USE OF SURFACE-GEOPHYSICAL METHODS TO ASSESS RIVERBED SCOUR AT BRIDGE PIERS

By S. R. Gorin and F. P. Haeni

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For the convenience of readers who prefer metric (International System) units rather than the inch-pound terms in this report, the following conversion factors may be used:

Multiply inch-pound units	by	To obtain metric units
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Flow	
cubic feet per second (ft^3/s)	.02832	cubic meter per second (m^3/s)
	Velocity	
feet per nanosecond (ft/ns)	0.3048	meters per nanosecond (m/ns)
feet per second (ft/s)	0.3048	meters per second (m/s)
	Temperature	
degree Fahrenheit (°F)	°C = 5/9 (°F - 32)	degree Celsius (°C)

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ABSTRACT

A ground-penetrating-radar system, a black-and-white fathometer, a color fathometer, and a tuned transducer were evaluated for their ability to measure riverbed scour at the Bulkeley, Charter Oak and Founder's Bridges in Hartford, Connecticut. Cross sections and some lateral sections were run at each bridge from June through July 1987, and significant scour at piers supporting each of these bridges was observed. Each of the four geophysical systems proved to have characteristic advantages and disadvantages.

A ground-penetrating-radar system with single and dual 80-megahertz antennae floating in the water was used. It was successful in water less than 25 feet deep and in resistive earth materials. With this geophysical method, the geometry of existing scour holes was clearly defined as was infilling in some holes. Penetration ranged from 1 foot to 20 feet, depending on the physical properties of the riverbed materials, and the resolution of the subbottom layers was 2 feet. This system was effective at distances greater than 3 to 5 feet from the piers.

The black-and-white fathometer was useful for defining existing scour holes. However, at a signal frequency of 200 kilohertz, it offered virtually no penetration except in soft muds. This system was effective for obtaining rapid and accurate depth determinations. The black-and-white fathometer was useful in conjunction with other methods for correlation and interpretation of geophysical data, because it substantiated the depth data obtained with other methods.

The color fathometer, operating at a signal frequency of 20 kilohertz, digitized the reflected seismic signals and assigned a color for every 6-decibel change in the acoustic impedence of the reflected signals. It delineated the existing scour-hole geometry, detected infilling of scour holes, and provided qualitative information about the physical properties of bottom and subbottom sediments. Side echo became a problem within 5 feet of the piers, and penetration ranged from 2 feet to greater than 20 feet, depending on riverbed materials. This method could not be used in water less than 5 feet deep.

The tuned transducer used in this study operated at a signal frequency of 14 kilohertz. It defined the existing scour-hole geometry and the extent of infilling of soft sediments. Penetration ranged from 2 feet in coarse- or hard-packed materials to greater than 30 feet in softer, fine-grained

sediments. As with the color fathometer, side echo was a problem within 5 feet of the piers, and the method could not be used in water less than 5 feet deep.

INTRODUCTION

Throughout the past decade, increasing attention has been paid to the problem of riverbed scour at bridge piers. The failure of many bridges throughout the United States may be directly attributed to this problem. In fact, nearly all bridge failures that occur during flood stages are a direct result of scouring around piers (Jarrett and Boyle, 1986; Murillo, 1987). The evaluation of alternative methods for detecting and measuring riverbed scour at bridge piers will aid state and Federal agencies in the development of an effective scour-monitoring program, and an improved understanding of scour and the processes that control it.

Riverbeds are scoured or eroded as a result of the action of flowing water. Total riverbed scour is a combination of three specific scour types--general scour, constriction scour, and local scour (Hopkins and others, 1980; Jarrett and Boyle, 1986). General scour processes are long term, and are a result of changes in the fundamental factors that control channel form. Causes of general scour include changes in sediment supply, changes in flow, and changes in river form. Obstructions such as dams, or increased sediment supply as a result of mining are examples of anthropogenic causes of this type of scour. However, the emplacement of piers during bridge construction is not a direct cause of general scour.

Constriction scour is the result of an increase in water velocity associated with the confinement of flow due to a decreased cross-sectional area. The spaces between bridge piers may be sites for constriction scour. Constriction scour also may occur during high flow at sites where a flood plain has been narrowed through the emplacement of fill during bridge construction. Local scour is the result of disturbances in flow caused by emplaced objects such as pilings and piers. Turbulent flow at bridge piers is the main cause of local scour. The combined problem of general and local scour is one that is particularly pertinent to any study of bridge stability.

One of the greatest obstacles to the study of riverbed scour at bridge piers is the problem of remote monitoring of scour processes. Both local and general scour are most prevalent during flood stages of the river. This is precisely the time when monitoring becomes difficult. Any permanent device for measurement of scour may easily be damaged by flood debris, and navigation of a boat, for measuring scour near bridge piers, during a flood would be very hazardous. Thus, monitoring of riverbed scour at bridge piers becomes most difficult at the time when scour is most prevalent. By using surface-geophysical methods, however, the maximum depth of riverbed scour that is reached during flood stage may be measured at times of normal or low flow despite the tendency of sediments to fill in scour holes as flow decreases.

Methods for studying the extent of scour after infilling occurs fall into two categories--coring and remote geophysical methods. Although coring may yield accurate, quantitative information, it is slow, expensive, and generally cannot provide a continuous profile. Less expensive geophysical methods provide rapid, continuous, subbottom profiles with qualitative information about subbottom materials. With appropriate processing, interpretation, and correlation with test-hole or sampling data, some of these methods may also yield quantitative information about the physical properties of subbottom materials. Thus, the use of surface-geophysical methods minimizes the need for coring and sampling, and provides unique information about the water bottom and subbottom sediments.

Purpose and Scope

This report discusses the use of four surface-geophysical methods for analysis of riverbed scour at bridge piers, conducted by the U.S. Geological Survey, in cooperation with the Federal Highway Administration. These methods are: ground-penetrating radar and three seismic methods--black-and-white fathometer, color fathometer, and tuned transducer. The use of seismic methods for mapping subbottom stratigraphy in rivers and lakes is well documented in the literature (Morrissey and others, 1985; Haeni, 1986b; Haeni, 1988; Reynolds and Williams, 1988). Ground-penetrating radar has also been used to map subsurface stratigraphy in lakes and on land (Wright, and others, 1984; Haeni and others, 1987). Each method has advantages and limitations and will be discussed in terms of theory, interpretation, and application to the study of riverbed scour at bridge piers.

Study Area

The Connecticut River is a 380-mile long water course which serves as a major outlet for runoff in New England. At Thompsonville, just north of Hartford, Connecticut, the average flow of the river from 1930 to 1960 was about 10,000 ft^3/s (cubic feet per second). However, the river often floods, increasing the flow to greater than 10 times the average (Ryder and others, 1981). Since 1935, there have been four spring floods in which the river rose more than 30 ft (feet) above base level in Hartford (Bell, 1985), and the maximum flow was 282,000 ft^3/s on March 20, 1936 (Cervione and others, 1987). During June and July 1987, when the study was conducted, the flow of the Connecticut River in Thompsonville varied from 3,570 ft^3/s to 27,200 ft^3/s (M. A. Cervione, U.S. Geological Survey, written commun., 1987). The study focused on three bridges spanning the Connecticut River in Hartford, Connecticut. These bridges listed north to south are the Bulkeley Bridge, the Founder's Bridge, and the Charter Oak Bridge (fig. 1).

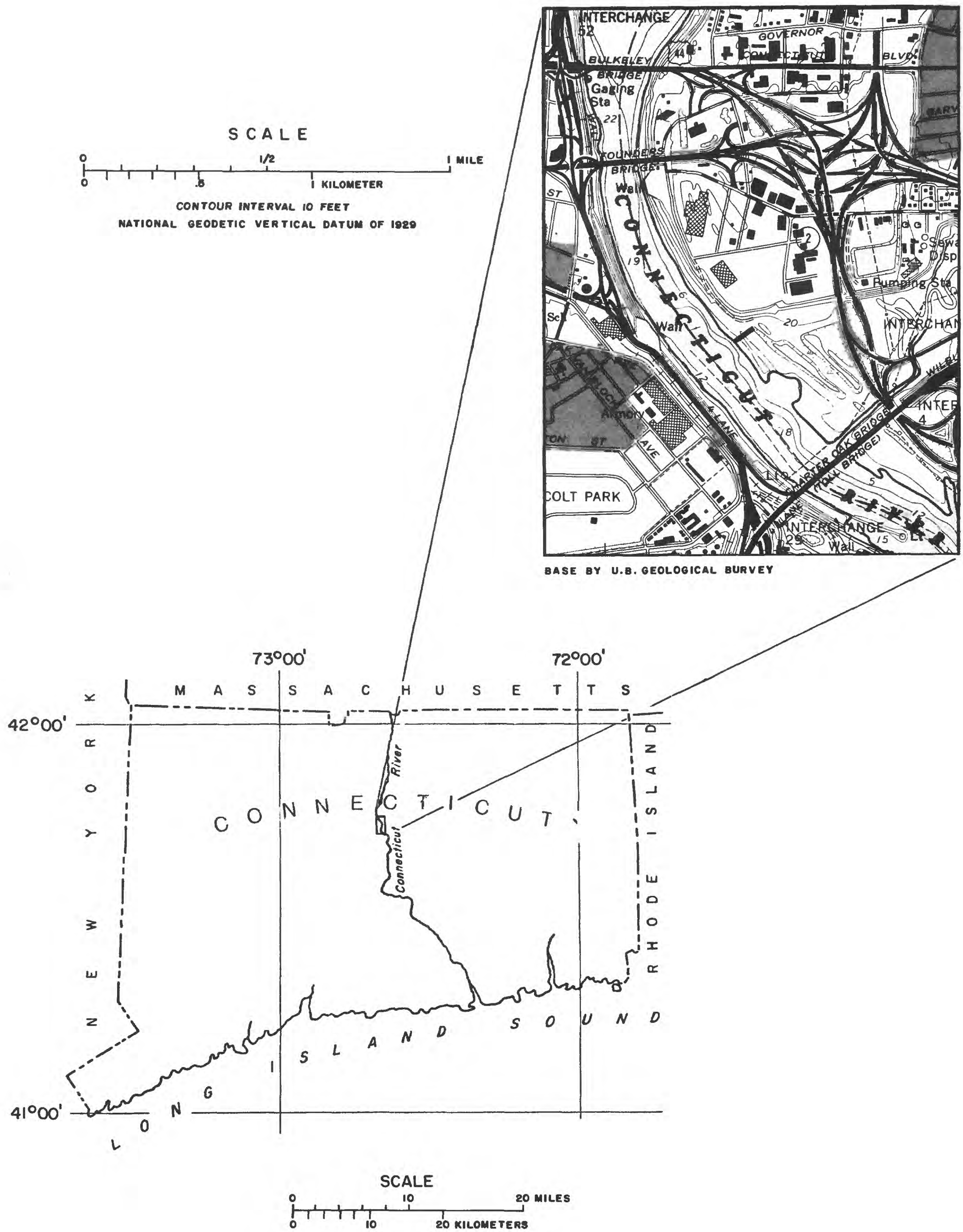

Figure 1.--The study area.

Acknowledgments

The technical assistance and financial support of the Office of Research, Development, and Technology of the Federal Highway Administration, which made this study possible, is greatly appreciated.

