# RESULTS OF A RECONNAISSANCE BRIDGE-SCOUR STUDY AT SELECTED SITES IN OREGON USING SURFACE-GEOPHYSICAL METHODS, 1989

By Milo D. Crumrine

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 90-4199

Prepared in cooperation with
OREGON DEPARTMENT OF TRANSPORTATION

Portland, Oregon
1991

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## CONVERSION FACTORS AND VERTICAL DATUM

| Multiply | By | To obtain |
|---|---|---|
| | LENGTH | |
| inch (in) | 25.4 | millimeter (mm) |
| foot (ft) | 0.3048 | meter (m) |
| mile (mi) | 1.609 | kilometer (km) |
| | AREA | |
| acre | 4,047 | square meter ($m^2$) |
| acre | 0.4047 | hectare (ha) |
| square mile ($mi^2$) | 259.0 | hectare (ha) |
| square mile ($mi^2$) | 2.590 | square kilometer ($km^2$) |
| | VOLUME | |
| cubic foot ($ft^3$) | 0.02832 | cubic meter ($m^3$) |
| | FLOW | |
| cubic foot per second ($ft^3/s$) | 0.02832 | cubic meter per second ($m^3/s$) |
| gallon per minute (gal/min) | 0.06308 | liter per second (L/s) |

SEA LEVEL: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)--a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

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## ABSTRACT

Three geophysical methods--ground-penetrating radar, high-frequency continuous seismic reflector (tuned transducer), and a color fathometer--were used to examine 14 bridge sites in Oregon, to determine the usefulness of each method in locating and determining depth of infilled scour holes around bridge piers in Oregon streams. Each geophysical method was capable of detecting infilling around piers, but because of equipment limitations, not every method was effective at each site. The softer infilled material present at nearly all sites was probed by a metal rod to verify data collected by the geophysical equipment. Scour equations were marginally successful in predicting two existing scour holes that were identified as having been caused by a peak flow. Most study sites had local conditions, such as riprap, debris, or remnants of old coffer dams that invalidated the use of equations.

## INTRODUCTION

Exposure or undermining of bridge piers and bridge-abutment foundations from the erosive action of flowing water can result in structural damage of a bridge, requiring major expenditures for repair or replacement. Scour of the streambed in the vicinity of bridge piers and abutments during floods has resulted in more bridge failures in recent history than all other causes (Murillo, 1987). Determining maximum scour at piers caused by high streamflows is critical for the maintenance of existing bridges and for the design of future bridges.

Scour can result from a combination of three interrelated phenomena:

(1) Local scour at bridge piers and abutments, which cause local flow disturbances,

(2) Constriction scour caused by changes in flow because the bridge openings are smaller than the natural channel, and

(3) General scour that is part of the natural processes of streambed degradation.

In the study reported here, the U.S. Geological Survey, in cooperation with the Oregon Department of Transportation, invoked the capability of three geophysical methods to measure scour at 14 bridge sites in Oregon.

Maximum local scour can be predicted using scour equations such as those developed by Laursen (1984), Froehlich (1988), Raudkivi (1989), and Richardson and Richardson (1989). Increased use of these scour equations has prompted interest in developing a data base of field measurements of scour depths at various bridge sites. Many recent technical reports and journal articles pertaining to bridge scour emphasize the need for onsite measurement of scour at bridges during high-flow events (Richardson, 1989). However, measurement of scour during a major flood event is difficult because of the infrequency of major floods, and field conditions at the time of the flood.

Because scour holes refill after a high-flow event and during low-flow periods, measurements of a remnant scour hole after the peak flow can be misleading. Coring and geophysical methods are two methods that have been used to determine depths of infilled scour holes (Haeni and Gorin, 1989). Obtaining an undisturbed core sample is difficult in streambeds composed of gravels or cobble sized materials. Haeni and others (1987) have shown that geophysical methods are effective in determining subsurface stratigraphy in lake beds, and Gorin and Haeni (1989) have shown that geophysical methods can determine the maximum scour that has occurred in the vicinity of bridge piers for many channel types.

## Purpose and Scope

The purpose of this report is to present results of a geophysical survey made at 14 bridge sites in Oregon during 1989, and to discuss the application of geophysical methods in determining the depth of infilled scour holes in the vicinity of bridge piers.

Fourteen bridges crossing five streams were selected from approximately 50 potential sites to test the surface-geophysical methods. The three surface-geophysical methods, in addition to the black-and-white fathometer, used in this study were GPR (ground-penetrating radar), TT (tuned transducer), and CF (color fathometer).

At each selected bridge site, scour was investigated at most of the piers in water were investigated for scour by traveling around them using a black-and-white fathometer and one of the three geophysical methods. Piers having the deepest scour holes and the most infilled material were selected for detailed study. Because of the limitations of each geophysical method, all three methods could not be used at every site. Comparison among geophysical methods was made when more than one method was used at a site. Interpretation of the geophysical data were verified by probing with a graduated rod. Measurements using the probing rod were made from the water surface to (1) pier footing, (2) seals, (3) bottom of scour holes, (4) bottom of infilled scour holes, and (5) emplaced riprap.

## Acknowledgments

The author would like to thank ODOT (Oregon Department of Transportation) personnel for their cooperation in providing support for this project, especially Lew Scholl for his direction, David Bryson and Ilene Poindexter for supplying bridge plans and scour site information, and Glen Thommen for providing bridge-engineering definitions for use in this paper. The author also would like to thank Christopher Dunn and Bruce Johnson from the Federal Highway Administration for their support and direction.

## DESCRIPTION OF GEOPHYSICAL METHODS

Even though GPR, TT, and CF are different geophysical devices, they are similar in operational principles. Each device transmits a signal and records the reflected signal. Depth tis measured a a function of the time it takes for the signal to go from the transmitter to the water bottom and layers in the subbottom, and back to the reciever. Measured depths are displayed on a screen or graphic recorder. Records of transmitted and reflected signals and can be stored on magnetic tape for future analysis.

The geophysical methods have been described in detail by Gorin and Haeni (1989), and are summarized in in table 1.

### Ground-Penetrating Radar (GPR)

GPR transmits electromagnetic signals in the 80-1,000 MHz (megahertz) frequency spectrum. The GPR signal is transmitted and received by antennae that are usually floated along the side of the survey boat. Although GPR can be operated over dry land, all of the radar profiles made for this study were done over water. The use of GPR in a small boat is shown in figure 1.

Figure 1.--Ground-penetrating-radar equipment being operated from a small boat.

Table 1.--Advantages and limitations of geophysical method (modified from Gorin and Haeni, 1989)

| Attributes | Methods: Ground-penetrating radar | Black and white fathometer | Color fathometer | High frequency profiler |
|---|---|---|---|---|
| FREQUENCY: | 80-1,000 megahertz | 200 kilohertz | 20 - 100 kilohertz | 3.5 - 14 kilohertz |
| PENETRATION: | <20 feet in water column (fresh).<br><80 feet in resistive material (depending on frequency).<br>A few feet in highly conductive materials. | None in typical marine sediments.<br>1 - 5 feet in very soft sediments. | 0 - 20 feet depending on frequency selected and subbottom material.<br>Little penetration in coarse-grained sediments. | 0 -20 feet depending on frequency and subbottom material.<br>Little penetration in coarse-grained sediments. |
| RESOLUTION: | A few inches to a few feet (depending on frequency). | A few inches. | A few inches. | A few inches to a few feet (depending on frequency). |
| LIMITATIONS: | Limited penetration in salt water, clays, and other conductive materials.<br>Multiple reflections may obscure data.<br>Signal may be scattered due to cobbles and boulders.<br>Difficult to operate and interpret.<br>Signal is highly attenuated in the water column. | No definition of subbottom materials. | Minimum water depth of 5 feet.<br>Will not penetrate gases/gassy organics.<br>Multiple reflections may obscure data.<br>Does not provide a hard copy record.<br>Little penetration in coarse-grained sediments. | Minimum water depth of 5-10 feet (depending on bottom materials).<br>Will not penetrate gases/gassy organics.<br>Little penetration in coarse-grained sediments. |
| ADVANTAGES: | Defines subbottom materials and stratigraphy.<br>Good for use on land and in shallow water.<br>Penetration through organic material.<br>High resolution in shallow subsurface.<br>No multiples on land.<br>A hard copy of data is obtained. | Good definition of sediment-water interface.<br>Accurate assessment of water depth.<br>Easy to operate.<br>A hard copy of data is obtained. | May penetrate conductive materials.<br>Variable frequency.<br>May be used to define subbottom materials and stratigraphy.<br>Good in deep water.<br>May indicate some physical properties of sediments (for example, density, porosity, grain size). | May penetrate conductive materials.<br>Variable frequency.<br>May be used to define subbottom materials and stratigraphy.<br>Good in deep water.<br>A hard copy of data is obtained |
| COST:(APROX) | $20,000 - $60,000. | $400 - $3,000. | $2,000 - $5,000. | $20,000 - $30,000. |
| 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. | 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. Cassette recordings of data may be obtained. | Operates with a variable frequency transducer (about 12 inches in diameter) which transmits acoustic pulses and receives the reflected signal from interfaces between layers or objects of differing acoustical properties. Cassette recordings of data may be obtained. |
| BRIDGE SCOUR ENVIRONMENT | In shallow, fresh water or land. | In shallow or deep water. | In greater than 5 feet of water. | In greater than 5 feet of water. |
| BRIDGE SCOUR STUDIES | May define existing and filled holes. | May define existing holes. | May define existing and filled holes. | May define existing and filled holes. |
| EXPECTED RESULTS | Good definition of shallow stratigraphy. | Accurate depth assessment. | May vary frequency to optimize penetration or resolution.<br>May indicate some physical properties of sediments | May vary frequency to optimize penetration or resolution. |

Signals from GPR reflect energy from changes in strata that have different electromagnetic properties. Infilled scour holes are best detected when the infilled material has different physical properties from the surrounding bed material.

Data from GPR measurements are displayed on a chart recorder and recorded on a magnetic tape recorder. Data can be reproduced by playing the magnetic tape back into the radar receiver and recording on the chart. This is useful for reviewing the data at different gain or contrast settings and for processing the data to obtain clearer records. An example of uncorrected GPR record is shown in figure 2.

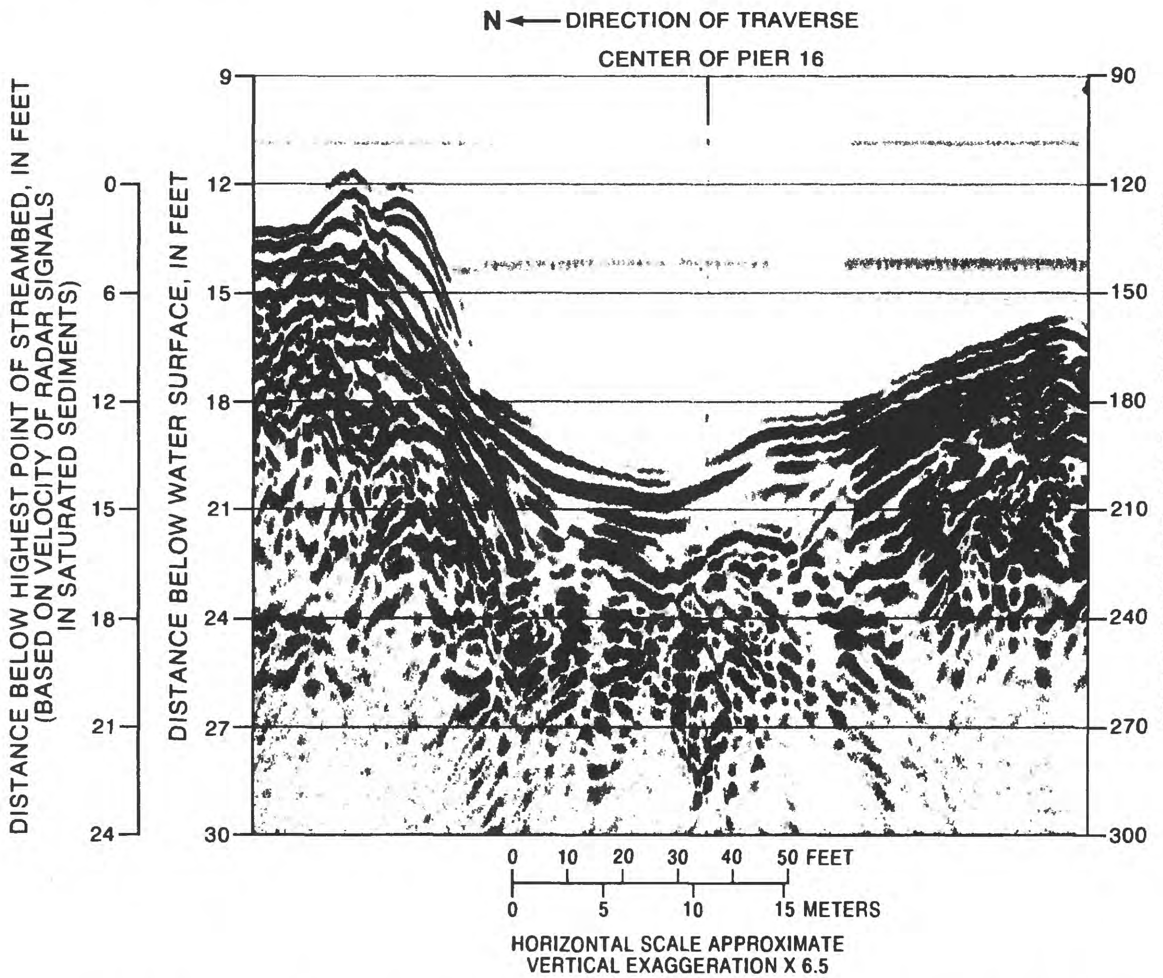



Figure 2.--Example of ground-penetrating-radar record (Columbia River at Highway I-205, 20 feet upstream from pier 16).

Water attenuates the radar signal and, in depths greater than 20 ft (feet), subbottom interfaces generally cannot be detected. During this study, however, GPR detected subbottom interfaces in water with low specific conductance at depths greater that 20 ft. Sea water or high conductivity water severely attenuates the signal and prevents GPR from being usable in this situation.

Signals from GPR have a velocity of 0.11 ft/ns (feet per nanosecond) in water and about 0.2 ft/ns in saturated sediment (Haeni and Gorin, 1989). This difference in velocity must be accounted for when calculating scour-hole and infilled scour-hole depths. The most accurate method of determining velocities of the radar signal is to measure a known elevation, such as the top of the pier footing or the bottom of the scour hole, determine the two-way travel time from the radar record, and calculate the radar wave velocity. During this study, measurements were made to determine the distance from the water surface to bed material. Figures showing GPR record have scales indicating both water and saturated sediment signal travel times, figure 2 left side.

## Tuned Transducer (TT)

The high frequency continuous seismic reflector (tuned transducer) transmits seismic signals that travel at approximately 5,000 ft/s (feet per second) in water and saturated unconsolidated sediments (Haeni and Gorin, 1989). Transducers used during this study were operated at frequencies of 3.5, 7, and 14 kHz/s (kilohertz per second). The selected transducer was secured along side a boat approximately 2 ft below the water surface, and the boat was maneuvered around bridge piers at a slow rate of speed. Data from TT are recorded on a graphic recorder and magnetic tape recorder. The TT system works well only in water deeper than 5 ft. Because TT signals travel approximately the same velocity in water as in bottom sediments, calculating respective depths of water and subbottom interfaces is not as difficult as with GPR.

Seismic signals are reflected when they encounter a boundary between two materials that have different physical properties; for example, the water and the channel bottom, and the armored layers of cobble and gravel beneath a softer infilled layer. The TT system measures the time a seismic signal takes to travel to and return from an interface. To convert this time scale to distance, the velocity of sound in water and saturated sediment must be known. Field measurements of the depth to interface are necessary to verify the geophysical interpretation. An example of TT record is shown in figure 3.

## Color Fathometer (CF)

The CF transmits signals in the 20 to 100 kHz frequency range. Transmitted and reflected signals are shown on a screen similar to that of a color monitor. The field data are recorded on a magnetic tape recorder for later replay and, at the time of this study, hard copies could can be obtained only by photographing the monitor. The color fathometer has the capability of selecting transducer frequencies from 20 to 100 kHz, but best results for this study were obtained using the lower frequencies. Colors ranging from red to blue represent the amplitude of the reflected signals. Red represents the largest and blue the smallest amplitude signal. The transmitted signal is seen on the screen by a band of colors, with red (strong signal) at the top and blue (weak signal) at the bottom (Haeni and Gorin, 1989). Reflectors, such as the river bottom, are shown on the screen as a change in color, from a small amplitude signal (for example, blue) to a bright color (for example, red). In uniform sediment the reflected signal amplitude decreases with depth.

