TWO NEW NON-DESTRUCTIVE METHODS TO MEASURE SCOUR DEPTH AND THE DEPTH OF UNKNOWN FOUNDATIONS

E. J. Mercado* and J. A. McDonald^

*North American Geotechnical Co. 3 Lakewood Lane
Seabrook, TX, 77586; ejmer@aol.com
^Department of Exploration Geophysics,- Curtin University of Technology, Perth 6845, Western Australia; mcdonald@geophy.curtin.edu.au

Abstract

Described are two methods for determining the depth of scour at bridge piers and abutments. One method also determines the depth of foundation. Each method has its own unique advantage depending on the river environment.

The Parallel Seismic Survey (PSS) is most useful for determining the depth of scour during non-flood stages of a river, even when the scour annulus may be filled in by mud or sand as the flood stage subsides. In addition, the PSS technique also provides information about the depth to the bottom of the foundation, and also can be used for just that purpose. A modified placement of the receiver and source geometry allows determination of both the scour depth and depth of piles in a multiple pile group. A field test of the method provided the depth of scour and depth of foundation to an accuracy of ± 0.3m (1-foot).

The Pneumatic Scour Detection System (PSDS) operates on a completely different principal and is designed to provide information about the immediate depth of scour during a flood stage. Its unique advantage is its ruggedness of construction and simplicity of measurement, which allow it to withstand flood-borne debris and is unaffected by water turbulence.

Introduction

Two new techniques for detecting depth of scour around bridge piers are presented. One technique, identified as the Parallel Seismic Survey (PSS), is based on analysis of seismic refraction waves generated in the pier and recorded by an adjacent vertical array of hydrophones also is uniquely able to measure the depth to the pier toe. This refraction-based method is especially efficient at measuring the thickness of the scour zone when the scour zone has been filled with mud or soft sand after the flood surge has passed. A simple extension of this technique allows the depth to the bottom of the pier to be determined . The extension is to record the seismic waves to a depth below the bottom of the pier where the refraction wave converts to a diffraction wave radiating from the bottom of the pier. Straightforward data analysis of noting where the first break pattern changes from a straight line refraction path to a hyperbolic diffraction path identifies the bottom of the pier. A field test of the PSS technique has successfully detected both the thickness of a mud-filled scour zone and the length of a model pier. (Davies, Mercado, O'Neill, and McDonald, 2001; Mercado and O'Neill, 2000).

The second technique, identified as the Pneumatic Scour Detection System (PSDS), is designed to operate under the most extreme flood conditions and monitor the development of a scour zone in real time. This technique is based on the differential resistance to air (or liquid) flow through a vertical array of porous plugs made of sintered glass. The array of porous plugs (about 1/4 to 1/2 in diameter) are sealed into the wall of a very strong steel pipe (such as 4 in diameter drill stem pipe) and battered into the river bottom adjacent to the pier. The PSDS technique has the advantages of ruggedness, as pipe is used of sufficient strength to withstand impact with flood-borne debris, and there are no mechanical parts, such as sliding collars, that can be jammed by debris. The PSDS technique has not yet been field-tested.

The Test Site

A test site facility was constructed consisting primarily of a water-filled pond containing a replica of a bridge with two cylindrical piers. The test facility was within the National Geotechnical Experimental site (NGES) located at the University of Houston.

Mahar and O'Neill (1983) and O'Neill and Yoon (1995) have published the results of their studies on the geological and geotechnical characteristics of the near-surface sediments within the NGES. Their findings, relevant to this test site are summarized here.

In terms of the near-surface geology, two shallow formations, the Montgomery formation and the Beaumont formation, are relevant to the test site. The lower formation, the Montgomery, was deposited on the gentle slope of an older Pleistocene formation by streams and rivers near the coastline. After deposition, the sea level lowered producing desiccation and consolidation of the clays and silts. Subsequently, the sea returned to its previous level. Rivers and streams again began deposition on top of the Montgomery formation. The resulting new formation, the Beaumont, primarily a fresh water deposit sloping toward the Gulf of Mexico, has the characteristics typical of deltaic environments. After deposition, the Gulf of Mexico again receded and thus caused desiccation in the Beaumont formation.

The design for the test pond and structure was that of a small-scale replica of a bridge augmented with cased boreholes at specific locations. The dimensions of this structure are about one quarter the size of any real bridge that might be of interest.

Figure 1 shows two views of the pond. Figure 1(a) is a plan view showing the pond dimensions and the locations of the piers and cased boreholes. Figure 1(b) is an end view at a pier location. The figure shows that the pond has sloping sides and a flat bottom. The sides of the pond were lined with geotextile wall restraining fabric. Also shown on the figure are the outlines of the initial configuration of the scour zone.

