Use of Fathometers and Electrical-Conductivity Probes to Monitor Riverbed Scour at Bridge Piers

By D.C. Hayes and F.E. Drummond

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FIGURES

TABLE

CONVERSION FACTORS AND ABBREVATIONS

Multiply	By	To obtain
inch (in.)	25.4	millimeter (mm)
millimeter (mm)	0.03937	inch (in.)
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
foot per second (ft/s)	0.3048	meter per second
cubic foot per second (ft^3/s)	0.02832	cubic meter per second

Water temperature expressed in degrees Fahrenheit (°F) can be converted to degrees Celsius (°C) by the following equation:

$$°C = 0.56\ (°F - 32)$$

Use of Fathometers and Electrical-Conductivity Probes to Monitor Riverbed Scour at Bridge Piers

By Donald C. Hayes and Fitzgerald E. Drummond

Abstract

Scour is the lowering of a river channel by erosion and is the leading cause of bridge failure. Monitoring the riverbed elevation at a bridge where scour is a potential problem provides for public safety as a temporary countermeasure until structural improvements can be implemented, or in some situations, as a permanent countermeasure. Monitoring of the riverbed elevation accurately during high flows using existing streamflow measuring equipment is difficult because of strong currents and large amounts of debris. Two systems, a fathometer system and an electrical-conductivity probe system, were developed to monitor riverbed elevations at bridge piers. The scour-monitoring systems consisted of a sensor (fathometer or electrical-conductivity probe), power supply, data logger, relay, and system program.

The fathometer system was installed and tested at a bridge over the Leipsic River at Leipsic, Delaware, and at a bridge over Sinepuxent Bay near Ocean City, Maryland. The fathometer calculates the distance from a transducer to the riverbed by measuring the two-way travel time of a reflected, acoustic wave.

Field data collected indicate that fathometers can be used to identify and monitor the riverbed elevation if post processing of the data and trends in the data are used to determine the riverbed location in relation to the transducer. The accuracy of the system is approximately the same as the resolution of the fathometer. Signal scatter, caused by electronic or physical interference, can be a major source of error. During periods of interference, the distance from the transducer to the riverbed can be difficult to determine. Other problems found with the use of a fathometer are identifying the exact location of the reflected pulse, sequencing multiple fathometers or other electronic equipment to prevent electronic interference, and protecting the system from damage by debris.

An electrical-conductivity probe system was installed and tested at a bridge over the Pamunkey River near Hanover, Virginia. The approximate elevation of the riverbed is determined by comparing conductivities of the surface-water flow with conductivities of submerged bed material from equally spaced sensors mounted on the probe. The ratio of the voltage across a known resistor and the voltage across a variable resistor or sample was measured using a six-wire full-bridge circuit, and is proportional to the conductivity of the surrounding surface water or submerged bed material.

Field data indicate that an electrical-conductivity probe, as tested, has limited usefulness in identifying and monitoring the riverbed elevation during high flows. As the discharge increases, the concentration of sediment in the surface-water flow increases, especially near the riverbed. Voltage ratios, measured at the sensors in the surface-water flow could not be distinguished from voltage ratios measured at the shallowest sensor in the submerged bed material. However, the voltage ratios of the sensors in the surface-water flow and the shallowest sensor in the submerged bed material vary much more than the voltage ratios of sensors located deeper in the submerged bed material. Other problems found with the use of an electrical-conductivity probe are a gradual decrease in readings with time, possibly because of corrosion of the electrodes or changes in moisture of the wooden probe, and vulnerability of the system to damage by debris.

INTRODUCTION

Many bridges are built over rivers that change over time as a result of natural causes and the effects of human activities. Scour is an active processes of the river system and is defined as the lowering of a river channel by erosion. Scour is a primary concern in bridge design in alluvial channels, and limited knowledge of the hydraulics related to scour can result in inadequate bridge design for current or future riverbed conditions.

Streambed scour is the leading cause of bridge damage and failure (U.S. Federal Highway Administration, 1990). Highway departments periodically inspect bridges for damage (existing or potential) that results from scour. When a scour problem is detected, highway departments need a method to monitor the streambed until scour countermeasures can be implemented. Also, a monitor system can be used to identify if a potentially dangerous bridge-scour situation is occurring.

In 1988, the U.S. Geological Survey (USGS) began a study in cooperation with the Delaware Department of Transportation, the Maryland Department of Transportation, and the Virginia Department of Transportation to improve knowledge of hydraulics and scour at bridges as part of a National program to improve bridge design and safety. As part of this study, scour-monitoring systems were developed and evaluated to monitor riverbed elevations at bridge piers.

Purpose and Scope

This report describes two methods to monitor riverbed elevations at bridge piers. Semiportable scour-monitoring systems that use a fathometer or an electrical-conductivity probe to monitor riverbed elevation were developed and evaluated. Study sites are described, theory of operation for each system is discussed, and design methods are evaluated.

Description of Study Sites

Three sites were used to develop and test scour-monitoring systems (fig. 1 and table 1), bridge 2–12B on Delaware State highway 9 over the Leipsic River (U.S. Geological Survey surface-water gaging station 01483530), bridge 23018 on Maryland State highway 611 over Sinepuxent Bay (U.S. Geological Survey surface-water gaging station 01484727), and bridge 6918 on Virginia State highway 614 over the Pamunkey River (U.S. Geological Survey surface-water gaging station 01673000).

Bridge 2–12B over the Leipsic River consists of 12 piers (4 of which are located within or near the main channel of the river) that are constructed from16-in. square, concrete piles. The Leipsic River is an estuary at the bridge site and marshes are found along both banks. Much of the tidal area is covered with marsh mud, except where stream velocities are high, such as around the piers. Marsh mud is removed and an indurated sand, gravel, or clay is exposed in the channel where the stream velocities are high.

Bridge 23018 over the Sinepuxent Bay consists of 30 piers (all located within the main channel of the bay) that are constructed from 18-in. round, concrete piles with steel casings. The Sinepuxent Bay is a tidal bay that connects the northern part of the Chincoteague Bay with the Atlantic Ocean and the southern part of the Assawoman Bay. The bed material in the area primarily is a loose, medium sand. Mud and a grassy vegetation cover the bottom of the bay where depths are shallow and stream velocities are low.

Bridge 6918 over the Pamunkey River consists of three piers. The piers are constructed from a solid, tapered webb, 4 ft wide at the base and 3 ft wide at the top. The webb is mounted on piles and is aligned with the flow at most stages. The river is not tidal at this location. The bed material is loose, medium-to-coarse sand.

Related Studies

Several cooperative studies between the USGS and different State Departments of Transportation and Federal agencies are ongoing (1994). Butch (1991) has instrumented a pier in New York State with a fathometer system. Crumrine (1992) is using fathometers to monitor riverbed scour before and during construction of a bridge over the Alsea River Estuary at Waldport, Oreg. In Kentucky, the USGS, in cooperation with the U.S. Army Corps of Engineers, is instrumenting a 3-mi reach of the Ohio River with fathometers to monitor sediment deposition during dam construction. Fathometer systems also are being used in USGS cooperative programs in North Carolina, Florida, Alabama, and South Dakota.

The Virginia Department of Transportation Highway Research Council has instrumented a pier known to have scour problems with a series of fathometers that are accessed by a portable cellular telephone. Dr. Ronald Erchul at Virginia Military Institute has designed and successfully operated a electrical-conductivity probe in the laboratory. The National Cooperative Highway Research Program has funded studies on fathometer systems and several types of electrical probes.