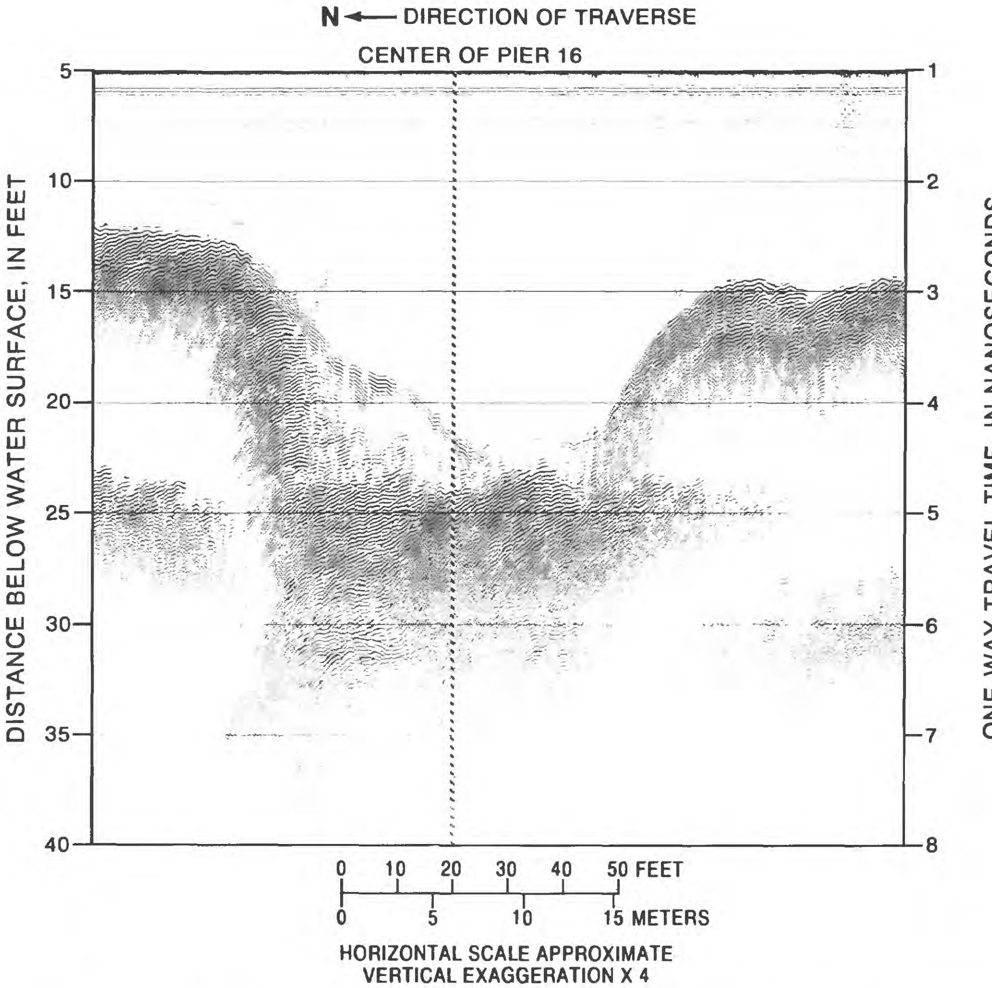



Figure 3.--Example of a 14 kilohertz tuned-transducer record (Columbia River at Highway I-205, 20 feet upstream from pier 16).

Using the CF method, subsurface layers are distinguished where the reflected signal amplitude goes from weaker to stronger with increased depth. This is seen on the monitor changing colors, such as a color change from blue to yellow or from green to red. This color change is the opposite from the normal decay (for example red to blue). Photographs showing a typical CF setup in a boat and CF data from a scour hole are shown in figures 4 and 5, respectively.

## SELECTION OF SITES

Approximately 50 sites were considered for their suitability for geophysical methods to measure the amount of infilling in scour holes. Sites were selected primarily from a list compiled by the Oregon Department of Transportation. Their list included bridges that have possible scour problems and bridges located over streams that can be navigated by boat. Three of the sites selected were not on the list and were chosen to provide a greater variety of streambed conditions.

Figure 4.--Color fathometer being operated from a boat.

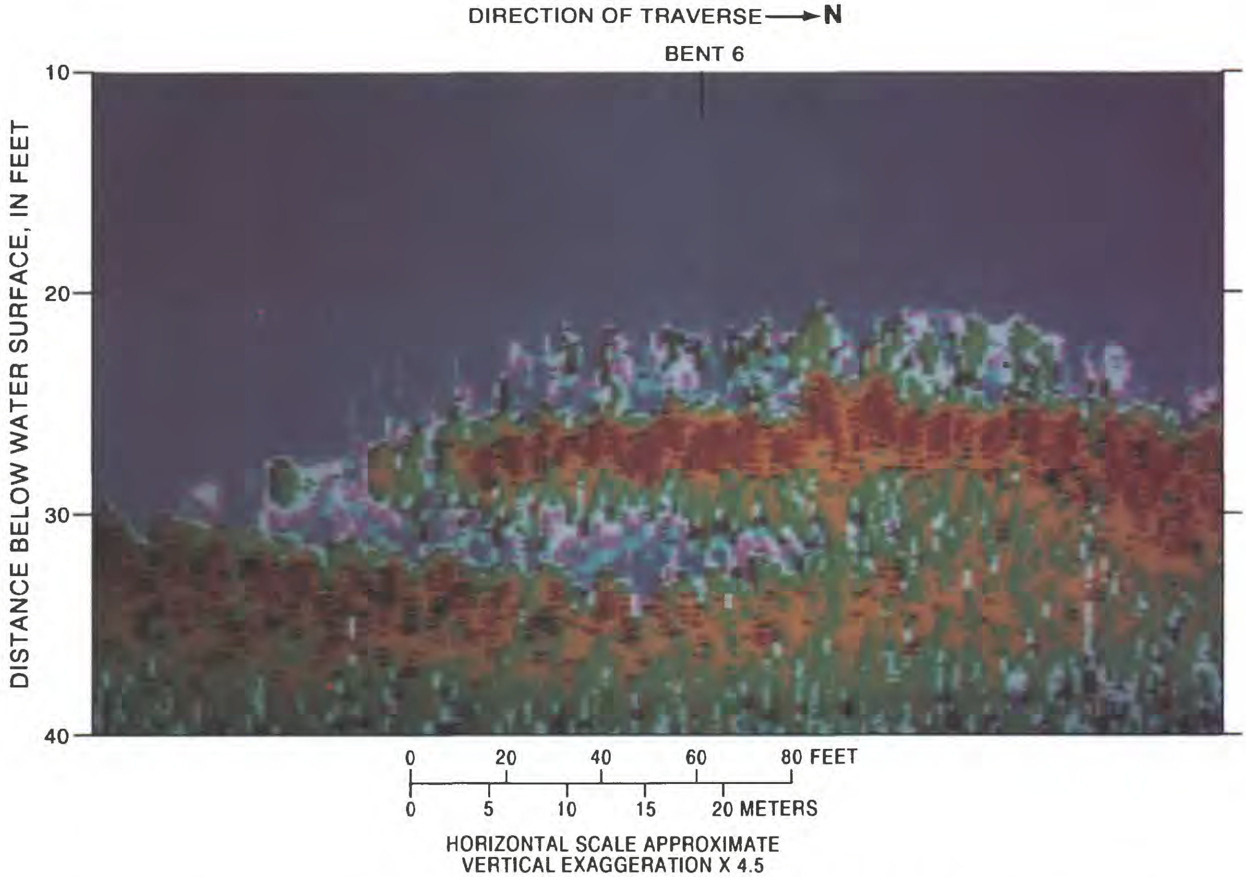


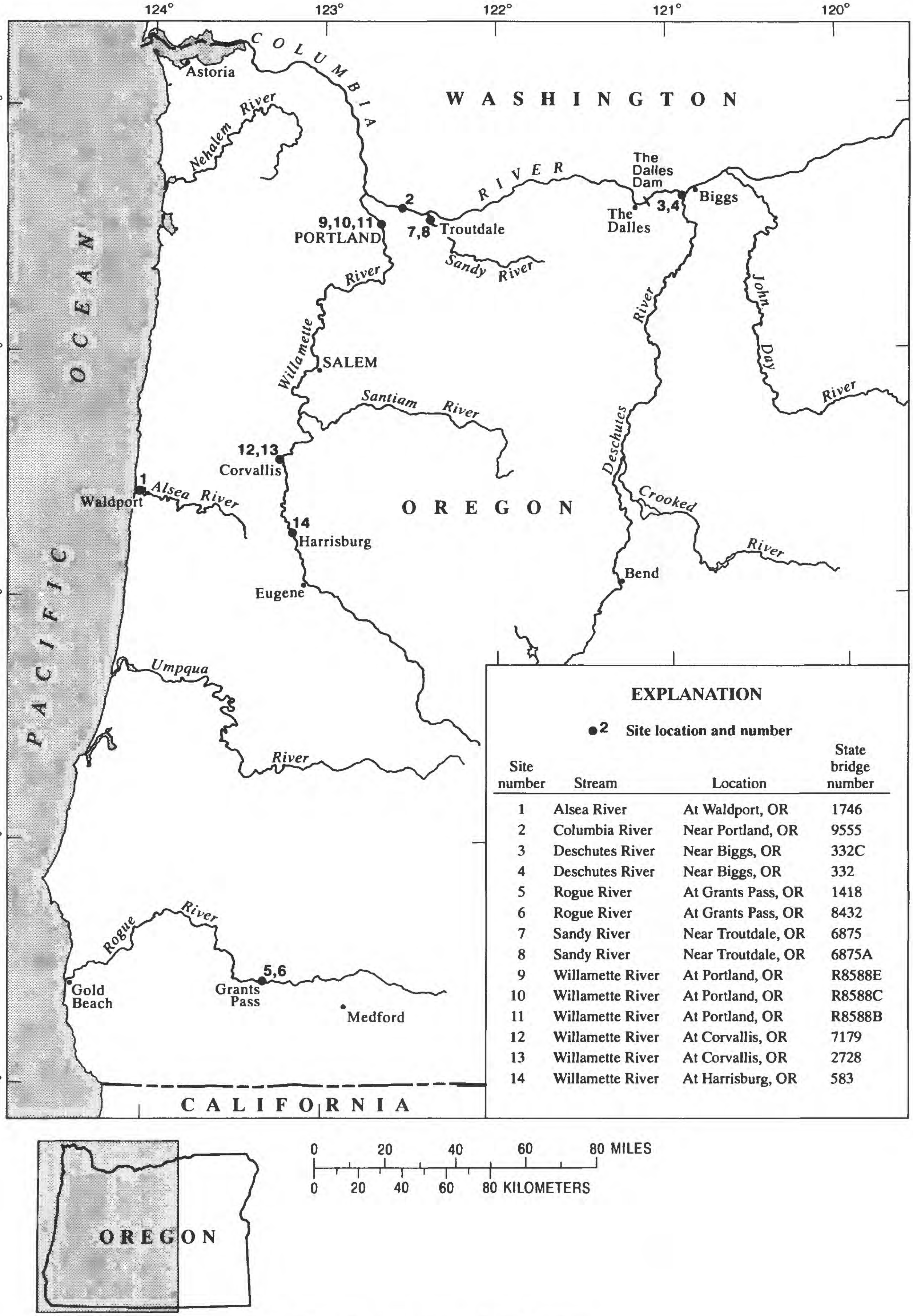

Figure 5.--Example of a 20-kilohertz color-fathometer record (Willamette River at Portland, Oregon). Color bands at the top of the figure indicates decay of the transmitted signal. The middle blue color represents the water column, and the colors at the bottom indicate the streambed and infilled layer.

Because the primary purpose of this study was to determine if geophysical methods would be useful in determining maximum scour depths around bridge piers in Oregon, an attempt was made to choose bridges over a variety of typical Oregon streams. Streams selected have bed-material sizes ranging from sand and silt to cobbles, and have median flow velocities ranging from 0 to 6.0 ft/s. Site selection was limited to 14 bridges because of time and funding constraints. The location and listing of the 14 sites selected are shown in figure 6 and table 2.

## RESULTS OF SURFACE-GEOPHYSICAL MEASUREMENTS AT SELECTED SITES

### Alsea Bay Bridge at Waldport, Oregon (Site 1)

Highway 101 bridge at Waldport spans the Alsea River Estuary, which is located near the Pacific Ocean (see fig. 6). At this location, the Alsea Bay is affected by tides ranging between -5.0 ft and 10.0 ft (NGVD of 1929). Velocities at the bridge reach about 6.0 ft/s when the water is running out of the bay and about 4.5 ft/s when sea water is running into the bay (U.S. Geological Survey, unpub. data, Portland, Oregon, 1989). At the location of the bridge, Alsea Bay is approximately 1 mile




**EXPLANATION**

● 2 Site location and number

| Site number | Stream | Location | State bridge number |
|---|---|---|---|
| 1 | Alsea River | At Waldport, OR | 1746 |
| 2 | Columbia River | Near Portland, OR | 9555 |
| 3 | Deschutes River | Near Biggs, OR | 332C |
| 4 | Deschutes River | Near Biggs, OR | 332 |
| 5 | Rogue River | At Grants Pass, OR | 1418 |
| 6 | Rogue River | At Grants Pass, OR | 8432 |
| 7 | Sandy River | Near Troutdale, OR | 6875 |
| 8 | Sandy River | Near Troutdale, OR | 6875A |
| 9 | Willamette River | At Portland, OR | R8588E |
| 10 | Willamette River | At Portland, OR | R8588C |
| 11 | Willamette River | At Portland, OR | R8588B |
| 12 | Willamette River | At Corvallis, OR | 7179 |
| 13 | Willamette River | At Corvallis, OR | 2728 |
| 14 | Willamette River | At Harrisburg, OR | 583 |

Figure 6.--Study area and site locations.

Table 2.--List of 14 sites in Oregon with highway numbers, bridge numbers, and river-mile locations

| Stream | Location | River mile | Highway number | State bridge number | State highway number |
|---|---|---|---|---|---|
| Alsea River | At Waldport | 0.9 | 101 | 1746 | 1 |
| Columbia River | Near Portland | 113.0 | I-205 | 9555 | 64 |
| Deschutes River | Near Biggs | .4 | I-84 | 332C | 2 |
| Deschutes River | Near Biggs | .5 | 206 | 332 | 301 |
| Rogue River | At Grants Pass | 101.2 | 199 S | 1418 | 25 |
| Rogue River | At Grants Pass | 101.2 | 199 N | 8432 | 25 |
| Sandy River | Near Troutdale | 2.4 | I-84 E | 6875 | 2 |
| Sandy River | Near Troutdale | 2.4 | I-84 W | 6875A | 2 |
| Willamette River | At Portland | 12.3 | I-84/I-5 | R8588E | 2 |
| Willamette River | At Portland | 12.3 | I-84/I-5 | R8588C | 2 |
| Willamette River | At Portland | 12.4 | I-84/I-5 | R8588B | 2 |
| Willamette River | At Corvallis | 131.3 | 34 W | 7179 | 210 |
| Willamette River | At Corvallis | 131.4 | 34 E | 2728 | 210 |
| Willamette River | At Harrisburg | 161.2 | 99 E | 583 | 58 |

wide with the main part of flow occurring near the north side. A new bridge is under construction about 100 ft upstream from the present Highway 101 bridge. This site was selected for study because of an ongoing bridge-pier scour study between the USGS and ODOT. A plan view showing part of the Alsea Bay, the old Highway 101 bridge, some new bridge bents, and the location of the work trestle are shown in figure 7.

Alignment of flow direction to the bridge piers changes with respect to tide. In the main part of Alsea Bay, the direction of flow is nearly parallel to the piers during ebb tide, while during flood tides the angle is about 15 degrees from parallel. For this reason, scour holes resulting from flood tides are deeper than scour holes resulting from ebb tide, even though flood tide velocities are lower (U.S. Geological Survey, unpub. data, Portland, Oregon, 1989).

Construction of the new bridge has caused a decrease in outgoing velocity in the vicinity of pier 6 of the old bridge. This drop in velocity, along with constriction scour from the work trestle and new coffer dam, has resulted in sand being deposited underneath the old bridge between piers 6 and 7.

Two geophysical methods (TT and CF) were used at this site. Because Alsea Bay consists mostly of seawater, GPR could not be used. The CF record indicated a subsurface layer underneath the old bridge between piers 6 and 7. The thickness of the infill material was interpreted from the CF to be about 5 ft thick. This agrees with field measurements made in the same location (U.S. Geological Survey, unpub. data, Portland, Oregon, 1989). The TT record showed some indication of infilling, but it was not as clear as it was on the CF record. A CF photograph showing infilling 20 ft south of pier 6 is shown in figure 8.

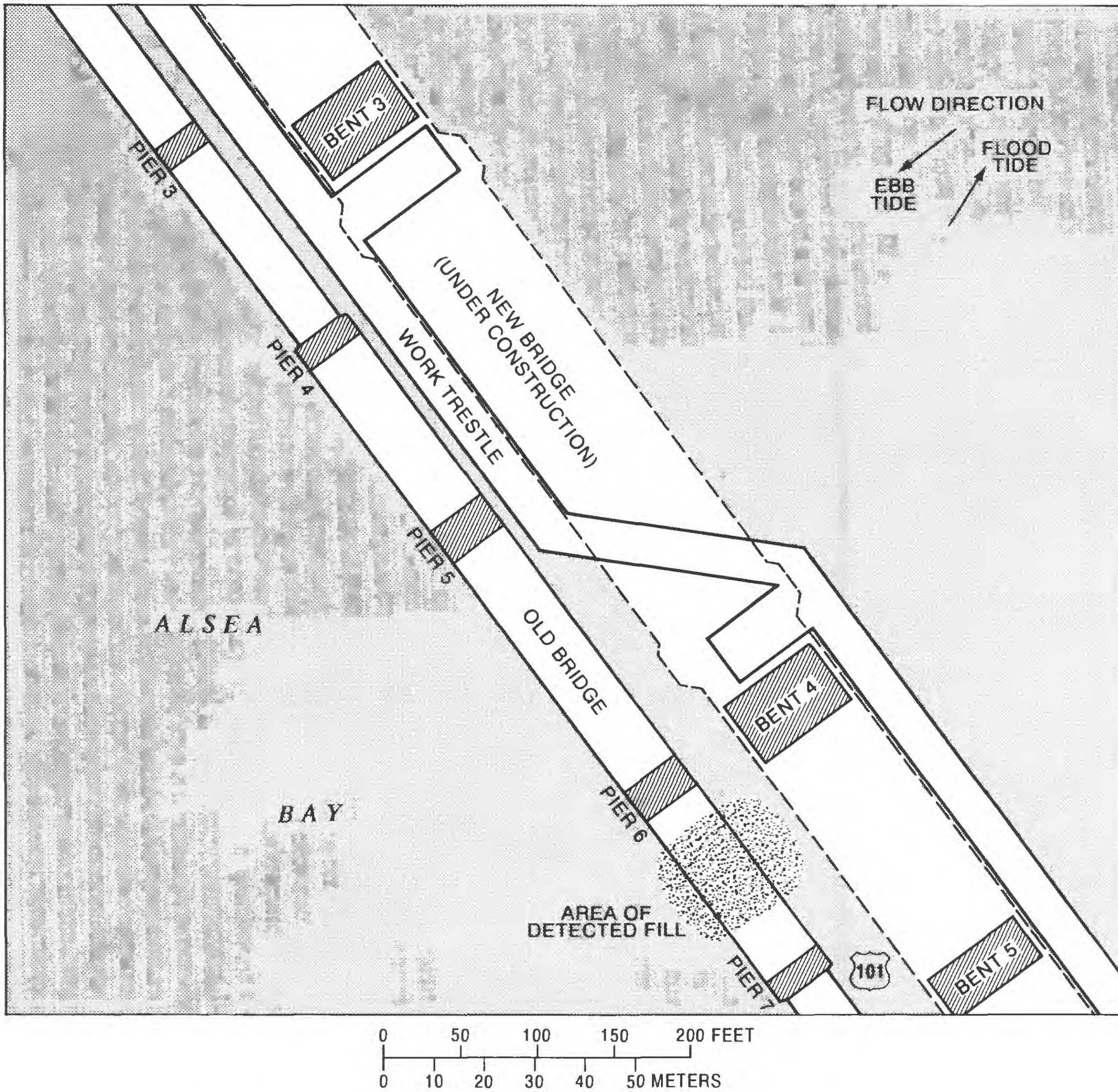



Figure 7.--Plan view of Highway 101 bridge and construction trestle at Alsea Bay, Oregon.