DESCRIPTION OF SURFACE-GEOPHYSICAL METHODS

Ground-Penetrating Radar

Ground-penetrating radar can be used on land or in relatively shallow water (less than 20 ft) to obtain high-resolution, continuous, subsurface profiles. With this method, short, 80 to 1,000 mHz (megahertz) electromagnetic pulses are transmitted into the subsurface by a transmitter located in the antenna, and energy reflected from subsurface interfaces is received. Interfaces are delineated where there are differences in electrical properties because of changes in the degree of saturation or compositional differences in subsurface materials. When the electromagnetic energy reaches a physical property interface between two layers or objects, some of the energy is reflected back to the surface, some is attenuated, and some is transmitted into deeper layers.

The reflected pulse is received at the antenna, and is sent, through the control unit, to a graphic recorder and a tape recorder. The two-way travel time in nanoseconds (10^{-9} seconds) is plotted and recorded. If the Er (relative dielectric permitivity) in a given medium is known or can be estimated or measured, the depth to each interface may be calculated. Relative dielectric permitivity is a ratio of the permitivity (ability to store an electrical charge) of a given medium to that of free space. Where the depth to a reflector is known from a test-hole or well, the relative dielectric permitivity may be calculated through the following equation:

$$Er = (t/2)^2 \times (c/d)^2,$$

where Er is relative dielectric permitivity (dimensionless ratio);

t is two way-travel time, in seconds;

c is speed of light in free space, equal to 9.835712×10^8 feet per second; and

d is depth to the reflector, in feet.

Seismic Systems

Seismic systems operate through the transmission and reception of acoustic waves through the subsurface and water column. Part of the seismic signal is reflected back to the surface where a change in acoustical impedence occurs at an interface between two layers or objects in the subsurface. Acoustical impedence (Z) is defined as the product of the density of a medium (e), and the velocity of the sound within the medium (V). The degree to which an interface reflects a seismic signal is a function of its reflection coefficient (RC) which is defined as follows:

$$RC = \frac{Z_2 - Z_1}{Z_2 + Z_1} = \frac{e_2 V_2 - e_1 V_1}{e_2 V_2 + e_1 V_1} = \frac{Ar}{Ai}$$

where RC is the reflection coefficient of the interface;

Z_1, Z_2 is the acoustical impedence of layers one and two;

Ar, Ai is the amplitude of the reflected and incident signals;

e_1, e_2 is the densities of layers one and two; and

V_1, V_2 is the velocity of sound in layers one and two.

The average velocity of sound in shallow, saturated, unconsolidated glacial outwash, silt, and clay in Connecticut is 5,075 ft/s (feet per second) (Haeni, 1986a). Assuming no salinity, the velocity of sound in the water column is 4,888 ft/s at an average water temperature of 22°C (degrees Celsius) (Sheriff, 1984). In this study, the average velocity of sound through both mediums was assumed to be 5,000 ft/s.

Three seismic methods were used to examine riverbed scour at bridge piers: black-and-white fathometer, color fathometer, and tuned transducer. A major variable which distinguishes these methods from one another is the frequency of the seismic signal. Lower-frequency signals achieve better penetration of the subbottom with poorer resolution of subbottom features. Higher-frequency signals have better resolution, but may afford little or no penetration (Sylwester, 1983).

Black-and-White Fathometer

A black-and-white fathometer, model X-15B, manufactured by Lowrance Incorporated, operating at a signal frequency of 200 kHz, was used in the study. At this frequency, the system had a resolution of a few inches and did not penetrate the river-bottom materials. It is a useful tool for defining existing scour holes, but it does not penetrate most sediments, and, therefore, will not show whether infilling has occurred. The sound

If the relative dielectric permitivity of a medium has been calculated, or estimated from published data, the depth to a given reflector may be calculated through the following equation:

$$d = Vm\ t/2,$$

where Vm, the radar-wave velocity, is equal to $c/Er^{1/2}$.

The velocity of radar waves is 0.11 ft/ns (feet per nanosecond) in fresh water (Geophysical Survey Systems Inc., 1987) and estimates, calculated from published relative dielectric permitivities, range from 0.17 ft/ns (Morey, 1974) to 0.23 ft/ns (Wright and others, 1984) for sand saturated with fresh water. The radar-wave velocity calculated in this study, through comparison of ground-penetrating-radar records with measured depths was 0.18 ft/ns. Other properties of subsurface materials, such as density and grain size, may also be determined by examining the strength, coherency, and character of the return pulses. Thus, a qualitative interpretation of the physical properties of subsurface materials, and a quantitative depth determination may be obtained.

Ground-penetrating radar seldom penetrates more than 100 ft into the subsurface (Wright and others, 1984), and, in highly conductive material, it may only penetrate a few feet (Olhoeft, 1984). The resolution of this method is less than 2 ft, depending on the operating frequency, and it is, therefore, well suited for the distinction of sedimentary structures and buried objects near the surface. The penetration depth of ground-penetrating radar depends on the electrical properties of the material through which the pulse will be propagated. Highly conductive (low resistivity) materials, such as clay minerals, severely attenuate radar signals. Similarly, radar is ineffective where sediments are saturated with or overlain by salt water or other conductive fluids. Fresh water also attenuates the radar signal and, generally, limits the use of radar to sites overlain by less than 20 ft of water.

For this study, an SIR 80 radar system built by Geophysical Survey Systems Incorporated was used. Either a single 80-mHz antenna was used as a transceiver, or two 80-mHz antennas were used, one as a high-powered transmitter and the other as a receiver. In general, the best results were obtained using the two-antenna combination, although some increase in side echo was observed near bridge piers. This interference was only a significant problem within 5 ft of the piers. Ground-penetrating radar is unique among the geophysical methods used in this study because it uses electromagnetic energy to penetrate the subsurface. The other geophysical methods use seismic waves of various frequencies.

1/ The use of trade and firm names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

source for this instrument is a transducer, a few inches in diameter, which is mounted on the bottom of the boat. The black-and-white fathometer is easy to operate and a hard-copy record of the water-bottom profile is obtained. It is very useful for obtaining accurate measurements of water depth, and generally is unaffected by side echo from bridge piers.

The black-and-white fathometer was most useful in conjunction with the other geophysical systems. It provided accurate information on water depth and water-bottom morphology that was clear and easy to interpret. The black-and-white fathometer also aided in interpreting the geophysical data obtained with other methods. For example, side echo from the piers, on the records obtained with the other systems, could be easily identified by comparing these records to the black-and-white fathometer records.

Color Fathometer

The color fathometer used in this study was a variable-frequency (20 to 100 kHz) seismic system, model HE-730, manufactured by Si-Tex Incorporated, that digitized the reflected signal and displayed a color image on a cathode-ray tube. This system has a resolution of a few inches and penetration of 0 to 20 ft of subsurface materials, depending on the selected frequency. It can be used to distinguish some physical properties of surficial and subsurface sediments. This system measures the ratio of amplitudes of the reflected and incident signals, in decibels, at the sediment-water interface and at shallow interfaces in the subsurface. A db (decibel) is defined as 20 times the logarithm of the amplitude ratio or the reflection coefficient:

$$20 \log (Ar/Ai)$$

or

$$20 \log (RC)$$

Color fathometers distinguish between different interfaces by assigning different colors to changes in the amplitude of the reflected signal. The system used in this study assigned a color change to every 6-db change in amplitude ratio or reflection coefficient. Note that a 6-db change is equivalent to a reflection coefficient of 2 or an amplitude ratio of 2:1.

Because the color fathometer delineates decibel changes in the reflected signal, which are directly related to reflection coefficients, certain physical properties of the bottom and subbottom materials may be calculated or estimated. A number of studies have shown that reflection coefficients are linearly related to bulk density, porosity, and median grain size of marine sediments (Faas, 1969; Hamilton, 1970; Parrott and others, 1980). When properly calibrated, the color fathometer may be used to define and identify sedimentary facies. Additional work is necessary before any quantitative determinations of physical properties of fluvial sediments can be made from the color-fathometer records. However, qualitative information is obtained from these records, and it appears likely that direct quantitative interpretations are possible.

Although no hard copies of the records were obtained, data were stored on high-density, chromium-dioxide cassette tapes for playback and processing. Because the data displayed on a color monitor are not easily reproducible, the color-fathometer records in this paper are represented as black-and-white photographs.

Tuned Transducer

The tuned transducer used in this study has a range of operating frequencies from 3.15 to 14 kHz (kilohertz), and was manufactured by Ferranti O.R.E., Incorporated. The resolution of the tuned transducer system ranges from a few inches to a few feet depending on the selected frequency. In fine-grained material, up to 100 ft of subbottom penetration may be achieved, whereas subbottom penetration may be limited to a few feet in coarser materials. Changes in frequency may be made to optimize penetration and resolution depending on the objectives of a particular study.

Multiple-tuned transducers may also be used in various combinations to meet specific needs. For example, the use of parallel transducers of equal frequency may be used to narrow the beam angle of the outgoing signal. Separate transmitter-receiver combinations may also be used to enhance the seismic record in shallow-water areas. It also is possible to traverse the same section at two distinct frequencies so that shallow as well as intermediate-depth results may be obtained.

ASSESSMENT OF RIVERBED SCOUR

The black-and-white fathometer, ground-penetrating radar, tuned transducer, and color fathometer were used to evaluate scour at three bridges spanning the Connecticut River in Hartford, Connecticut, and the results of the different techniques were compared. All piers were numbered from east to west, starting with the first pier that was in the water at the time of the study. Riverbed scour was associated with nearly every pier in the study. The geometry and size of scour holes varied, depending on the pier location and position in relation to the direction and magnitude of the current. Cross sections were run in both directions upstream from the piers, and lateral sections were run on both sides of a number of selected piers. Ground-penetrating radar, color fathometer, and tuned transducer surveys were all run at the Charter Oak and Bulkeley Bridges along with the 200 kHz black-and-white fathometer. Founder's Bridge sections were surveyed with ground-penetrating radar and black-and-white fathometer only. In all cases, existing scour was clearly observed, and, at several sites, the depth to a deeper scour surface, formed during a previous flood event, could be determined.

Bulkeley Bridge

The Bulkeley Bridge, the northernmost bridge in the study area, is the Connecticut River crossover for Interstate 84 between East Hartford and Hartford. A total of eight bridge piers were in the water at the time of the study. The piers are 100 ft long and 20 ft wide with pointed ends, and are evenly spaced, 150 ft apart, across the entire span. The average water depth 100 ft upstream from the piers was 8 ft. Figure 2 shows a cross-sectional ground-penetrating-radar record from a section 15 ft upstream from this bridge. The scour holes were 6 to 8 ft deeper than the adjacent water-bottom (water-bottom base level), and 60 to 70 ft wide in a cross sectional view. Piers 1 through 7 had scour holes that were directly in front of them in a cross-sectional view. However, the scour associated with pier 8 was to the east of the pier, possibly due to the direction of the current, which was flowing east to west at this point. The depth of the scour generally increased from east to west as might be expected, since the river is curving, and the current is greatest on the western side.

Infilling was observed on the cross-sectional radar records at piers 3, 4, 5, and 6. In each case, this infilling consisted of 2 to 5 ft of soft sediments overlying a harder, more reflective surface. The deeper interfaces are interpreted as old scour surfaces, and may consist of gravel and pebbles that settled into the scour holes during flood stages of the river, on top of the eroded surface of glaciolacustrine clays.

