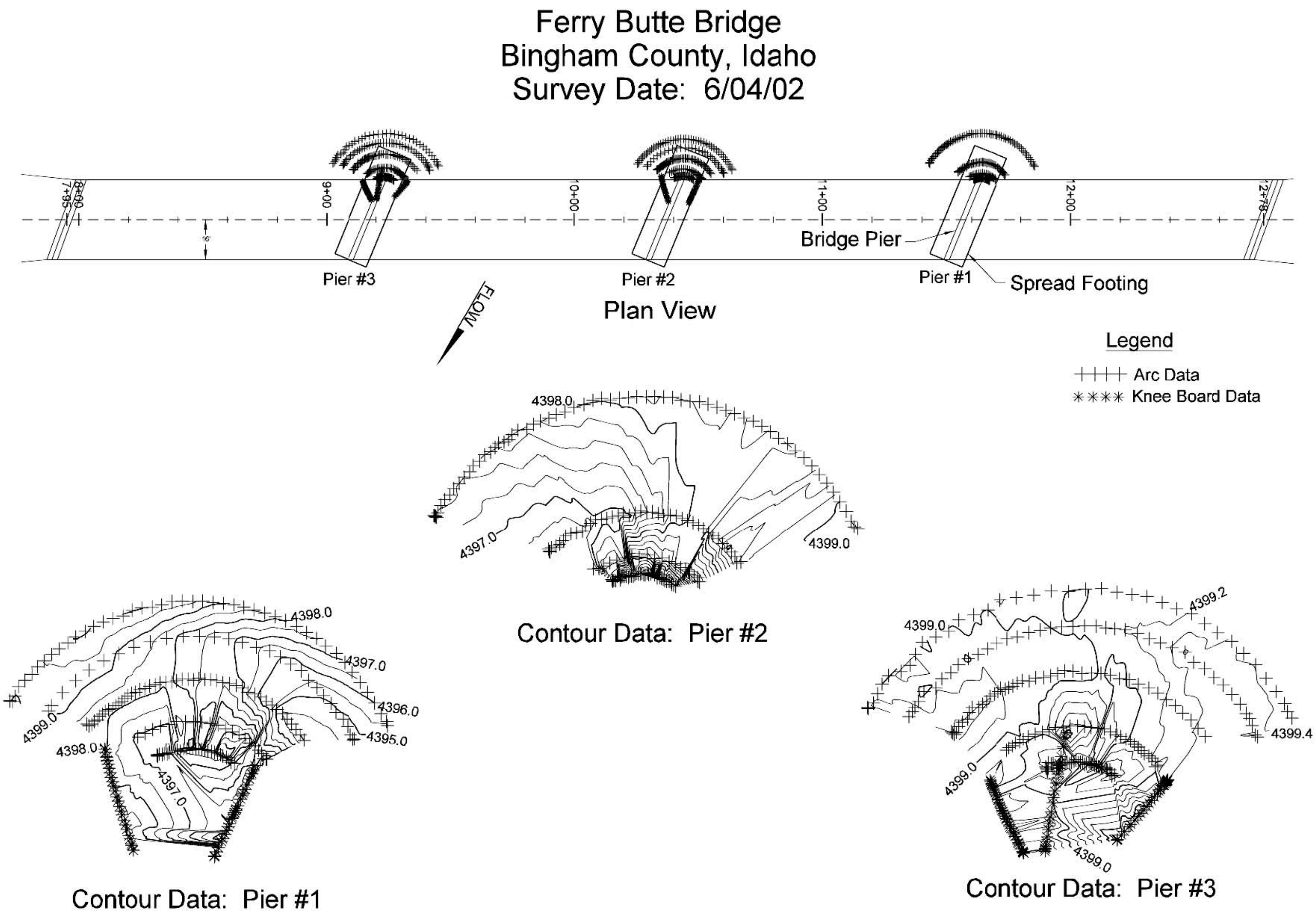


Figure B41a. Ferry Butte results.