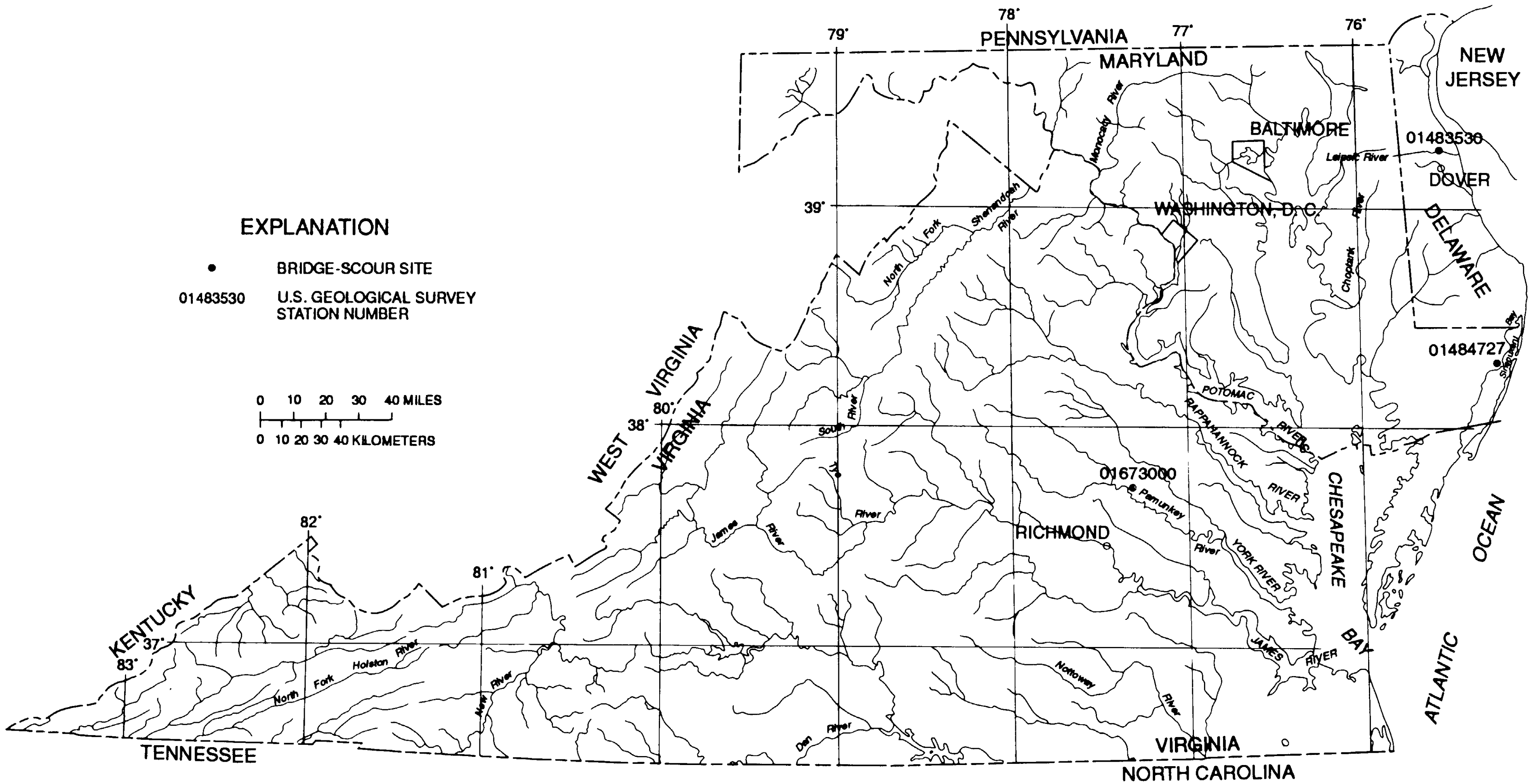

Figure 1. Locations of bridge-scour study sites in Delaware, Maryland, and Virginia.

Table 1. Location, equipment, and bed-material size of bridge-scour study sites in Delaware, Maryland, and Virginia

[Latitude and longitude are reported in degrees, minutes, seconds; DE, Delaware State Highway; MD, Maryland State Highway; VA, Virginia State Highway; F, site instrumented with a fathometer; C, site instrumented with an electrical-conductivity probe; D50, median grain size of bed material at pier; and mm, millimeter]

Station number	Name	Latitude	Longitude	Bridge number	Road	Equipment	Flow conditions	D50 (mm)
01483530	Leipsic River at Leipsic, Del.	391444	0753105	2–12B	DE 9	F	Tidal	8.0
01484727	Sinepuxent Bay near Ocean City, Md.	381441	0750923	23018	MD 611	F	Tidal	.47
01673000	Pamunkey River near Hanover, Va.	374603	0771957	6918	VA 614	C	Non-tidal	.43

Acknowledgments

Personnel from the Departments of Transportation in Delaware, Maryland, and Virginia are gratefully acknowledged for their support of this project and their assistance in providing site recommendations, bridge plans, and technical advice. Milo Crumrine, from the USGS in Portland, Oreg., is gratefully acknowledged for his assistance in installing and programming the fathometer system used for this study.

FATHOMETER METHOD OF MONITORING SCOUR

The fathometer transmits a discrete, acoustic wave from a transducer through a column of water and measures the two-way travel time of the reflected wave. The distance to any object that reflects the acoustic wave is computed by use of a predetermined speed of sound through water. The distance calculated is the distance from the face of the transducer to the acoustically reflective object.

The fathometer consists of a signal processor and transducer. The signal processor controls the electrical signal sent to the transducer and interprets the return signal. The transducer converts the electrical signal sent by the signal processor into a discrete, acoustic wave or pulse, and transmits the pulse through the column of water. The transducer receives the reflected pulse, and converts the pulse back into an electrical signal that is processed by the signal processor.

The riverbed elevation is monitored at a desired location, such as the face of a pier or footer, by mounting the transducer at a fixed location near the area of interest and directing the pulse into the center of the area. As the riverbed scours or fills, the distance measured by the fathometer will vary accordingly. The elevation of the riverbed can be computed if the elevation of the transducer and the angle that the pulse is transmitted are known. Several locations can be monitored simultaneously by installing multiple transducers and directing the pulse from each transducer at a different riverbed location.

System Design and Operation

The speed of sound through water varies with the density of the water, which is affected by temperature, salinity, and sediment. Some fathometers can be calibrated for different water densities; however, most low-cost commercial fathometers cannot be calibrated by the user. The associated distance error is usually small. For example, the speed of sound through water at 50 °F is 4,758 ft/s, and the speed of sound through water at 70 °F is 4,879 ft/s. If the two-way travel time of the pulse is 0.0040 seconds, the distances calculated are 9.52 ft and 9.76 ft, respectively. The difference between the distances calculated is 0.24 ft, which is less than the accuracy of many commercial fathometers. The fathometer used for this study was not corrected for different water densities.

The resolution, which is the ability to separate objects or accurately measure the distance to the riverbed, is determined by the length of the acoustic pulse. Short pulse lengths have good object definition but are limited to short ranges, whereas long pulse lengths have poor object definition but provide for long ranges. The fathometer used in this study has a resolution of 1 ft and a maximum range of 700 ft.

The acoustic pulse transmitted by the transducer expands in a manner similar to the light emitted from a flashlight. The farther the pulse travels before being reflected, the larger the area that is covered. Narrow-angle transducers (8°) will cover approximately a 14-ft-diameter circle at a 100 ft distance, and wide-angle transducers (20°) will cover approximately a 36-ft-diameter circle at a 100 ft distance. Narrow-angle transducers concentrate more energy to a small area and, therefore, have longer ranges than the wide-angle transducers. Commercial fathometers are normally sold with wide-angle transducers because they can cover a large area in shallow-depth and medium-depth water. The narrow-angle transducer was preferred for this study because the energy is concentrated to a small area. However, only wide-angle transducers were available with the selected unit.

Fathometers are subject to signal scatter caused by electronic or physical interference. Electronic interference is produced when the unit interprets electronic noise, either from outside the unit or from the unit itself, as actual data. Examples of equipment that can create electronic noise and cause electronic interference include boat motors, radio transmissions, and power lines. When electronic interference occurs, depth values can be random and unreliable. Physical interference is produced when an obstruction in the water column other than the intended object reflects or absorbs the acoustic pulse. Examples of obstructions that can cause physical interference include seaweed or grasses, air bubbles, and suspended sediment. When physical interference occurs, there can be either no depth determination or the depth values will be less than the actual values (Crumrine, 1992). Multiple reflections can occur when the pulse is reflected off the riverbed to the water surface and then back again to the riverbed. Several multiple reflections can be observed if the signal is strong enough. When the transducer is located near the water surface, the depth of the multiple reflections will approximate multiples of the actual riverbed depth.