## Columbia River Glenn Jackson Bridge at Portland, Oregon (Site 2)

Interstate-205 Bridge crossing the Columbia River was chosen as a good location to test all of the surface-geophysical methods. The flow of the Columbia River at this site is affected by tide. Maximum velocities in the main channel at this site reach about 6 ft/s, and bed material consists of sand-sized particles. Specific conductance at this site is normally less than 20 $\mu$S/cm (microsiemens per centimeter). At this location, the Columbia River is divided by Government Island, with the main part of the river flowing north of the island (fig. 9). The main channel of the river is dredged to a depth of 40 ft at normal flow, for navigational purposes. Interstate-205 bridge piers along the south side of Government Island were not investigated. Preliminary investigation indicated that because of the high velocities and the depth

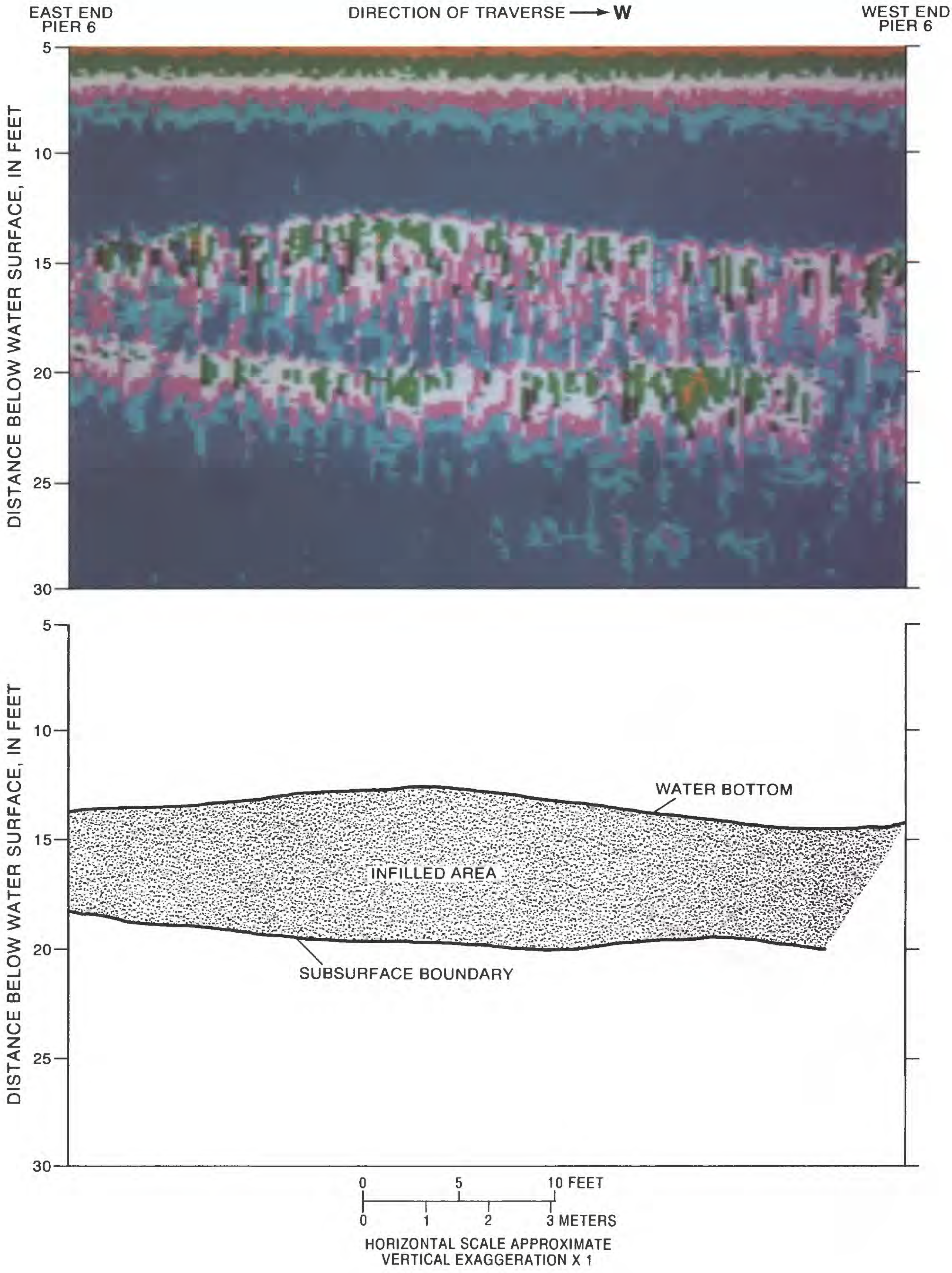



Figure 8.--A 20-kilohertz color-fathometer record and interpretation of infilled area at Alsea Bay, Oregon. Location of lateral run is 20 feet south of pier 6.

of waters, existing scour holes around piers in the main channel appear to be about 25 ft below the nearby streambed. Further study using surface-geophysical methods showed that soft infilled material exists above a riprap layer. Riprap was found at the bottom of pier 16 scour hole, indicating that bed material had been backfilled over the riprap or this material had been deposited naturally since placement of the riprap.

The initial investigation, using TT in conjunction with black-and-white fathometer, showed that pier 16, located north of Government Island and just south of the dredged channel, had the most infilled material (15 ft along side of the scour hole and 3 ft at the center of the scour hole). This pier was selected for further study using the other geophysical methods. The TT record (fig. 10A) clearly showed the presence of material over riprap. The GPR worked well at this site, even though depths were near 30 ft, showing 3 ft of infilled material at the center of the scour hole (fig. 10B). Relatively low specific conductance of the Columbia River (less than 200 $\mu S/cm$) allowed penetration of the GPR signals beyond the normal 20 ft limitation. The CF record clearly outlined the existing scour holes, but the buried riprap was harder to detect with this method than the other two methods (fig. 10C). Interpretations made from the geophysical records were verified by probing. The riprap layer at the upstream side of pier 16 was located at -23.5 ft, which is about 17 ft above the bottom of the pier and is approximately at the same elevation as shown on the original bridge plans.

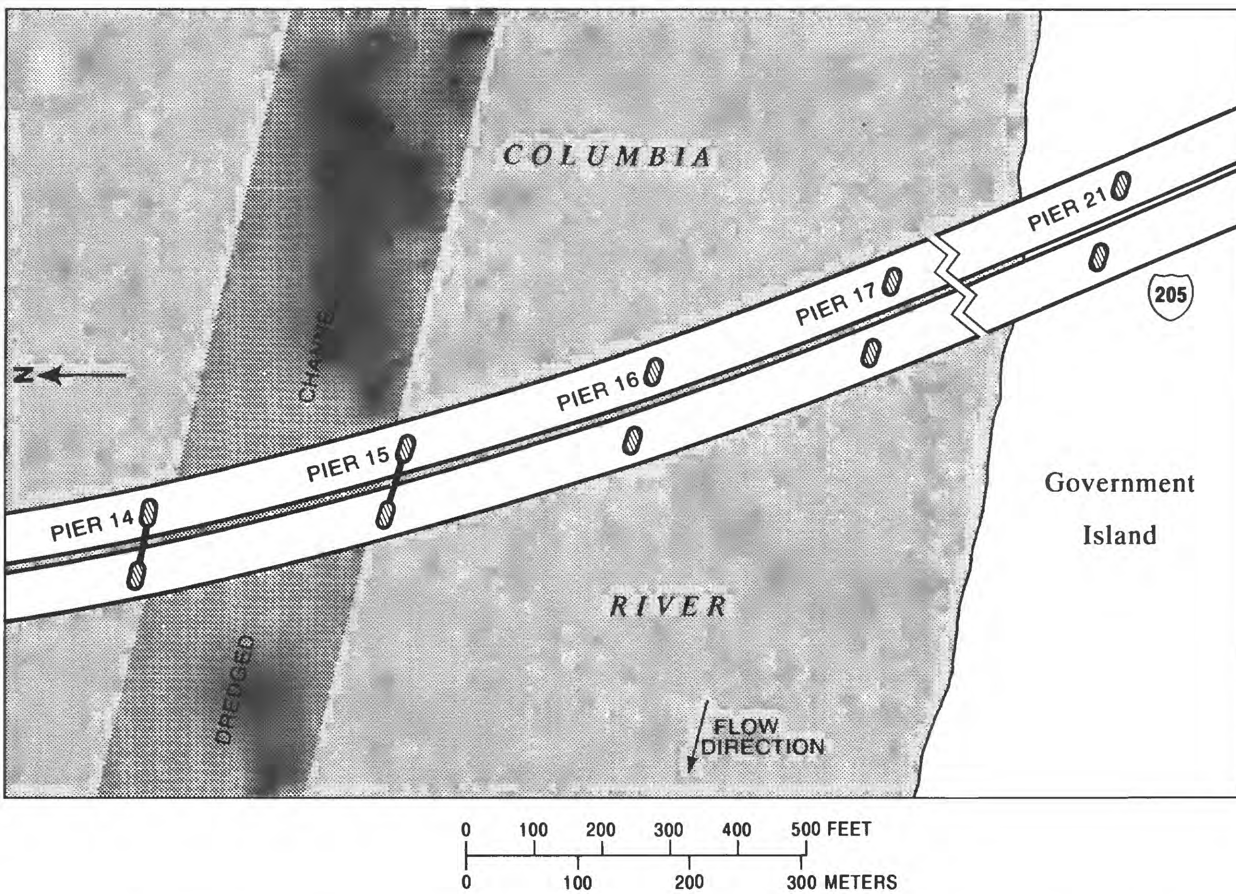



Figure 9.--Plan view showing Interstate-205 bridge over the Columbia River near Portland, Oregon.

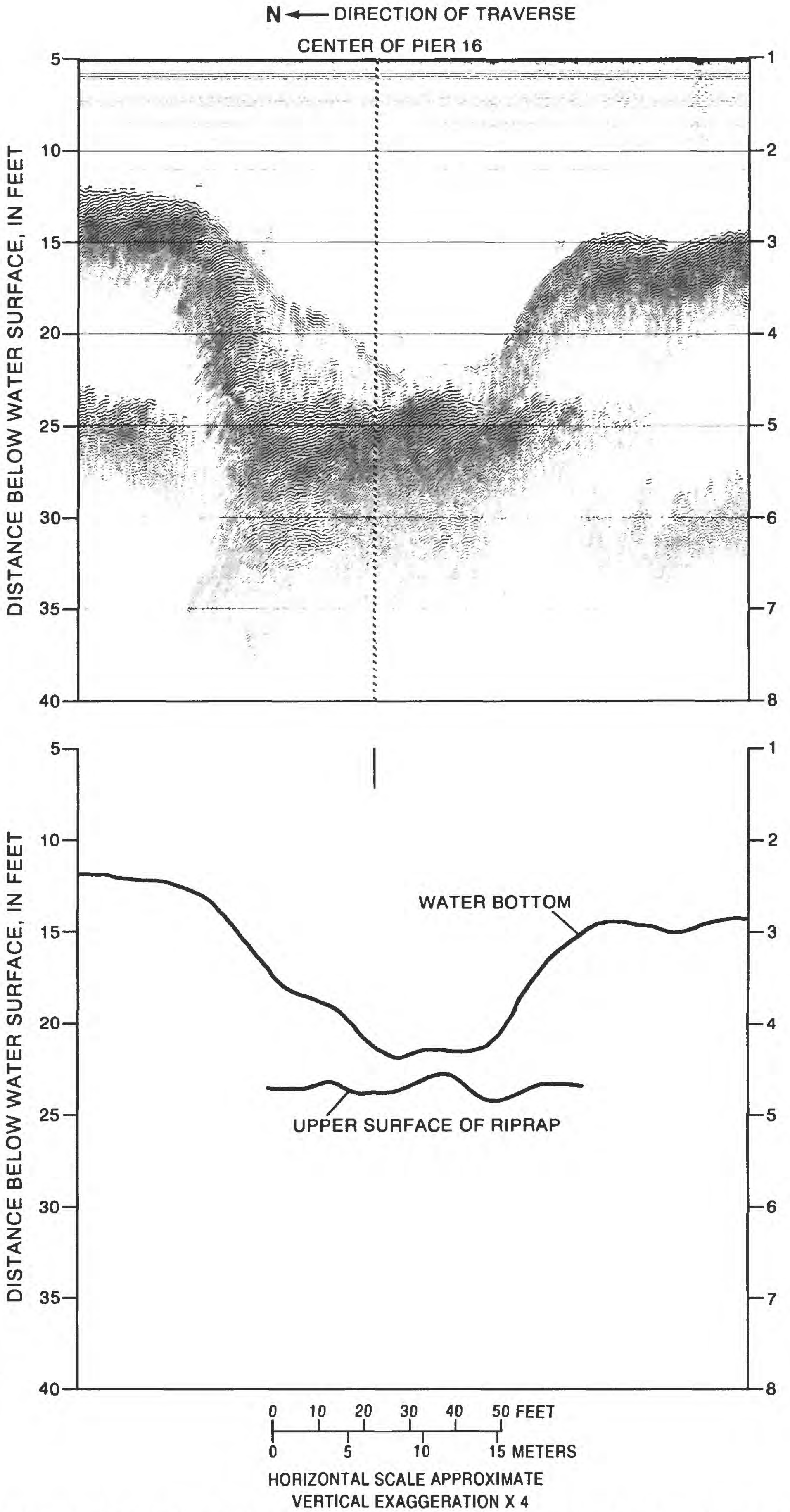



Figure 10A.--Surface-geophysical 14-kilohertz tuned-transducer records showing scour holes and riprap layers of the Columbia River at Highway Interstate-205 Bridge, and interpretation, 20 feet upstream from pier 16.

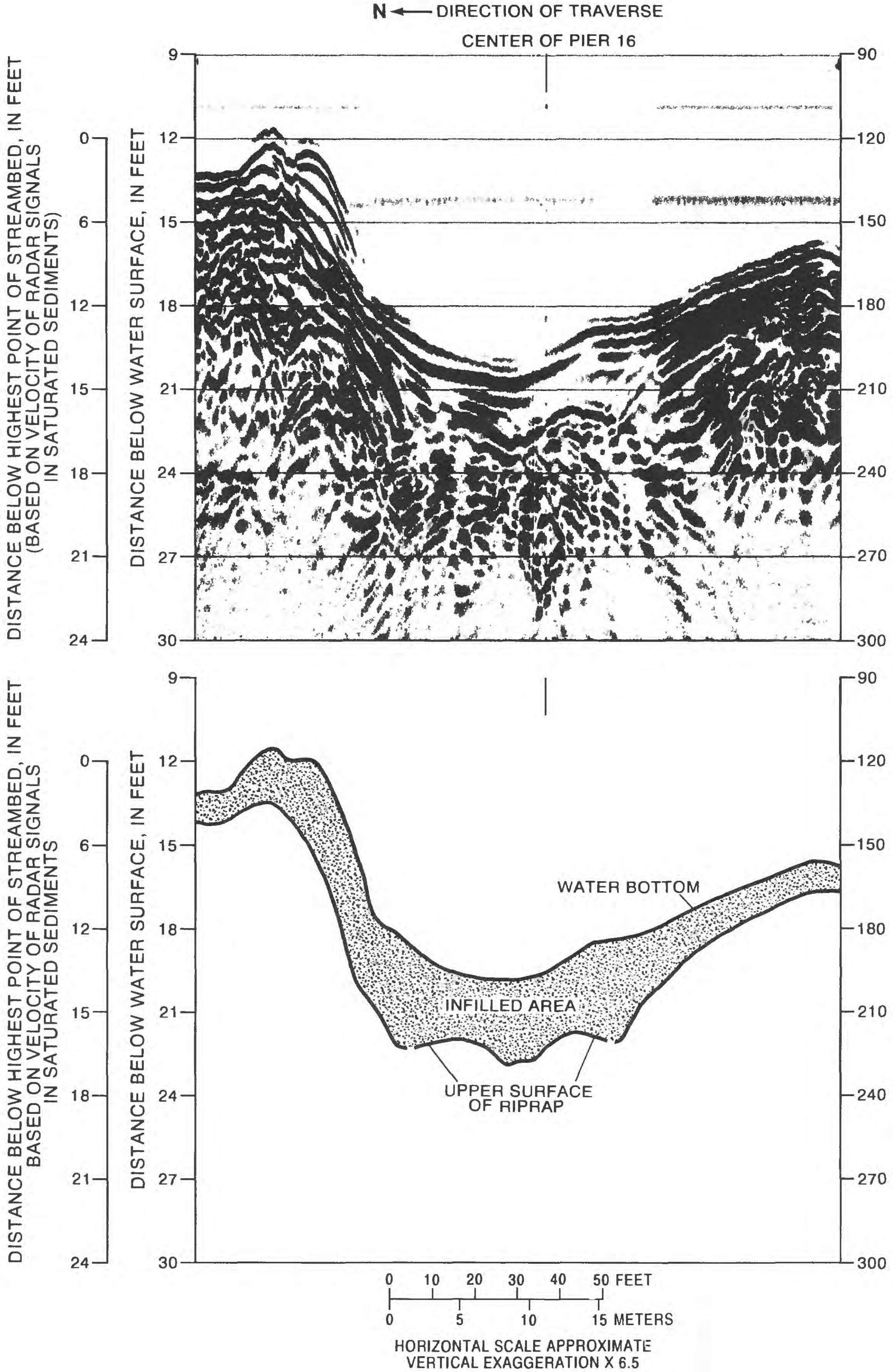



Figure 10B.--Surface-geophysical ground-penetrating-radar record and interpretation showing scour holes and riprap layers of the Columbia River at Highway Interstate-205 Bridge, and interpretation, 20 feet upstream from pier 16.