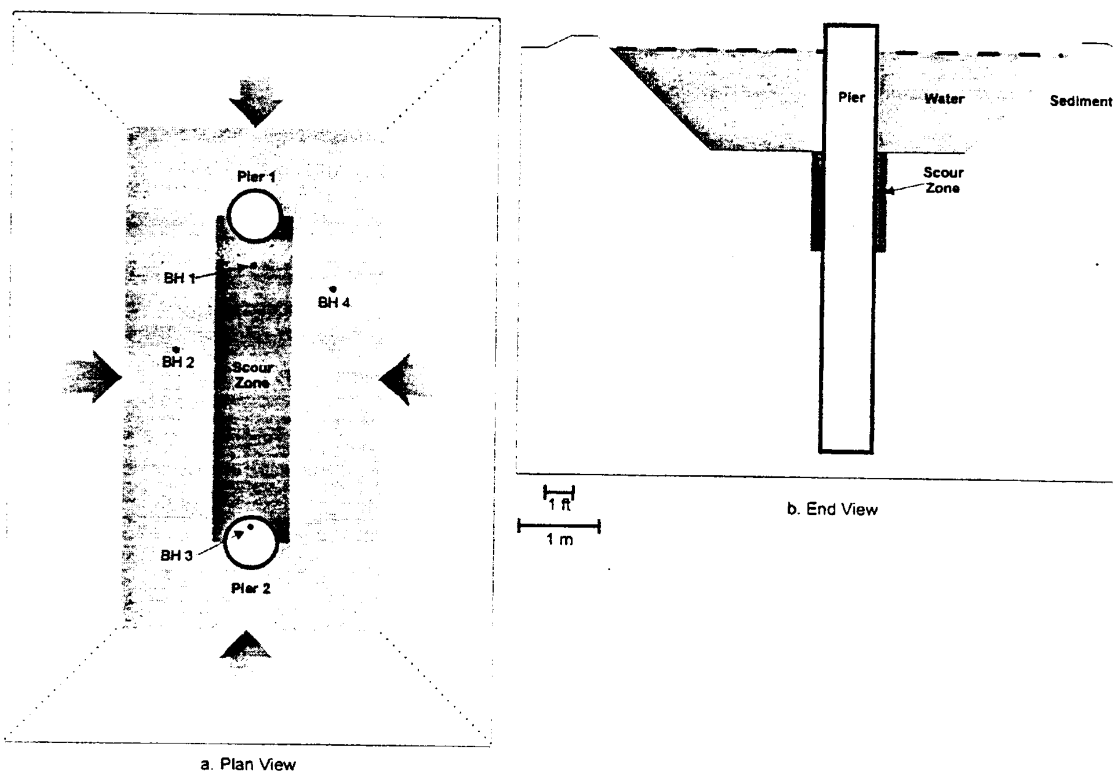

Figure 1. *Schematic display of the test site pond. Figure 1(a) is a plan view showing the pond structure and the location of the piers, cased boreholes, and the scour zone. Figure1(b) is an end view at a pier location.*

Figure 2 is a photograph of the pond while the PSS experiment is in progress. The engineer is lowering the hydrophone array into the PVC cased borehole to obtain a seismic record.

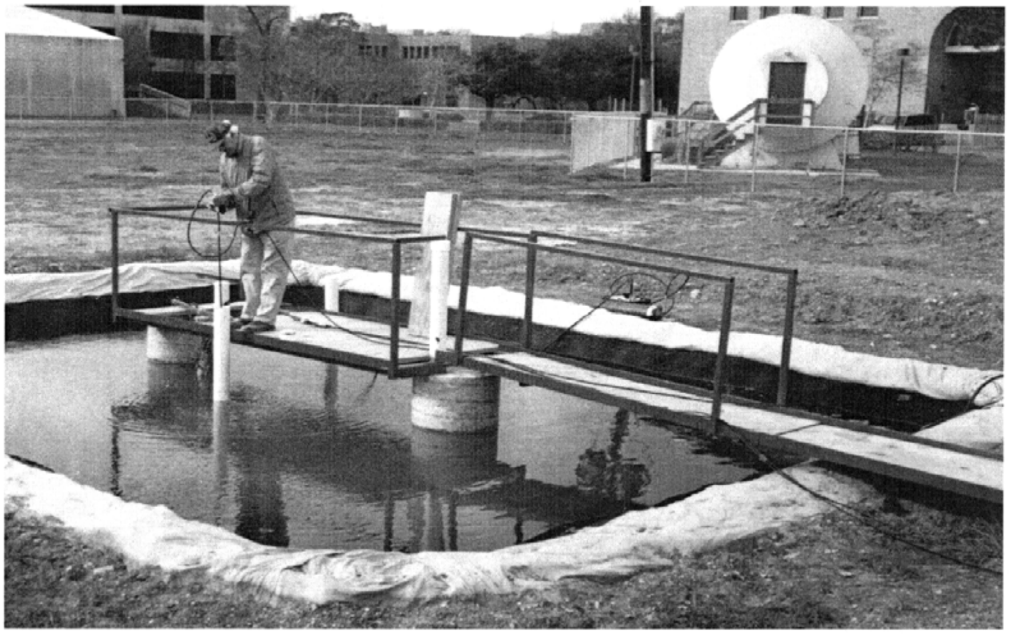

Figure 2. Test site for the Parallel Seismic Survey at the University of Houston NGES. The engineer is lowering the hydrophone array into the instrument access tube.