The focus of this study is on the application of various geophysical methods to the evaluation of riverbed scour at bridge piers. With that end in mind, the results of each geophysical method at pier 5 of the Bulkeley Bridge are compared. Each method was useful in describing the existing geometry of the scour hole at this pier. Eight feet upstream from the pier, a scour hole was observed to be 6 to 8 ft deeper than the adjacent river bottom, 60 ft wide, and symmetrical about the center of the pier. This scour hole extended 30 ft upstream from the pier. A deeper scour hole, adjacent to the pier near its downstream end, was also identified. The water reached a depth of 22 ft, 12 ft below water-bottom base level, in this hole. Downstream from the pier, the water became shallow, 2 to 3 feet deep, at a topographic rise. Relief of the water bottom between the scour hole adjacent to the pier and the top of the sandbar exceeded 20 ft over a horizontal distance of 80 ft.

The 200-kHz black-and-white fathometer quickly and accurately defined the depth and geometry of the existing scour. However, virtually no penetration of the subbottom materials was achieved with this instrument. Qualitative information about the reflectivity of the bottom materials could be derived by observing whether or not multiple reflections were present (in relatively hard bottoms, multiples would be present), and by observing the tone of the record at the sediment-water interface. No information regarding the thickness or extent of infilling could be ascertained. A lateral 200-kHz fathometer record run 6 ft east of pier 5, and a cross section run 8 ft upstream from pier 5 are shown in figure 3. The cross

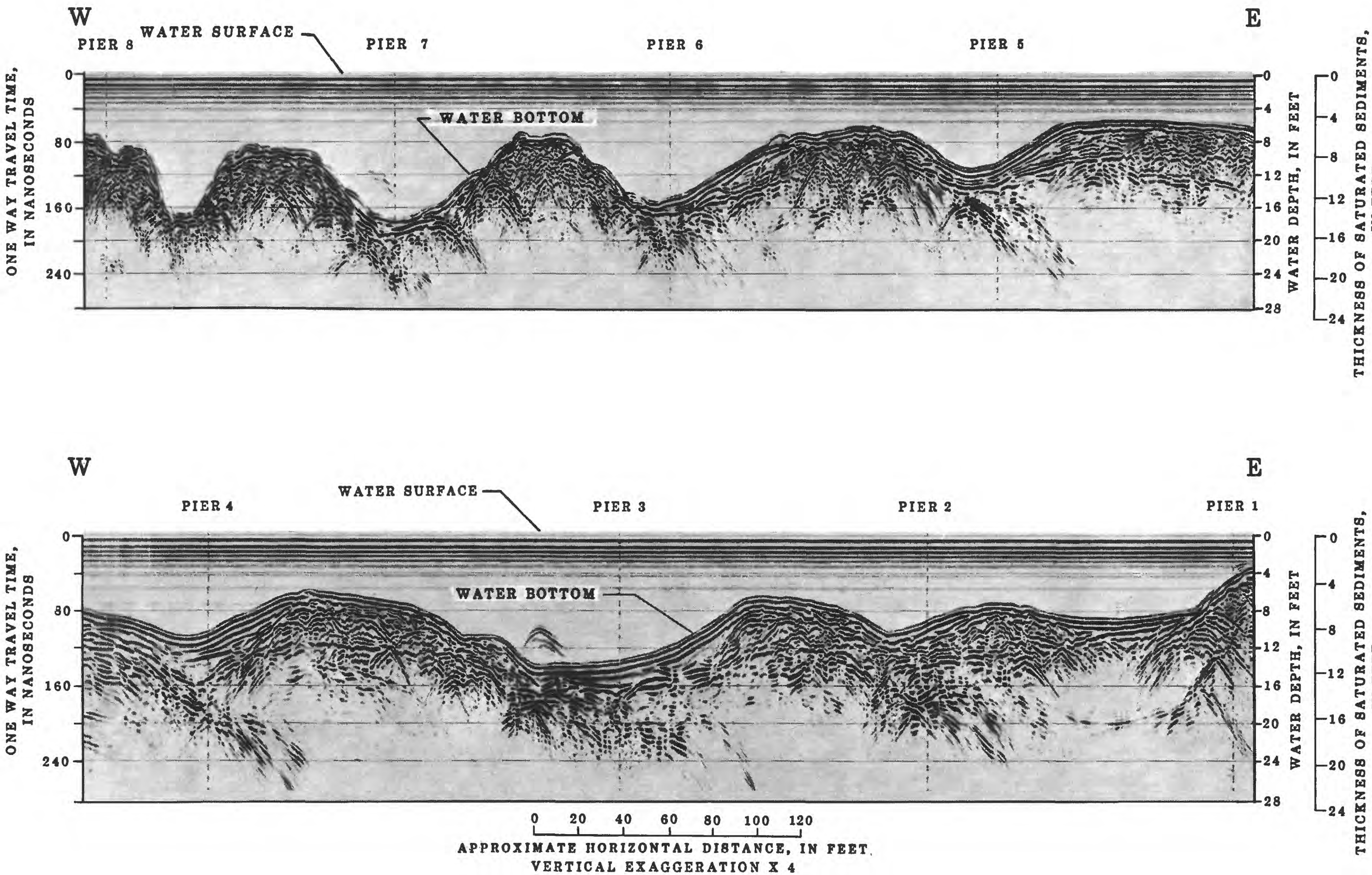

Figure 2.-- Ground-penetrating-radar cross section 15 feet upstream from the Bulkeley Bridge.

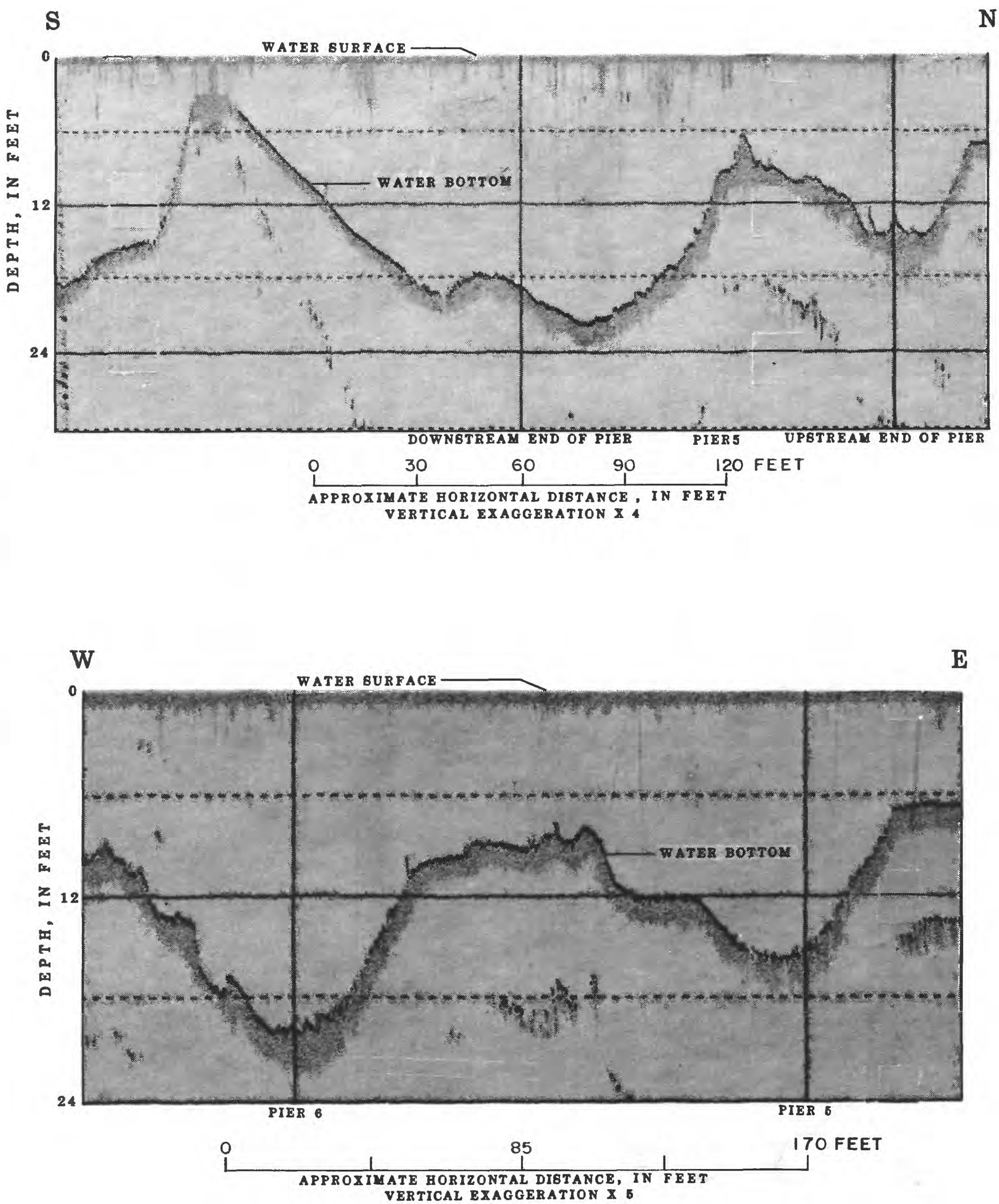

Figure 3.-- A 200-kilohertz black-and-white fathometer cross section (8 feet upstream from the pier) and lateral section (6 feet east of the pier) at pier 5 of the Bulkeley Bridge.

section correlates with the tuned transducer section shown in figure 6 and not with the ground-penetrating-radar records in figures 2 and 4, which were run 7 ft further upstream. Multiples are apparent on the black-and-white fathometer records, indicating a relatively reflective water bottom. The existing scour geometry is clearly defined, and the sediment-water interface is distinct, also indicating a reflective water bottom.

Ground-penetrating radar proved to be effective for detecting sub-bottom layers at this pier. An interpreted cross-sectional radar record run 15 ft upstream from pier 5 is shown in figure 4. Infilling of the scour hole is evident on the radar record, and the infilled material is probably fine-grained sediments deposited in the hole during periods of normal or low streamflow. The apparent thickness of material deposited in the center of this hole is 4 to 5 ft. It is important to note that the shapes of reflectors on time sections are controlled, in part, by variations in the thickness of, and velocity of wave propagation through overlying layers. Because the velocity of radar waves increases from fresh water to saturated sediments, the topography of the water bottom is positively superimposed on subbottom interfaces on ground-penetrating-radar records. Because of this phenomenon, a flat-lying layer beneath a scour hole may appear as a depression on a radar record. For this reason, the slope of the subbottom reflector on the radar record, is greater than the true slope of the old scour surface. The interpretation of the radar section, shown in figure 4, takes this factor into account, and shows the true topography of the old scour surface.

A lateral radar section run 8 ft to the east of pier 5 is shown in figure 5. Three to 5 ft of infilled material is again apparent upstream from the pier. In the deeper scour hole, on the eastern-downstream side of the pier, no post-scour deposition is evident on the radar record. In this area, however, the water depth was approaching the limit for radar use and there was virtually no penetration of the subbottom sediments by the radar signal. Some side-echo signals reflected from the pier masked some of the subbottom signals at distances within 3 to 5 ft of the pier. However, at greater distances, there was little side-echo interference. Water-bottom multiple radar signals were not observed at this pier, because of the relative depth of the water column and the physical properties of the sediments.

The 14-kHz tuned transducer also defined the geometry of the scour hole at this pier. A record of a cross section 8 ft upstream from the pier, and a lateral section 10 ft to the east of the pier are shown in figures 6 and 7 respectively. Post-scour deposition upstream from the pier is apparent on the cross-sectional record and is interpreted to be 3 to 4 ft of uncompacted, fine-grained sediments, which correlates with the radar reflection at this pier. In the lateral view, the geometry of the existing scour was clearly defined. No infilling was evident in the scour hole adjacent to the eastern-downstream side of the pier, but the infilling upstream from the pier was apparent. The depth of the water column was not a problem for the tuned transducer, and side echos were observed only when the transducer was within 5 ft of the pier.