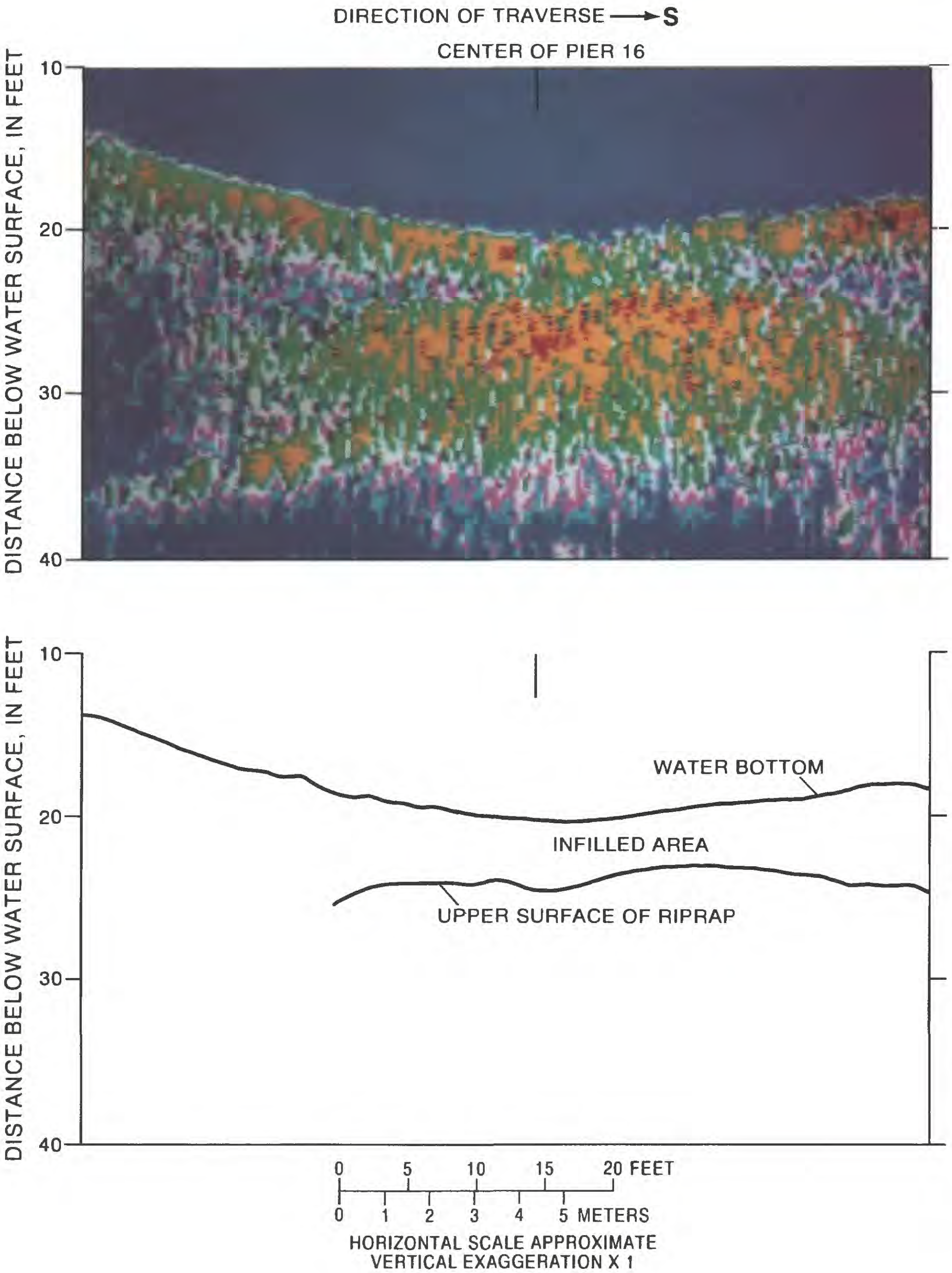



Figure 10C.--Surface-geophysical 20-kilohertz color-fathometer record and interpretation showing scour holes and riprap layers of the Columbia River at Highway Interstate-205 Bridge, and interpretation, 20 feet north of pier 16.

Deschutes River near Biggs, Oregon (Sites 3 and 4)

Two bridges were studied at the Deschutes River near Biggs: bridge number 332C (Highway I-84 Bridge) that crosses the Deschutes River near its confluence with the Columbia River, and Bridge number 332 (frontage road 378) that parallels I-84 about 300 ft upstream. The Columbia River is controlled at this point by The Dalles Dam located 12 miles to the west and puts these bridges in backwater at certain times. A sketch of the Deschutes River and the approximate location of the bridges is shown in figure 11.

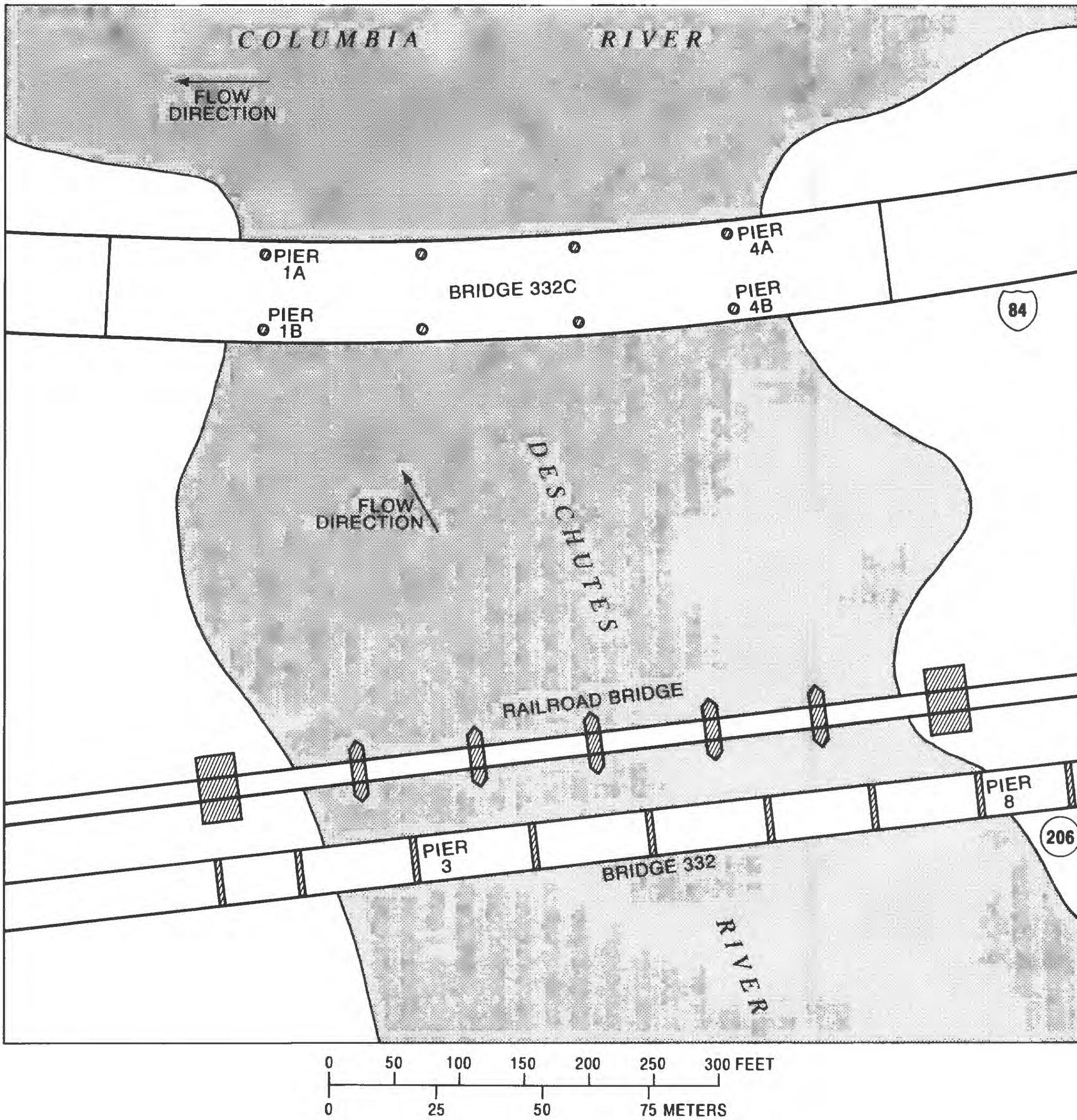



Figure 11.--Plan view of Deschutes River Bridges 332C and 332 near Biggs, Oregon.

The Deschutes River at these bridges is constricted because of the bridge openings, and even though flows are fairly tranquil most of the time, the potential for accelerated velocities exists because of the constriction (Don Dean, Oregon Department of Transportation, oral commun., 1989). Oregon Department of Transportation has documented that when water levels behind The Dalles Dam are low and the water level of the Deschutes River is high, large diameter (2.9 ft) riprap has been removed from around the bridge piers. Bed material of the Deschutes River at this site consists of gravel- and cobble-sized material overlying bedrock.

The TT, in conjunction with black-and-white fathometer, was used to determine the most suitable piers to study. Piers 1a and 1b, two separate circular columns located near the left (west) bank of the river, were selected at bridge 332C (Highway I-84 Bridge). Piers 1a and 1b are supported by pilings driven to bedrock. Pier 3, selected at bridge 332 (Highway 206 Bridge), is located near the left bank of the river and is supported by a spread footing on bedrock. Direction of flow from the Deschutes River was nearly parallel to all piers in water at both bridges at the time of the survey made during low stage. At high stages, water striking pier 1 of bridge 332C and pier 3 of 332 is reported to be about 15 degrees from parallel.

Riprap is located at pier 1b (the upstream column) at bridge 332C (Highway I-84 Bridge). The riprap elevation of pier 1b was about 5 ft higher than the bottom of the footing. Geophysical measurements at pier 1a (the downstream column) indicated an infilled scour hole about 2 ft deeper than the present scour hole, which is about 3.5 ft above the bottom of the footing. An example of TT record of pier 1a is shown in figure 12.

An existing scour hole about 5 ft deep is present at the upstream end of pier 3 at bridge 332 (frontage road bridge) and has little infilling. Immediately downstream from pier 3 at bridge 332, the river channel deepens rapidly to an elevation 3 ft lower than the bottom of the spread footing located about 50 ft downstream from pier 3. The river bottom then rises rapidly to the base of the railroad bridge pier. Tuned transducer record indicates about 0.5 ft of rubble and silt covering the bedrock bottom at the end of pier 3, while the river bottom along the east side is scoured to bedrock. Both CF and TT methods worked well at this site and were verified by probe measurements. An example of TT record of the east side of pier 3 is shown in figure 13.

## Rogue River at Grants Pass, Oregon (Sites 5 and 6)

Two Highway 199 bridges over the Rogue River at Grants Pass were studied (fig. 14). Bridge 1418, built in the 1930's, was the original Highway 199 Bridge and is now the southbound bridge. This bridge has two massive piers in water, supported at each end by spread footings, with about a 6-ft gap between the footings. Bridge 8432, built in the 1960's, is the north bound Highway 199 Bridge. This bridge has two piers in water but only one pier was in water deep enough to be examined. Bridge 8432 piers are supported by one continuous spread footing. The piers in the water at both bridges were studied using the TT and black-and-white fathometer. Pier 3 at bridge 8432 and pier 2 at bridge 1418 were studied in more detail using GPR and TT. The CF did not work well at these sites because of the shallow water depths.

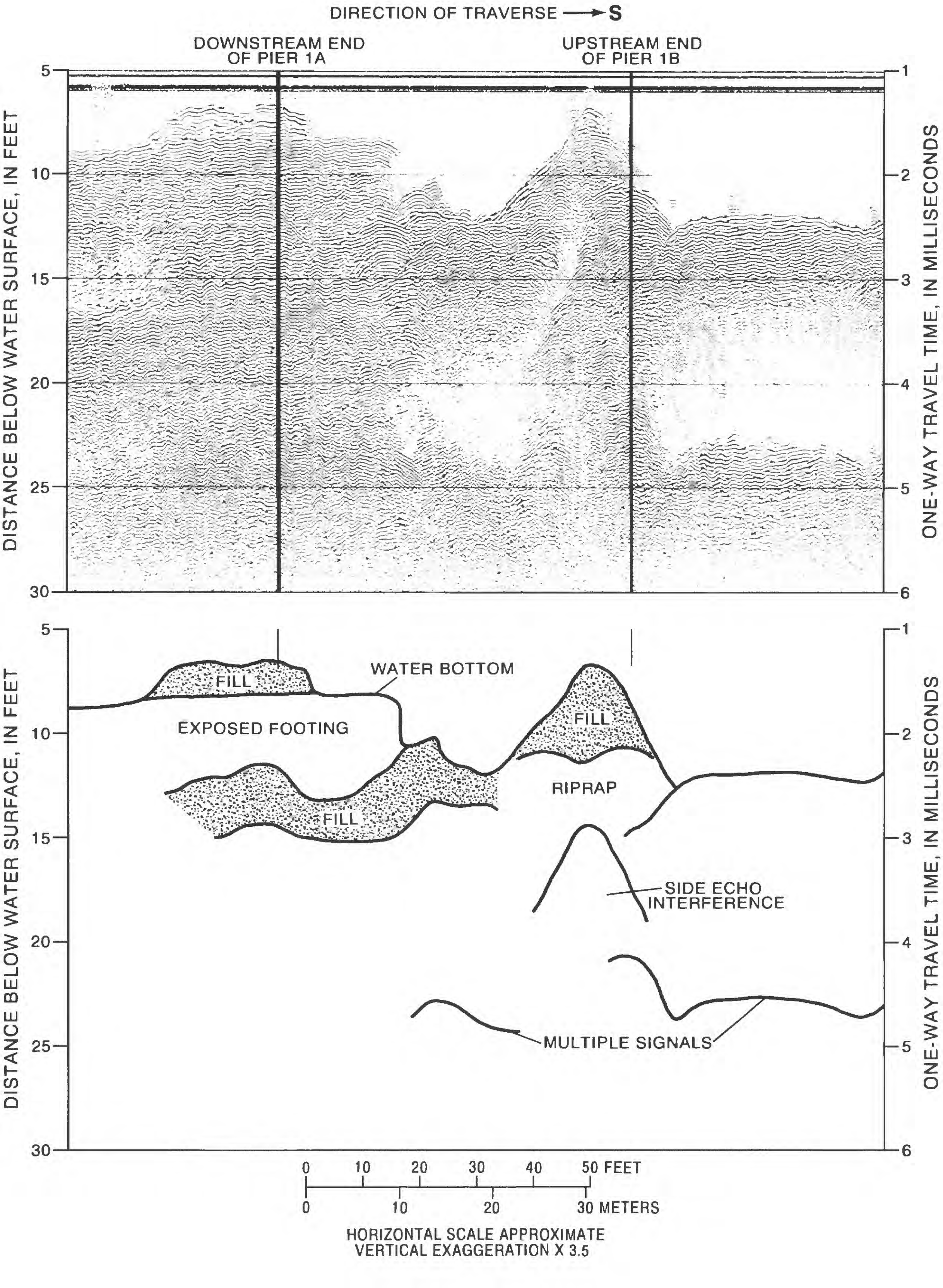



Figure 12.--A 14-kilohertz tuned-transducer record and interpretation of a lateral run 5 feet west of pier 1 of bridge 332C at the Deschutes River near Biggs, Oregon.

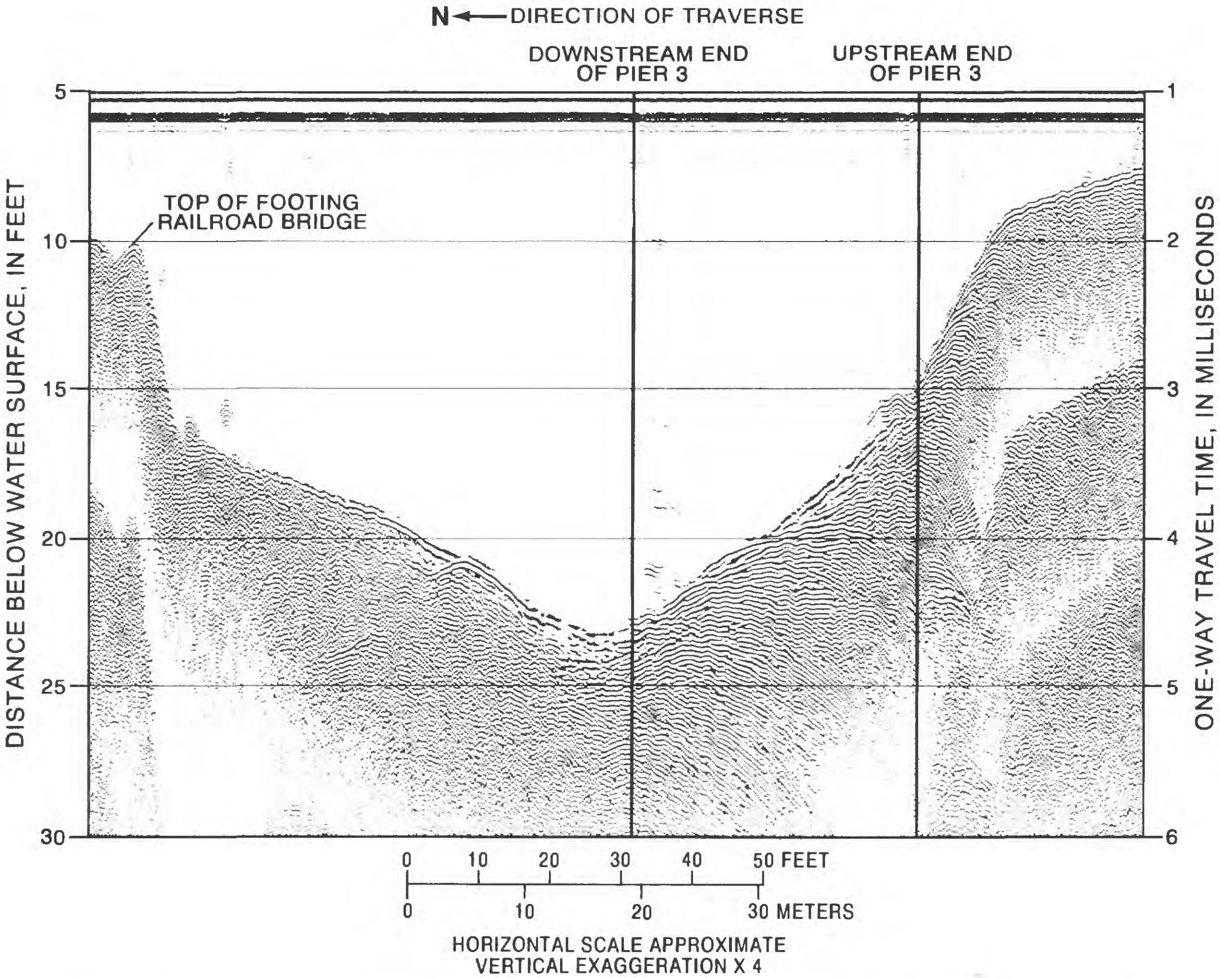



Figure 13.--A 14-kilohertz tuned-transducer record of a lateral run 2 feet east of pier 3 of bridge 332 at the Deschutes River.

