MONITORING BRIDGE SCOUR:
AN APPLICATION OF GROUND PENETRATING RADAR

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Abstract

The University of Missouri-Rolla (UMR) and the Missouri Department of Transportation (MoDOT) acquired 2-D ground penetrating radar (GPR) profiles across selected streams and drainage ditches at ten bridge sites in southeast and central Missouri. The objective was to determine if GPR is an effective tool for monitoring bridge scour, and estimating the depths and breadths of in-filled (paleo) scour features.

The interpretation of the suite of acquired profiles (as individual lines and pseudo 3-D presentations) indicates the GPR tool can be used to accurately estimate water depths in shallow fluvial environments (maximum depths in study areas were less than 20 feet). The GPR tool can also be used to monitor fluctuations in water depths over time, and to study depositional and erosional patterns. In certain instances, in-filled scour features can also be imaged and mapped. Paleo-scour features are important because they can provide information about maximum scour during peak flow periods.

GPR has certain advantages over alternate methods for estimating water depths. GPR can provide essentially continuous 2-D and/or 3-D images of the stream channel and the sub-water bottom sediment. The GPR antenna are non-invasive and can be moved rapidly across (or above) the surface of a stream at the discretion of the operator. Additionally, the GPR tool does not need to be physically coupled to the water surface and can be operated remotely, ensuring that neither the operator nor equipment need be endangered by floodwaters. Perhaps the most significant disadvantage of GPR is that the tool does not work well in “clayey” sedimentary environments.

Introduction

The determination of seasonal variations in water depth and the assessment of erosional and depositional patterns in the vicinity of existing or planned bridge piers (monitoring of bridge scour) is essential to understanding the fluvial scour process on a site-specific scale. The design of preventative (during bridge construction) or remediation measures is most efficient and cost-effective if the local scour process is understood. Unfortunately, riverbed scour occurs mostly during high flow stages. Scour depth/breadth information can be very difficult (and dangerous) to acquire at such times. Additionally, scour features are often in-filled as peak flow subsides making the direct measurements of maximum scour depth/breadth essentially impossible after the fact.

In an effort to assess the utility of GPR when employed as a bridge scour monitoring/investigation tool, UMR and MoDOT acquired multiple parallel GPR profiles across streams and drainage ditches at ten different bridge sites in southeastern and central Missouri. The GPR profiles were acquired using a GSSI SIR-10B radar unit equipped with a 200 MHz monostatic antenna. (At some sites, duplicate GPR profiles were acquired using an additional higher frequency antenna.) A scaled rod was used to manually measure stream depths at specific control locations for calibration and verification purposes. The acquired data were processed and displayed as 2-D profiles and 3-D images.

Types of Bridge Scour: Classification

The erosion of riverbed material at bridge sites is a result of natural stream processes, particularly seasonal variations in water depth and velocity. Indeed, maximum scour depths are often estimated by assuming that scour depth is proportional to the rise of the water surface elevation (Xanthakos, 1995). Bridge scour is also influenced by bridge components such as piers, abutments, roadway embankments, and the superstructure itself, and is classified as general, contraction, or local (Figure 1).

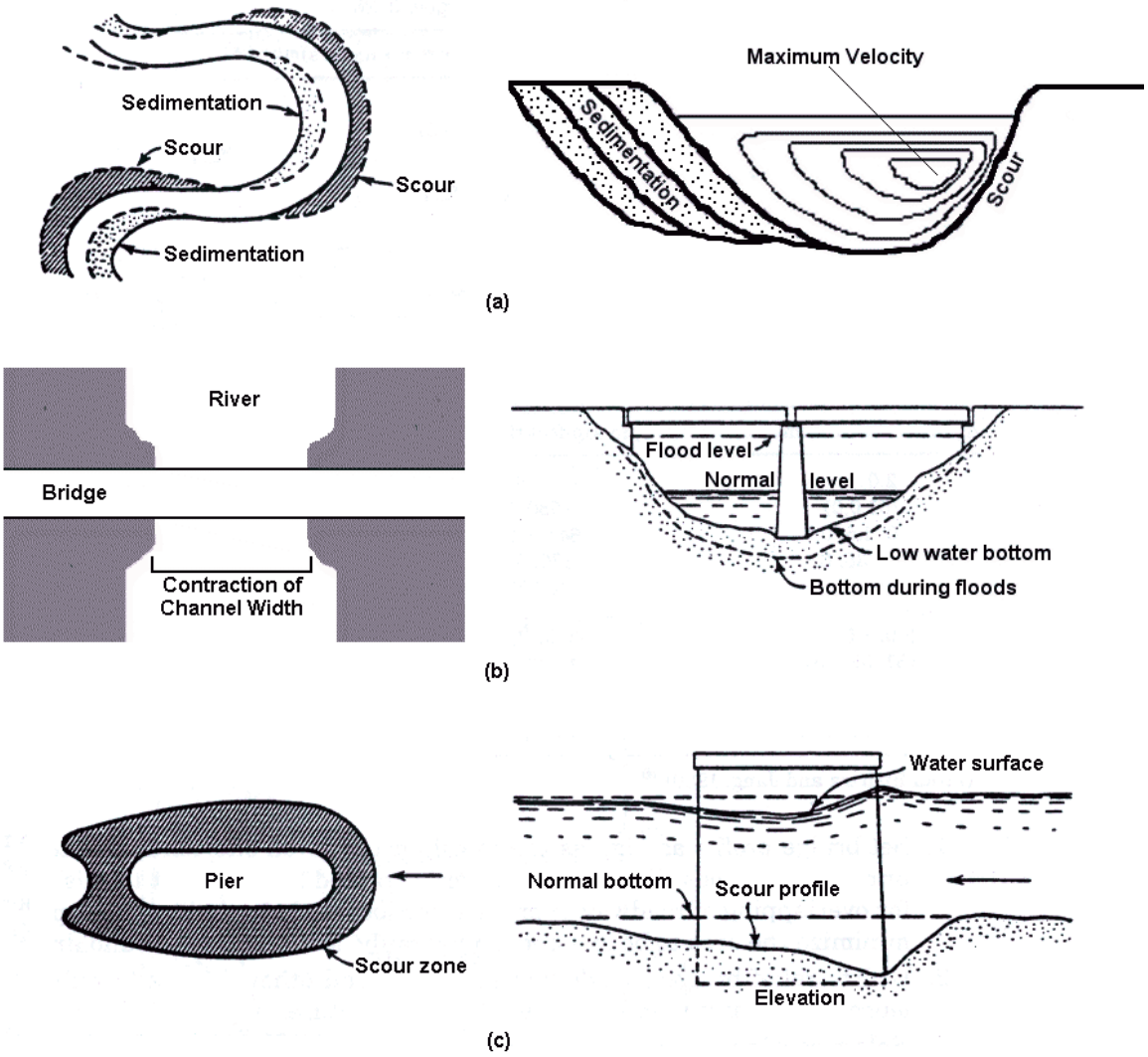

Figure 1: Forms of scour in waterways: (a) general scour, (b) contraction scour, and (c) local scour (after Xanthakos, 1995). Left side depicts plan view; right side depicts cross-section.