The fathometer was mounted at a fixed site to monitor the same location on the riverbed. The two-way travel time of the acoustic pulse was measured by the fathometer and transferred to the data logger to be filtered, converted into distance, and stored. Sites were instrumented so that the transducer would be below the water surface most of the time, directly above the area of interest, and perpendicular to the riverbed. The transducer was placed inside the structural framework or between piles to protect it from ice and debris, and was mounted on a removable arm or near the water surface so that it could be cleaned without diving. The signal processor was mounted close to the transducer, but above expected high water to protect it from damage by debris.

The scour-monitoring system consisted of a data logger, data-storage module, relay, fathometer, stage recorder, batteries, and solar panel. The data logger stored the program, operated the system, and stored the data. The normal sequence for sampling the data was for the program to instruct the data logger to open a relay that turned on the fathometer. The fathometer remained on for 1 minute to stabilize the signal prior to any measurements being recorded. Two-way travel times were measured by the fathometer and transferred to the data logger. Values were checked for reasonableness (travel time had to be greater than the travel time associated with a distance of 4 ft but less than the travel time associated with a distance of 60 ft), converted into distance, and transferred to and stored in the data-storage module. The fathometer was then turned off and the stage data were read and stored in the data-storage module.

Two measuring procedures were used to collect and process the fathometer data. The initial measuring procedure used one temporary register to process the data and one final register to store the data at each time interval. The reading consisted of measuring the depth five times. Each measurement was checked for reasonableness in which the measurement had to be greater than 4 ft and less than 60 ft. The measurement was stored in the temporary register if the criteria were met. Each additional measurement that met the criteria overwrote the previous measurement. After the fifth measurement was processed, the content of the temporary register was copied to the final register and saved as the reading for that time interval. Five measurements were collected to ensure that one measurement met the criteria, but only the last measurement meeting the criteria was stored. A total of five measurements was collected at each time interval that resulted in one stored data value.

A refined measuring procedure was later developed in which five temporary registers were used to process the fathometer data, and five final registers were used to store the data at each time interval. Five measurements were collected, checked to meet the above criteria, and processed through the temporary registers for each final register. A total of 25 measurements was collected at each time interval that resulted in 5 measurements stored as data values. The median value of the five stored values was used as the final data value.

The equipment was initially installed on bridge 2-12B over the Leipsic River at Leipsic, Del. (fig. 2). The transducer was mounted approximately 1.5 ft upstream from the upstream pile of pier C3. The bottom of the transducer was located below the low-tide water-surface

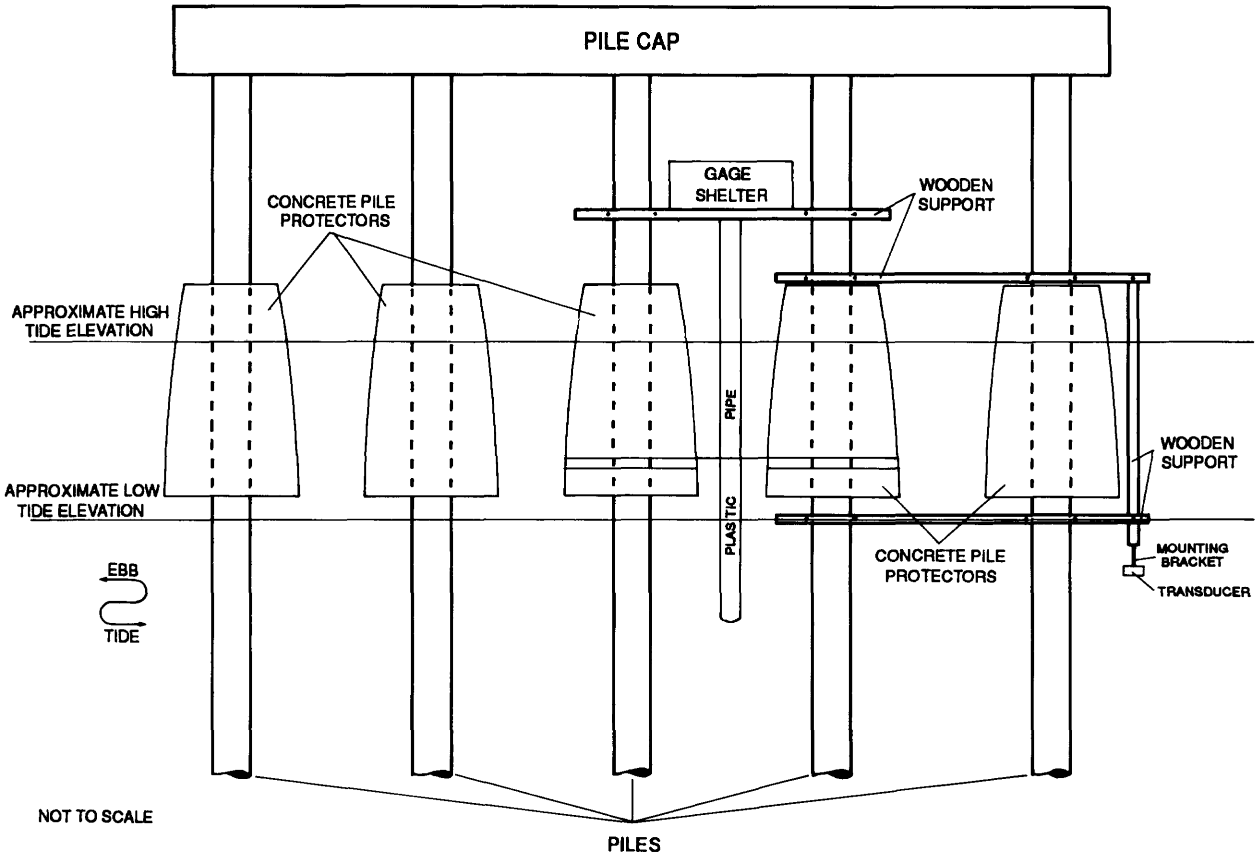

Figure 2. Schematic diagram of pier C3 and gage at bridge 2-12B over the Leipsic River at Leipsic, Delaware.

elevation. The signal processor, relay, stage recorder, data logger, and batteries were mounted in the gage shelter under the bridge deck and above any expected high water. Threaded galvanized steel rods were used to clamp wooden posts to the bridge piles. The gage shelter and transducer structure were bolted to the wooden post, and the solar panel was clamped to the bridge rail on the bridge deck. This type of gage structure was used to prevent damage to the bridge structure from the gage installation. The initial sampling procedure was used to collect the data. The system was operated from October 4, 1990, through December 4, 1990, when it was removed to prevent ice damage. Depth readings were collected every 15 minutes.

The system was reinstalled at the Leipsic River site and operated from July 13, 1992, through September 6, 1992. The transducer was mounted at a slightly higher elevation during the second installation because of structural modifications to the transducer mount. The refined sampling procedure was used in an attempt to reduce scatter and better define the riverbed location. Depth readings were collected every 15 minutes. The equipment was removed from the Leipsic site because the riverbed around the piles was extremely hard with only minor movement of any bed material.

The equipment was installed on bridge 23018 on Maryland highway 611 over Sinepuxent Bay near Ocean City, Md. (fig. 3). The Sinepuxent Bay site was selected because it had previous scour problems and a mobile, sandy riverbed. A similar system was used to clamp wooden posts to the bridge piles to prevent damage to the bridge structure. The gage shelter and transducer structure were mounted to the wooden post. The refined sampling procedure was used at the Sinepuxent Bay site. The system was operated from August 20, 1992, through May 24, 1993. Depth readings were collected every 15 minutes.