The streambed material of the Rogue River at this location is composed of naturally cemented gravels, which are overlain by loose gravels in areas of deposition. Stream velocities in the vicinity of the bridge piers were less than 2 ft/s, and water depths were generally less than 5 ft at the time of study. The direction of water approaching the bridges were parallel to the piers at the time of study and appear to be parallel at all stages (U.S. Geological Survey, unpub. data, Portland, Oregon, 1989).

Bridge 8432 had a scour hole 2.5 ft deeper than the surrounding channel bed elevations at the upstream end of pier 2. There is a log buried along side pier 2 with part of the base exposed in the upstream scour hole (fig. 15). It is possible that about 0.5 ft of infilling exists beneath the log, but the presence of the log makes an accurate determination difficult. The bottom of the spread footing of bridge 8432 is located about 5.5 ft beneath the existing upstream scour hole. A small amount of scour (less than 0.5 ft) exists along the sides of and at the downstream end of pier 2, with no infilling detected.

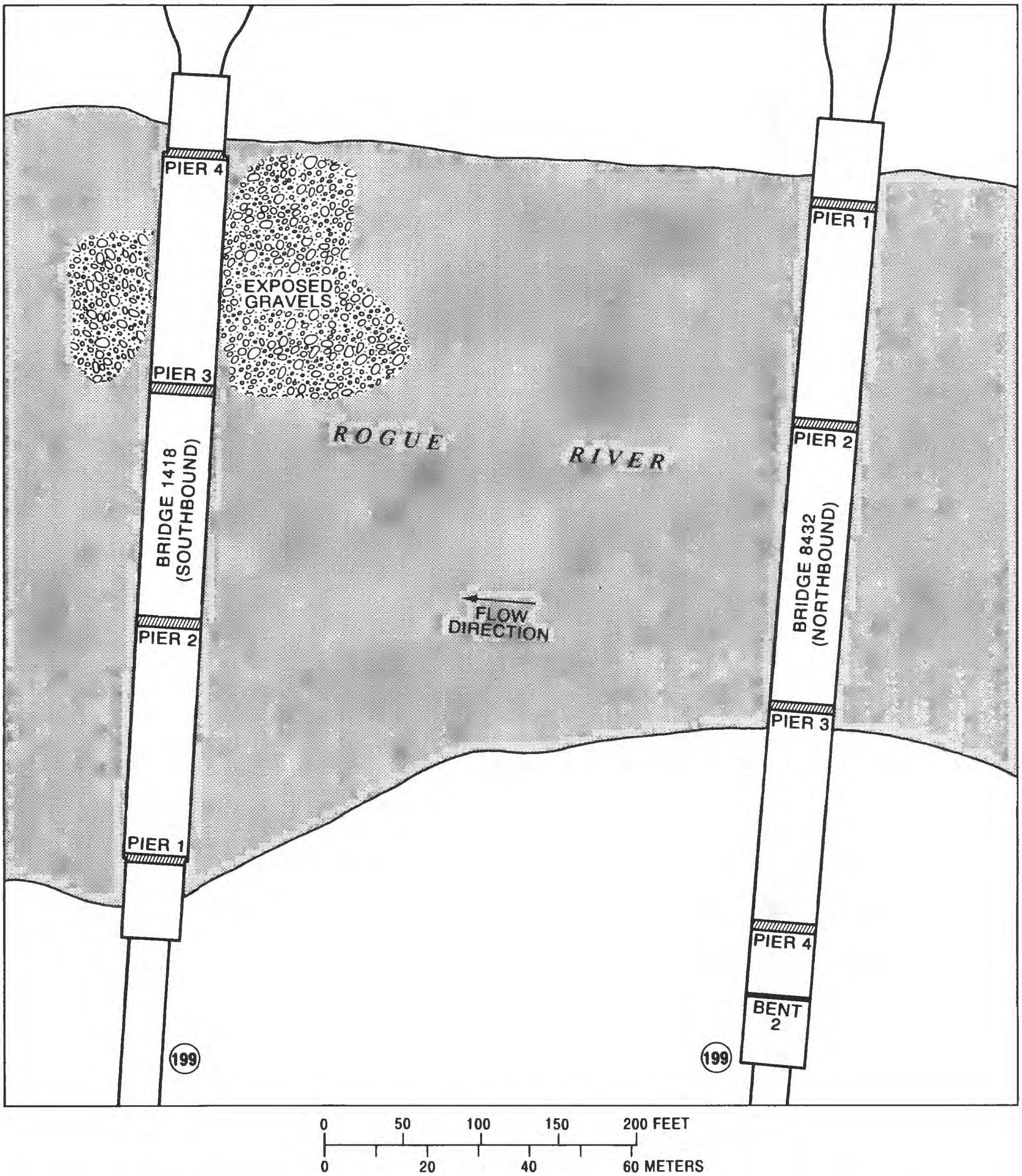



Figure 14.--Plan view of bridges 8432 and 1418 over the Rogue River at Grants Pass, Oregon.

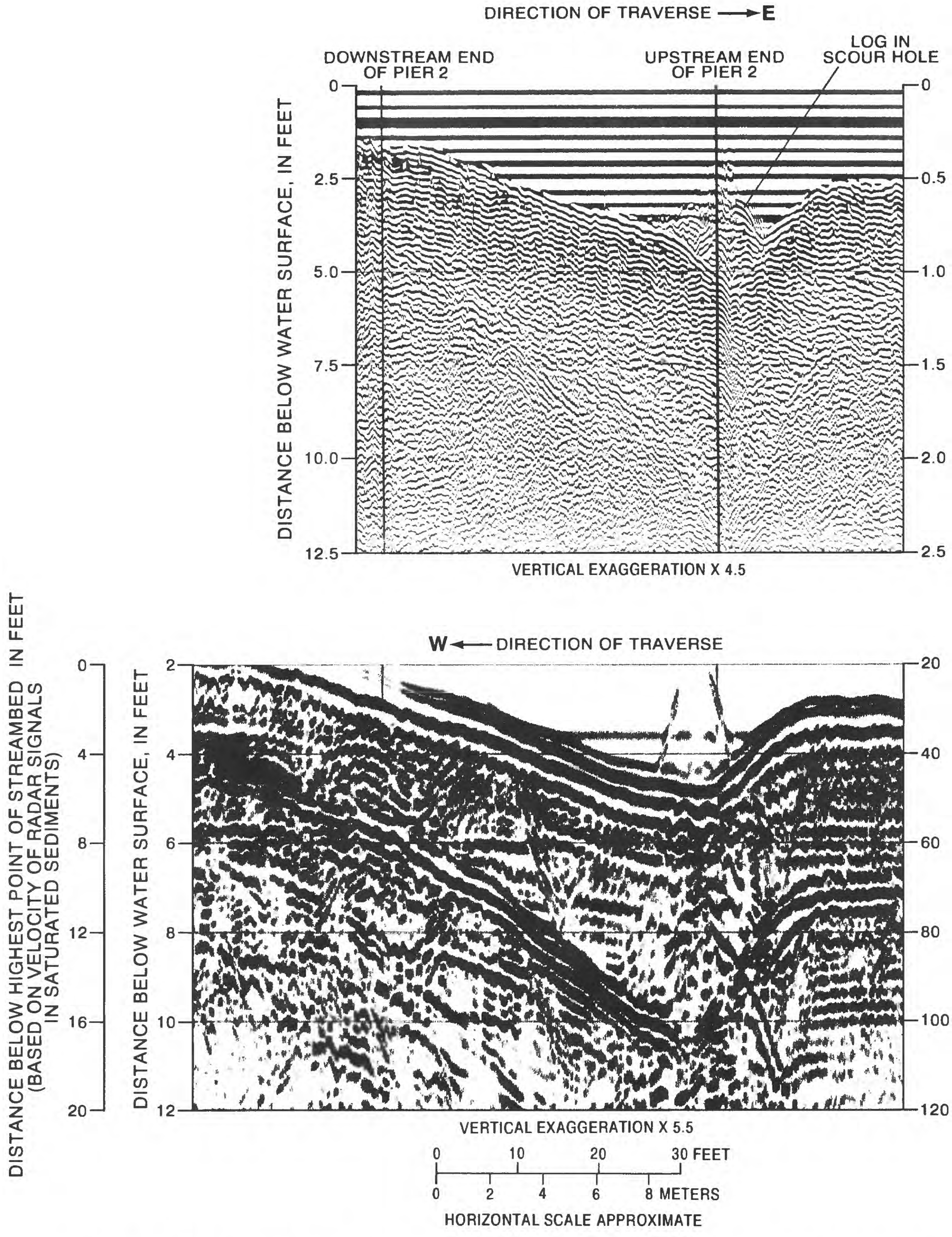



Figure 15.--A 14-kilohertz tuned-transducer record (top) and ground-penetrating-radar record (bottom) of a lateral run 5 feet south of pier 2 of bridge 8432 at the Rogue River.

During the time of study, bridge 1418 had a scour hole 2.5 ft deep (bottom elevation 880.5 ft above mean sea level) at the upstream end of pier 1, with deeper holes along each side of the pier between the spread footings. About 10 ft out from the south side of pier 1, an exposed hole 6.0 ft deep (bottom elevation 870.0 ft) exists between the spread-footing sections, which is about 0.5 ft deeper than the bottom of the spread footing (bottom elevation 870.5 ft) [fig. 16]. A 3.0 ft trough runs parallel to pier 32 along the south side. The existing hole and trough along the north side of pier 1 is similar to the south side, but is not as deep. The bed material at the base of these holes and troughs is bedrock and large cobbles.

## Sandy River near Troutdale, Oregon (Sites 7 and 8)

The two Interstate I-84 bridges (6875 eastbound and 6875A westbound) that cross the Sandy River near Troutdale were investigated in this study. During high flows, it is estimated that the Sandy River flows through a 1,000-feet-wide channel with depths to 24 ft and velocities to 5 ft/s. The bed material of the Sandy River is composed of poorly sorted sand, gravel and cobbles up to 0.8 ft in diameter. During low flow, the width of the channel is about 80 ft wide and about 3 ft deep, with water velocities less than 2 ft/s.

Because of the shallow depths, GPR was the only geophysical method used at this site, and a small boat was needed to navigate around the piers. Each of the bridges only had one pier in water at this river stage with two square piling supported poured footings beneath each pier (fig. 17A). Because of the pier design (fig. 17B), probe measurements could be made by standing on the footings and measuring down to the foundation seal, river bottom and subbottom interface. Probe measurements were used to calibrate the GPR record at these bridges. Because of the presence of debris and coffer dam remnants, GPR record at this site is complicated to interpret due to echoes and multiple reflections that obscure returns from any interfaces. Probe depths are shown table 3.

Pier 2 of bridge 6875 (I-84 Eastbound) had parts of the old piling and coffer dam in place, with debris lodged around the pier, making navigating around this pier difficult. Ground-penetrating radar worked well at this site except for side echo and multiple signals complicating the record. No infilled scour holes were detected at this site, either from the geophysical methods or by probing, but probe data did indicate that an existing scour hole is located near the upstream streamward side, 5.0 ft lower than the top of the footing, and about 2.3 ft above the bottom of the footing (table 3).

Pier 2 of bridge 6875 A (I-84 Westbound) had less debris than bridge 6875 pier 2 and GPR results were better. Side echo and multiple signals obscured some of the data around the pier, and without probe readings, interpretation of scour-hole depths would have been difficult. Results from probing data collected at this site indicate that existing scour holes are within 1.5 ft of the bottom of the footing, and some infilling (1.5 ft) was detected along the downstream end of pier 2a by GPR and probing. It is possible that less than 2 ft of infilling would not be detected because resolution of GPR is about 2 ft when using 80 megahertz antennae (table 1). An example of GPR data collected is shown in figure 18.

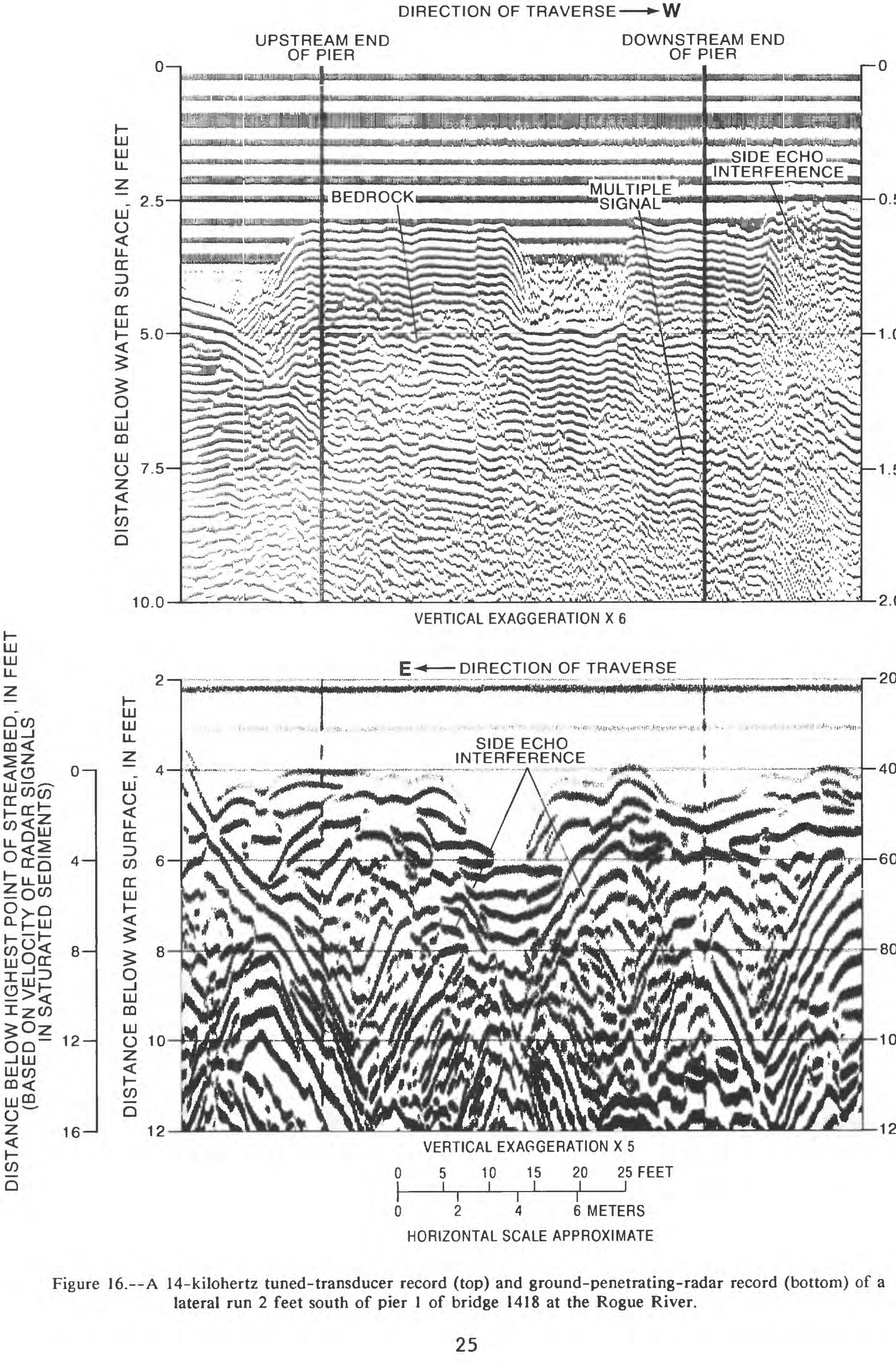



Figure 16.--A 14-kilohertz tuned-transducer record (top) and ground-penetrating-radar record (bottom) of a lateral run 2 feet south of pier 1 of bridge 1418 at the Rogue River.