The cylindrical piers were made of reinforced concrete, 0.6 m (2.0 ft) in diameter and 5.2 m (17 ft) in total length. The tops of the piers were 0.3 m (1.0 ft) above grade and extended to a depth of 4.9 m (16.0 ft) below grade. The tops of the piers were taken as datum. The boreholes were drilled to a depth of between 7.6 and 7.9 m (25 and 26 ft) below grade and cased with 102 mm (4.0 in) diameter, 9.5 mm (3/8 in) thick wall, PVC pipe. Casing was set in the drilled holes. Between 0.4 and 1.0 m (1.4 and 3.3 ft) of casing remained above datum. The casings were cemented to the surrounding sediments but no information was taken as to the quality of the cement bonds. A work platform was constructed to connect the bank to the piers and to provide access to the boreholes.

Based on the depths described above, it would seem that the piers lie entirely within the Beaumont formation, while the cased boreholes just penetrated the top of the Montgomery formation. This meant that the sediments involved in the field experiments consisted mainly of stiff clays.

In the no-scour condition, the bottom of the pond was flat over the area around the piers and boreholes. Following experiments with no-scour, a scour zone was excavated between the piers as shown in Figure 1(a). After excavation, the scour zone consisted of a vertically sided trench 0.9-m (3.0-ft) wide and 1.2 m (4.0-ft) in depth below the original bottom of the pond. This trench was centered about the centerline between pier 1 and Pier 2, and extended between the two piers. The pond was filled with water and, after several days, the water was removed. It was noted that considerable slumping of the vertical sides of the trench had taken place, with the slump material having moved down into the trench as the sides became saturated and turned into mud. The bottom topography after the occurrence of the wall collapse was mapped by taking a grid of measurements relative to surface datum.

The Recording Instruments

The detector system consisted of an array of six Mark Products Model P-44 hydrophones, spaced 1.2 m (4.0 ft) apart with a 15.2 m (50 ft) lead-in cable. The hydrophone sensitivity was rated as 14 microvolts per microbar. The array allowed for the occupation of six detector locations for each set-up. An OYO

Geospace Model DAS-1 digital data acquisition system was used for the seismic field tests. The field data were recorded with a broadband (3 Hz to 4000 Hz) pre-amplifier filter, 2400 samples per trace and with a sample interval of 62.5 μs.

The PSS Technique

Two 24-inch diameter, 17-ft long model piers were constructed. The depth of the pit before excavating the scour zone is 5 ft. Adjacent to Pier 1 (24 inches away) a 4 in diameter, 26 ft deep hole was drilled and lined with PVC pipe. A refraction wave was generated in the pier by striking the top of the pier with a hammer. The refraction wave was recorded at 1ft intervals in the PVC pipe. The pit was emptied and a 4 ft deep scour zone was hand-dug around the pier, then filled with soft mud created by liquefaction of the trench sides that slumped into the trench. This placed the bottom of the scour zone at a depth of 9 ft. The refraction experiment was repeated, and the data analyzed.

The PSS Technique-Scour Detection Mode.

Figure 3 shows the observed data from a Pier 1 test where the soft mud has been removed from the trench; thus the water-soil interface is water over stiff competent clay. The seismic data shows strong, continuous energy transmission across this interface, and the first breaks fall along the straight line A-B, corresponding to a refraction velocity of 4,730 m/s (15,500 ft/s), which represents the P-wave velocity in the concrete pier. The acoustic characteristics of the mud are its strong energy attenuation as a function of frequency. The high frequencies are more strongly attenuated than the low frequencies, and much stronger than the attenuation characteristics of either water or competent soil.