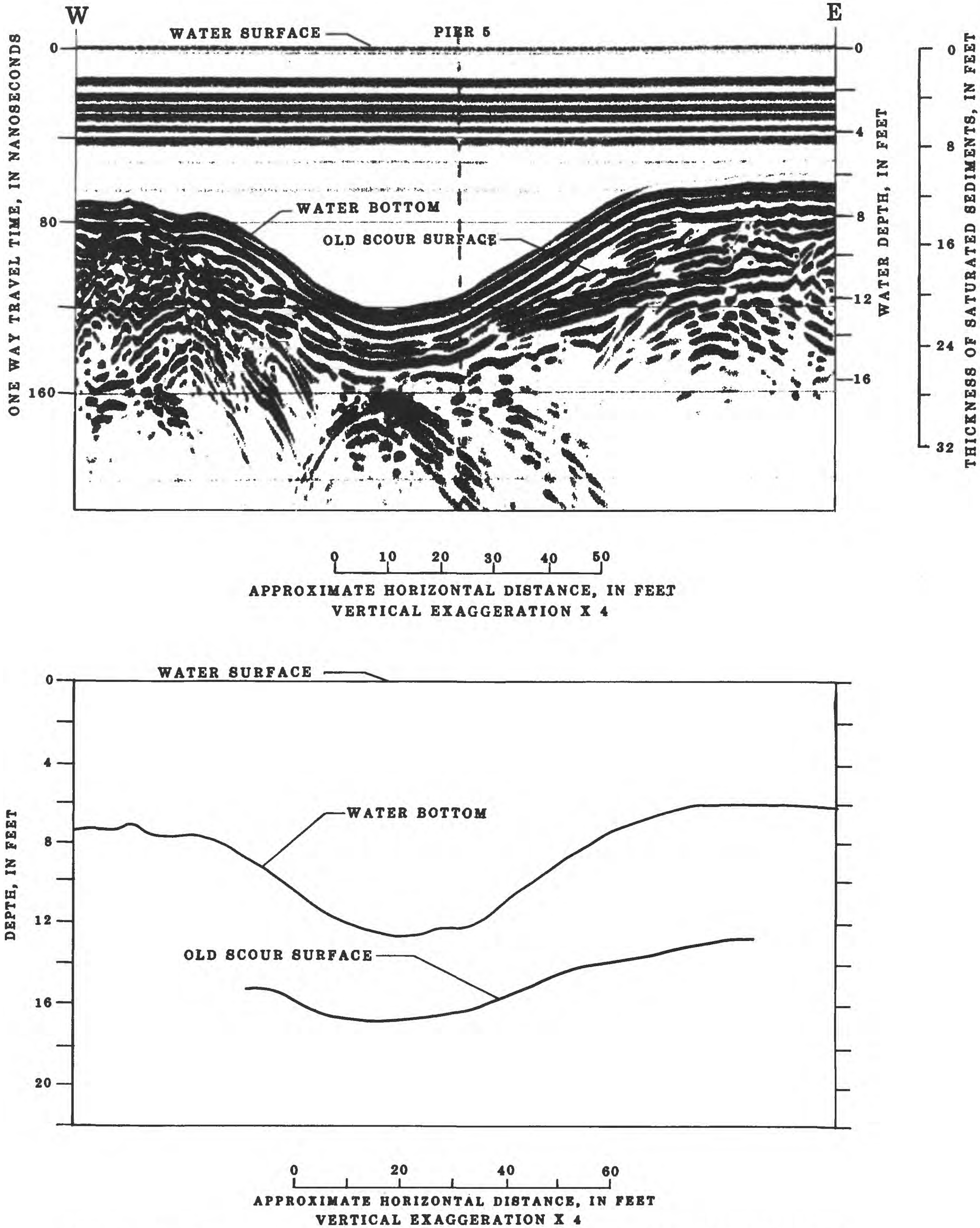

Figure 4.-- Ground-penetrating-radar cross section and interpretation 15 feet upstream from pier 5 of the Bulkeley Bridge.

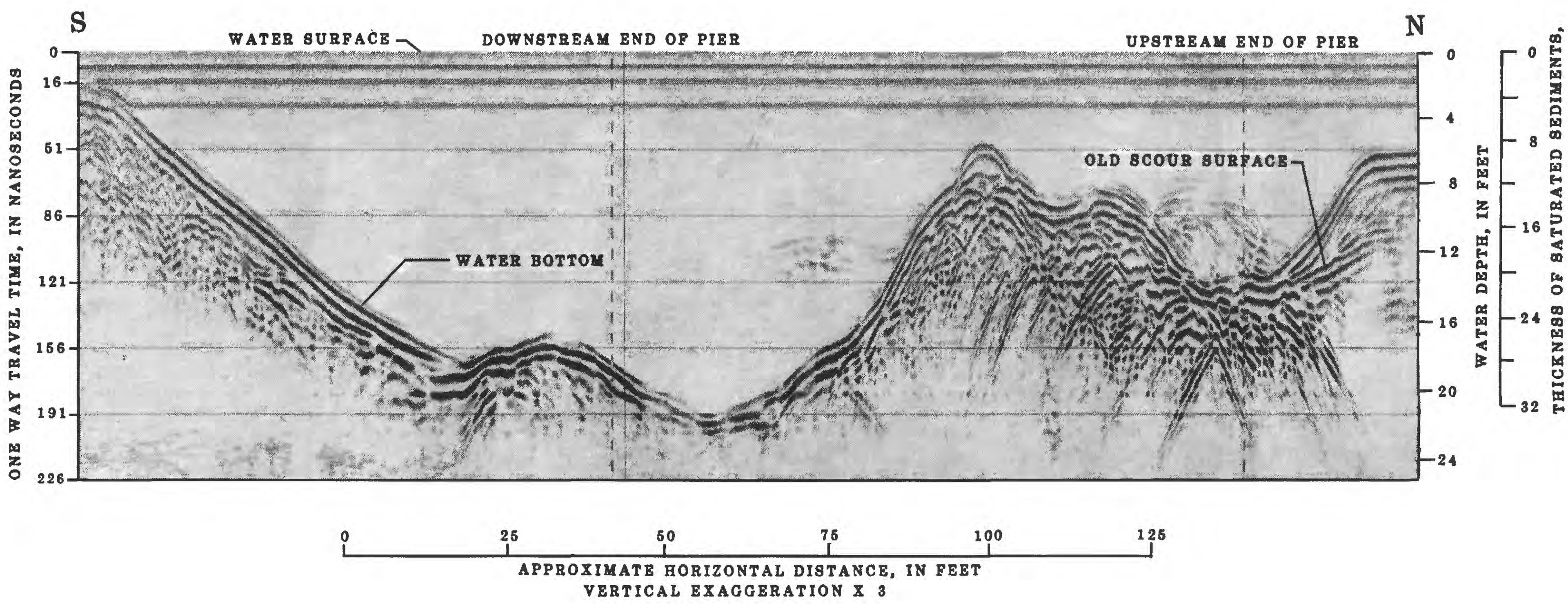

Figure 5.-- Ground-penetrating-radar lateral section 8 feet to the east of pier 5 of the Bulkeley Bridge.

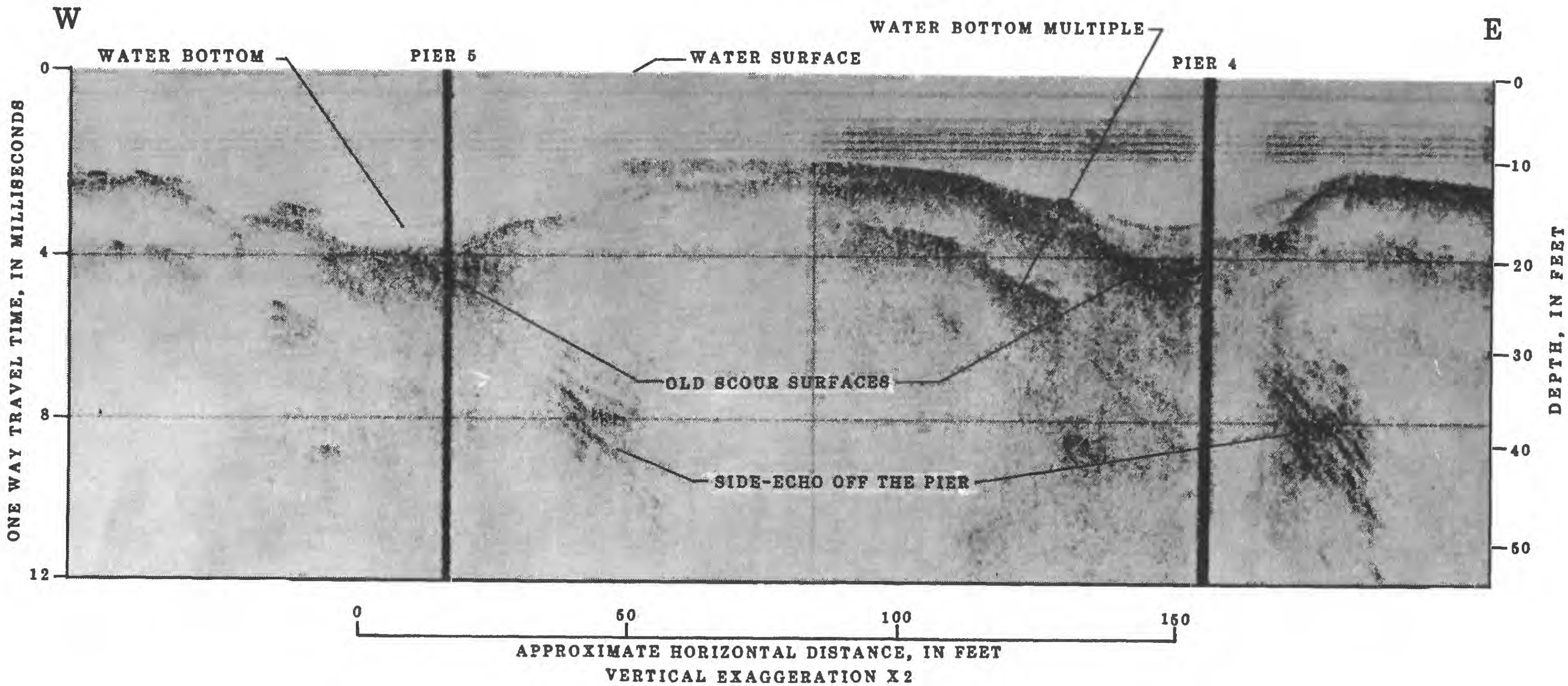

Figure 6.-- A 14-kilohertz tuned-transducer cross section 8 feet upstream from piers 4 and 5 of the Bulkeley Bridge.