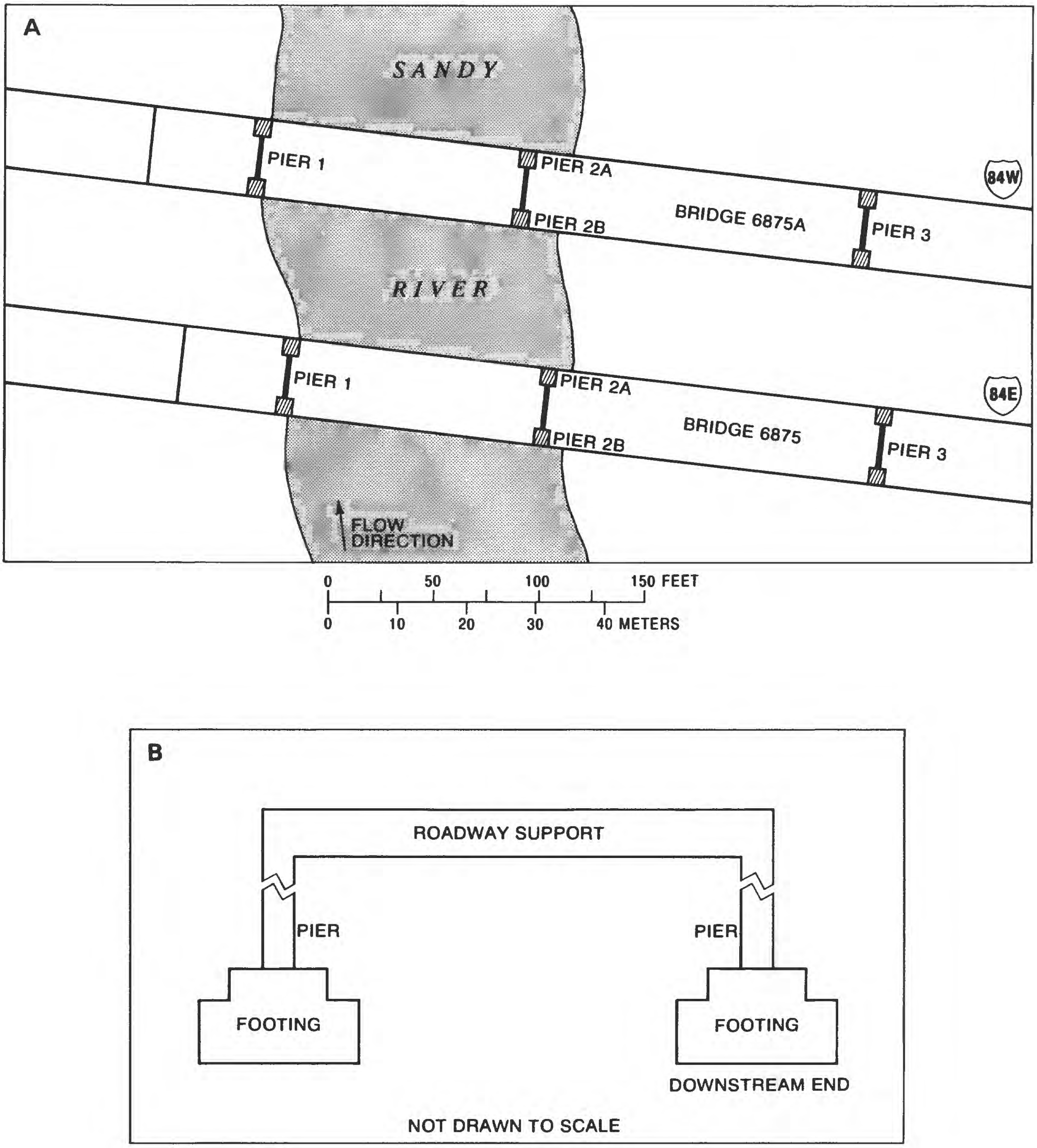



Figure 17.--Configuration (A) and pier design (B) of Sandy River Bridges 6875 and 6875A located near Troutdale, Oregon.

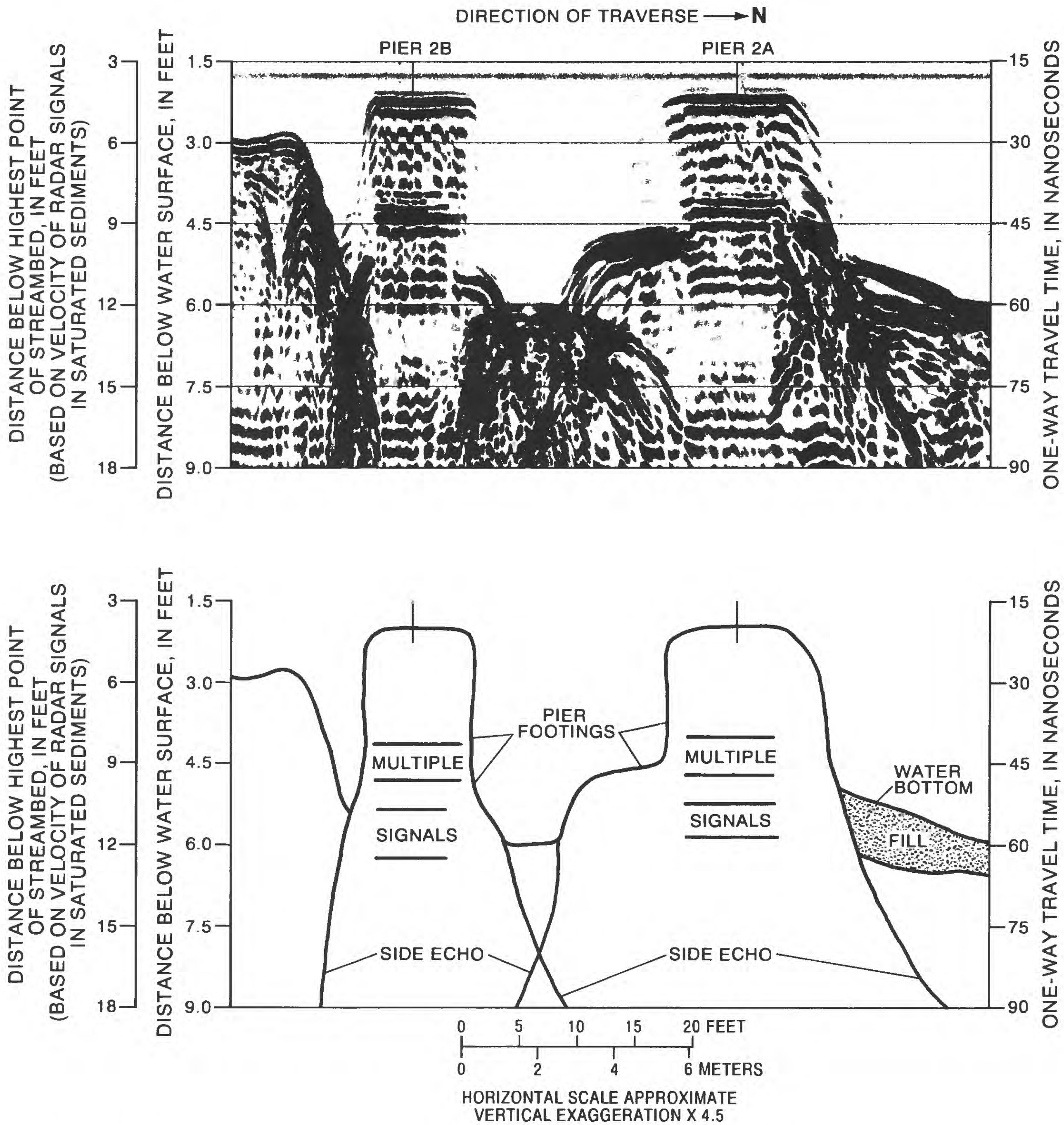



Figure 18.--Ground-penetrating-radar record and interpretation, Sandy River Bridge 6875A, 1 foot east of pier 2.

Table 3.--Probe log of Sandy River near Troutdale Bridges 6875 and 6875A, September 18, 1989

[(1) = Measurement from water surface to top of footing.
(2) = Measurement from water surface to top of footing step.
(3) = Measurement from water surface to river bottom.
(4) = Measurement from water surface to bottom of infill]

| | Probe readings, in feet | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | South | East | North | West | Corner | | | |
| Measurement | (Upstream) | (Shoreward) | (Downstream) | (Streamward) | Southeast | Southwest | Northeast | Northwest |
| | | | Bridge 6875, downstream of pier 2a | | | | | |
| (1) | 2 | 1.9 | 1.9 | 1.9 | 2 | 1.9 | -- | -- |
| (2) | 5.1 | 3.4 | 4.7 | 3.5 | 3.6 | 6 | -- | -- |
| (3) | 6.1 | 3.9 | 4.9 | 4.6 | 5.7 | 6.1 | -- | -- |
| (4) | 6.2 | 4 | 5.2 | 5 | 6 | 6.3 | -- | -- |
| | | | Bridge 6875, upstream of pier 2b | | | | | |
| (1) | 1.9 | 1.9 | 1.9 | 1.9 | -- | -- | 2 | 2 |
| (2) | (rocks) | (debris | (no step) | (no step) | -- | -- | 3.5 | 5.9 |
| (3) | (debris | (debris) | 4.3 | 4.6 | -- | -- | 4.1 | 6.4 |
| (4) | 2.1 | (debris) | 4.8 | 5 | -- | -- | 4.6 | 7 |
| | | | Bridge 6875A, downstream of pier 2a | | | | | |
| (1) | 2.1 | 2.1 | 2.1 | 2.1 | 2.1 | 2.1 | -- | -- |
| (2) | 5.1 | 5 | 5.2 | 5.5 | 5.1 | 5.4 | -- | -- |
| (3) | 7.1 | 7.7 | 5.6 | 6 | 7.7 | 6.1 | -- | -- |
| (4) | 7.4 | 7.9 | 7 | 6.1 | 7.9 | 6.4 | -- | -- |
| | | | Bridge 6875A, upstream of pier 2b | | | | | |
| (1) | 2.1 | 2.1 | 2.1 | 2.1 | 2.1 | 2.1 | -- | -- |
| (2) | 5.3 | 5.4 | 5.5 | 5.4 | 5.4 | 5.3 | -- | -- |
| (3) | 7.5 | 7.3 | 5.9 | 6.4 | 6.7 | 7.9 | -- | -- |
| (4) | 7.9 | 7.6 | 6.2 | 7.1 | 7 | 8.1 | -- | -- |

## Willamette River at Portland, Highway 84 and Interstate-5 Interchange (Sites 9, 10, 11)

Three bridges (R8588B, R8588C, R8588E) were examined at this location using geophysical methods. A sketch showing the configuration of these bridges in relation to the highway system is shown in figure 19. All of the bents and piers studied at this site are are supported by piling.

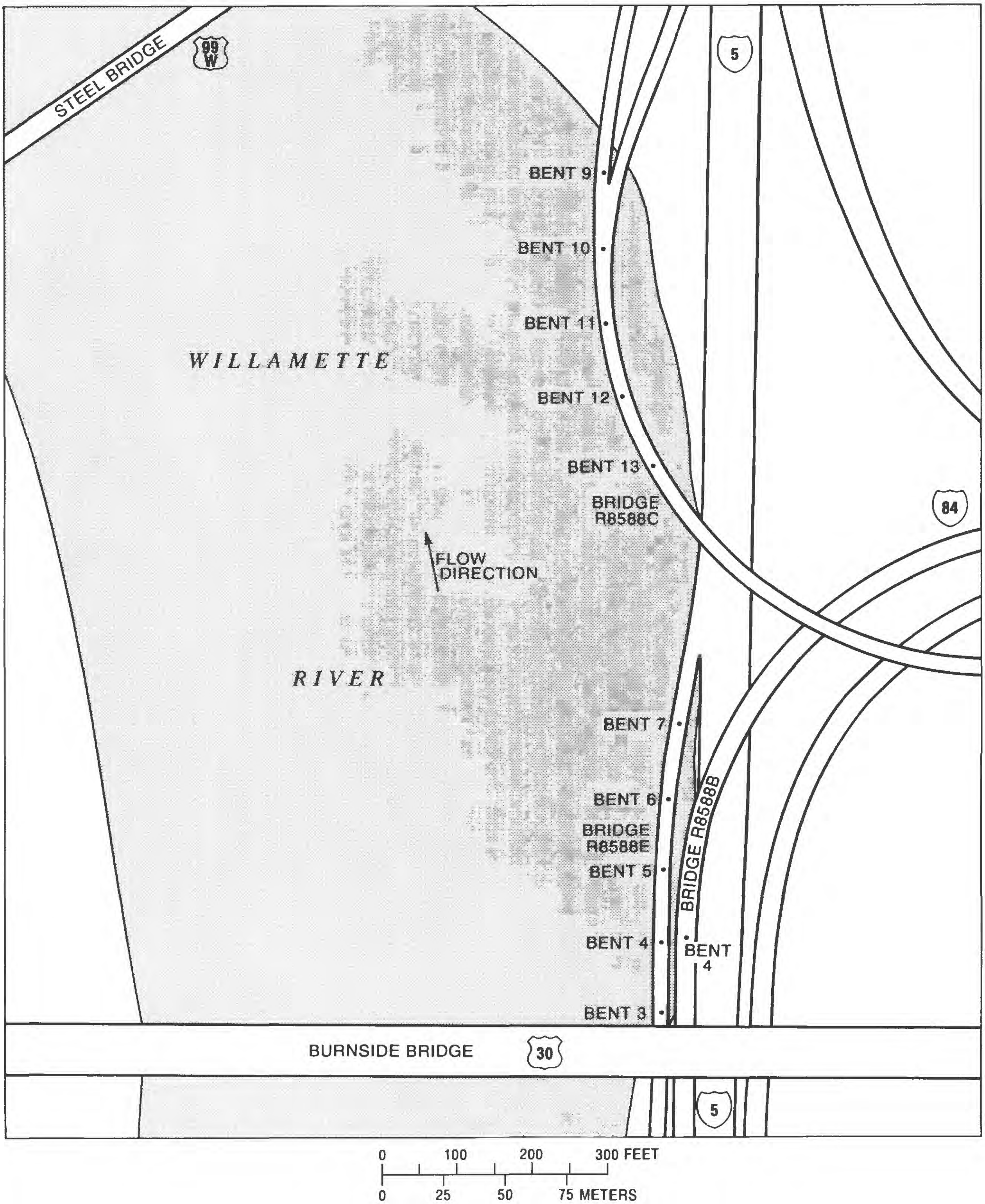



Figure 19.--Configuration of bridges R8588B, R8588C, and R8588E, Willamette River at Portland, Oregon.

Bridge R8588B is the exit ramp from the west end of I-84 leading to I-5 southbound. This bridge had only one pier (bent 5) in the water at the time of this study. The GPR record showed that the footing was exposed and no infilled scour holes were present near the bottom of the footing. Water depths at this site ranged from 1 ft on the shoreward side to about 5 ft on the streamward side. Stream velocities are slow at this pier and there appear to be no pier scour problems. GPR worked well at this pier, but navigation around the pier was difficult because the pier was close to the shore.

Bridge R8588C is the exit ramp from I-5 southbound to I-84 eastbound. This bridge has several piers in the water which were examined using all three geophysical methods. Water depths at this site ranged from near zero to about 30 ft. Maximum velocities in the vicinity of these piers were less than 2 ft/s and probably would not exceed 5 ft/s during high flows (U.S. Geological Survey, unpub. data, Portland, Oregon, 1974). None of the geophysical methods provided conclusive evidence of infilled scour holes below the bottom footing elevation; however, by probing through the bottom material it was evident that there is an infilled scour hole 3.5 ft lower than the bottom of the footing at pier 12 and 0.5 ft lower at pier 11. None of the surface-geophysical methods used at this site detected the infilling, probably because of the water depths and agal conditions of the water at the time of study. Results of black-and-white fathometer and GPR measurements around piers 11 and 12 are shown in figures 20 A-D.

Bridge R8588E is part of I-5 southbound exit to Morrison Street bridge and S.E. Belmont. This bridge had five piers in water during the study period. Water depths at this site ranged from near zero to about 30 ft. Maximum velocities in the vicinity of these piers were less than 2 ft/s and probably would not exceed 5 ft/s during high flows (U.S. Geological Survey, unpub. data, Portland, Oregon, 1974). All three geophysical methods were used to search for infilled scour holes at these piers. An infilled scour hole was detected along the streamward side of bent 6 about 15 feet out using the CF and was verified by probing. The GPR and TT geophysical methods did not detect infilling at this location. Finding the infilled scour hole at pier 6 using CF shows that all three methods are needed to examine scour holes in the vicinity of bridges, because it is difficult to forecast which method will provide the best results. An example of CF data in the vicinity of pier 6 of Bridge R8588E is shown in figure 21.

### Willamette River at Corvallis, Oregon (Sites 12, 13)

Two Highway 34 bridges over the Willamette River at Corvallis, Oregon were investigated in this study. This reach of the Willamette River has a gravel/cobble bottom and water velocities less than 2 ft/s in the vicinity of these bridges during the time of this study. Each bridge has two piers in the water surrounded by large amounts of riprap.

Piers under bridge 2728 (Highway 34 eastbound) and bridge 7179 (Highway 34 westbound) were examined using a black and white fathometer and the CF. A part of footing at pier 6 of bridge 7179, and pier 3 of bridge 2728 was exposed. No infilled scour holes were detected in the vicinity of the piers.