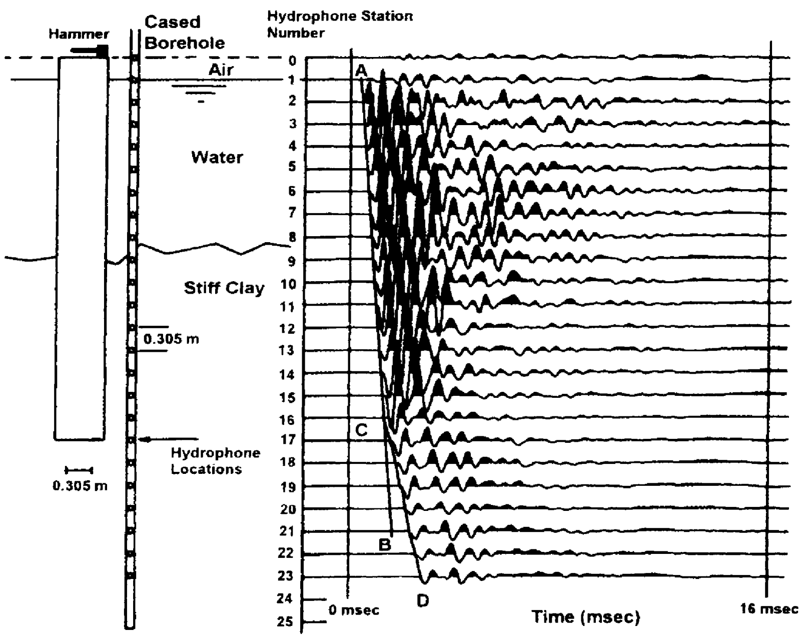

Figure 3. No-scour case. Data not filtered. Note the uniform data amplitudes across the water-sediment interface. The linear refraction first-arrival pattern A-B changes to the hyperbolic first-break pattern C-D at C, which occurs at the base of the pier.

Figure 4 shows the seismic data under the condition that the scour zone has been partially filled with soft mud that has slumped in from the sides of the trench. The anomalously low amplitude of the seismic data at recording depths 6 through 9 ft is a consequence of the strong energy attenuating nature of the mud compared to water above and competent soil below the mud filled scour hole.

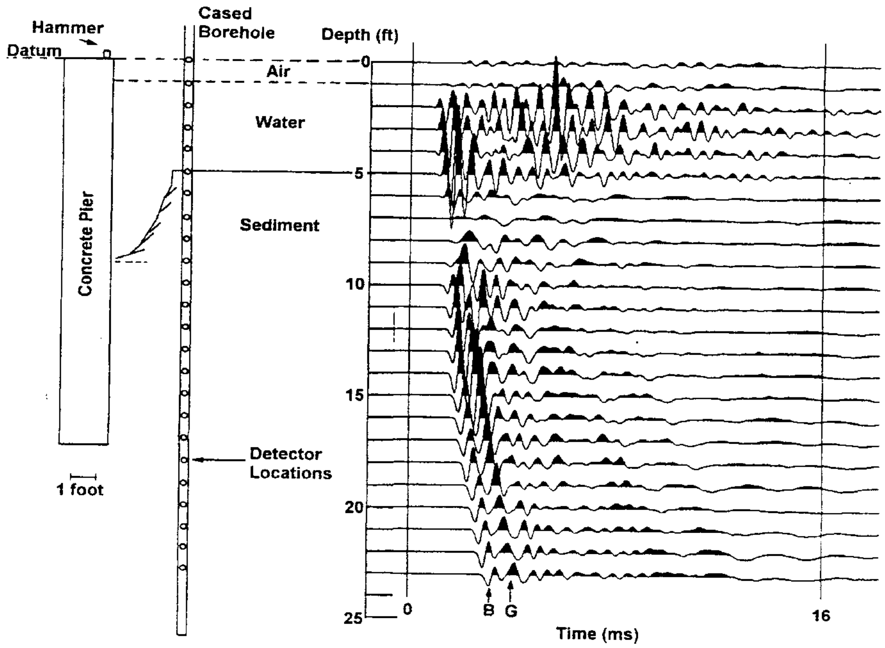

Figure 4. Scour case. Data not filtered. Note the strong attenuation of data amplitudes where the seismic energy traverses the mud-filled scour zone.

To take further advantage of this characteristic, the data were digitally filtered with a strong low-cut filter. The filtered data are shown in Figures 5(a), the no-scour case, and 5(b), the scour case. The no-scour case, Figure 5(a), shows uniform data amplitude across the water-bottom interface. Figure 5(b), the scour case, shows virtually no high frequency in the mud-filled depth range 6 to 9 ft.

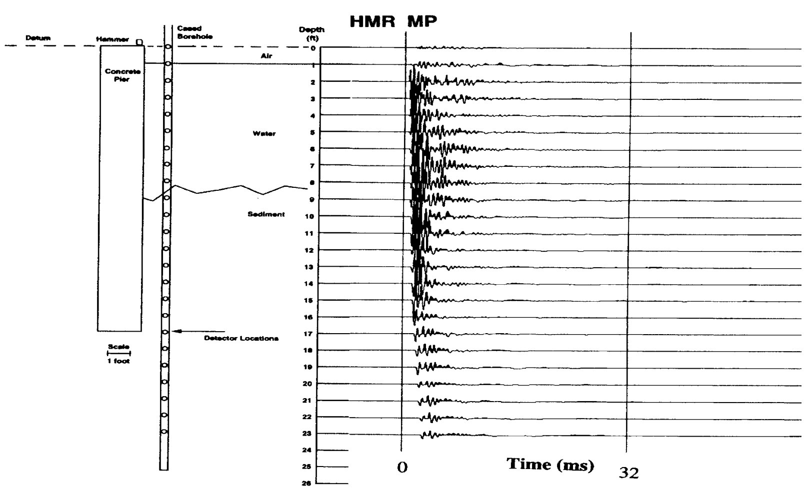

Figure 5(a). No-scour case. Seismic data after digital filtering with a strong low-cut filter. Note the uniform amplitudes across the water-sediment interface