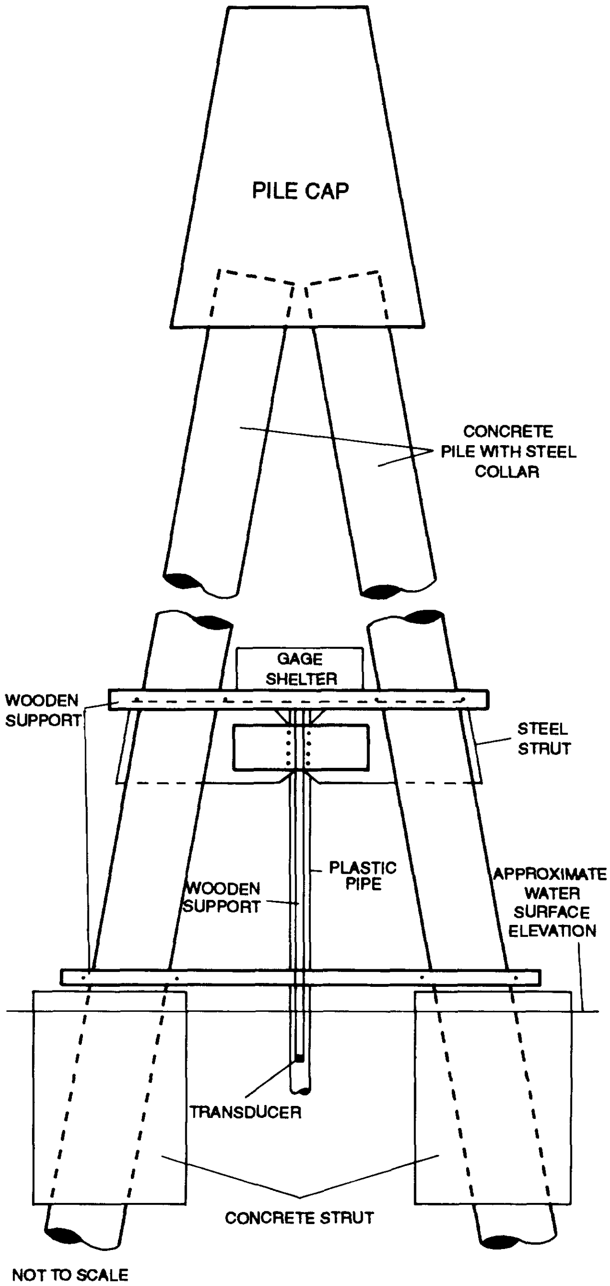

Figure 3. Schematic diagram of pier and gage at bridge 23018 over Sinepuxent Bay near Ocean City, Maryland.

During each installation and periodically during the gage operation, soundings were collected with a weighted line to verify the depth readings from the fathometer.

Analysis and Results

Field data collected indicate that the fathometer can be used to identify and monitor the riverbed elevation if post processing of the data and trends in the data are used to determine the riverbed location in relation to the transducer. Problems associated with the fathometer are signal scatter, determining the exact location of the reflected pulse, sequencing additional fathometers or other electrical equipment, and protecting the system from damage by debris.

The data collected at the Leipsic River site from October 9, 1990, through October 29, 1990, using the initial sampling procedure are shown in figure 4. The sample data are characteristic of the data collected at the site from October 4, 1990, through December 4, 1990. Three groups of data are evident in figure 4. One group of data is a band of depth measurements that tends to define the riverbed location. These data are concentrated between 11.5 and 12.5 ft below the transducer. This approximate 1 ft variation in values defining the riverbed location is consistent with the 1-ft resolution of the fathometer. Other possible sources for the variation within the 11.5- and 12.5-ft depth measurements are pulse reflections from an uneven bottom, and electrical or physical interference. Another group of data are the depth measurements that are less than the depth to the riverbed or less than 11.5 ft below the transducer. These data indicate the existence of some type of physical interference, such as bubbles or grasses in the surface-water flow between the transducer and riverbed. Physical interference causes the acoustic pulse to be reflected before reaching the riverbed, and the distance calculated is less than the actual distance from the transducer to the riverbed. The final group of data are the depth measurements that are greater than the depth to the riverbed or greater than 12.5 ft below the transducer. The data values are not multiples of the measured depths; therefore, the values do not represent the travel time of pulses reflected from the water surface. The large data values could be caused by electronic interference, however, or by reflections from combinations of objects, such as the bridge structure, the riverbed, and the water surface. Because of the extremely hard bottom exposed to the surface-water flow around the piers, only slight changes in the riverbed elevation are apparent during the period of record. Soundings confirmed the location of the riverbed between 11.5 and 12.5 ft below the transducer.

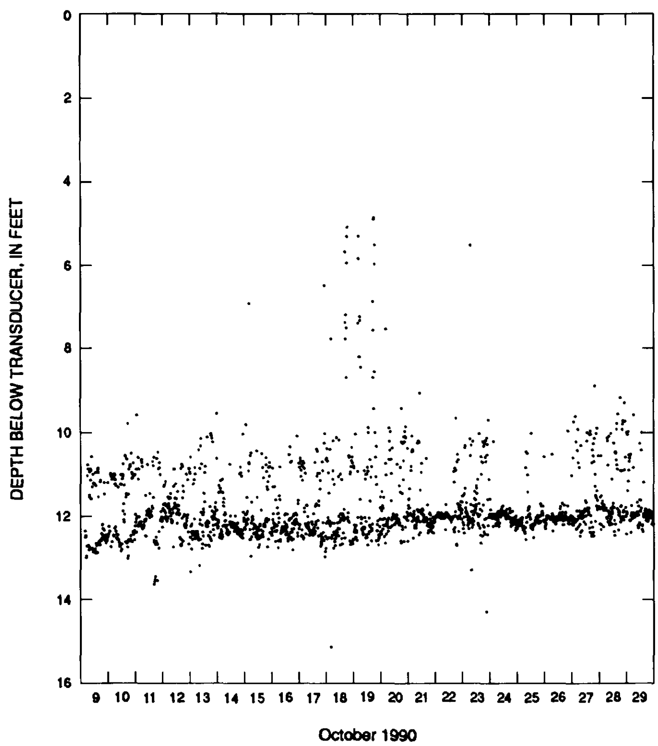

Figure 4. Fathometer data for the Leipsic River at Leipsic, Delaware, October 9, 1990, through October 29, 1990.

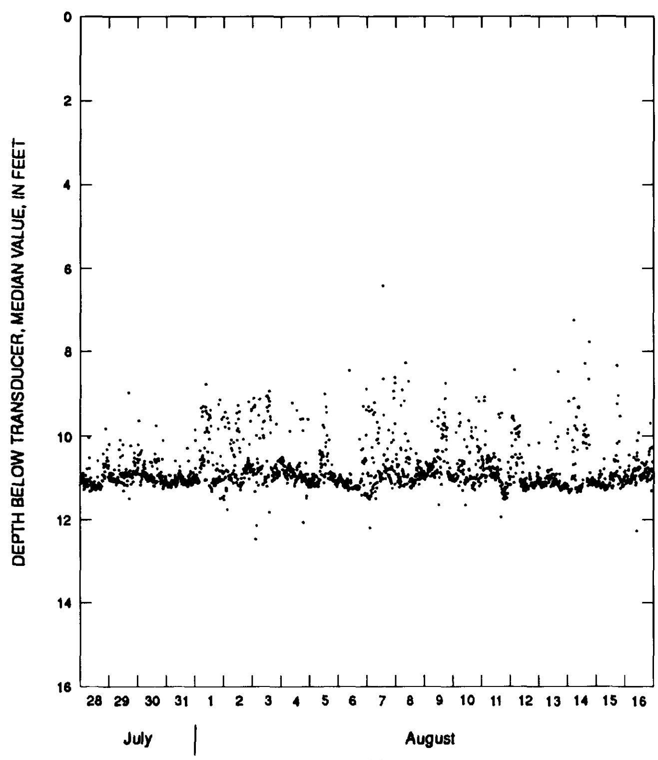

Figure 5. Fathometer data for the Leipsic River at Leipsic, Delaware, July 28, 1992, through August 16, 1992.

The data collected at the Leipsic River site from July 28, 1992, through August 16, 1992, using the refined sampling procedure are shown in figure 5. The sample data are characteristic of the data collected at the site from July 13, 1992, through September 6, 1992. Again, three groups of data are evident. One group of data is a band of depth measurements that tends to define the riverbed location. These data are concentrated between 10.8 and 11.3 ft below the transducer. The variation in values (0.5 ft) defining the riverbed is approximately half the variation in values (1.0 ft) observed in the initial sampling procedure and is less than the 1-ft resolution of the fathometer. Another group of data are the depth measurements that are less than the depth to the riverbed or less than 10.8 ft below the transducer. These data also indicate the existence of some type of physical interference. The final group of data are the depth measurements that are greater than the depth to the riverbed or greater than 11.3 ft below the transducer. The density of data in this group is less than the density of data in the same group in figure 4, which indicates that much of the electronic interference or reflection from the structure could have been filtered by the post processing of the data. The small variation in values between readings that define the riverbed and few individual readings greater than the distance to the riverbed indicate that the post processing can reduce much of the interference. Because of the extremely hard bottom, no significant change in elevation of the riverbed was apparent during the period of record. Soundings confirmed the location of the riverbed between 10.8 and 11.3 ft below the transducer.