General Scour is illustrated in Figure 1a. In this process, progressive erosion at the outer bend along a meandering stream causes the progressive lateral shifting of the stream channel and attendant variations in water depths. General scour can result in the undermining of abutments if certain precautionary measures (such as the placement of concrete or asphalt mats over the riverbank and the installation of abutment foundations below the lowest depth of possible scour) are not taken.

Contraction Scour is illustrated in Figure 1b. In this process, the narrowing of the waterway at a bridge site increases water velocity and accentuates erosion. A remedy is to enlarge the channel or ensure the channel under the bridge is the same size as the channel adjacent to the bridge.

Local Scour is illustrated in Figure 1c. In this process, river obstructions such as bridge piers cause the contraction of channel cross section resulting in higher flow velocities and accentuated erosion. The magnitude of scour is dependent upon pier configuration and inclination with respect to flow, contraction of waterways, and volume of debris accumulated at bridge.

Geophysical Methods for Evaluating Scour

Several geophysical techniques are commonly used to measure water depths and/or the depth/breadth of in-filled scour features. Techniques include reflection seismic profiling, echo sounding (in continuous or spot survey mode) and electrical conductivity probing. The GPR tool is presented herein as an effective alternative in certain circumstances. Each tool has characteristic strengths and weaknesses.

Reflection Seismic Profilers

The reflection seismic profiling technique typically employs a coupled acoustic source transducer/ receiver transducer placed immediately beneath the surface of the water. The acoustic source transducer produces a short period (frequencies in kilohertz range) pulsed acoustic signal at regular time or distance intervals as it is towed across the surface of the water (Figure 2). The high-frequency pulsed seismic signal propagates through the water column and into the sub-water bottom sediment. Some of the acoustic energy is reflected at the water bottom and at other prominent acoustic impedance interfaces (e.g., lithological and/or facies interfaces; Figure 2) and returned to the receiver. The receiver measures and digitally records the magnitude of the reflected energy as a function of two-way travel time. Magnitude of reflected signal vs. arrival time for each source/receiver location is visually displayed as a time-trace. Time-traces from adjacent source/receiver locations are plotted side-by-side forming an essentially continuous time-depth profile of the stream bottom and shallow sub-strata (including in-filled scour features). Estimated seismic interval velocities can be used to transform the time-depth profile into a depth profile (Figure 3). Water velocities are a function of suspended sediment load and can vary appreciably.

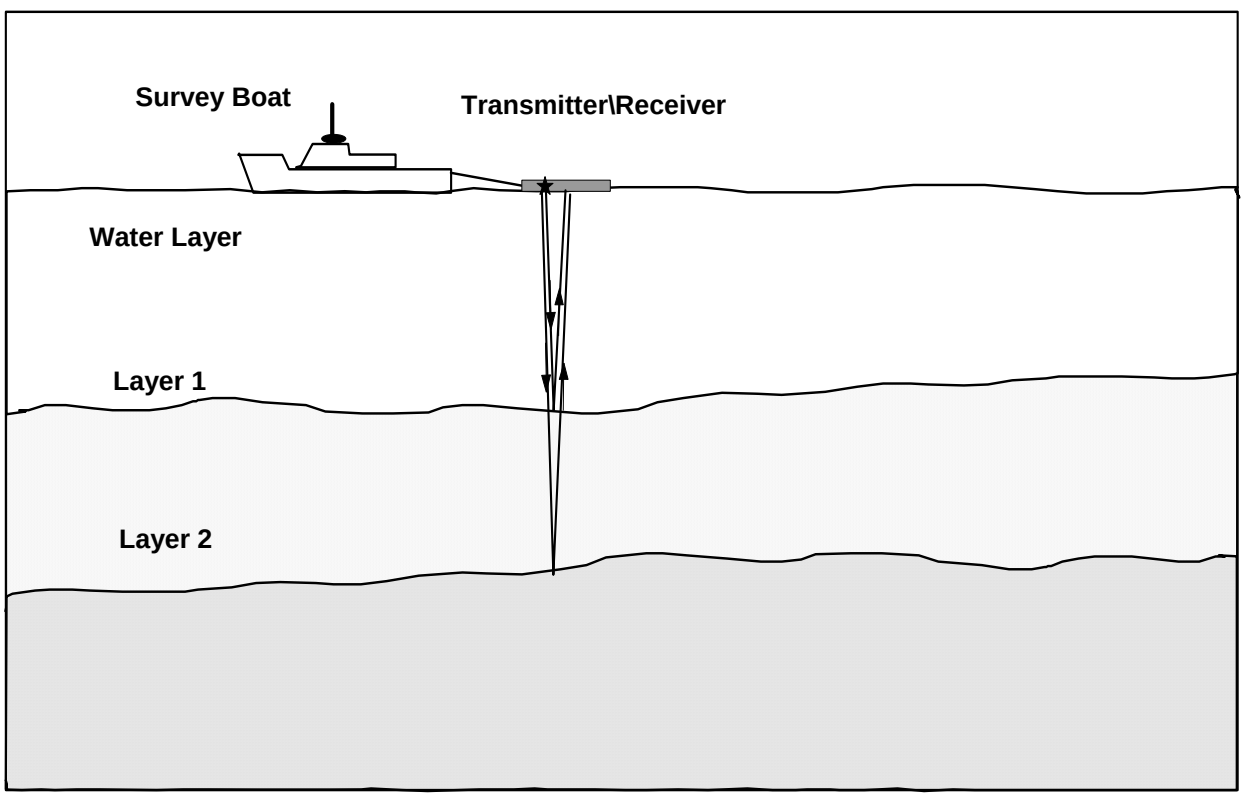

Figure 2: Schematic diagram for the seismic profiling survey showing coupled source/receiver data acquisition using a small boat. (Down-going and up-going ray-paths are generally treated as though they were perpendicular to reflecting horizons.)