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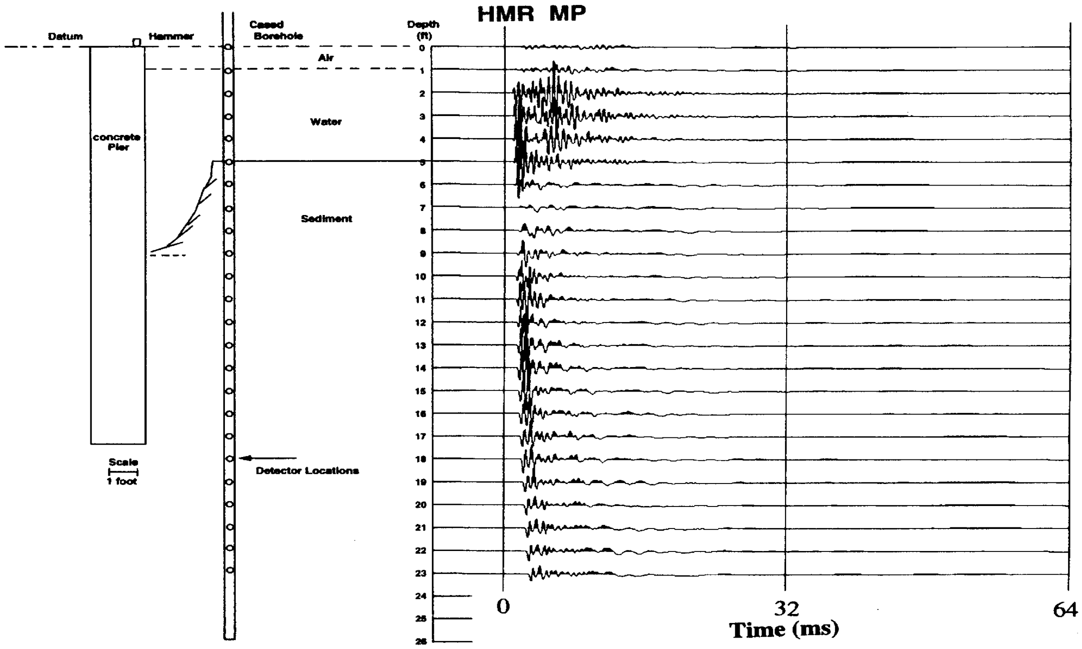

Figure 5(b). Scour case. Seismic data after digital filtering with a strong low-cut filter. Note the severe energy attenuation of data transmitted through the mud-filled scour zone.

In general, visual inspection of the filtered data adequately identifies the extent of the scour zone. The energy received at the hydrophone stations can be calculated and graphically displayed as a function of depth. This relative energy as a function of depth can be measured in several ways. Figure 6 displays the average absolute amplitude of recorded seismic energy over a fixed time gate from 0.0 to 18.0 ms as a function of depth. The anomalous energy zone caused by the mud filled trench is clearly seen as a major break in the normal attenuation of energy with depth pattern seen above and below the scour zone. By either visual or computer analysis of the received energy as a function of depth, the bottom of the scour zone is determined with an accuracy of ± one-foot.

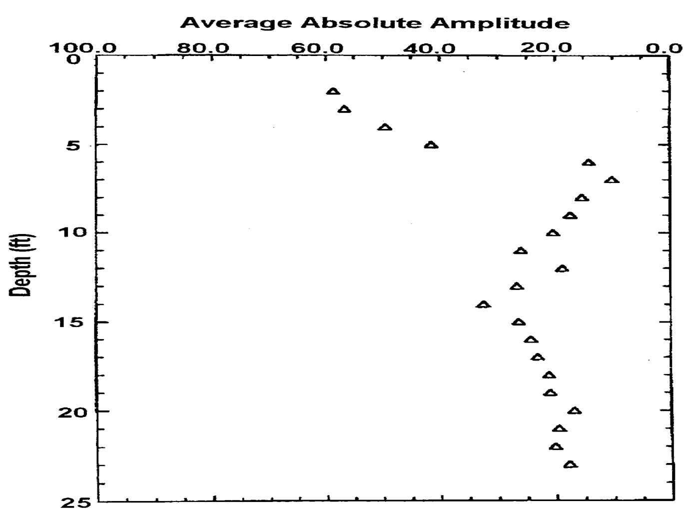

Figure 6. Plot of Average Absolute Amplitude versus depth of filtered seismic data in figure 5(b). Note the strong energy anomaly coinciding with the mud-filled scour zone.