The data collected at the Sinepuxent Bay site from February 9, 1993, through March 5, 1993, using the refined sampling procedure are shown in figure 6. The sample data are characteristic of the data collected at the site from August 20, 1992, through May 24, 1993. Again, three groups of data are evident. One group of data is a band of depth measurements that tends to define the riverbed location. These measurements are concentrated between 8.5 and 9.0 ft below the transducer. The variation in values (0.5 ft) defining the riverbed is approximately half the variation in values (1.0 ft) observed in the initial sampling procedure used at the Leipsic River site, and similar to the variation in values (0.5 ft) observed in the refined sampling procedure used at the Leipsic River site. Another group of data are the depth measurements

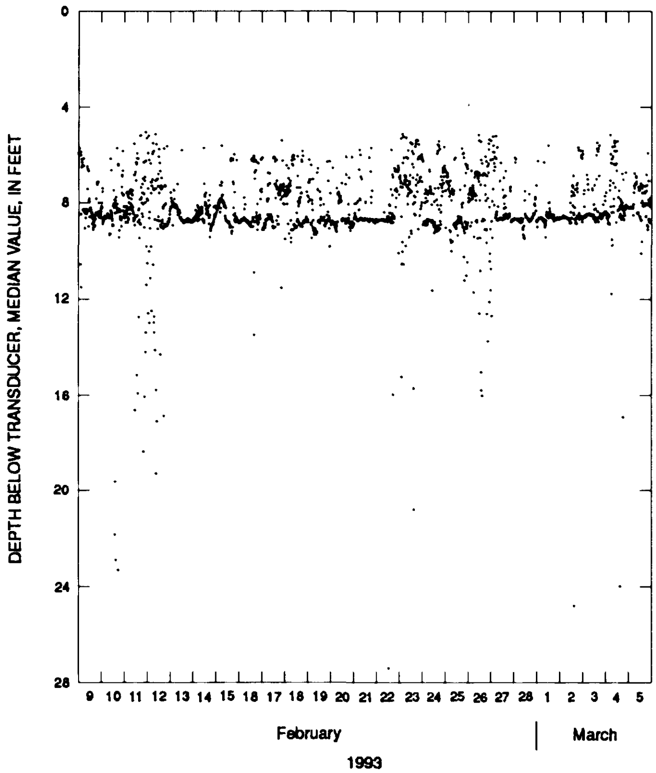

Figure 6. Fathometer data for Sinepuxent Bay near Ocean City, Maryland, February 9, 1993, through March 5, 1993.

that are less than the depth to the riverbed or less than 8.5 ft depth below the transducer. The density of data in this group is similar to the density of data in the same group at the Leipsic River site, using both the initial sampling procedure and refined sampling procedure; therefore, the physical interference may be similar at both sites. The final group of data are the depth measurements that are greater than the depth to the riverbed or greater than 9.0 ft below the transducer. The density of the data in this group is greater than the density of the data in the same group at the Leipsic River site, using both the initial sampling procedure or the refined sampling procedure. These comparisons indicate that much of the electronic interference or reflection from the structure is not being filtered by the post processing of the data, or that there is additional interference. Soundings confirmed the location of the riverbed between 8.5 and 9.0 ft below the transducer; however, there appears to be slight bed movement shown in figure 6 on February 14, 1993, where the readings change from approximately 8.0 ft below the transducer to 9.0 ft below the transducer. No physical measurements were made to confirm or contradict the bed movement.

During two intervals February 11–13, 1993, and February 23–27, 1993, the fathometer could have been influenced by electronic interference (fig. 6). The location of the riverbed could not be accurately determined during these periods. The data appear to be random and range from 4 ft below the transducer to 24 ft below the transducer. Similar problems were encountered at both sites during all three test periods. The duration of the problem was from several hours to several days. Attempts to determine the cause of the problem were unsuccessful. All connections, batteries, relays, and programming were checked. The probable causes of the problem are the quality of the system and the field conditions in which the system was used, or possible discrepancies in the interface to the fathometer, which allowed the data to be read by the data logger. The data indicate minor changes in elevation of the riverbed during the period of record with the maximum changes in riverbed elevation of 1.5 ft. The elevation changes appeared to be bed forms moving through the area.

Field data collected at the two sites indicate that fathometers can be used to identify and monitor the riverbed elevation; however, individual readings cannot be used to identify or monitor the riverbed elevation. Signal scatter, possibly associated with electronic or physical interference, necessitates the use of multiple-depth measurements, post processing, and analysis of trends in the data to determine the riverbed location. Much of the error in the measurements is caused by the location of the transducer and quality of the system. The transducer needs to be placed close to the riverbed to reduce the physical interference, but the transducer also needs to be accessible for cleaning. In addition, the transducer needs to be mounted below the depth where surface debris could destroy the system and above the depth where debris rolling along the bottom could destroy the system. The system resolution needs to be able to define the riverbed elevation to the accuracy required by the highway department, and the system needs to be cost effective because it will be exposed to a harsh environment. Less than high quality fathometer systems also require multiple readings and post processing to define the riverbed elevation. Multiple fathometers or electronic shielding can reduce the need for post processing of the data, and small cone angles can reduce the physical interference.

Other problems associated with the fathometer are that the exact location of the reflected pulse is not easily located, and additional fathometers or other electronic equipment can interfere with the signal. Seldom is the riverbed flat around bridge piers; therefore, when the fathometer pulse is directed toward the area of interest, determining what part of the reflective area is returning the signal that is being processed can be difficult. In addition, multiple fathometers need to operate on different frequencies, or the sampling must be sequenced by time, to eliminate interference between units. Also, if other electronic equipment is used, such as velocity meters, the other equipment must also be sequenced to prevent electronic interference.

ELECTRICAL-CONDUCTIVITY PROBE METHOD OF MONITORING SCOUR

Electrical conductance or conductivity is the ability of a material to conduct an electric current (Hem, 1985, p. 66). Fluids conduct electrical current from ion to ion, while most solids conduct electrical current from atom to atom. Both the surface water and the riverbed will conduct electricity.

Dissolved ions allow water to conduct electricity; therefore, pure water has a very low electrical conductivity. As the concentration of ions increases, the electrical conductivity of the water increases. Natural surface water contain different types and amounts of dissolved solids, suspended sediment, and dissolved ions, which have different effects on the electrical conductivity of water. The electrical conductivity of the surface water also varies according to its chemical characteristics.

The electrical conductivity of the bed material depends upon the composition of the parent material. In alluvial channels, the riverbed can consist of particles from several types of parent material, each of which can have different electrical conductivities. When the riverbed is submerged, the water below the riverbed will contain different types and amounts of dissolved solids and dissolved ions. The electrical conductivity of the riverbed varies according to the physical and chemical characteristics of the bed material and water.

The riverbed elevation is monitored at a desired location by using an electrical-conductivity probe to measure the conductivity of the submerged bed material and the surface-water flow at selected elevations. An electrical-conductivity probe consists of multiple conductivity-measuring sensors spaced at equal increments along a rod. The rod is driven or jetted vertically into the riverbed at a location where the elevation of the riverbed is to be monitored, such as the face of a pier footer. The majority of the sensors are placed below the riverbed, but at least one sensor remains above the riverbed in the surface-water flow. Sensors located above the riverbed measure the conductivity of the surface-water flow. The sensors located below the riverbed measure the conductivity of the bed material and water. Additional sensors will be exposed to the surface-water flow if the riverbed scours at the probe. These sensors then measure the conductivity of the surface-water flow rather than the conductivity of the submerged bed material. The elevation of the riverbed can be estimated if the electrical conductivities of the riverbed and surface water differ sufficiently. Changes in the riverbed elevation are estimated by comparing historical riverbed and surface-water conductivities with current conductivity readings at each sensor.

System Design and Operation

Either conductivity or resistivity can be measured to estimate the riverbed elevation. Several methods to measure conductivity or resistivity are available, such as a four-electrode conductivity sensor, a two-electrode resistivity sensor, and the use of ac (alternating current) or dc (direct current). Multiple programming options are available with each method.