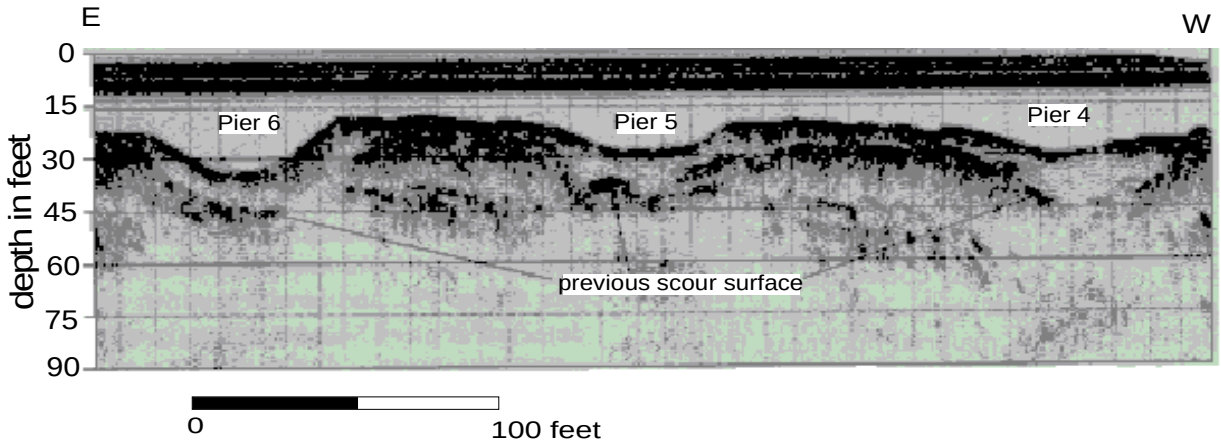

Figure 3: Example 7-kilohertz continuous seismic-reflection profiling data (after Placzek and Haeni, 1993).

The main advantages of reflection seismic profiling are as follows:

1. The tool can provide an accurate depth-structure model of the water bottom (to depths on the order of hundreds of feet).
2. Post-acquisition processing (including 2-D migration) can be applied.
3. The tool can provide an accurate image of the sub-water bottom sediment to depths on the order of tens of feet (dependent upon the frequency of the acoustic source). Lithological/facies units with thickness on the order of 0.3 feet can be imaged with higher-frequency antenna (14 kHz units).

The main disadvantages of the reflection seismic profiling tool are as follows:

1. The source and receiver need to be submerged. Profiles cannot be extended across emerged sand bars or onto the shore.
2. The equipment is relatively expensive (hardware and software).
3. Data may be contaminated by noise (multiple reflections, and echoes from the shoreline, water bottom and/or bridge piers).

Echo Sounders (Fathometers)

Echo sounders (fathometers) are similar to the reflection seismic profilers in that they also employ a coupled acoustic source transducer/receiver transducer placed immediately beneath the surface of the water. Echo sounders differ from reflection seismic profilers in that they emit a higher frequency acoustic source pulse (dominant frequency in 100 kHz range), some of which is reflected at the water bottom, returned to the receiver, and stored digitally (Figure 4). (Because of the rapid attenuation of the high frequency pulsed acoustic energy, relatively little signal is transmitted into or reflected from within sub-water bottom sediment.) Traces from adjacent source/receiver locations are plotted side-by-side to form an essentially continuous time-depth profile of the stream bottom. Figure 4 depicts an example fathometer depth profile recorded data at new Baldwin Bridge, Old Saybrook, Conneticut. Estimated seismic interval velocities can be used to transform the time-depth profile into a depth profile (Figure 5). Water velocities are a function of suspended sediment load and can vary appreciably.

The main advantages of the echo-sounding tool (in continuous mode) are as follows:

1. The tool can provide an accurate depth-structure model of the water bottom (if acoustic velocities are known).
2. Post acquisition processing (migration) can be applied.

The main disadvantages of the echo sounding tool (in continuous mode) are as follows:

1. The source and receiver need to be submerged. Profiles cannot be extended across emerged sand bars or onto the shore.
2. The equipment is relatively expensive (hardware and software).
3. Data may be contaminated by noise (multiple reflections, and echoes from the shoreline, water

bottom and/or piers).

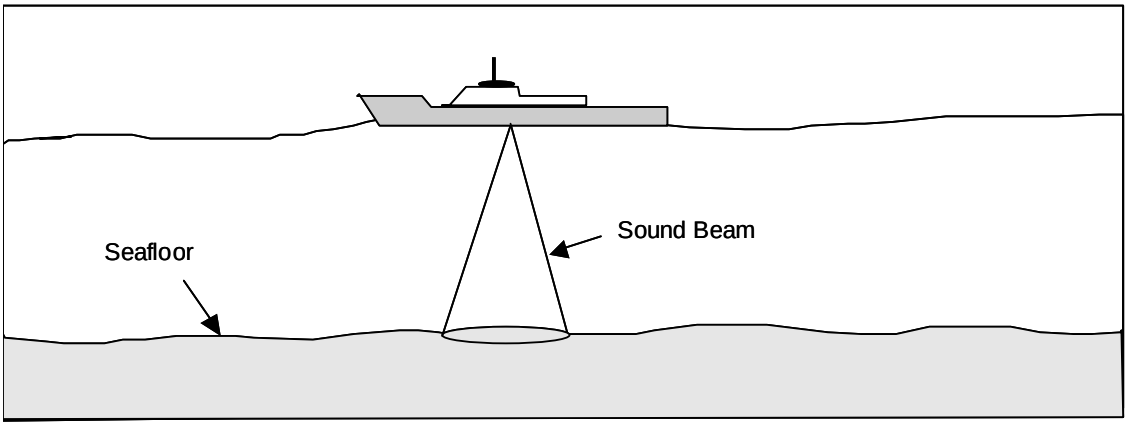

Figure 4: A schematic diagram showing collection of echo sounding data.

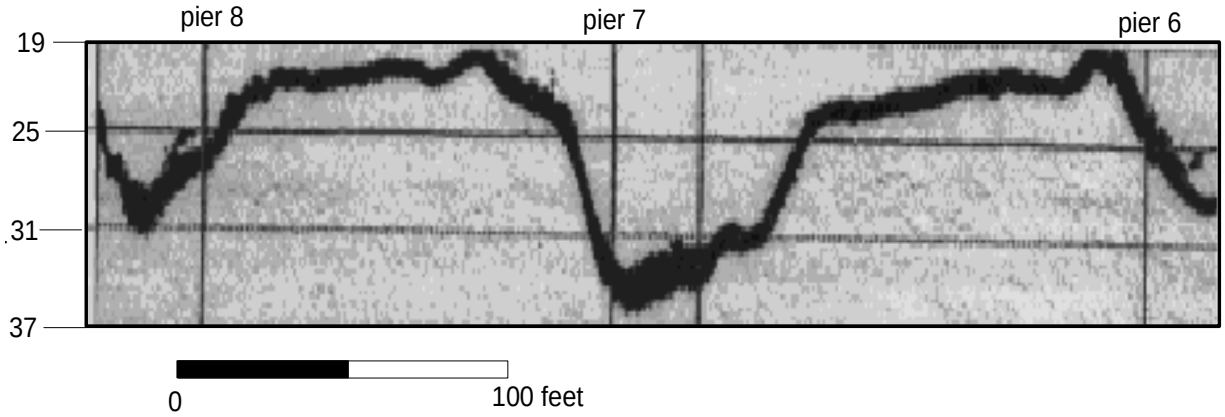

Figure 5: Unpositioned 200-kilohertz fathometer data collected 15 feet upstream from the new Baldwin Bridge, Old Saybrook, Conneticut (after Placzek et al., 1993).