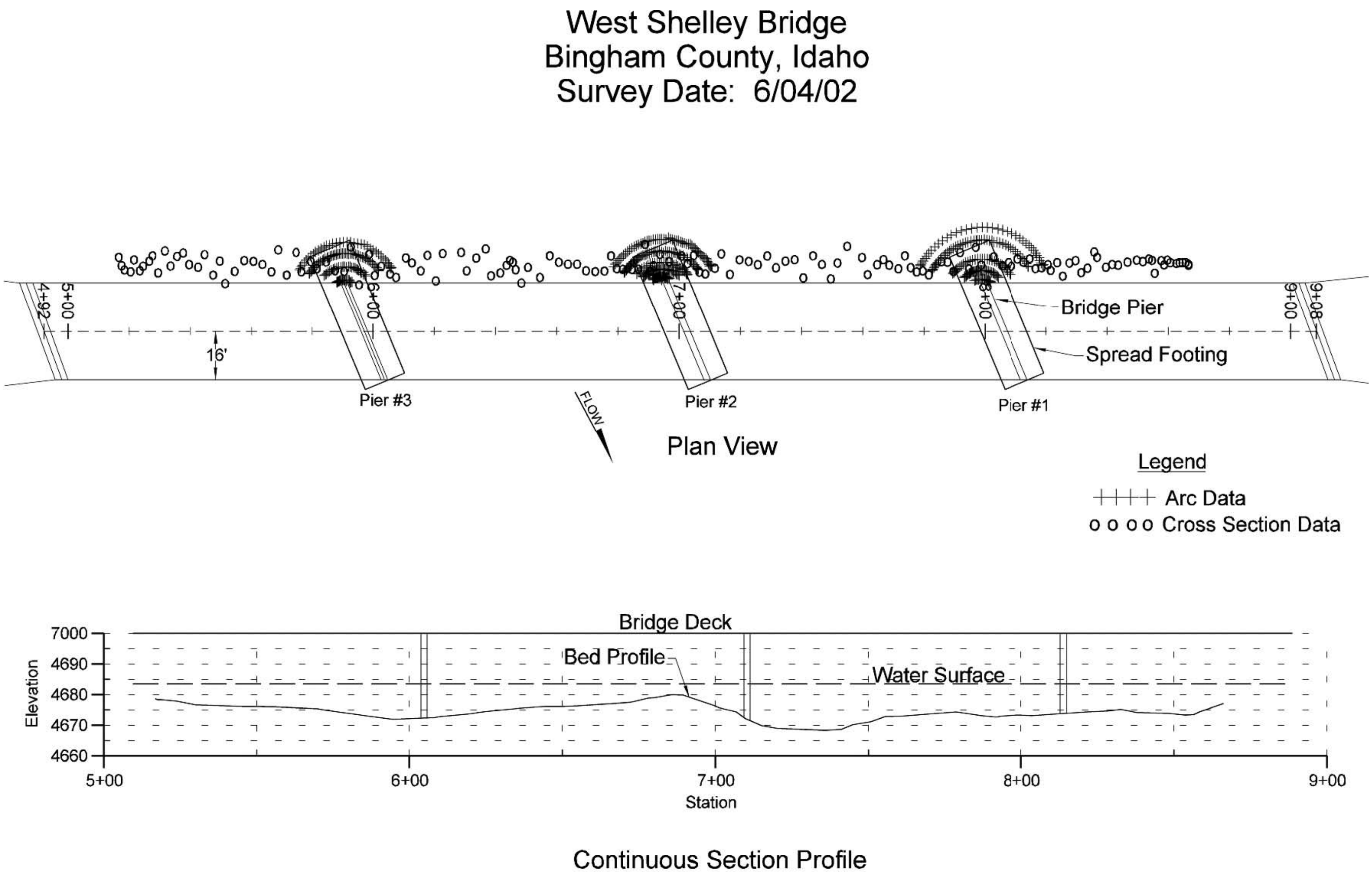


Figure B41b. West Shelley cross section results.