Conductivity is the inverse of resistivity; thus, by measuring either conductivity or resistivity, the other can be determined. Electrical conductivity is determined by passing electrical current through two electrodes and measuring the voltage drop across a separate pair of electrodes. The voltage drop is measured at the end of the electrodes or load cell; therefore, differences between the electrodes are not a large source of error. Convention dictates that a resistivity measurement passes a fixed voltage through two electrodes and the voltage drop across the electrodes is measured. Resistivity is measured by passing electrical current through, and sampling from, the same electrodes; therefore, any differences between the electrodes, such as cable length, can cause a noticeable difference in the voltage reading (Campbell Scientific, Inc., 1986). In order to determine which method to use, a test was performed using sand and water collected at the test site. An uncalibrated, four-electrode conductivity sensor was immersed in sample water and submerged sand. The differences between the measured values were noted. The measured value was 50 percent higher in the sample water than in the submerged sand. An uncalibrated, two-electrode resistivity sensor also was immersed in the same sample water and submerged sand, and the differences between measured values were noted. The measured value was 20 percent lower in the sample water

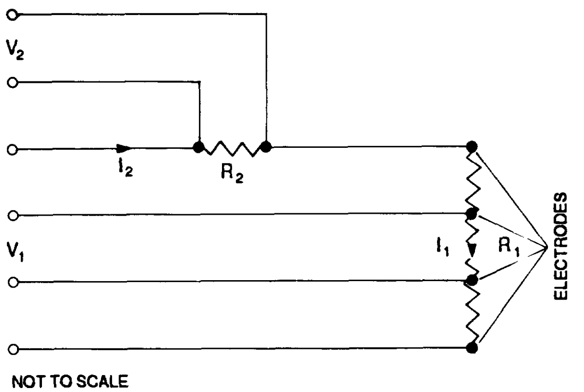

Figure 7. Schematic diagram of four-electrode conductivity probe.

than in the submerged sand. The sample water could be more easily differentiated from the submerged sand by using the four-electrode conductivity sensor than by using the two-electrode resistivity sensor. In addition, the variation between multiple readings of resistivity was greater than the variation between multiple readings of conductivity. The four-electrode conductivity measurement was selected because of a greater difference in readings between the submerged sand and surface-water flow than the two-electrode resistivity measurement and smaller difference between consecutive readings.

Conductivity can be measured using either ac or dc; however, several problems are associated with using dc. Because dc flows in only one direction, the ion flow is unidirectional, and ions plate onto the electrodes. Plating causes changes in the data values as a function of time and can cause acute malfunction. In addition, polarization can occur in which the electrodes develop a charged field that repels the desired current flow. The direction of ac flow switches continually and, thus, does not cause plating or polarization; therefore, ac was selected as the best available method.

Three programs for measuring conductivity were available with the data logger, a differential voltage, a voltage ratio for a four-wire full-bridge circuit, and a voltage ratio for a six-wire full-bridge circuit. The programs for the differential voltage and four-wire full-bridge circuit were not used because both measure the voltage at the power source, as in the resistivity measurement, and not at the load cell. The program for the six-wire full-bridge circuit with excitation compensation program (Campbell Scientific, Inc., 1986), measures the voltage drop across both a fixed resistance and a variable resistance. Excitation compensation refers to the measurement of voltage across both resistances at once. The six-wire full-bridge circuit program was chosen because it uses ac and measures voltage at the load cell and not at the power supply.

A schematic diagram of the four-electrode sensor used to measure conductivity is illustrated in figure 7. The electrical conductivity of the sampled material, K, can be determined by using the following equation:

$$K = \frac{C_1 I_1}{R_2 I_2} \times \frac{V_2}{V_1} \qquad (1)$$

where C_1 is a constant associated with the particular conductivity sensor, I_1 is the current through the sampled material at the electrodes, R_2 is the series resistor of known value, I_2 is the current through R_2 and also the total current through the sampled material, V_2 is the voltage drop across R_2 caused by I_2, and V_1 is the voltage drop across the sampled material caused by I_1. If the geometry of the sensor does not change, C_1I_1/R_2I_2 is a constant that can be determined by measuring the voltage ratio while the sensor is immersed in a solution of known conductivity (J.H. Ficken, U.S. Geological Survey, written commun., 1991).

The data logger was used to store the sampling program, execute the program, and store the data. The program written for the electrical-conductivity probe used a self-contained function of the data logger to compute the ratio of the voltage across the variable resistor or sample (V_1) and the voltage across the fixed resistor (V_2) in a six-wire full-bridge circuit (Campbell Scientific, Inc., 1986).

Because the value C_1I_1/R_2I_2 is a constant for each sensor, only the values of the ratio V_2/V_1 at each sensor were compared.

Wood was selected for construction of the electrical-conductivity probe because it supplied adequate room for the electrodes and wires, simplified manufacturing of the probe, and had sufficient strength to withstand the forces of driving or jetting. Standard 2 by 4 in. White Spruce lumber was used for the mounting plate and back plate (fig. 8). Each sensor consisted of four electrodes made from no. 10, 3/4-in. round-head brass wood screws. A total of four sensors were mounted on the probe at 4 in. intervals. The electrodes were connected to the data logger by 4-conductor, 22-gage, tinned, copper wire.

Above each sensor, a horizontal channel was cut into the wood to protect the wires and electrical connections from being damaged during installation. Filling this channel with non-conductive caulk further protected the wires and prevented short circuiting between the electrodes. In the center of each channel, a hole was drilled to carry the wires from the face of the mounting plate to a vertical channel cut on the back side of the mounting plate. The vertical channel was at the center of the probe when the mounting plate and cover plate were bolted together. Because driving was the preferred option for probe placement, the wires could not extend out of the top of the probe and were directed out of a hole in the cover plate. A flexible conduit (garden hose) was used to protect the wires from the probe to the rigid conduit at the pier face. The mounting plate and cover plate were bolted together with 4- by 3/16-in. machine bolts. The bolts were counter-sunk to prevent snagging during driving. The tip of the probe was cut on a 45° angle to provide a point for driving.

The conductivity probe was driven into the riverbed approximately 3 ft upstream from the center pile cap (fig. 9) at bridge 6918 in the Pamunkey River, near Hanover, Va. The probe could not be driven closer to the pile cap because of either buried debris or an upstream extension of the pile cap beneath the riverbed. Measurements at the test site show that the riverbed in front of the pile cap was approximately 1.8 ft below the top edge of the pile cap. The distance from the front edge of the pile cap to the pier was approximately 1.2 ft. The top sensor was mounted so that the top of the probe was at the same elevation as the top of the pile cap when the top sensor was approximately 2 in. above the riverbed. In such a position, the wires from the probe were protected between the probe and a rigid conduit attached to the pier. The probe was driven to a depth where the top of the riverbed was halfway between sensor 1 and sensor 2. Wire leads ran from the electrodes, through the probe and flexible conduit, into the rigid conduit and up the face of the pier. The wire leads exited the rigid conduit on top of the pier. The wires were spliced at this location to provide for a breakaway point and for assistance in the installation. The wires were placed under the bridge deck to the abutment and then in a shallow trench to the data logger

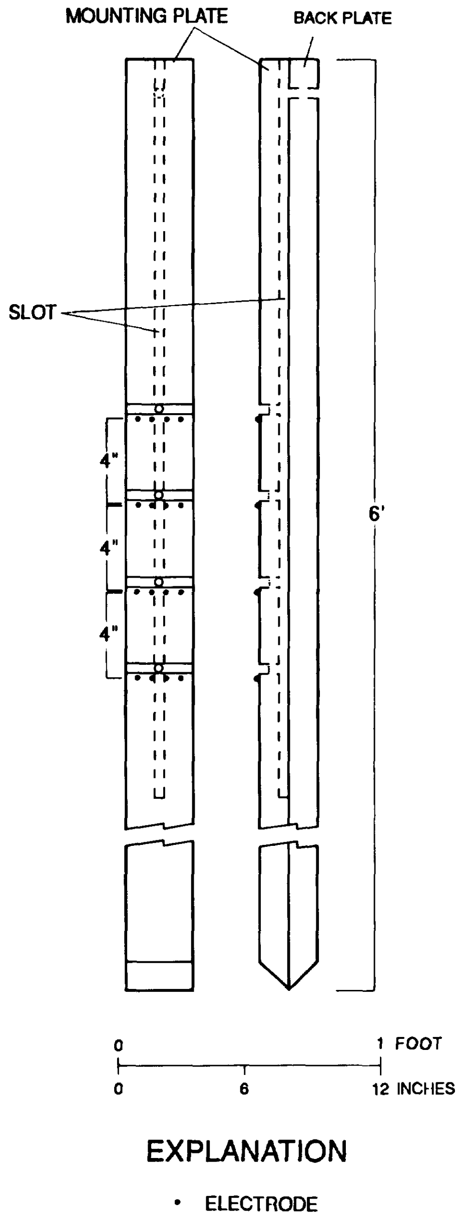

Figure 8. Diagram of conductivity probe.