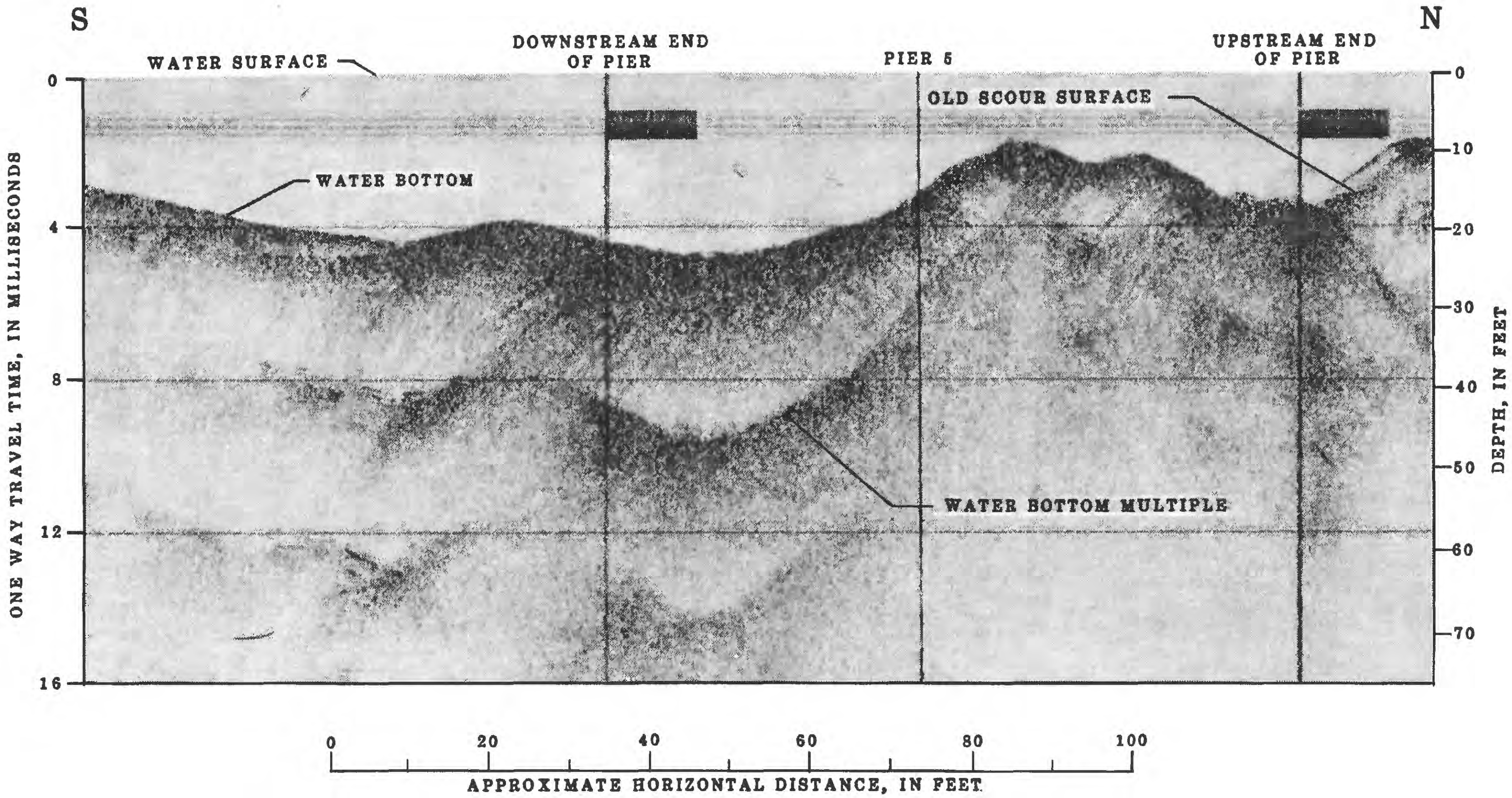

Figure 7.-- A 14-kilohertz tuned-transducer lateral section 10 feet to the east of pier 5 of the Bulkeley Bridge.

The color fathometer, operating at a signal frequency of 20 kHz, delineated the geometry of the existing riverbed scour and infilling of scour holes at this site. Black-and-white photographs of a cross-sectional color fathometer record 12 ft upstream from pier 5 and a lateral record 8 ft to the east of pier 5 are shown in figures 8 and 9 respectively. In a cross-sectional view, 4 to 5 ft of soft sediments were observed to overlie a harder layer at the center of this scour hole. Infilling is evident in the lateral section, both upstream from and adjacent to the pier. The extent of infilling adjacent to the pier is estimated to be 0.5 to 1 ft. As in the case of the tuned transducer, the depth of the water column was not a concern. Side echoes were evident on the records, but this interference was only observed within 5 ft of the pier and could be readily identified. Multiple reflections were observed on the color record, but with penetration limited to only a few feet, they did not pose a problem.

Charter Oak Bridge

The Charter Oak Bridge is the southernmost bridge in the study area. It serves as the crossover for Connecticut Route 15, 1 mi (mile) south of Hartford. There were two rectangular piers with pointed ends, 100 ft long and 25 ft wide, in the water at the time of the study, and riverbed scour was observed at both. The largest scour hole in the study area was located at pier 1 of this bridge. Upstream from this pier, the scour hole extended 18 ft below the water-bottom base level. There was considerably less scour at pier 2 because of the presence of boulders and debris from a pier that collapsed during the construction of the bridge (James Matula, Connecticut Department of Transportation, written commun., 1988). The typical parabolic reflections associated with point reflectors (boulders) are evident on all of the geophysical records at pier 2.

A cross-sectional ground-penetrating-radar record, 10 ft upstream from the piers, is shown in figure 10. Note that the depth of the water at pier 1 approaches the limit of radar penetration in fresh water at this site. The geometry of the existing scour was defined on the radar record, but no subbottom penetration was achieved. A 200-kHz black-and-white fathometer record from the same line, shown in figure 11, yields similar information regarding the geometry of this scour hole, but again, no subbottom penetration was achieved and presence of any infilling could not be detected.

A black-and-white photograph of a 20 kHz, lateral color-fathometer record run 8 ft to the east of pier 1 is shown in figure 12, and figure 13 shows a black-and-white photograph of a cross section run 10 ft upstream from the piers. The soft bottom and fine-grained subbottom sediments at this bridge site resulted in greater than 20 ft of penetration for the color fathometer. The cross-sectional record clearly defines the scour-hole geometry. The scour hole is symmetrical around the pier, with a maximum depth 18 ft below the water-bottom base level. About 5 ft of soft sediments deposited since the scour occurred was present in the cross-sectional view.

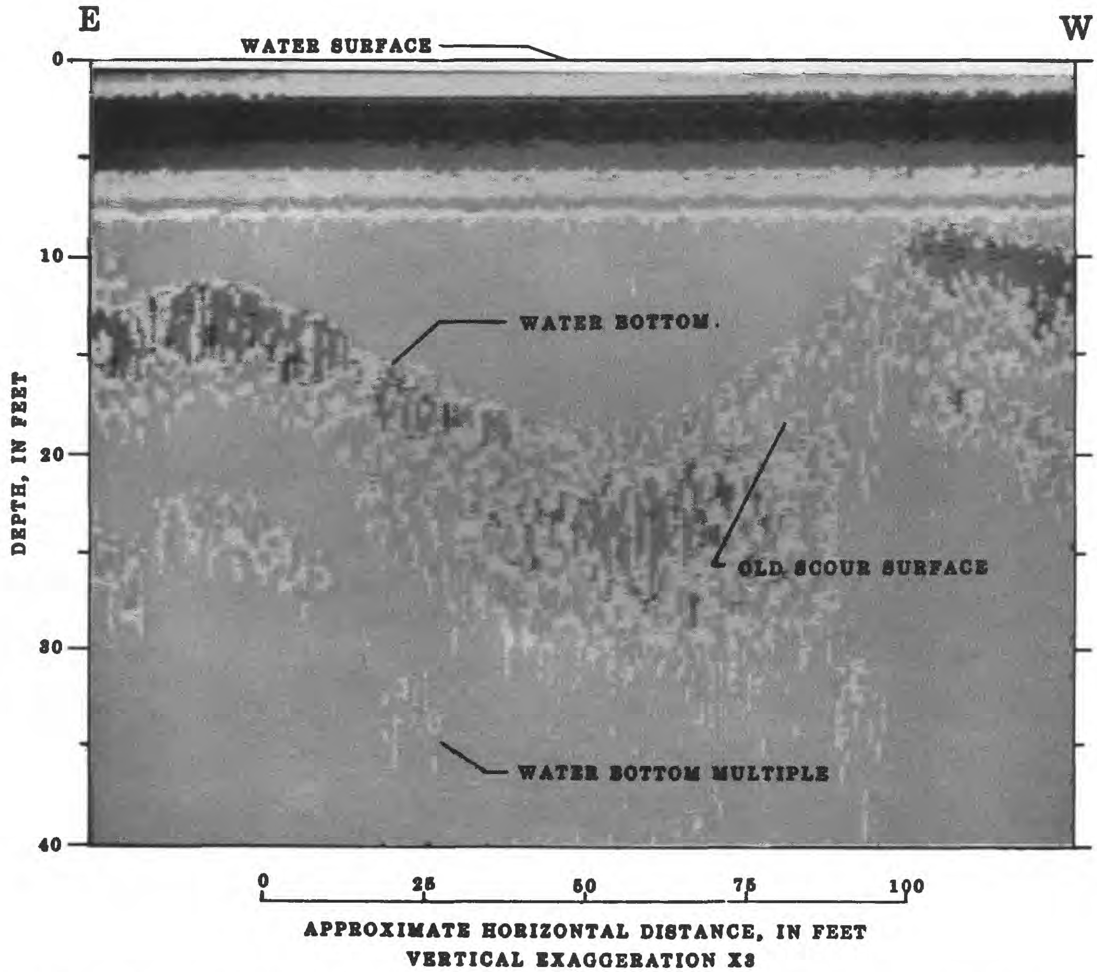

Figure 8.-- A 20-kilohertz color-fathometer cross section 12 feet upstream from pier 5 of the Bulkeley Bridge (black-and-white photograph).