4. Post acquisition processing (migration) may be required in areas where significant structural relief is present.
5. The tool cannot be used to image in-filled scour features within sub-water bottom sediments.

Echo sounders are also employed in a spot survey mode. In this type of survey, sounding data (single reflection traces) are acquired at irregularly (or uniformly) spaced intervals (typically on the order of feet) at the water surface. The first high-amplitude reflected event is usually interpreted to be the water bottom reflection. Note, that spot data usually cannot be accurately migrated because of aliasing problems.

The main advantages of the echo sounders (in spot mode) are as follows:

1. The tool can provide an accurate depth-structure model of the water bottom if acoustic velocities are known.
2. The equipment is relatively inexpensive.

The main disadvantages of the echo sounders (in spot mode) are as follows:

1. The source and receiver need to be submerged. Data cannot be acquired across emerged sand bars or onto the shore.

2. Data may be contaminated by noise (i.e., the first high amplitude event may not be from the water bottom).
3. Water depths may be significantly underestimated in areas of extreme water bottom relief (curved surfaces with radii less than water depth).

Electrical Conductivity Probes

Electric conductivity probes measure the ability of a solution to conduct an electric current between two electrodes. In solution, current flows by ion transport. Therefore, an increasing concentration of ions in the solution will result in higher conductivity values. Conductivity Probes actually measure conductance (reciprocal of resistance). When resistance is measured in ohms, conductance is measured using the SI unit, siemens (formerly known as a mho). An example electrical conductivity probe is shown as Figure 6.

Use of the electrical conductivity probe to measure the depth to riverbed is based on the principle that the conductivity of the riverbed and the river water differ. (The nature of suspended sediments, dissolved ions and chemical characteristics of water determines its conductivity. Parent materials and the composition of the water in the sediments determines the electrical conductivity of the riverbed.) In this technique, multiple conductivity sensors are placed on a probe, which is driven vertically into the riverbed at the desired location and left for periodic monitoring. At least one of the probe's sensors extends above the riverbed, while multiple sensors are placed within the sub-water bottom sediments (Hayes 1995). If scour occurs at the location of the probe to the extent that one or more previously buried sensors are exposed to water, these newly exposed sensors will measure the conductivity of the flowing water instead of the sediments in the riverbed. Hayes (1995) states the method works well only if the conductivity of the riverbed and water differ significantly. Hayes (1995) also states that the tool cannot be used for direct measurement of in-filled scour features.

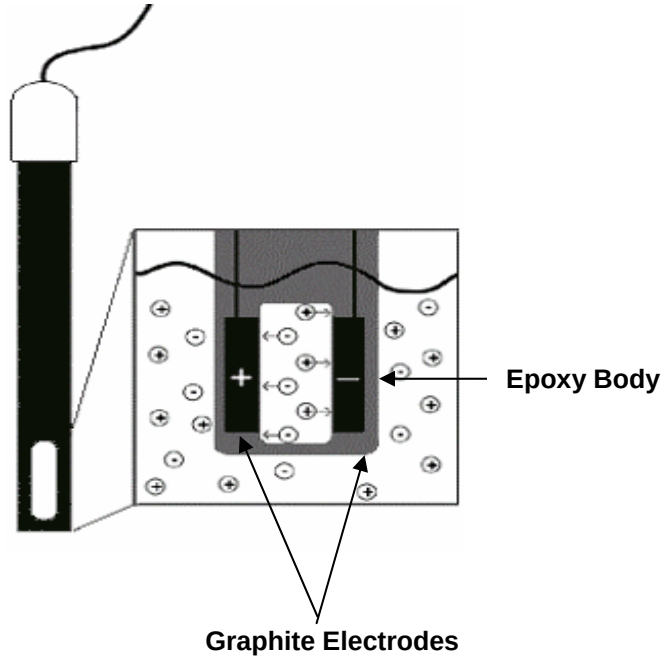

Figure 6 : Electrical conductivity probe used for the educational purposes (after Vernier Software and Technology, 2000).

The main advantages of the electrical conductivity probe method are as follows:

1. The tool allows for long term monitoring.
2. The method is relatively inexpensive.

The main disadvantages of the electrical conductivity probe method are as follows:

1. The tool monitors scour only at the location of the probe.
2. The tool can be used effectively only where water and sediment conductivities differ appreciably.
3. The tool may pose a hazard to navigation.
4. Scour features can be underestimated.
5. The tool cannot be used to image scour features within the sub-water bottom sediments.

Ground Penetrating Radar (GPR)

The ground penetrating radar (GPR) tool typically employs a coupled source antenna/receiver antenna placed on or immediately above the surface of the water as it is shown in Figure 7. The source transducer produces a short period (frequencies in megahertz range) pulsed electromagnetic signal at regular time or distance intervals as it towed across or above the surface of the water. Some of this pulsed electromagnetic (EM) energy is reflected from the water bottom and other prominent dielectric interfaces (facies contacts), and returned to the receiver. The arrival time and magnitude of the reflected energy is recorded at the surface by the receiver antenna (Figure 8). Traces from adjacent source locations are generally plotted side-by-side to form an essentially continuous time-depth profile of the stream bottom and shallow sub-strata (including in-filled scour features). Estimated EM velocities can be used to transform the time-depth profile into a depth profile (Figure 9). Velocities are a function of suspended sediment load, and can vary appreciably.

Figure 7: GPR system mounted inside cable car with 100MHz antenna suspended up to 10 feet above the water surface.

The main advantages of the GPR profiling tool are as follows:

1. GPR can provide an essentially continuous image of the stream channel and the sub-water bottom sediment along the route selected.
2. The GPR tool can provide an accurate depth-structure model of the water bottom and sub-water bottom sediments (to depths on the order of 30 feet). Lithological/facies units with thickness on the order of 0.3 feet can be imaged with intermediate-frequency antenna (200 MHz).
3. The GPR antennae are non-invasive and can be moved rapidly across (or above) the surface of a stream at the discretion of the operator. The GPR tool does not need to be physically coupled to the water surface and can be operated remotely, ensuring that neither the operator nor equipment need be endangered by floodwaters.
4. Profiles can be extended across emerged sand bars or onto the shore.
5. The digital GPR data can be stored, and post acquisition processing (including migration) can be applied.

The main disadvantages of the GPR profiling tool are as follows:

1. The equipment is relatively expensive (re: hardware and software).
2. Data may be contaminated by noise (multiple reflections and echoes from pier footings).
3. Post acquisition processing (migration) may be required in areas where significant structural relief is present.
4. The tool is not normally effective when water depths exceed 30 feet.
5. The tool cannot be used in saline waters.
6. The tool does not work well in clayey environments.