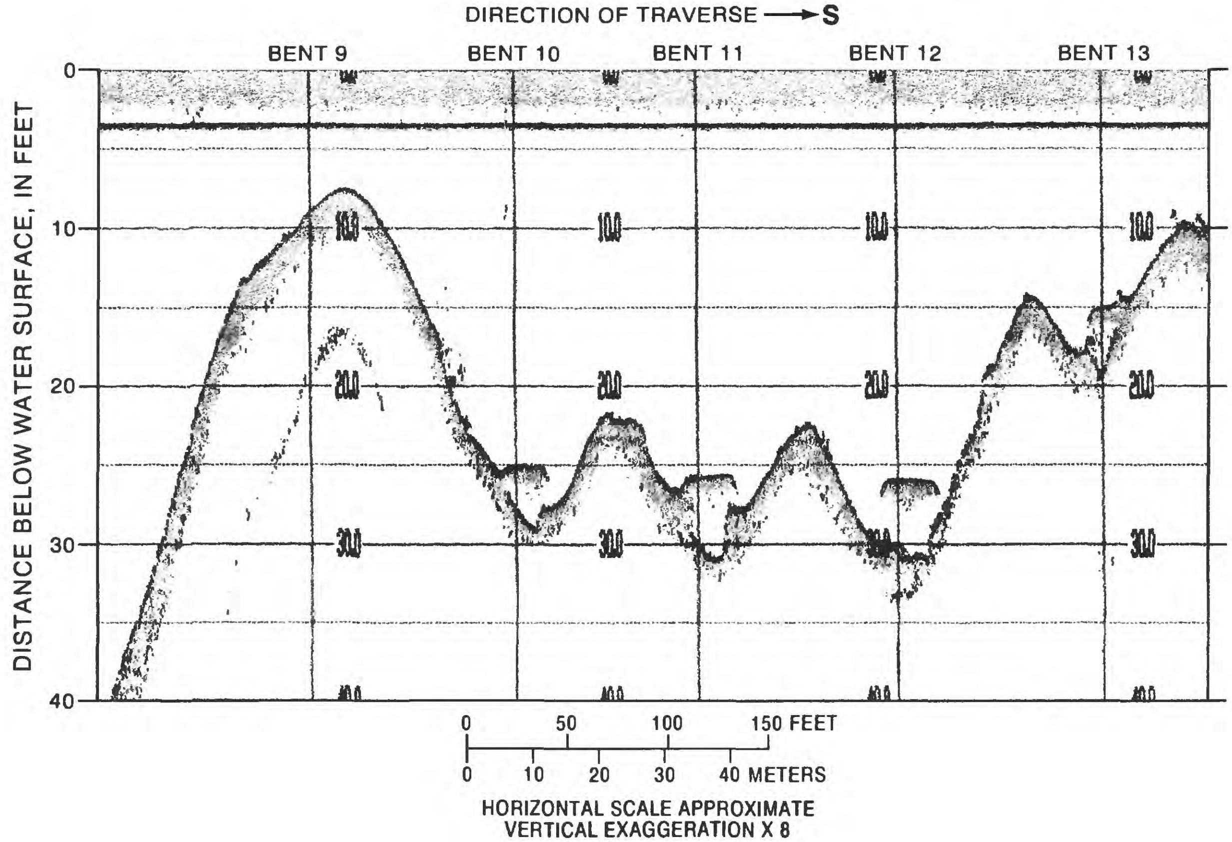



Figure 20A.--Surface-geophysical black-and-white fathometer record at Willamette River bridge R8588C. Record was taken about 15 feet west of bents 9-13 traveling in a southerly direction.

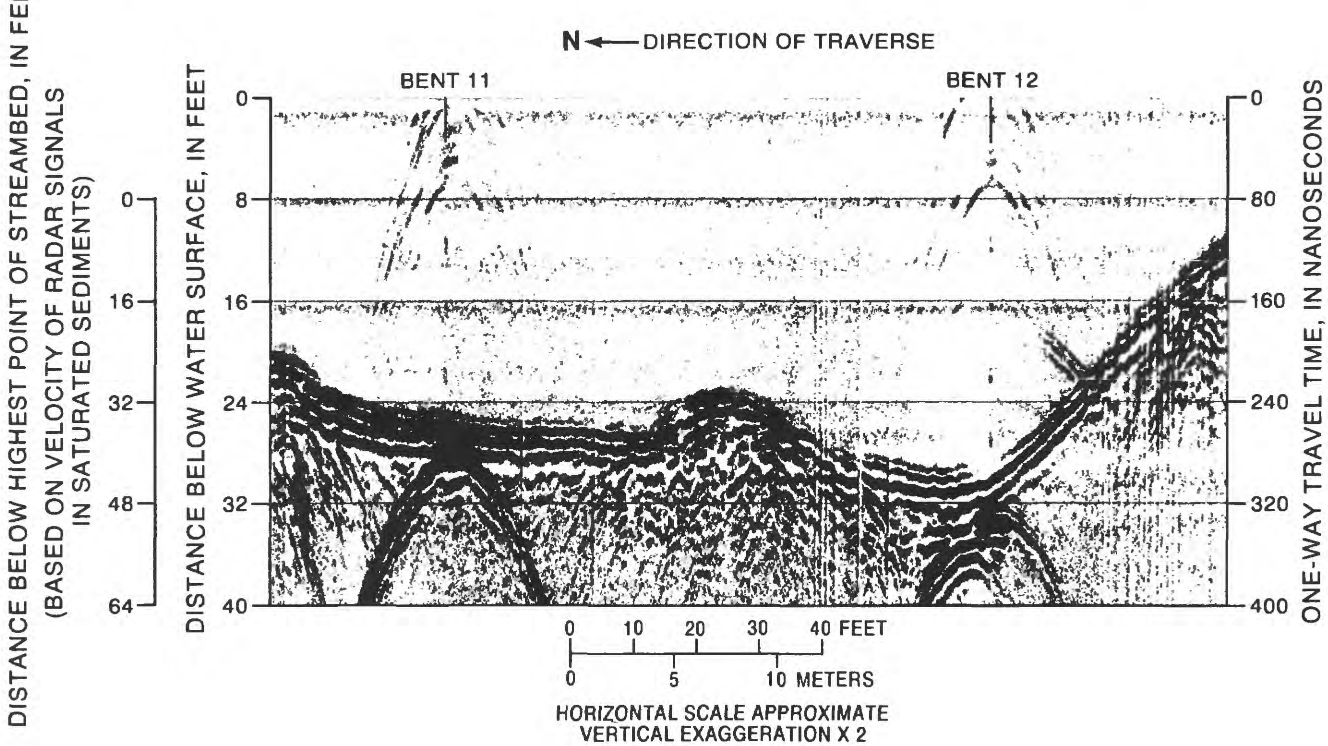



Figure 20B.--Surface-geophysical ground-penetrating-radar record at Willamette River bridge R8588C. Record of bents 11 and 12, 10 feet streamward (west) of bridge.

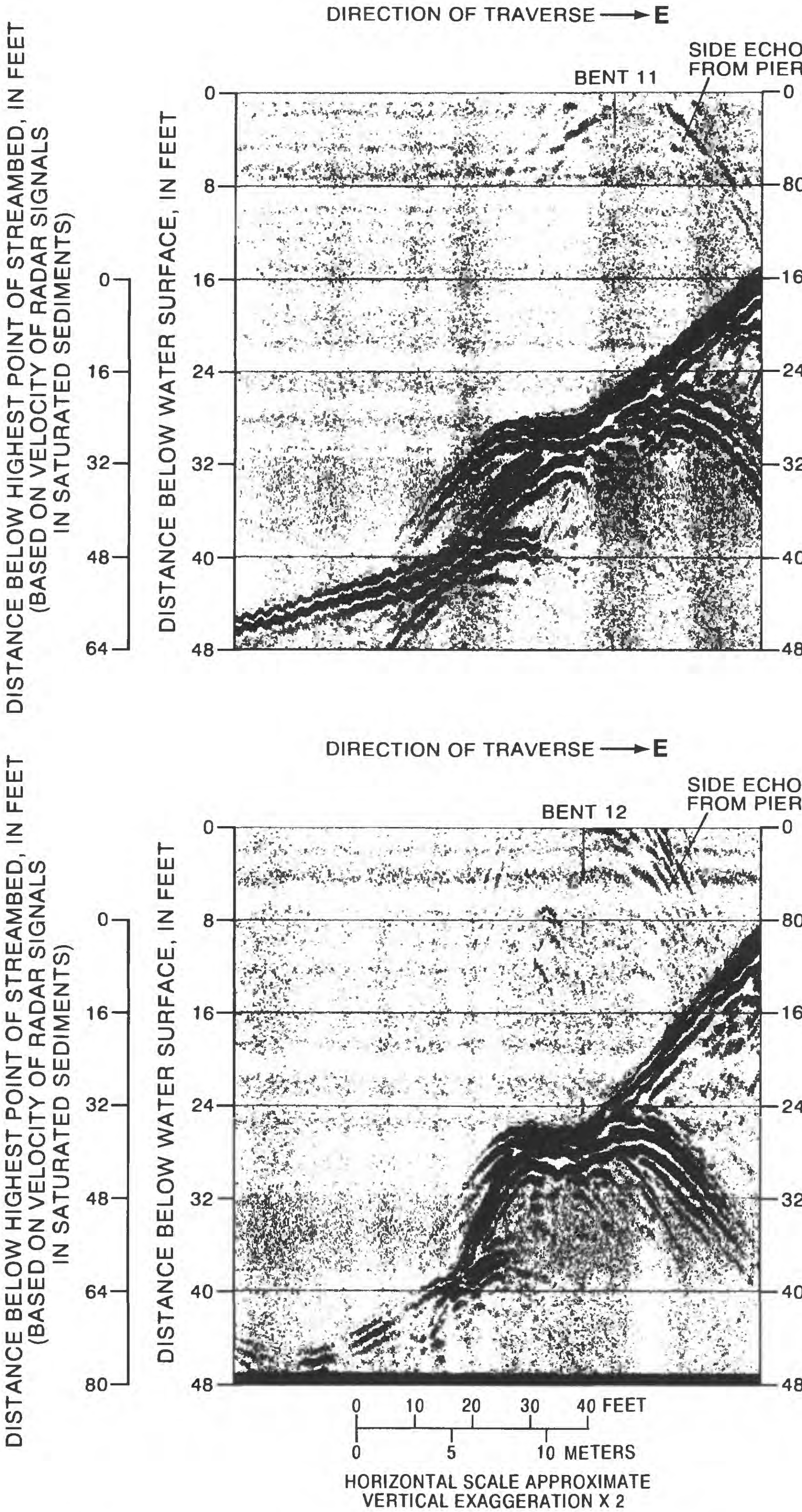



Figure 20C.--Surface-geophysical ground-penetrating-radar record at Willamette River bridge R8588C. Record of bents 11 and 12, 10 feet upstream (south) of bents.

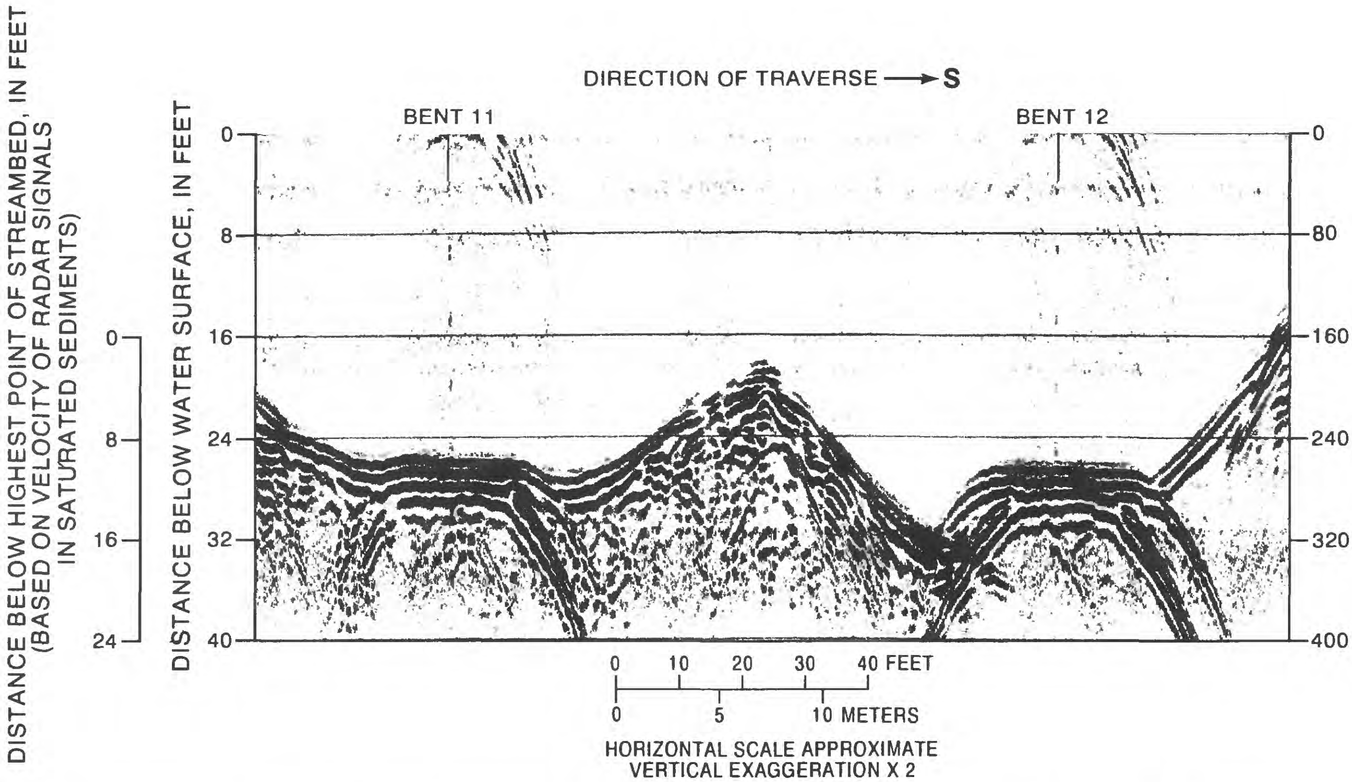



Figure 20D.--Surface-geophysical ground-penetrating-radar record at Willamette River bridge R8588C. Record of bents 11 and 12, 10 feet shoreward (east) of bents.

<u>Willamette River at Harrisburg, Oregon (Site 14)</u>

The bridge located at Willamette River at Harrisburg, Oregon was selected for study because of possible scour beneath the bottom of the seal at pier 3. Upstream from this bridge the Willamette River flows mainly along the left bank (south) side of the channel, curves abruptly at the bridge and strikes pier 3 at a 45 degree angle. Water velocities at the time of study were about 3.5 ft/s. The channel consists mostly of sand, gravel and cobbles, and the bridge is obstructed by a gravel bar 50 ft upstream from pier 3 and by numerous logs around piers 2 and 3. A photograph showing pier 3 and the approaching flow angle is shown in figure 22.

Ground-penetrating radar was determined to be the best geophysical method to use at this site, because of shallow water depths around the bridge. It was found that velocities were too rapid and the water too turbulent around pier 3 to physically obtain any data safely. One profile of GPR data was collected about 20 ft downstream from pier 3. A second attempt was made to collect GPR data along the side of pier 3, but the water forced the boat into logs and debris nearly capsizing it. Not all bridges over navigable streams can be inspected using geophysical methods, and the Willamette River at Harrisburg is one of them.

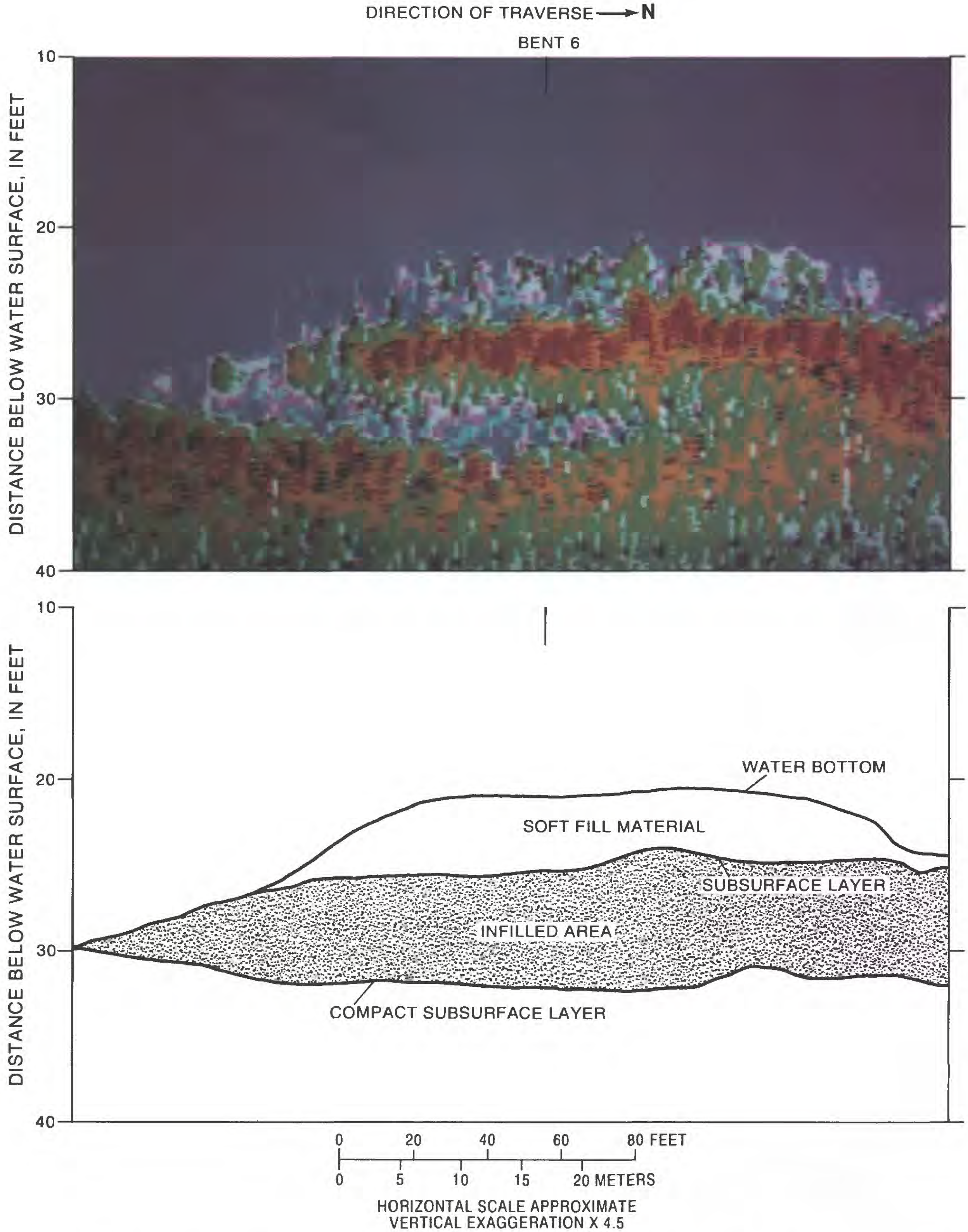



Figure 21.--20-kilohertz color-fathometer record and interpretation of subsurface layers 15 feet streamward (west) of bridge R8588E, bent 6, on the Willamette River in Portland, Oregon.