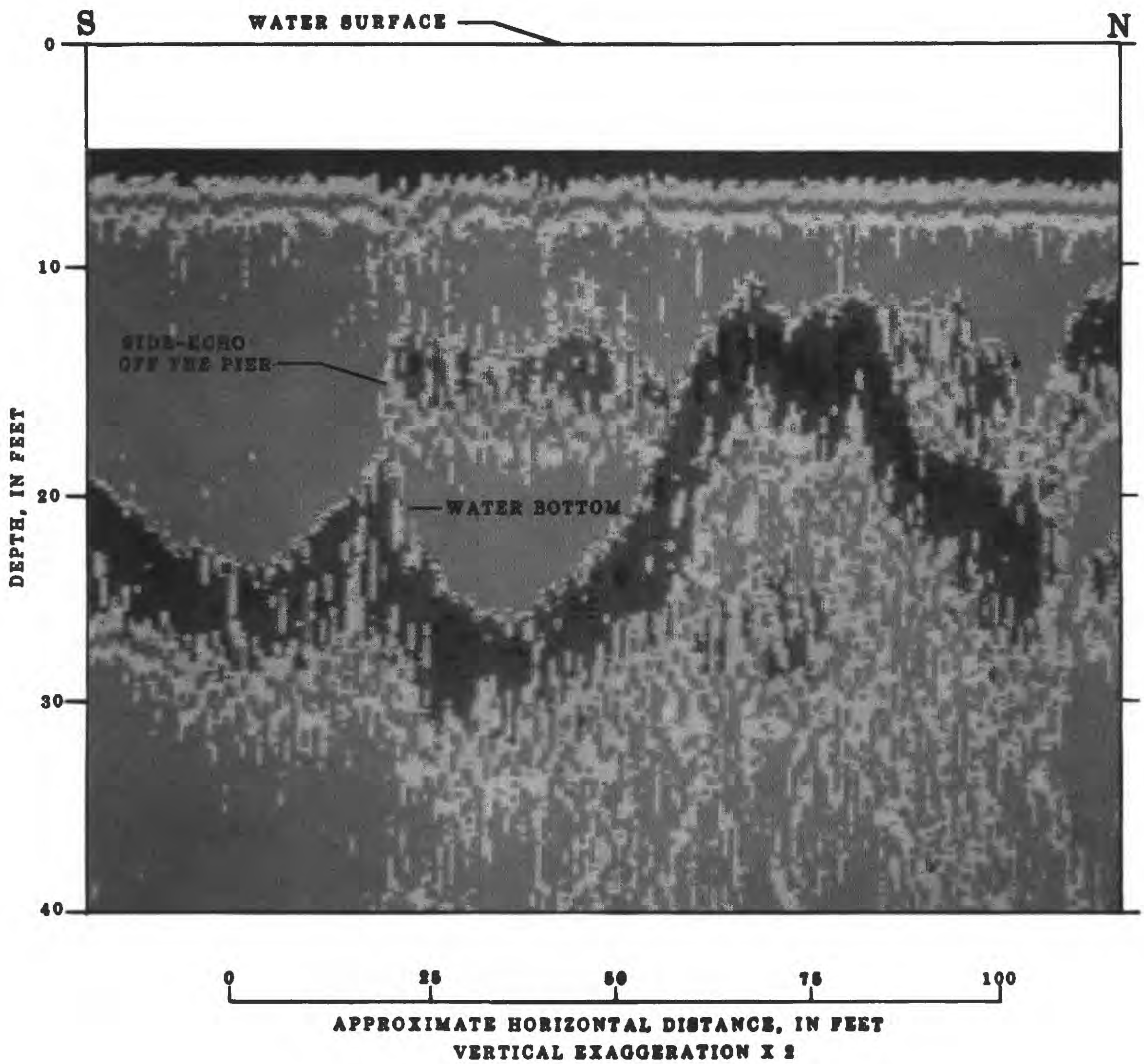

Figure 9.-- A 20-kilohertz color-fathometer lateral section 8 feet to the east of pier 5 of the Bulkeley Bridge (black-and-white photograph).

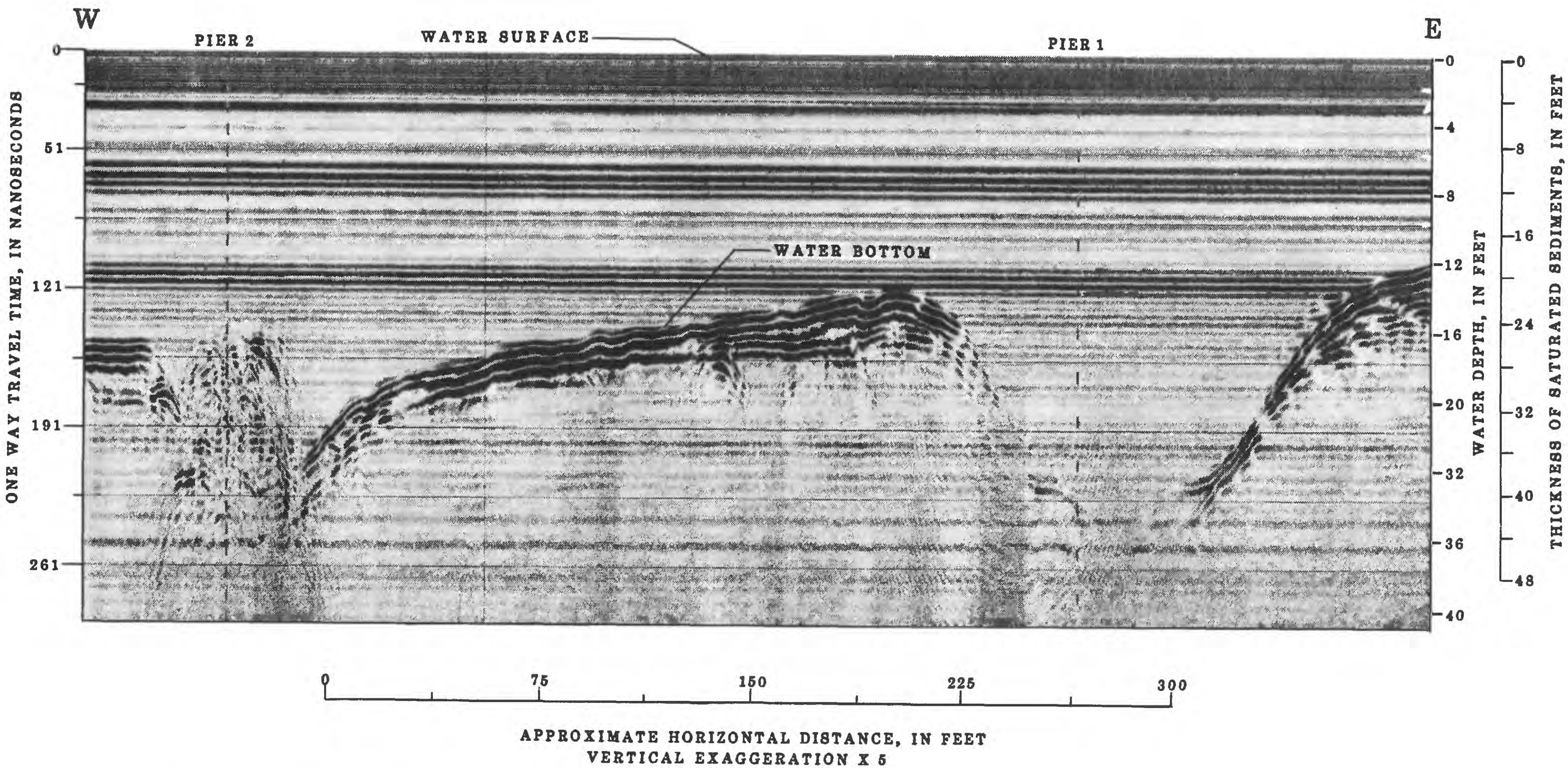

Figure 10.-- Ground-penetrating-radar cross section 10 feet upstream from the Charter Oak Bridge.

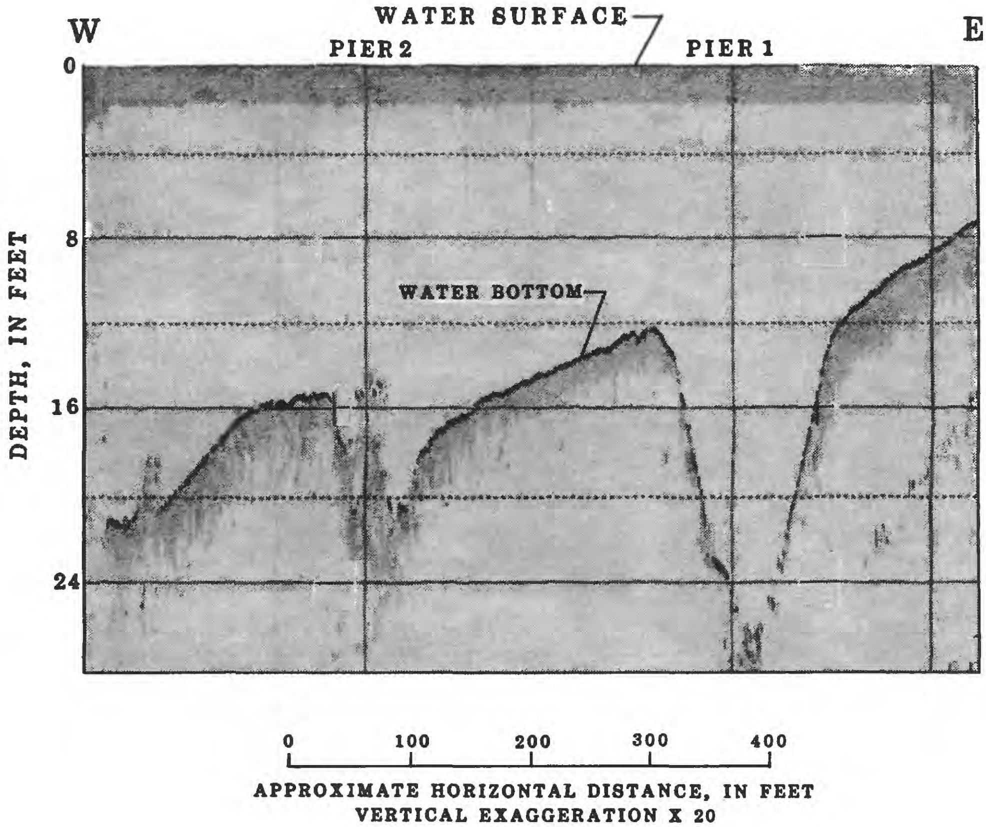

Figure 11.-- A 200-kilohertz black-and-white fathometer cross section 10 feet upstream from the Charter Oak Bridge.

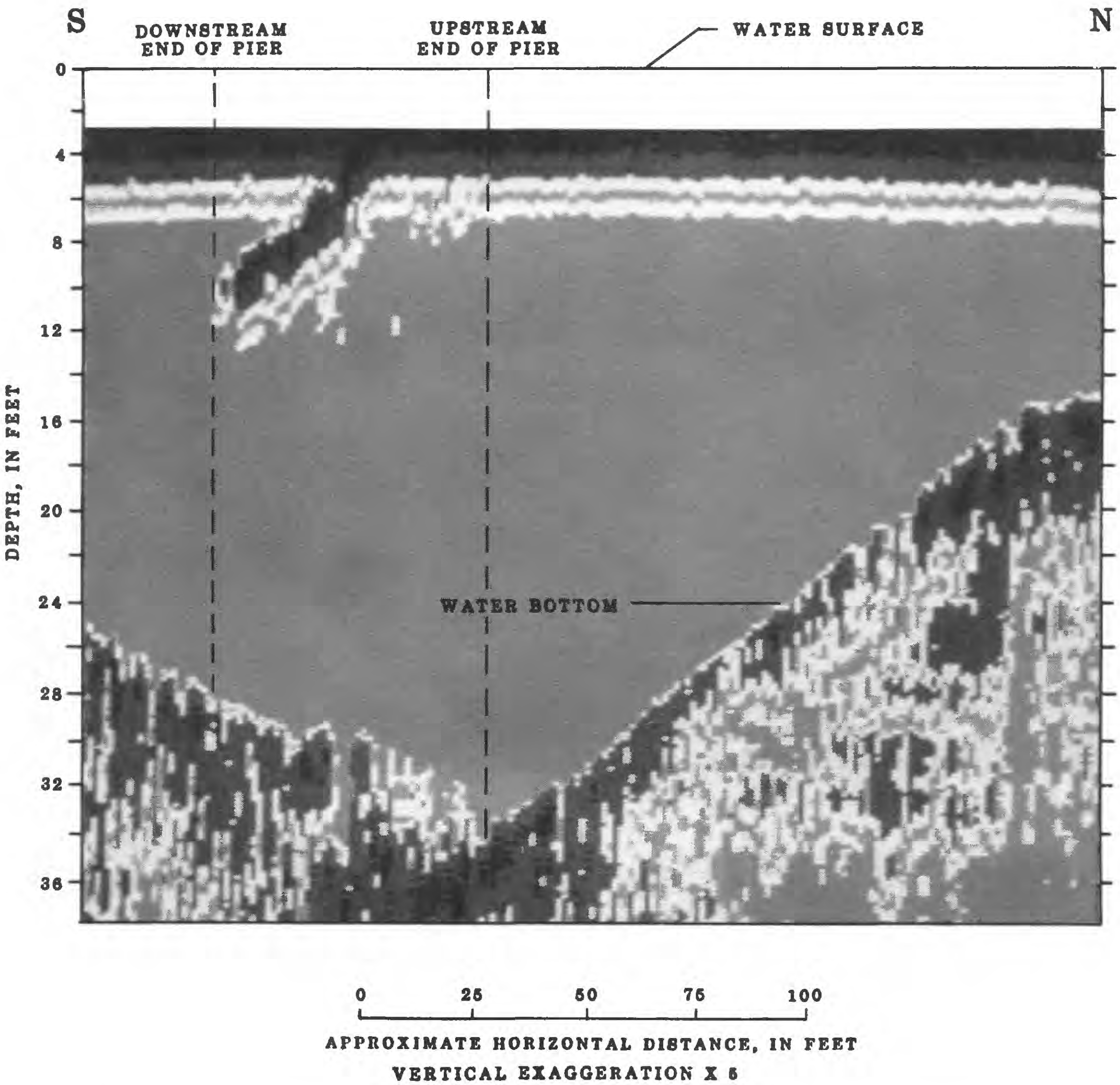

Figure 12.-- A 20 kilohertz color-fathometer lateral section 8 feet to the east of pier 1 of the Charter Oak Bridge (black-and-white photograph).