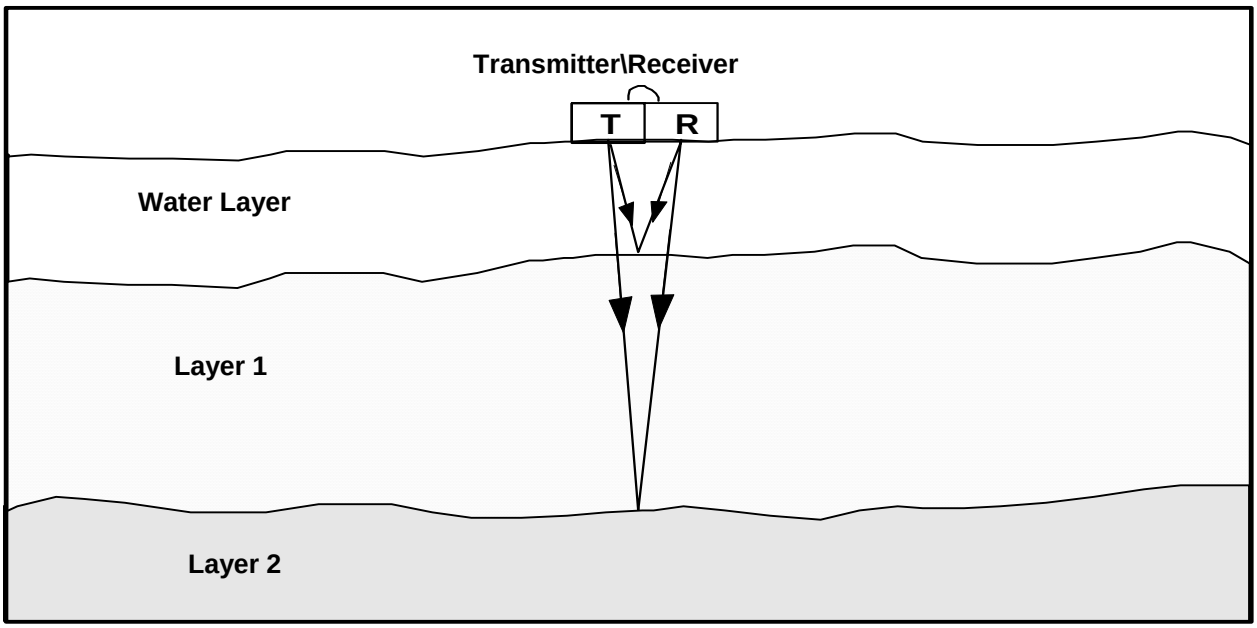

Figure 8: Principles of GPR technique. (Down-going and up-going ray-paths are generally treated as though they were perpendicular to reflecting horizons.)

Acquisition of Ground Penetrating Radar at Ten Bridge Sites

In an effort to assess the utility of GPR when employed as a bridge scour investigation tool, GPR profiles were acquired at ten different bridge sites in southeastern and central Missouri. River-bed

sediment at all sites consisted of clean clastics (devoid of clay), and quality GPR data were expected. A Geophysical Survey Systems (GSSI) SIR-10B unit equipped with a 200 MHz antenna was employed. A sampling rate of 50 scans/second and ranges (trace lengths) between 125 and 350 nanoseconds were employed. At most sites, duplicate GPR profiles were acquired using a 400 MHz antenna.

At each bridge site, GPR profiles were collected both parallel and perpendicular to current flow. At some bridge sites, GPR data could not be collected immediately adjacent to piers, due to obstructions (usually snagged debris). Data were acquired by maneuvering the antenna across the surface of the water in one of three ways: from the bridge deck, manually or by boat.

Processing of GPR Data

The acquired GPR data were processed on a Pentium PC using the commercial processing package RADAN. The following run stream was employed.

1. Distance normalization
2. Horizontal scaling (stacking)
3. Vertical frequency filtering
4. Horizontal filtering
5. Velocity corrections
6. 2-D Migration
7. Gain
8. Construction of pseudo 3-D data set.
9. Interpolation between parallel profiles in 3-D grid.

The applied processing steps increased the interpretability of the GPR profiles by removing unwanted random noise and enhancing the amplitude of events of interest (reflections from water bottom and base of in-filled scour features). Unfortunately some of the GPR data were contaminated by high-amplitude water-bottom multiple reflections which could not be removed effectively using the RADAN software. These multiple events arrived after the primary water bottom reflection and in places mask reflections from the base of in-filled scour features.

Example GPR Profiles

Representative example GPR profiles are shown as Figures 9, 10 and 11. Note that river-bed sediment at these sites consisted of essentially clean clastics, and quality GPR images of sub-bottom strata were acquired. If significant clay had been present in the sedimentary section, the GPR tool would not have provided quality images of sub-bottom sediment.

In Figure 9 non-interpreted stacked, migrated, and velocity-corrected versions of example GPR profile 1 are presented as captions 9a, 9b, and 9c, respectively. Interpreted stacked, migrated, and velocity-corrected GPR sections are shown as captions 9d, 9e, and 9f, respectively. The depth scales on the stacked and migrated sections were calculated using EM (electromagnetic) water velocities only. As a result, the estimated water bottom depths on the stacked and migrated sections are relatively accurate, however depths to sub-water bottom structures (including in-filled scour features) are inaccurate. In contrast, scaled depths on the velocity-corrected profiles were calculated using different EM velocities for the water and sub-water bottom sediment. Estimated depths on the velocity-corrected profiles are therefore more accurate, particularly within the sub-water bottom section. (Note: Water velocities were estimated on the basis of known water depths and recorded GPR transit times. Sub-water bottom velocities were estimated on the basis of on-site field tests during which metal plates were buried beneath fluvial sediment.)

The superposed gray line on the interpreted GPR profiles (Figure 9) represents the interpreted water bottom. The superposed white line on the interpreted GPR profiles represents reflections from the base of interpreted in-filled scour features. The thickness of in-filled scour features (represented by “S”) can be estimated by measuring the distance from the white line to the top of the gray line on velocity-corrected profiles (only). Piers along the profile are displayed as rectangular columns on the sections. Reflections from the flanks or footings of some of piers are characterized as prominent diffractions on the GPR profiles.

Multiple versions of example GPR profile 2 are shown in Figures 10 and 11. Non-interpreted stacked

and migrated GPR sections are presented as captions 10a and 10b, respectively. Interpreted stacked and migrated GPR sections are shown as captions 11a and 11b, respectively.