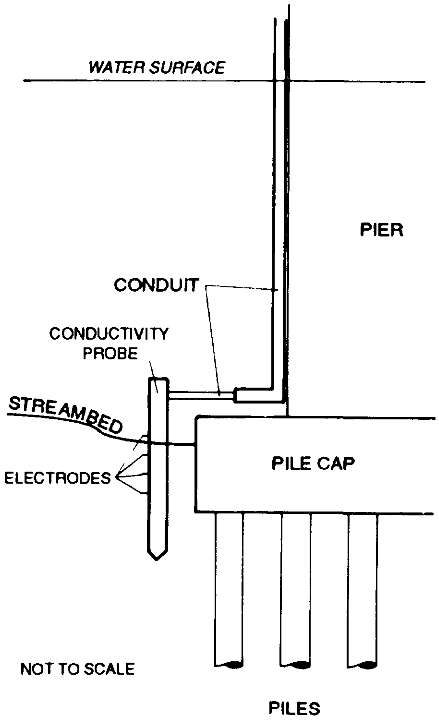

Figure 9. Schematic diagram of pier and conductivity probe at bridge 6918 over the Pamunkey River near Hanover, Virginia.

located in the gage house. The total length of wire from the data logger to each electrode was approximately 400 ft.

The electrical-conductivity probe was installed on June 27, 1991, and operated from June 28 through August 8, 1991. The individual sensors were read every hour with a 2 second delay between deactivation of one sensor and activation of the next sensor. The 2 second delay was necessary to prevent electrical interference between the sensors. The data logger could only measure three sensors; therefore, the top three sensors were monitored while the bottom sensor (sensor 4) was sampled only during site visits and for 3 days at the end of the field test.

Analysis and Results

Electrical-conductivity probe readings and discharge data collected at the Pamunkey River near Hanover, Va., are shown in figure 10. Sensor readings were normalized at the end of the test when the probe was removed. The proportional value of $C_1 l_1/R_2 l_2$ in eq. 1 was determined for each sensor. Readings were collected from each sensor after the probe was removed from the riverbed but was still submerged. Readings from sensors 1 and 3 were greater than 1 v/v (volt per volt) (1.290 and 1.898 v/v, respectively), and readings from sensors 2 and 4 were less than 1 v/v (0.556 and 0.654 v/v, respectively). Because the readings from the four sensors bounded 1.0, they were normalized to that number (K=1). All readings collected by sensor 1 were multiplied by 0.775, readings from sensor 2 were multiplied by 1.799, readings from sensor 3 were multiplied by 0.527, and readings from sensor 4 were multiplied by 1.529. Normalizing the probe readings eliminated variation because of manufacture of the sensors. The normalization values were determined at the end of the field test because initial laboratory testing indicated that the sensor readings could be affected either by corrosion of the electrodes or by the wood absorbing moisture, both of which could interfere with the measurement of voltage potential across the electrodes. Because equation 1 was solved for the assumed value of K=1, the sensor readings are proportional to the actual conductivities and are comparable.

Discharge data were collected during two small floods (peak discharges of 3,740 ft^3/s on July 8, and 2,750 ft^3/s on July 15) except for the period July 12-14, where probe data are missing because of a programming error. The bed elevation could not be physically monitored during the floods because of the depth of the water and velocity of the water at the probe. Divers observed the probe on July 18 and discovered that sensor 1 (the top sensor) had been covered with approximately 1 ft of loose, coarse sand and plant debris. On July 26, attempts to uncover the top sensor were unsuccessful; however, removal of most of the loose material that covered the probe caused the readings from sensors 1 and 2 to decrease.

The electrical-conductivity readings and discharge data indicate that the electrical-conductivity probe as tested has limited usefulness in identifying and monitoring the elevation of the riverbed during high flows (fig. 10). Problems associated with the electrical-conductivity probe are the inability to locate the riverbed from sensor readings, decreasing readings with time (possibly as a result of corrosion of the electrodes or from the wooden probe absorbing moisture), and protecting the system from damage by debris.

The plot of readings from sensor 1, which was initially located above the riverbed, shows that the conductivities measured in the surface-water flow increased as the discharge increased and decreased as the discharge

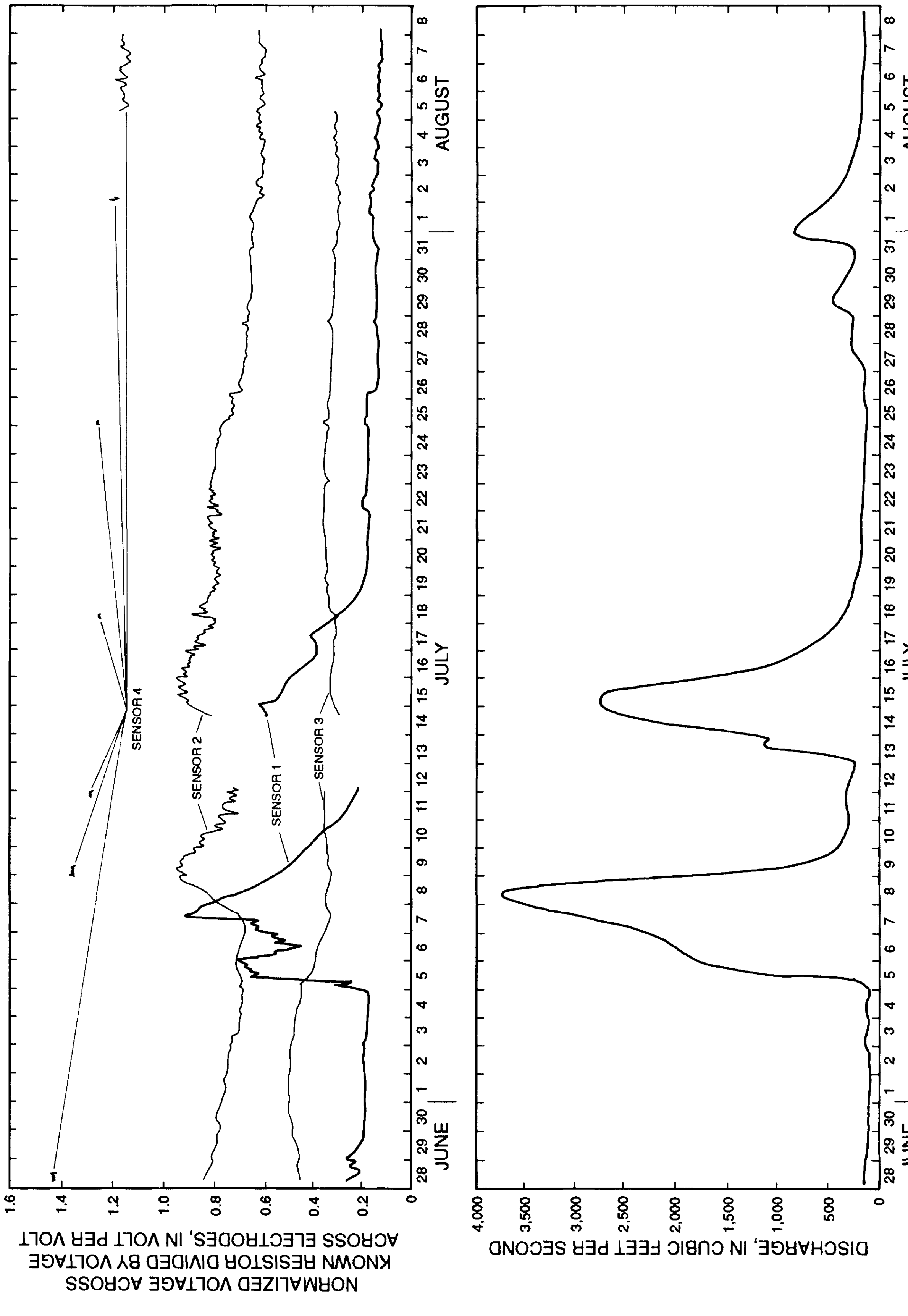

Figure 10. Electrical-conductivity probe readings and discharge for the Pamunkey River near Hanover, Virginia, June 28, 1991, through August 8, 1991.

decreased. This observation is consistent with the simultaneous increase and decrease of sediment concentration and discharge results by Guy (1970). Variations in consecutive readings indicate that the sensor was located where conductivities change rapidly. This observation indicates that the sensor was near the interface of the riverbed and surface-water flow where there can be movement of bed material. Inspections following the two floods showed that approximately 14 in. of loose sand and debris were deposited at the site of the probe, which covered sensor 1 with approximately 1 ft of bed material.