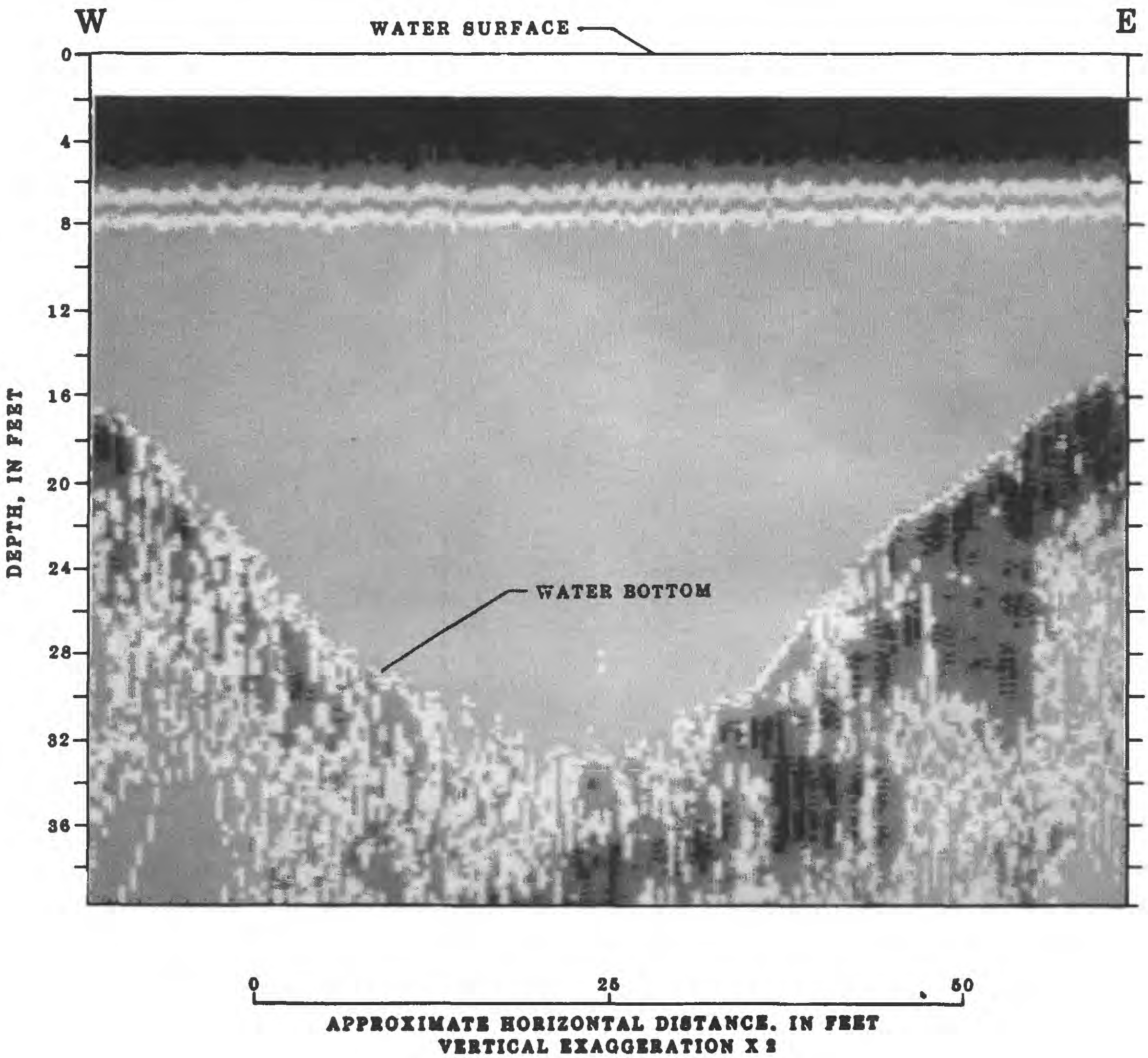

Figure 13.-- A 20-kilohertz color fathometer cross section 10 feet upstream from the Charter Oak Bridge (black-and-white photograph).

In the lateral view, the geometry of the scour hole at the upstream end of the pier was defined and about 5 ft of infilling by post-scour sediments was again detected.

A cross-sectional, 14-kHz tuned-transducer record, from a section 10 ft upstream from the piers, is shown in figure 14. Greater than 20 ft of subbottom penetration was achieved. The record defines the scour-hole geometry and shows 4 to 5 ft of infilled material, and slump deposits on the western side of the scour hole. Reflectors are present within this slumped material that intersect laminar glaciolacustrine sediments. A record of a lateral section 8 ft east of pier 1, also run at 14 kHz, is shown in figure 15. Again, greater than 20 ft of subbottom penetration was achieved. The geometry of the scour hole was clearly defined, and 5 ft of infilled material was evident in the upstream side of the hole. However, no post-scour sedimentation was evident in the deepest part of this scour hole.

Founder's Bridge

The Founder's Bridge, located between the Bulkeley and Charter Oak Bridges connects Interstate 86 between Hartford and East Hartford. There were four rectangular piers, 90 ft long and 20 ft wide, in the water at the time of the study. Pier 1, near the east bank, was located in water too shallow to be navigable. Only ground-penetrating radar and black-and-white fathometer records were obtained at this site. Ground-penetrating radar achieved greater than 10 feet of subbottom penetration, whereas the black-and-white fathometer did not penetrate the river bottom. A ground-penetrating-radar cross section run 8 ft upstream from this bridge is shown in figure 16. Scour, 8 ft upstream from pier 4, extended 10 ft below water-bottom base level and no post-scour sediments were detected. The scour hole at pier 3 extended 8 ft below water-bottom base level, and 4 ft of infilled material is evident on the radar record. No scour was apparent at pier 2, where the water was 25 ft deep. The lack of scour at pier 2 may be attributable to the eastward bend in the Connecticut River, that concentrates flow along the west bank. This was the only pier in the study where there was no significant scour.

CONCLUSIONS

Each of the geophysical methods investigated was useful in assessing riverbed scour at bridge piers. However, each method had characteristic advantages and disadvantages. Consequently, some methods may not be suited for use at a particular site. In most cases, a combination of geophysical methods was the most effective means of assessing scour conditions.

Ground-penetrating radar was the most useful method in shallow water. It provided information about existing scour-hole geometry and the extent of infilling of scour holes by post-scour sediments. This geophysical method

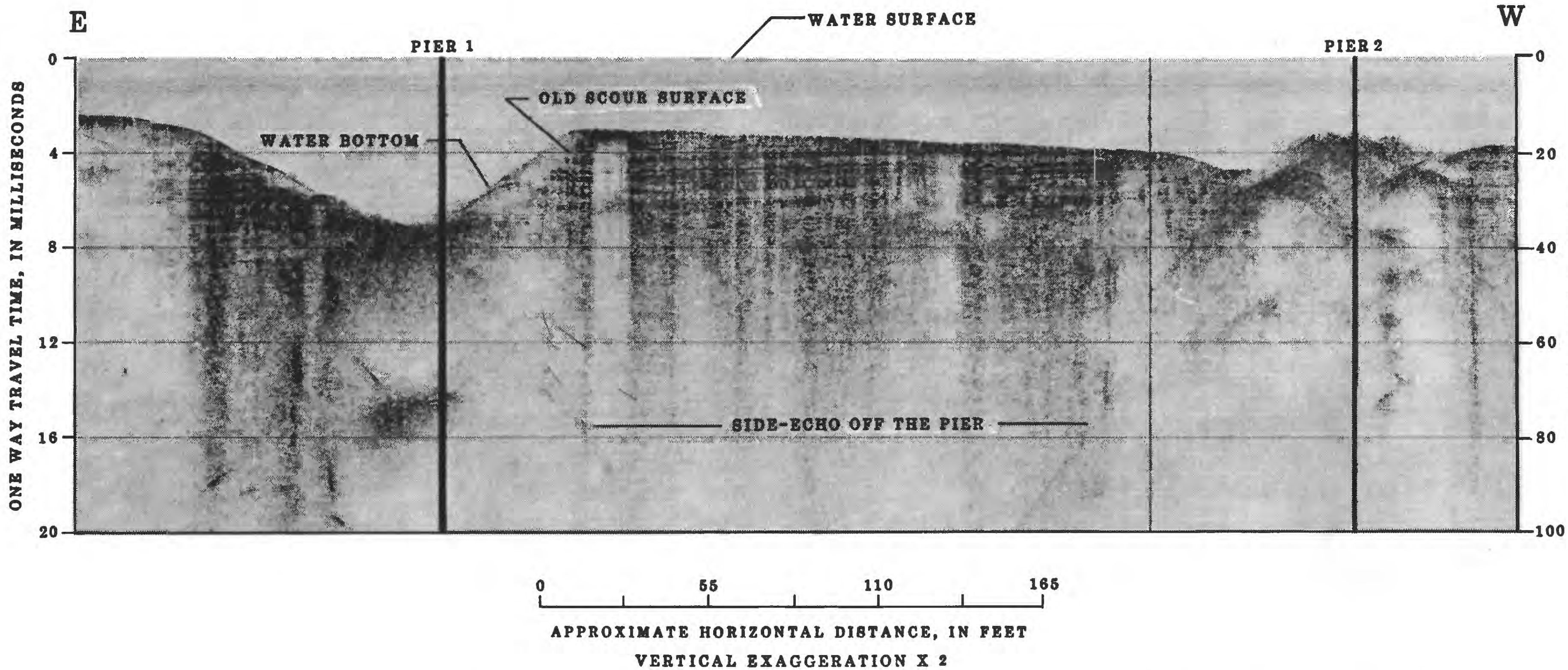

Figure 14.-- A 14-kilohertz tuned-transducer cross section 10 feet upstream from the Charter Oak Bridge.