Figure 12 is a 3-D depth image of the river bottom at test site 3. This pseudo 3-D image (data were not migrated; control was interpolated between parallel profiles) was constructed using depths to water bottom as estimated on 31 parallel (1 m spacing) GPR profiles. The plan view map of Figure 13 depicts lateral variations in depth to water bottom in the same study area. The comparison of 3-D images obtained at different times of the year will provide important information about seasonal variations in depositional and erosional processes and patterns. GPR control obtained before, during and after floods will provide information about the fluvial system's localized response to rapid increases in water volumes.

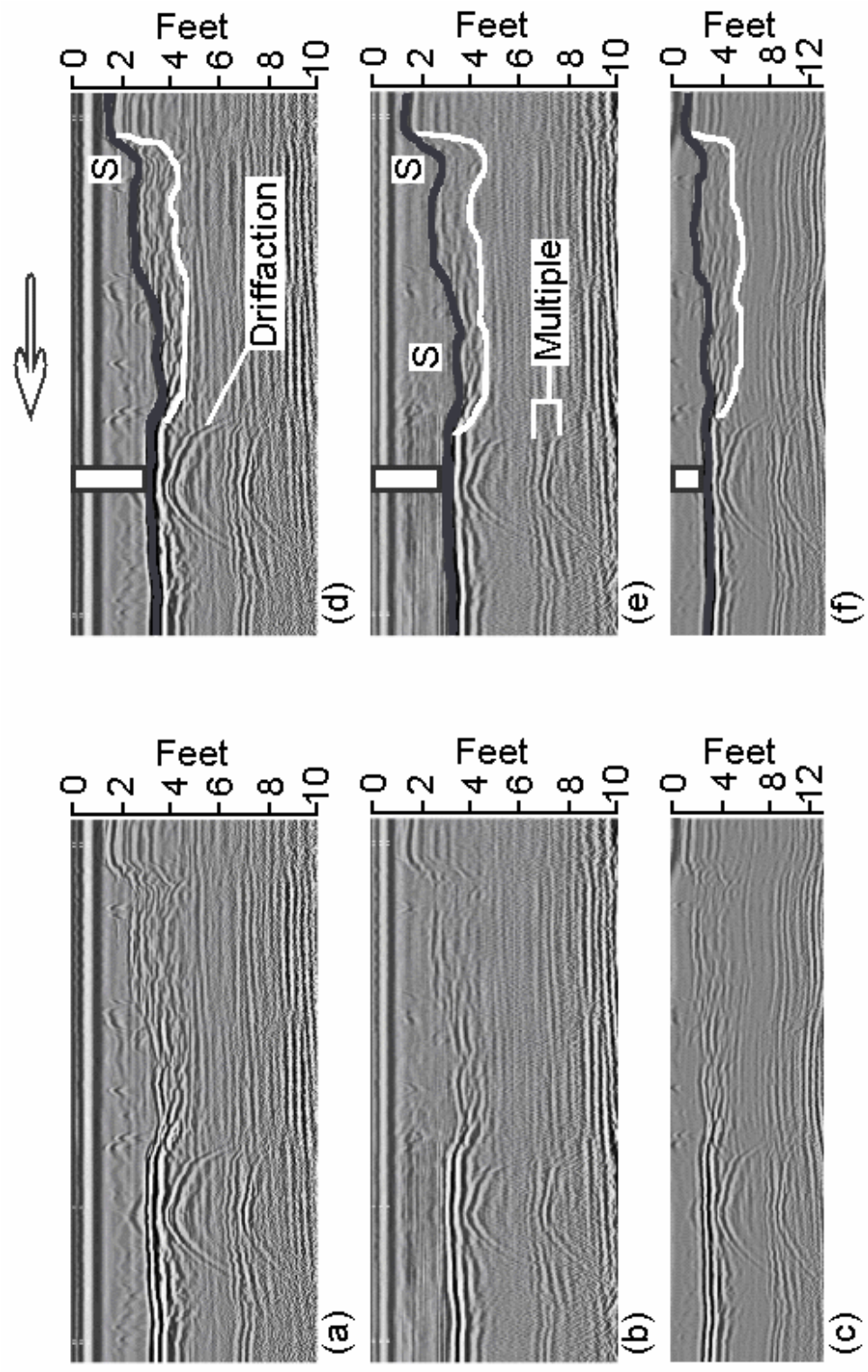

Figure 9: Multiple processed versions of example GPR profile 1: (a) stacked; (b) migrated; (c) velocity-corrected; (d) interpreted stacked; (e) interpreted migrated; and (f) interpreted velocity-corrected. Gray and white lines identify water bottom and extent of in-filled scour, respectively.

Conclusion

During high-flow stages streambed materials around bridge piers are frequently removed by floodwaters. This process can compromise the structural integrity of the bridge and in extreme cases, lead to failure or collapse. An understanding of local scour processes at specific bridge sites is therefore essential.

Ground penetrating radar (GPR) data were collected, processed and interpreted in an effort to test this tool's ability to image water bottom and in-filled scour features in shallow Missouri waterways. Multiple parallel GPR profiles were acquired at ten bridge sites, each of which was characterized by different channel characteristics.

Based on the analysis of the acquired data, it is concluded that GPR can be a useful, cost-effective tool for estimating water depths and identifying/mapping in-filled scour features in a clastic fluvial environment. However, the GPR tool will not provide quality images of sub-bottom strata if significant clay is present.

GPR data can be interpreted in either 2-D or 3-D format. The comparison data obtained at different times of the year will provide important information about seasonal variations in depositional and erosional patterns. GPR control obtained before, during and after floods will provide information about a fluvial system's local response to rapid fluctuations in water volumes.