The plot of readings from sensor 2, which was installed 2 in. below the riverbed, shows that the sensor remained buried until the discharge exceeded 3,000 ft^3/s. Readings decreased with very little variation between consecutive readings until midday on July 7, at which time, the readings varied with discharge similar to readings from sensor 1. This variation indicates that the riverbed had scoured and uncovered sensor 2, or the interface of the riverbed and surface-water flow was near sensor 2. During the second flood, the readings from sensor 2 increased with discharge indicating that the sensor was above the riverbed; however, the readings did not decrease as the discharge decreased, indicating that the sensor was buried. Variation in the readings for sensor 2 during the floods indicates that the sensor was exposed, or the sensor was near the interface of the riverbed and surface-water flow where there could have been movement of the bed material.

The plot of readings from sensor 3 indicates that the sensor remained buried during the entire test. The readings decreased as discharge increased during the first flood and then remained fairly constant during the remainder of the test. The initial decrease in readings could have resulted from the increased flow, inducing a vibration in the probe and compacting the bed material at the sensor's electrodes. Readings from sensor 3 did not vary with discharge, nor was there much variation in consecutive readings. This indicates that sensor 3 remained buried and was not affected by the movement of bed material.

The plot of readings from sensor 4 indicates that the sensor remained buried during the entire test. The readings remained constant throughout the test. Readings from sensor 4 did not vary with discharge, nor was there much variation in consecutive readings. This indicates that sensor 4 remained buried and was not affected by the movement of bed material.

Laboratory tests using bed material and water from the Pamunkey River at the test site indicated that sensor readings could be higher in the surface-water flow than in the submerged bed material. Field data plotted in figure 10 shows higher sensor readings in the submerged bed material than in the surface-water flow. The figure also shows large differences between readings for all sensors in the submerged bed material. The installation method (driving) could have caused bed material or debris to lodge against the electrodes in such a manner that the readings were not characteristic of the surrounding bed material, or possibly, the bed material at the probe location is not uniform with depth.

Sensor 1 was initially located in the surface-water flow approximately 2 in. above the riverbed, and the readings (0.2 v/v) represent conductivities of the surface-water flow before the first flood. Sensors 2, 3, and 4 were initially buried and the readings represent conductivities of the water and bed material surrounding the electrodes (0.4 to 1.4 v/v before the first flood). The readings from sensor 1 increased from 0.2 to 0.9 v/v during the first high water and from 0.3 to 0.6 v/v during the second flood. All readings collected from sensor 1 during the floods were within the range of values measured from the sensors that were buried. Conductivities of the surface-water flow near the riverbed during a flood are similar to conductivities of the bed material, therefore, conductivities cannot be used to differentiate between the surface-water flow and bed material.

Readings from sensors 1 and 2 rapidly converge toward 1.0 volt per volt during the floods and are more variable than sensor 3. The data indicate that sensors 1 and 2 were located where conductivities change rapidly, such as in the surface-water flow or near the riverbed and surface-water flow interface where there can be movement of bed material. However, after the second peak discharge, readings from sensor 1 continued to decrease to 0.2 v/v, while readings from sensor 2 decreased gradually. The variations between consecutive readings continued when sensor 1 was buried by 1.0 ft of loose sand and debris and sensor 2 was covered by 1.5 ft of loose sand and debris. Therefore, rapid changes in conductivities cannot be used to differentiate between the surface-water flow and bed material.

Readings output from all four sensors decreased steadily throughout the test except during the floods. Tests in the laboratory also showed a decrease in readings with time from a similar type probe. Gradual corrosion of the brass electrodes can be one possible explanation for the decrease in readings. Another possible explanation for the decrease in readings could be that the brass electrodes were mounted in wood. As the submerged wood absorbs moisture, the moisture content of the wood changes and causes a change in conductivity of the wood. Readings from the sensors that were buried were less than readings from the same sensors when they were in the surface-water flow only; therefore, if the riverbed scoured and exposed the sensors, the sensor readings could represent the higher conductivities of the surface-water flow. Normalization of the sensor readings was not accomplished until the test was completed because the effect of the decrease in readings was not known. Sensors were not calibrated to actual conductivities for the same reason.

SUMMARY AND CONCLUSIONS

Scour is the lowering of a river channel by erosion and is the leading cause of bridge failure. Monitoring the riverbed elevation at a bridge where scour is a potential problem provides for public safety as a temporary countermeasure until structural improvements can be implemented, or in some situations, as a permanent countermeasure. Monitoring of the riverbed elevation accurately during high flows is difficult because of surface-water flow conditions. Two methods, a fathometer system and an electrical-conductivity probe system, were developed to monitor riverbed elevations at bridge piers. The scour-monitoring systems consisted of a sensor (fathometer or electrical-conductivity probe), power supply, data logger, relay, and system program.

A fathometer system was installed at bridges over two tidal sites, the Leipsic River at Leipsic, Del., and the Sinepuxent Bay near Ocean City, Md. The fathometer calculates the distance from a transducer to the riverbed by measuring the two-way travel time of a reflected, acoustic wave. Two sampling procedures were used to collect and process the data. The initial procedure measured the depth below the transducer five times, checked each reading for reasonableness, and stored the last valid reading in the final register of the data logger. A total of five readings were collected at each time interval to ensure that one reading met the criteria. The refined procedure measured the depth below the transducer five times, checked each reading for reasonableness, and stored the last valid reading in one of five final registers of the data logger. The process was repeated for each of the five final registers. A total of 25 readings were collected at each time interval to ensure that one reading met the criteria for each of 5 final registers. The median value was used to analyze the performance of the method.

Field data indicate that fathometers can be used to identify and monitor the riverbed elevation if post processing of the data and trends in the data are used to determine the riverbed location in relation to the transducer. Use of better quality fathometers, multiple fathometers, or electronic shielding may reduce the need for post processing of the data. The accuracy of the system is approximately the same as the resolution of the fathometer. Signal scatter, caused by electronic or physical interference, is a major source of error. During periods of interference, measured distance values from the transducer to the riverbed are erroneous. Other problems associated with the use of a fathometer are determining the exact location of the reflected pulse, sequencing multiple fathometers or other electronic equipment to prevent electronic interference, and protecting the system from damage by debris.

An electrical-conductivity probe system was installed at a bridge over the Pamunkey River near Hanover, Va. The approximate elevation of the riverbed is determined by comparing conductivities of the surface-water flow with conductivities of submerged bed material. The probe was driven into the riverbed such that three of four equally spaced sensors were buried. The ratio of the voltage across a known resistor and the voltage across a variable resistor was measured using a six-wire full-bridge circuit, and was proportional to the conductivity of the surrounding surface water or bed material.

Field data indicate that an electrical-conductivity probe, as tested, has limited usefulness in identifying and monitoring the riverbed elevation during high flows. As the discharge increases, the concentration of sediment in the surface-water flow increases, especially near the riverbed. Voltage ratios measured at the sensors in the surface-water flow could not be distinguished from voltage ratios measured at the shallowest sensor in the bed material. Other problems associated with the use of an electrical-conductivity probe are a gradual decrease in readings with time, possibly because of corrosion of the electrodes or changes in moisture of the wooden probe, and potential damage to the system by debris. A conductivity probe with a different design, a probe measuring temperature rather than conductivity, or a probe sensing flow movement may improve results.

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