The PSS Technique-Depth of Foundation Mode.

The refraction wave changes to a diffraction mode of travel geometry below the bottom of the pier. By analyzing the first arrival times of the seismic energy as a function of depth, the change from refraction to diffraction path geometry is readily detected and determines the depth to the bottom of the pier to within one foot. With reference to Figure 3, Line A-B traces the first arrivals below a depth of about 4.88-m (16 ft) from the top of the pier. The point at which the linear refraction wave front changes to a curved wave front (Point C), which is rather easily seen in Figure 3, represents the depth at which waves diffracted from the toe of the drilled shaft begin to be received. In normal practice, the depth at this break point is simply interpreted as the length of the drilled shaft through visual inspection of the data. This practice can be confirmed through a simple migration process for the diffracted waves as follows, and as illustrated in Figure 7. At each hydrophone station below Point C, a circle is drawn with a radius equal to the measured P-wave velocity in the soil times the offset time between lines AB and CD at the depth of the hydrophone. The diffracted wave must originate at some point on the circumference of this circle. When circles for all stations below C are drawn, they coalesce within a 0.3 m (1 ft) zone near the known toe of the drilled shaft, which indicates that this must be the origin of the diffracted waves and thus the depth of the drilled shaft.

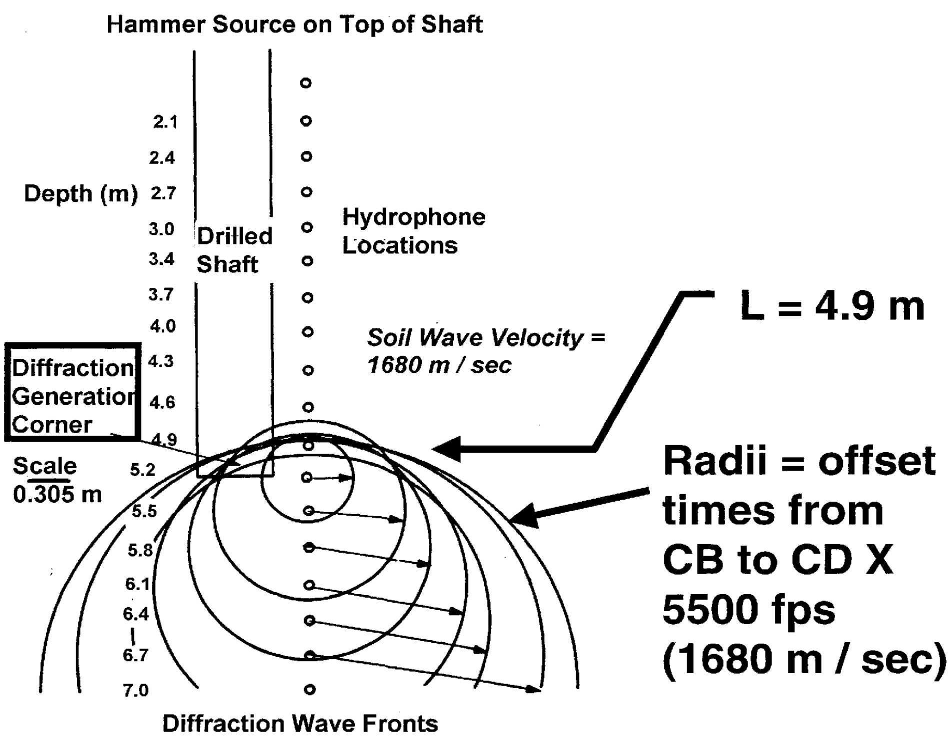

Figure 7. Simple migration technique to locate the diffracting source, which is where the migration circles intersect.

The scour and depth of foundation technique can be simply modified to determine the depth of individual piles in a pile group. Figure 8 illustrates a 3-pile group with a pile cap (which is unimportant in this situation). What is critical is the ability to fasten individual geophones to the individual piles. Figure 8 illustrates the piles penetrating through the water layer, the soft river bottom mud/sand layer, and into the competent soil below the level of scour (mud-filled). To generalize the example, the middle pile is assumed shorter than the others.