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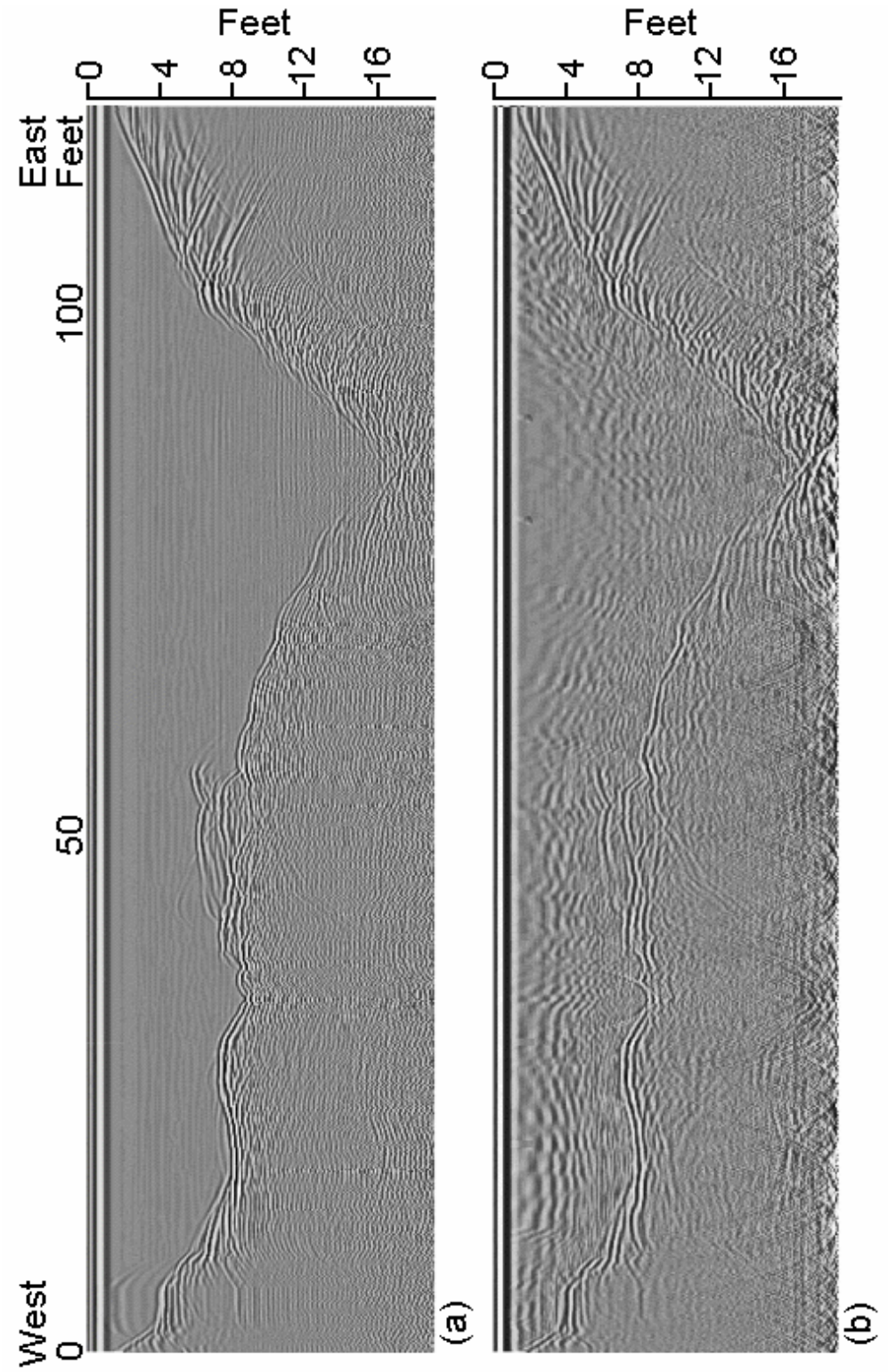

Figure 10: Multiple processed versions of example GPR profile 2: (a) stacked; and (b) migrated. Existing scour feature is marked with an "S".

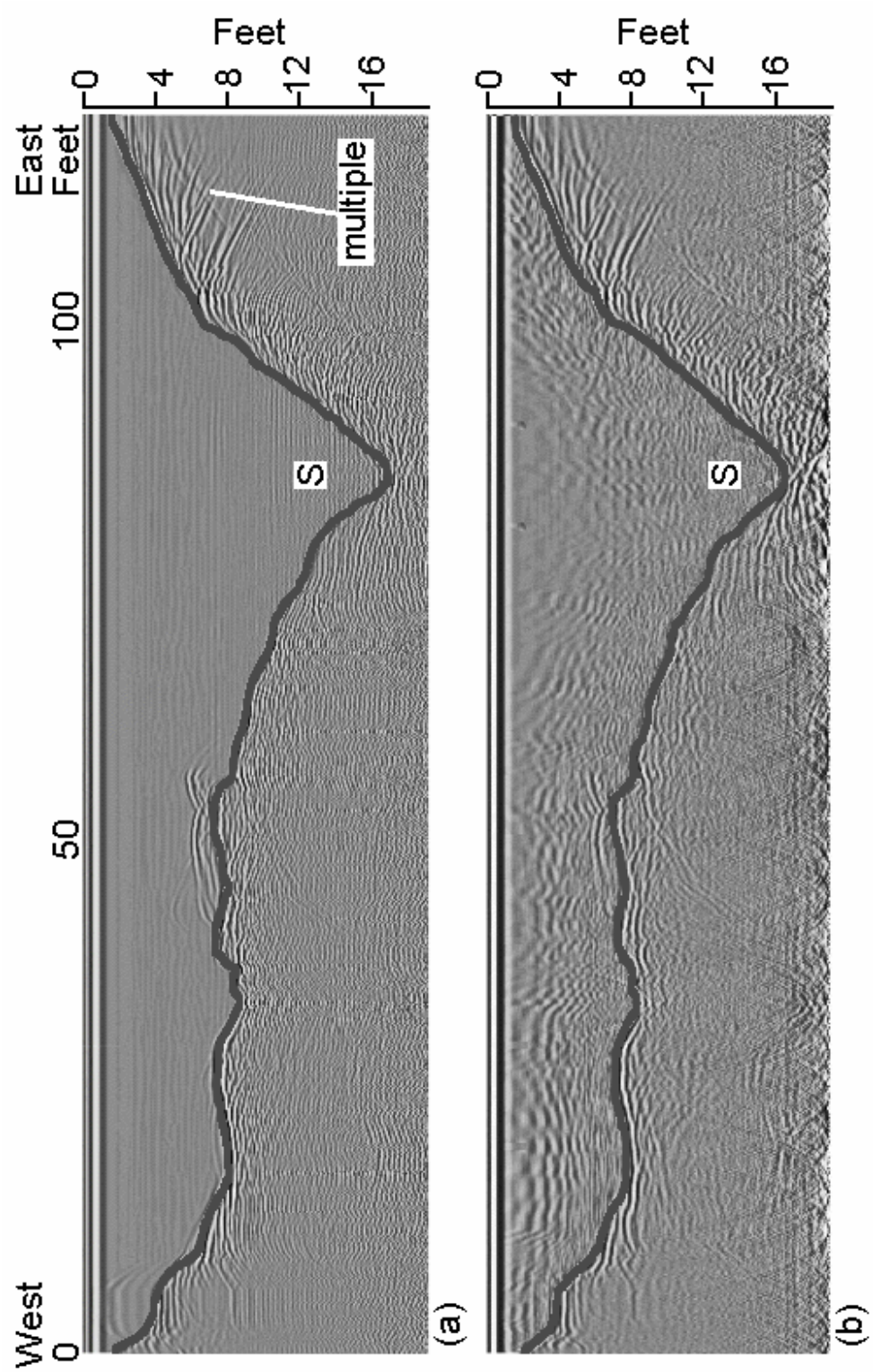

Figure 11: Multiple processed versions of example GPR profile 2: (a) interpreted stacked; and (b) interpreted migrated. Existing scour feature is marked with an "S". The gray line identifies the water bottom.