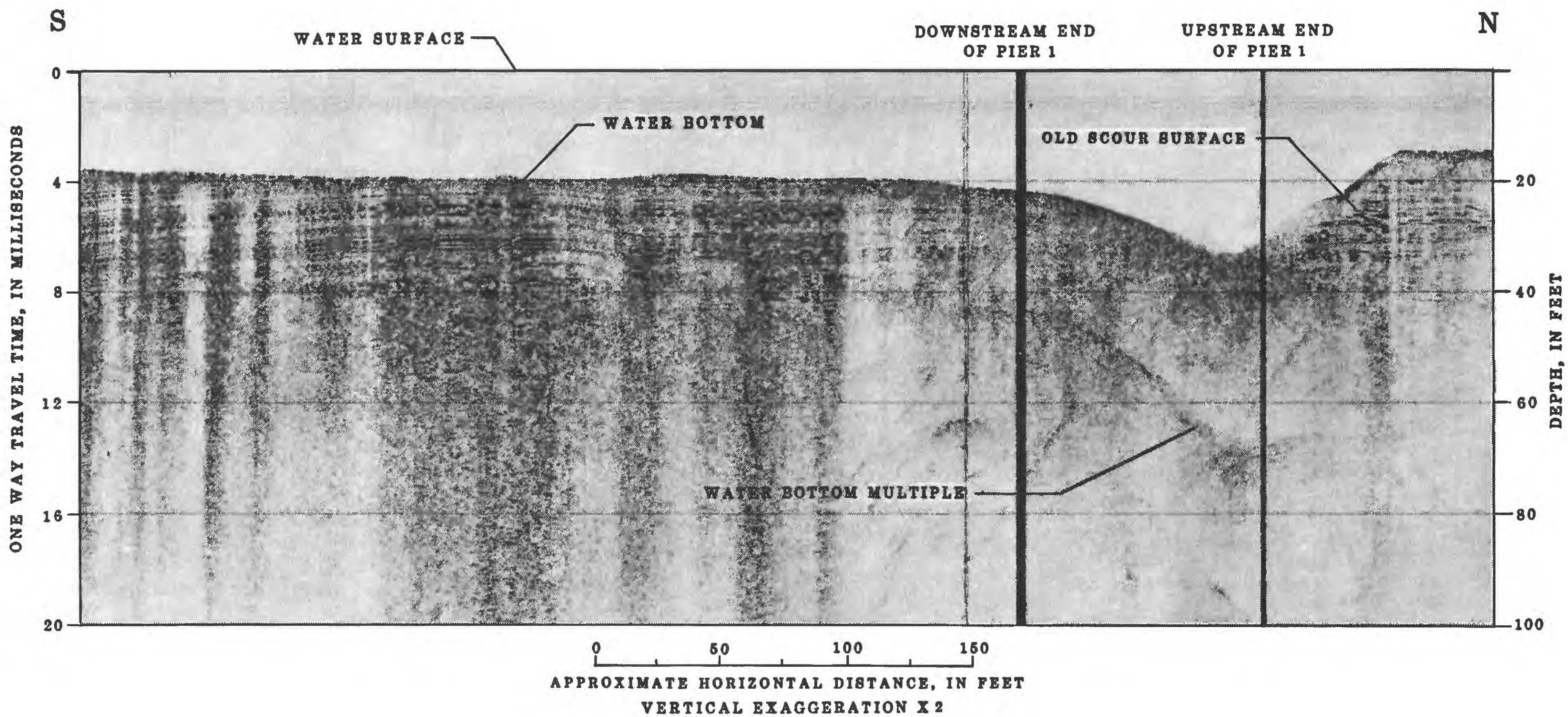

Figure 15.-- A 14-kilohertz tuned-transducer lateral section 8 feet to the east of pier 1 of the Charter Oak Bridge.

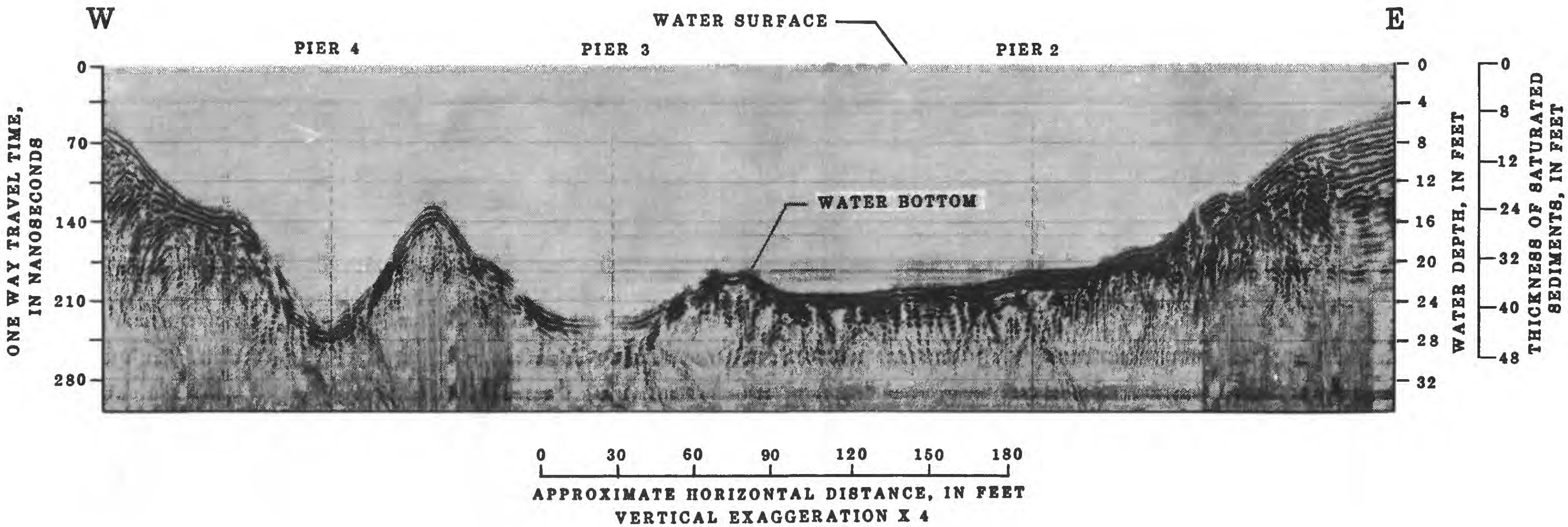

Figure 16.-- Ground-penetrating-radar cross section 8 feet upstream from the Founder's Bridge.

is limited by the depth of water and the electromagnetic and physical properties of subbottom sediments and the water. It should be noted that radar can also be used in dry streambeds to detect scour holes filled by post-scour sediments.

The 200-kHz black-and-white fathometer was useful in determining scour-hole geometry and depth. However, no penetration of the water-bottom was achieved with this instrument. The black-and-white fathometer is most most useful when run in conjunction with other geophysical equipment. It is easy to operate and provides reliable information about water depth without interference from side echos.

The color fathometer was effective in providing information about scour-hole geometry and infilling of scour holes. It also provided qualitative information about the physical properties of bottom and subbottom sediments. Infilling of scour holes by soft sediments above more compact, reflective sediments was detected with this instrument. The color fathometer is most effective in water greater than 5 ft deep and in soft or fine-grained, uncompacted sediments.

The tuned transducer was able to define existing and refilled scour holes. It is most advantageous in water greater than 5 ft deep; at shallower depths, multiple water-bottom reflections may obscure the subsurface data. The tuned transducer may achieve subbottom penetration of 50 ft or more depending on sediment properties such as compactness and grain size. At 14 kHz, resolution of a few inches may be achieved.

The characteristics of each geophysical method are summarized in table 1. Although each method has advantages and disadvantages, no single one proved to be ideal for studying riverbed scour. The degree to which any one method is advantageous for a study depends on several factors. In situations where radar is ineffective, such as in salt water or deep fresh water, the color fathometer or tuned transducer may provide excellent results. Conversely, in shallow fresh water, radar generally provides the best information. In some cases, such as boulder-strewn streambeds, none of these methods will be successful. In most cases, a combination of these geophysical methods can be used to provide the most comprehensive and accurate information on riverbed scour at bridge piers. The geophysical surveys may be conducted during periods of normal or low streamflow, without the need for extensive coring or direct sampling.

Table 1.-- Summary of the geophysical methods used to assess riverbed scour at bridge piers

	GROUND-PENETRATING RADAR	BLACK-AND-WHITE FATHOMETER
FREQUENCY	80 - 1,000 mHz.	200 kHz.
PENETRATION	Less than 20 feet in fresh water.	None in typical marine sediments.
	Less than 80 feet in resistive material (depending on frequency).	1 - 5 feet in very soft sediments.
	A few feet in highly conductive materials.	
RESOLUTION	A few inches to a few feet (depending on frequency).	A few inches.
LIMITATIONS	Limited penetration in salt water, clays, and other conductive materials.	No definition of subbottom materials.
	Multiple reflections may obscure data.	
	Signal may be scattered due to cobbles and boulders.	
	Difficult to operate and interpret.	
	Signal is highly attenuated in the water column.	
ADVANTAGES	Defines subbottom materials and stratigraphy.	Good definition of sediment-water interface.
	Good for use on land and in shallow water.	Accurate assessment of water depth
	Penetration through organic material.	Easy to operate.
	High resolution in shallow subsurface.	A hard copy of data is obtained.
	No multiples on land.	
	A hard copy of data is obtained.	
APPROXIMATE COST	$20,000 - $60,000.	$400 - $3,000.
OPERATION	Operates through the transmission of electromagnetic energy into the subsurface, and the subsequent reception of energy reflected at interfaces between layers or objects of differing electrical properties.	Utilizes a small transducer (a few inches in diameter) to transmit high frequency acoustic pulses, and receive signals reflected at interfaces between layers or objects of differing acoustical properties.
BRIDGE SCOUR STUDIES-ENVIRONMENT	In shallow, fresh water or on land.	In shallow or deep water.
BRIDGE SCOUR STUDIES-EXPECTED RESULTS	May define existing and filled holes.	May define existing holes.
	Good definition of shallow stratigraphy.	Accurate depth assessment.

	COLOR FATHOMETER	TUNED TRANSDUCER
FREQUENCY	20 - 100 kHz.	3.5 - 14 kHz.
PENETRATION	0 - 20 feet, depending on frequency and subbottom material.	0 - 100 feet depending on frequency and subbottom material.
	Little penetration in coarse-grained sediments.	Little penetration in coarse-grained sediments.
RESOLUTION	A few inches.	A few inches to a few feet (depending on frequency)
LIMITATIONS	Minimum water depth of 5 feet.	Minimum water depth of 5 - 10 feet (depending on bottom materials)
	Will not penetrate gases/gassy organics.	Will not penetrate gases/gassy organics.
	Multiple reflections may obscure data.	Difficult to operate.
	Does not provide a hard copy record.	Little penetration in coarse-grained sediments.
	Little penetration in coarse-grained sediments.	
ADVANTAGES	May penetrate conductive materials.	May penetrate conductive materials.
	Variable frequency.	Variable frequency.
	May be used to define subbottom materials and stratigraphy.	May be used to define subbottom materials and stratigraphy.
	Good in deep water.	Good in deep water.
	May indicate some physical properties of sediments (ie. density, porosity, grain size).	A hard copy of data is obtained.
APPROXIMATE COST	$2,000 - $5,000.	$20,000 - $30,000.
OPERATION	Operates with a variable frequency transducer (about 4 inches in diameter) which transmits acoustic pulses and receives the reflected signal from interfaces between layers or objects of differing acoustical properties.	Operates with a variable frequency transducer (about 4 inches in diameter) which transmits acoustic pulses and receives reflected signals from interfaces between layers or objects of differing acoustical properties.
	Cassette recordings of data may be obtained.	Cassette recordings of data may be obtained.
BRIDGE SCOUR STUDIES-ENVIRONMENT	In greater than 5 feet of water.	In greater than 5 feet of water.
BRIDGE SCOUR STUDIES-EXPECTED RESULTS	May define existing and filled holes.	May define existing and filled holes.
	May vary frequency to optimize penetration or resolution.	May vary frequency to optimize penetration or resolution.
	May indicate some physical properties of sediments.	

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