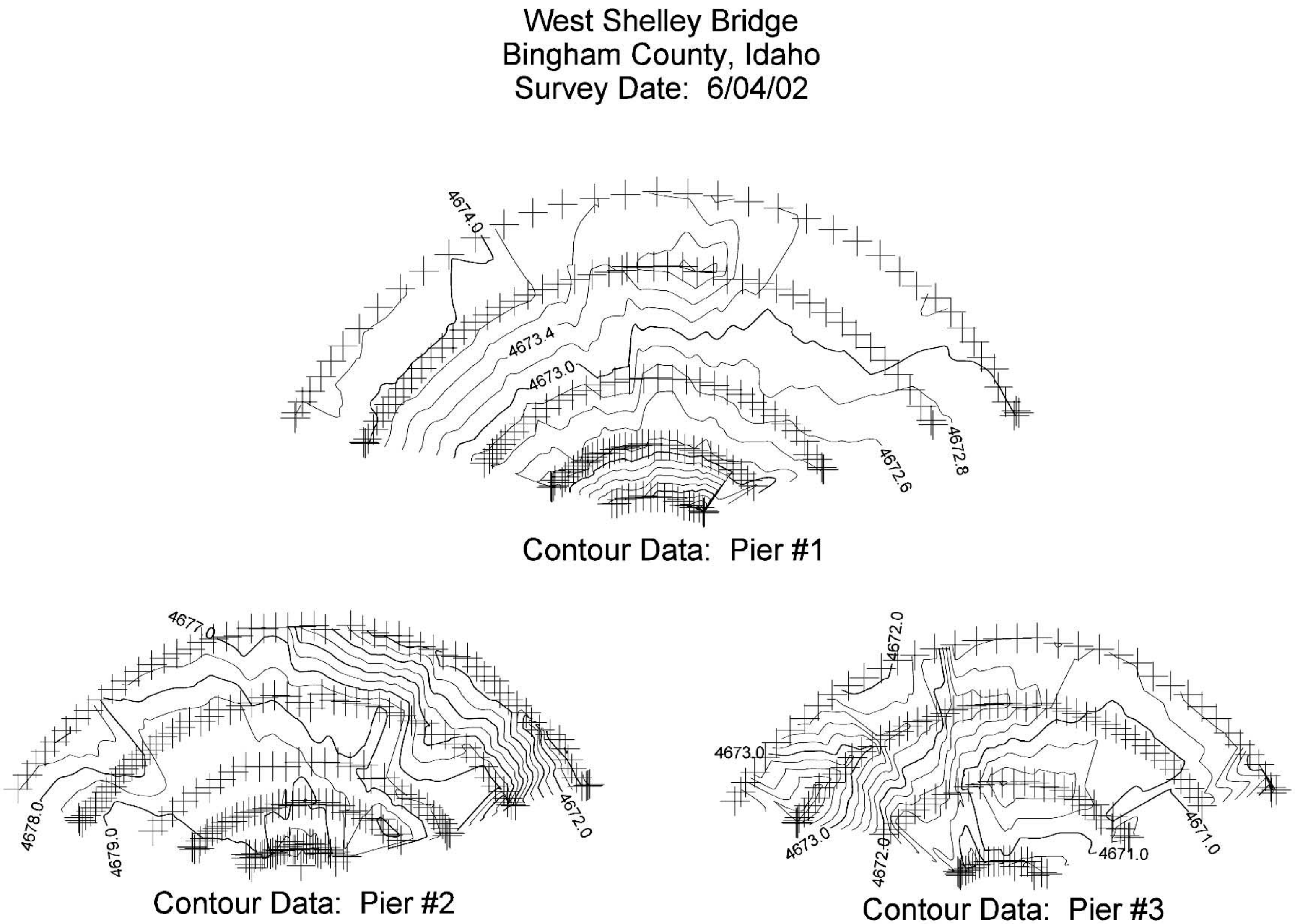


Figure B41c. West Shelley pier results.

Abbreviations used without definitions in TRB publications:

AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety 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
NTSB	National Transportation Safety Board
SAE	Society of Automotive Engineers
TCRP	Transit Cooperative Research Program
TRB	Transportation Research Board
U.S.DOT	United States Department of Transportation