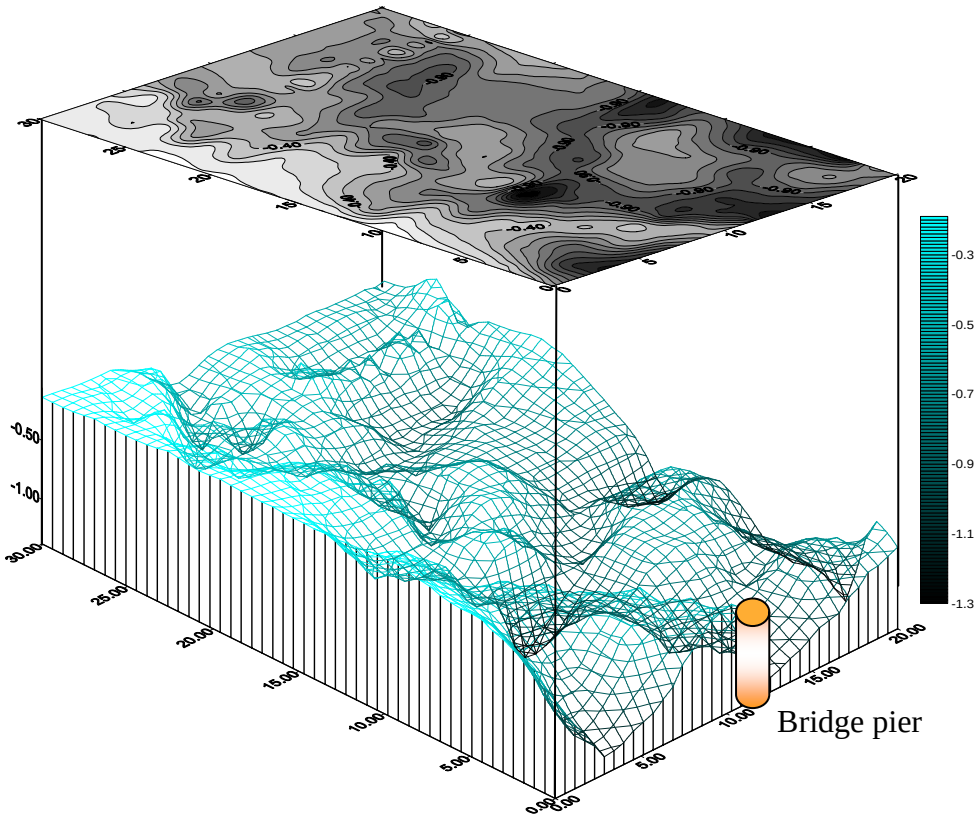

Figure 12: 3-D image of river bottom at a test site. The 3-D image was constructed on basis of depth information obtained from 31 parallel GPR profiles (spaced at 1m intervals).

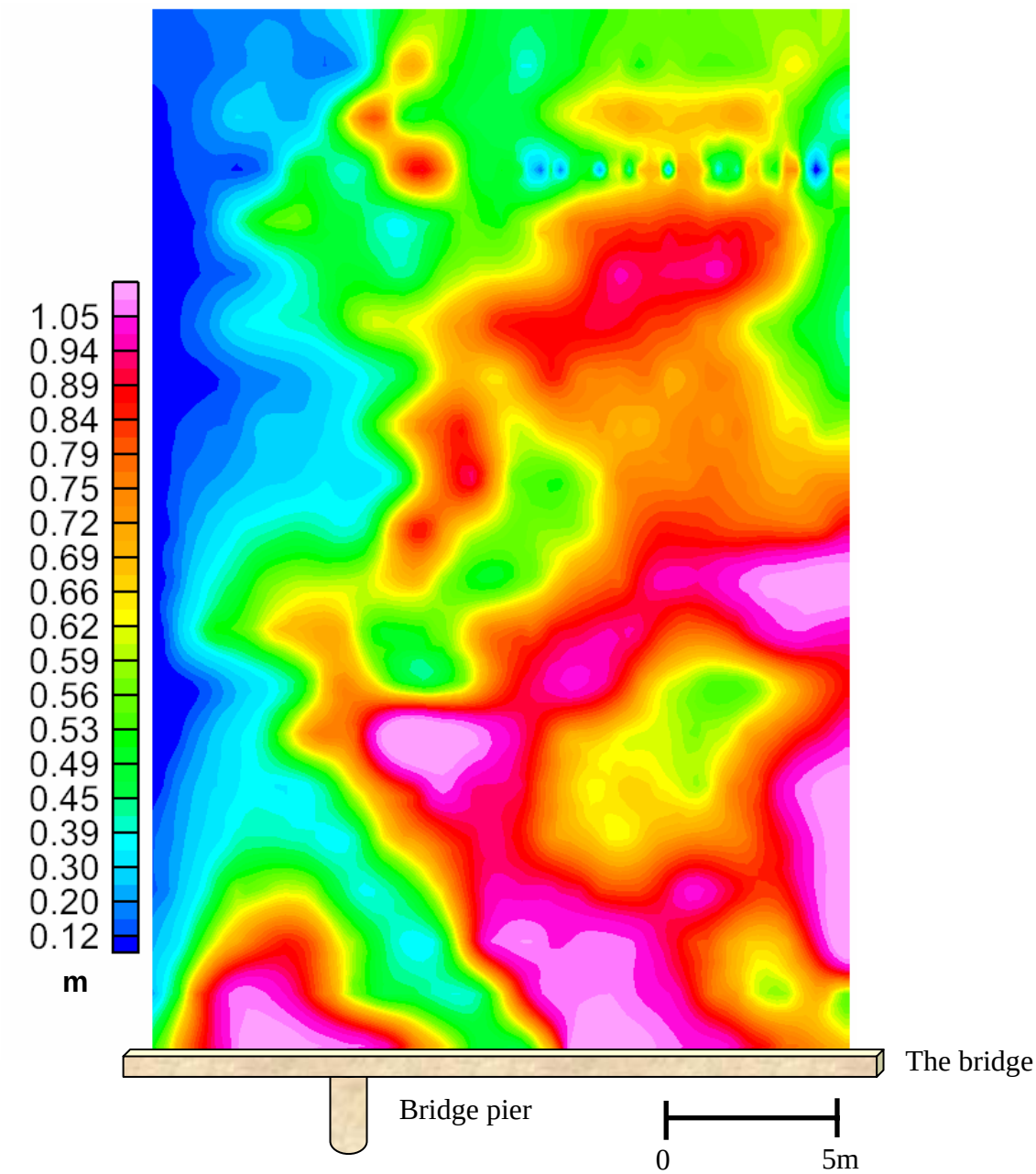

Figure 13: 3-D image of river bottom at a test site. The 3-D image was constructed on basis of depth information obtained from 31 parallel GPR profiles (spaced at 1m intervals).