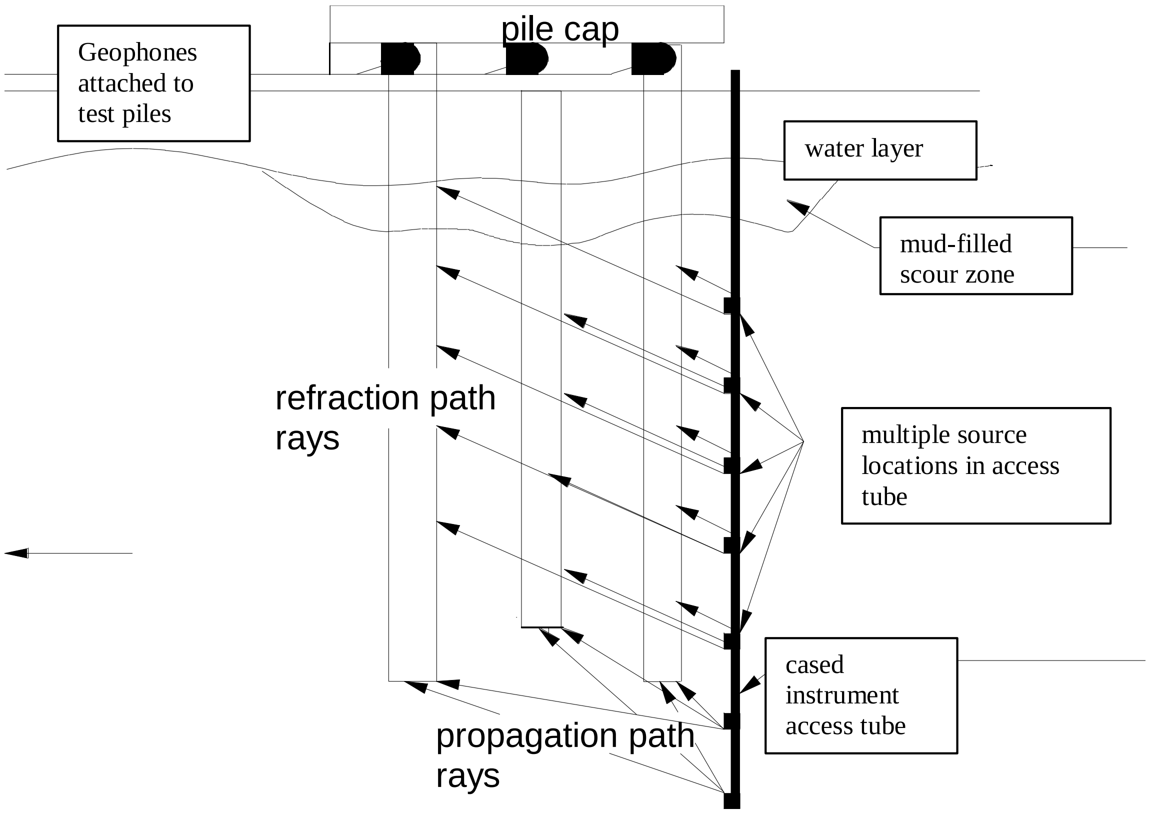

Figure 8. Sketch of PSS reversed source-detector geometry and ray paths to determine both depth of scour and depth of foundation in a multiple pile group.

Sketched in Figure 8 are propagation path rays generated from the two deepest source locations traversing to the bottom of the individual piles where they generate up-going P waves that excite the geophones at the top of the piles. As the source moves up the hole, the ray paths finally intersect the individual piles at the critical angle to convert to refraction waves, which travel up the piles to excite the geophones. The same first-break pattern recorded at each geophone on the individual piles will duplicate the first-break patterns seen on the seismic records where the source is on the pile and the hydrophones are in the instrument access hole. This relationship is called reciprocity in seismology. While the propagation paths, and travel times are identical for pier-source to downhole-receiver, or reversed path, the energy received at the receivers may differ. This difference in energy transmission efficiency can be compensated for by varying the source strength. For the downhole source, air gun size and operating pressure can be readily varied to suit the site characteristics under study.

The geophysics industry calls these types of surveys "up-hole surveys" and are routinely performed to quantify the near-surface layering for velocity control of the weathering corrections when conducting seismic subsurface mapping surveys. More recently, this technique has been refined to conduct Vertical Seismic Profiles (VSP surveys) with the original intent of studying oil and gas reservoir properties. Next, the technique was extended to study reservoir properties using well-to-well surveys and analyzing the data as a tomographic survey.

The difference between the survey proposed here and the VSP-Tomographic techniques is its specialization to measure the depth where the refraction/diffraction conversion takes place and identify this transition with the bottom of the individual piles.

Advantages of the PSS technique are its ability to both determine the extent of a mud-filled scour zone, and verify the depth to the toe of the pier. It is most effectively implemented between major flood events in the quiescent phase of the river when field operations are easiest and allows bridge inspection to be done on a scheduled basis. No instrumentation is left at the test site, so vandalism is not a problem. The instrument access hole is sketched adjacent to the pile group. (We have successfully obtained data with the access hole 5 ft from the piles, and believe longer distances are viable. At worst, longer distances might need a stronger source (such as higher pressure in an air gun or multiple seismic caps detonated together.)   Only one access hole; and the equipment developed to conduct VSP and Tomographic surveys is directly applicable to the short-pile application, with some clever re-definition of how to adapt the equipment to the short-pile problem.