Figure 22.--Cross-stream view of bridge and pier 3 from left bank, Willamette River at Harrisburg, Oregon, September 27, 1989.

## USE AND LIMITATIONS OF SURFACE-GEOPHYSICAL METHODS

### Use of Geophysical Equipment

Each of the geophysical methods used in this study was able to locate infilled scour holes around bridge piers in Oregon. In some instances all three methods worked well at the same site; most of the time, however, only one or two methods were able to define the thickness of the infilled material. It is important to utilize all three methods when trying to locate infilled scour holes around bridge piers because the methods compliment each other. A summary of results of geophysical methods is shown in table 4.

It was found that best results from the geophysical methods were obtained (1) when bed material was sand or sand-and-gravel size or smaller, and (2) when the boat speed was slow with accurate positioning. Geophysical methods worked best in streams where the infilled material is different from the parent material, such as sand over gravel. It was found that many traverses from different directions, moving at a slow rate of speed (less than 1 ft/s) improved the quality of the geophysical data. Verification of infilled material thickness by probing proved to

Table 4.--Summary of results of surface-geophysical methods

[TT = tuned transducer, CF = color fathometer, GPR = ground-penetrating radar,
* = Infilled layers were detected by probing and not by geophysical methods
† = Spread footings, -- = not applicable]

| Site | Stream, highway/ bridge | Pier/ bent number | Method | Method rated | Elevation (bridge datum in feet): Bottom of footing or pile cap | Elevation (bridge datum in feet): Exposed scour hole | Elevation (bridge datum in feet): Bottom of infilled scour hole | Thickness infilled material | Infilling verified by probing | Bed material | Location or comment |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Alsea River 101/1746 | 6 | TT<br>CF | Fair<br>Good | -30.0 | -16.0 | -22.0 | 6.0 | Yes | Sand | 20 feet south |
| 2 | Columbia River I-205/9555 | 16 | GPR<br>TT<br>CF | Good<br>Good<br>Good | -40.5 | -20.0 | -23.0 | 3.0 | Yes | Sand<br>Riprap | 20 feet upstream |
| 3 | Deschutes River I-84/332C | †1A<br>†1B | TT<br>CF | Good<br>Good | 136.9<br>136.3 | 148.0<br>149.0 | 146.0<br>146.0 | 2.0<br>3.0 | Yes | Sand/gravel<br>Riprap | 5 feet west |
| 4 | Deschutes River 206/332 | 3 | TT<br>CF | Good<br>Good | 134.0<br>136.1 | 134.0<br>144.0 | 133.0<br>144.0 | 1.0<br>0.0 | Yes | Bedrock | Upstream 5 feet<br>Downstream 5 feet |
| 5 | Rogue River 199S/1418 | †3 | GPR<br>TT | Fair<br>Fair | 874.5 | 875.0 | 875.0 | 0.0 | Yes | Cemented gravels | Shoreward side of pier |
| 6 | Rogue River 199N/8432 | †2 | GPR<br>TT | Fair<br>Fair | 872.4 | 878.0 | 877.0 | 1.0 | Yes | Cemented gravels | Upstream 1 foot, streamward 5 feet |
| 7 | Sandy River I-84E/6875 | 2A<br>2B | GPR | Good | -27.0<br>-27.0 | -25.5<br>-26.5 | -25.5<br>-26.5 | 0.0<br>0.0 | Yes | Sand - cobble | Upstream corner<br>Downstream corner |
| 8 | Sandy River I-84W/6875A | 2A<br>2B | GPR | Good | -27.0<br>-27.1 | -23.0<br>-25.5 | -24.5<br>-25.5 | 1.5<br>0.0 | Yes | Sand - cobble | Downstream corner<br>Upstream corner |
| 9 | Willamette River I-84/R8588E | 6<br>7<br>8 | *<br>*<br>* | --<br>--<br>-- | -26.0 | -19.0 | -9.0 | 10.0 | -- | Silt and gravel<br>Rubble | Upstream, streamward corner |
| 10 | Willamette River I-84/R8588C | 11<br>12<br>13 | *<br>*<br>* | --<br>--<br>-- | -40.0<br>-39.0<br>-25.0 | -37.5<br>-36.5<br>-14.0 | -40.5<br>-42.5<br>-17.0 | 3.0<br>6.0<br>3.0 | --<br>--<br>-- | Silt and gravel<br>Rubble | Upstream, streamward corner |
| 11 | Willamette River I-84/R8588B | 5 | GPR | Fair | -23.0 | -9.0 | -9.0 | 0.0 | No | Gravel/ cobble | Upstream, streamward corner |
| 12 | Willamette River 34W/7179 | 6 | CF | Fair | 169.5 | 177.0 | 177.0 | 0.0 | Yes | Gravel<br>Riprap | |
| 13 | Willamette River 34E/2728 | 3 | CF | Fair | 182.2 | 190.0 | 190.0 | 0.0 | Yes | Gravel<br>Riprap | |
| 14 | Willamette River 99E/583 | 3 | GPR | Poor | 268.0 | -- | -- | -- | No | Sand - gravel | Dangerous to boat |

be necessary for the geophysical data interpretation. Although coring was not attempted during this study, it has been found to be a good method of verifying infilled layers in scour holes (Gorin and Haeni, 1989).

Exposed scour holes around bridge piers were present at nearly every site studied. Infilled score holes were located using geophysical methods at several of the sites studied. Elevation of exposed scour and the bottom of infilled scour holes can be determined using data from geophysical methods. Because most geophysical methods measure the two- way travel time to a reflector, the depths to that reflector can only be calculated if the velocity of sound and electromagnetic waves are known or can be estimated (Haeni and Gorin, 1989). Geophysical data must be carefully analyzed and compared with physical measurements to verify the interpreted results.

Prior to use of each type of geophysical equipment, training is required to learn equipment operation and maintenance, recording techniques, and basic interpretation of the data. When preparing a scour study using geophysical methods, time must be budgeted for travel to the site, setup, a reconnaissance survey, some detailed surveying, disassembly, and return travel. For the actual field work, approximately 12 hours is required to do the following:

(1) Setup and make a reconnaissance of up to 10 bridge piers, using black-and-white fathometer and one geophysical method;

(2) Select one pier for detailed study;

(3) Record data at selected pier using same method as in the reconnaissance;

(4) Setup equipment, and record data using second method, and dismantle equipment;

(5) Setup equipment, and record data using third method, and dismantle equipment.

A minimum crew of two people is needed to collect geophysical data and operate the boat, but three is recommended. For this study, a 17-foot long boat with a large (150 hp [horsepower]) engine was used in larger rivers to travel to the site and a smaller (10 hp) outboard motor for slower speeds and maneuvering around the piers while the data were being collected. A smaller 12-foot boat with a 15 hp motor was used in small, shallow streams. When stream velocities were greater than 4 ft/s, the boat was anchored upstream from the pier and the anchor line released slowly allowing the boat to float past the pier at a slow rate of speed.

### Limitations of Geophysical Equipment

Use of geophysical equipment is limited by the suitability of the site, operating limitation of the equipment, and the interpretations derived from the geophysical data. Geophysical methods cannot detect scour beneath riprap under most conditions (figs. 9A and 9B). Bridges with debris, remnant coffer dams, and turbulent or deep water around the piers are difficult to properly examine using these methods. Infilled scour-hole elevations are difficult to detect when (1) streamflows are affected by debris, (2) pier alignment is grossly skewed to the flow, (3) when excavation holes are still present, or (4) piers are riprapped. Geophysical methods, like any other tool, have limitations and will not provide all the answers.

## COMPARISON OF SURFACE-GEOPHYSICAL RESULTS WITH SCOUR EQUATIONS

The relation of infilled scour-hole elevations to the magnitude of the high-water event which caused them was examined. Assuming maximum scour was detected using surface-geophysical methods, and that the explanatory variables for a scour equation can be determined. Measured scour depths could be compared to calculated scour depths. At sites with historic streamflow data and with maximum scour data determined by surface-geophysical methods, scour equations were used to calculate maximum scour depth and test the effectiveness of the equations. The three scour equations used for this comparison are: Froehlich (1988), Neill (1964), and Copp and Johnson (1987). Two sites were selected to compare the maximum depths of scour calculated by three scour equations, with measured maximum scour depth.

Selecting bridge sites to be used to calculate scour is difficult because scour equations are generally developed for ideal conditions. Scour equations do not account for bridge piers with debris, excessive skew to the flow, obstruction upstream, or riprap (Jarrett and Boyle, 1986). In this study, several of the bridges had riprap around the base of the piers, some had debris around the piers, and others had streamflow approaches at a skew greater than 20 degrees. None of the 14 sites studied had ideal conditions for bridge-scour computation. Two sites were considered suitable to calculate bridge pier scour using published scour equations. Rogue River Bridge 8738 at Grants Pass, Oregon, and Sandy River Bridge 332A near Troutdale, Oregon, were selected for comparison with bridge-scour equations.

The highest water discharge since the Rogue River Bridge 8738 was built occurred in December of 1964. Maximum instantaneous discharge near the peak was 152,000 $ft^3/s$ (cubic feet per second) with maximum depths at the bridge of 36 ft and a mean velocity of 13 ft/s. Water depths and velocities at the Rogue River Bridge were taken from U.S. Geological Survey field discharge measurements notes.

The highest water discharge since the Sandy River Bridge 6875A was built occurred in December 1964. Maximum instantaneous discharge was 84,400 $ft^3/s$ at the gaging station 15.2 miles upstream. At the bridge, the peak flow was computed to have a discharge of 96,000 $ft^3/s$, with depths of 24.5 ft and a mean velocity of 5 ft/s. Discharge at the Sandy River Bridge were derived from 1964 flood data (Waananen, 1970) and U.S. Geological Survey field measurements at gaging station 15.2 miles upstream and was recomputed for this bridge site. Velocity was determined by applying adjusted discharge to measured cross-sectional area at the bridge. Water depths were taken from 1964 flood data (Waananen, 1970).

Three bridge scour equations were used to predict scour depths at each site:

Scour prediction equation by Froehlich (1988) is

$$ds/b = 0.32\phi\ (b'/b)^{0.62}\ (y/b)^{0.46} Fa^{0.20} (b/d_{50})^{0.08}, \qquad (1)$$

where

- ds = computed depth of local scour
- b = pier width
- $\phi$ = pier nose shape
  - where 1.3 for a square nosed pier
  - 1.0 for a round nosed pier
  - 0.7 for a sharp nosed pier
- b' = ($b \cos \alpha + \ell \sin \alpha$) pier width projected normal to the approach flow
  - $\alpha$ = approach angle (0 for aligned flow)
  - $\ell$ = pier length
- Fa = Froude number $v/\sqrt{(g*y)}$
  - y = approach flow depth
  - v = mean velocity of the approach flow at the pier

$g$ = force of gravity 33.2 $ft^2/s$
$d_{50}$ = median diameter of bed material.

The Neil (1964) equation is

$$\frac{ds}{b} = 1.5k\,(y/b)^{0.3}, \qquad (2)$$

where

ds = computed depth of scour
b = width of pier
y = average flow depth
k = 1 to 7 for angle of attack

The third equation is based on Copp and Johnson (1987:

$$ds = (dsm)\,(k\delta)\,(k\alpha)\,(ks)\,(kfs), \qquad (3)$$

where

ds = computed depth of scour
dsm = uncorrected value of scour depth due to pier width
$k\delta$ = particle size coefficient
$k\alpha$ = design factor for angle of attack of stream to pier
ks = pier nose shape (use 1.0 if pier is not aligned to flow)
kfs = safety factor coefficient (not used for this determination).

Results of this comparison showed that the Rogue River bridge 8432 had a measured scour depth of 2.5 ft and the calculated scour depths rnaged from 2.6 to 12.2 ft depending on the equation used. Sandy River bridge 6875A had a measured scour depth of 5.1 ft and the calculated scour depths ranged from 5.2 to 20.7 ft. Computation results of these equations are shown in table 5.

Table 5.--Comparison of predicted scour-hole depths from formulas with field measurements of old scour-hole depths

| Site location | Bridge number | Conditions | Equation predictions in feet: Froehlich | Neill | Copp and Johnson | Field measurements of maximum scour (feet) |
|---|---|---|---|---|---|---|
| Rogue River at Grants Pass, OR Pier 3 | 8432 | Well-graded Particle size | 4.2 | 13.6 | 2.6 | 2.5 |
| Sandy River nr Troutdale, OR Pier 2 | 6875A | Approach angle 15-degrees Well-graded Particle size | 7.1 | 20.7 | 5.2 | 5.1 |

## APPLICATION OF SURFACE-GEOPHYSICAL METHODS TO FUTURE BRIDGE-SCOUR STUDIES

Surface-geophysical methods methods have several useful applications to future bridge-scour studies, such as surveillance, scour equation verification, riprap inspection, and inspecting scour around bridge piers after major floods.

Surface-geophysical methods can be used as part of a surveillance program during routine inspections to locate scour-prone sites. When these scour prone sites are located, periodical inspections for infilling can be made using these methods. Background information, such as the depth and width of holes excavated during construction and the type of material used to backfill around piers after completion, would improve the surveillance application of the surface-geophysical methods.

Scour equations can be evaluated, given certain conditions and assumptions using data collected with surface-geophysical methods. Infilling often occurs after the initial scour has taken place, making accurate determination of the actual scour-hole depth difficult when using conventional methods (Gorin and Haeni, 1989). During this study, surface-geophysical methods provided infilled scour data which were compared with computed scour from three equations.

The effectiveness of riprap as a deterrent to pier and abutment scour has been studied for some time (Parola and others, 1989). Surface-geophysical methods detected riprap at several locations during this study. At the Columbia River I-205 Bridge, riprap could be seen on surface-geophysical record even when it was covered by sediment (figs. 9A, 9B, 9C). Surface-geophysical measurements would be helpful in determining the effectiveness of riprap as a scour deterrent.

## SUMMARY AND CONCLUSIONS

Three surface-geophysical methods--ground-penetrating radar, high frequency continuous seismic reflector method (tuned transducer), and color fathometer--were used to examine fourteen bridge sites in Oregon. Bridge piers were studied using one or more of the geophysical methods from a boat. Results of the surface-geophysical methods were verified by measuring the depth from the water surface to the pier footing, existing scour hole, and bottom of the infilled scour hole with a probe.

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

Results from surface-geophysical measurements showed that the bottom of infilled scour holes are about 2.5 ft beneath the bottom of the pile caps at bridges R8588C and R8588E in the Willamette River at Portland. Sandy River bridges 332 and 332A have existing scour holes with little infilling. The bottom elevations of the scour holes are near the bottom of the seal. Geophysical results showed that 4 to 5 ft of new sand has moved in over the existing channel bottom beneath the old Highway 101 bridge at Waldport in the vicinity of piers five and six. Scour has occurred as deep as the bottom of the spread footings at the Deschutes River bridge 332 and at the Rogue River bridge 1418.

Measured scour depths were compared to calculated scour depth derived from three scour equations. Scour equations used in predicting maximum scour around piers require: (1) flow direction to be nearly parallel to the piers, (2) piers to be clear of debris, and (3) no riprap around piers. Of the 14 bridges studied, none met all three requirements needed for accurate prediction of maximum scour. Two sites were selected where the maximum scour depths were calculated and compared with measured data. Rogue River bridge 8432 had a measured scour depth of 2.5 ft and the calculated scour depths ranged from 2.6 to 12.2 ft depending on the equation used. Sandy River bridge 6875A had a measured scour depth of 5.1 ft and the calculated scour depths ranged from 5.2 to 20.7 ft. A larger data base is needed to be able to compare the effectiveness of scour equations with actual scour depths.

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## DEFINITION OF TERMS

Bent is a bridge substructure element immediately below the superstructure. It may be a bridge pier, column, abutment or a pile supported cap.

Black-and-white fathometer is a sonic depth finder.

Color fathometer (CF) is a sonic depth finder that displays signals on a screen in color. These colors represent the amplitudes of the reflected signals that are related to the physical properties of the sediment interfaces. This device is used to detect subbottom stratigraphy beneath water covered areas.

Ground-penetrating radar (GPR) is a geophysical method that propagates electromagnetic signals in the 80-1,000 megahertz frequency range. It is designed to send signals into the ground and record reflections from subsurface layers.

Multiples are reflected GPR, TT, and CF signals that reverberate in the water column. Water-bottom multiples may occur more than one time and appear on the record as a separate image at twice (three-times, four-times, etc.) the depth of the water. Multiples sometimes interfere with bottom and subbottom signals by being recorded over the original signal, thus covering up or masking the desired trace.

Pier is a substructure element either constantly or occasionally inundated by water.

Pier footing see definition of spread footing. The footing may be the bottom of the substructure placed on dense sands and gravel or bedrock or may be above a concrete seal. Pier footings may be pile supported.

Pilings are slender deep foundation units, made of materials such as wood, steel, or concrete, or combinations thereof, which is either pre-manufactured and placed by driving, jacking, jetting, or screwing, or cast-in-place in a hole formed by driving, excavating, or boring. Their purpose is to resist or transfer vertical, horizontal, or combination loads imposed upon them.

Seal is a concrete mass (usually not reinforced) poured under water in a cofferdam that is designed to resist hydrostatic uplift. The seal facilitates construction of the footing in dry conditions.

Seismic waves are sound waves transmitted by TT, or CF that pass through the water column into the subbottom sediments.

Side echo is a signal that reflects off an object adjacent to the transducer or antenna. This occurs when the transducer or antenna is close to an object (such as a pier). Side echoes obscure bottom and subbottom signals and can make interpretation of the data difficult.

Sonar signals are sound waves transmitted through water.

Spread footing is the bottom of the substructure, and is a reinforced concrete mass supporting the weight of substructure and superstructure components. The spread footing may either support an abutment, pier, bent, column, or retaining wall. Spread footings are usually placed on scour resistant dense sands and gravel or bedrock. Spread footings may be pile supported.

Tuned transducer (TT) is a geophysical device that propagates seismic signals in the 3-14 kilohertz frequency range. It is designed to transmit seismic signals into the water column and subbottom and record reflections from subbottom layers beneath the river. This device is sometimes referred to as a subbottom profiler.