The PSDS Technique-Scour Detection During Flood Events

The historical problem facing scour measurement during a flood event is developing a system that can withstand the violent nature of a flood and particularly the impact of flood-borne debris. This requires the measurement technique to not have any mechanical or moving parts that can be jammed by debris, or fouled by sand and silt. Electrical based sensing instruments are unsatisfactory for the same reasons plus the problem of short circuits created by abrasion of the electrical wires immersed in a fluid with finite conductivity because of dissolved minerals. Sonar and radar based devices are severely hampered by the collection of debris around the bridge piers, which mask the water bottom from these remote type sensors.

The concept proposed here for measuring the depth of scour during a flood event is based on the difference in air, or fluid flow through a vertical array of porous and permeable plugs when the plugs are expelling air against water vs. against mud/soft sand vs. against competent soil. The design concept is illustrated in Figure 9.

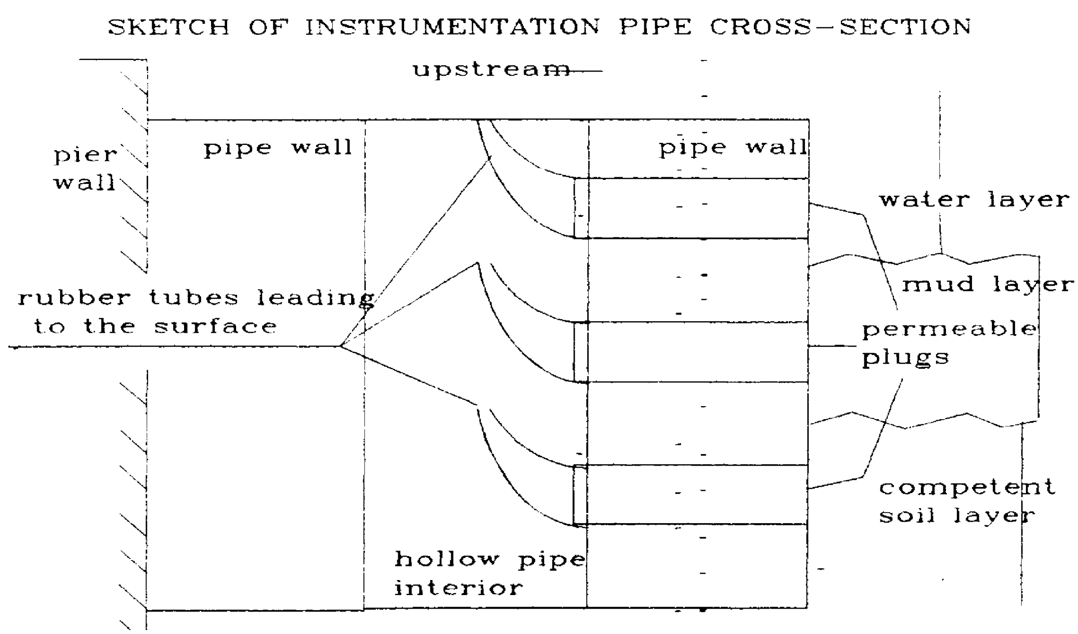

Figure 9. Sketch of PSDS pipe showing the vertical array of porous plugs with flexible tubes leading to the surface through the pipe interior. Porous plugs with their exterior surfaces in contact with the water will bleed-off excess test pressure at a measurably different rate than plugs in contact with competent soil.

Figure 9 is a cross-sectional view of the pipe battered vertically into the river bottom against, or near the pier. The pipe contains a series of plugs inserted through the pipe wall, forming a vertical array of plugs at known spacing and depth below grade. The external faces of the plugs are machined to conform smoothly to the outer surface of the pipe. Since the faces of the plugs conform to the shape of the pipe, battering the pipe into competent soil will create a seal to the plug. This sealing action will strongly impede airflow through the plug when a positive (slightly greater than hydrostatic) pressure is applied to the plugs through flexible tubes inside the steel pipe. The measurement of bleed-off rate through the plugs as a function of depth will differ significantly when the plugs external face is exposed to water (thus in the scour zone) versus when pressed against competent soil (thus below the scour zone). The data analysis simply consists of monitoring the change of bleed-off rate as a function of depth. That is, when a given plug positioned against competent soil becomes exposed to water because scour has removed the competent soil to its depth, its bleed-off rate will increase dramatically.

The plugs are commercially manufactured for use as filters and can be obtained with specified pore size and permeability. The pore size is chosen to not allow mud and clay particles to enter and clog the plug.

The advantages of the PSDS are its innate simplicity and ruggedness. There are no moving parts to jam by debris or suspended sediments in the water. No electrical down-hole or in-water circuits or transducers are required. The plugs are small and cannot be made inoperative by debris accumulating around the pier. The pipe containing the plugs can be made as strong as desired, and further strengthened by placing it adjacent to or very close to the pier under investigation. The flexible air hoses can be brought out under the bridge, or even run to the riverbank so personnel can run the scour tests safely off the bridge. Finally, the simplicity of the system makes it inexpensive to construct.

Acknowledgements

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