METHODS TO MEASURE SCOUR DEPTH AND THE DEPTH OF UNKNOWN FOUNDATIONS

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Abstract

Described are three methods for determining the depth of scour at bridge piers and abutments. Two methods also determine 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 when the scour annulus may be filled in by silt or loose 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 field test of the method provided the depth of scour and depth of foundation to an accuracy of ± 0.3m (1ft).

The Reverse Parallel Seismic Survey (RPSS) interchanges the positions of the receiver and source as used in the PSS geometry. This reversed source/receiver geometry allows determination of both the scour depth and depth of piles in a multiple pile group.

The Pneumatic Scour Detection System (PSDS) operates on a completely different principle 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 it is unaffected by water turbulence.

Introduction

Three techniques for detecting depth of scour around deep bridge foundations are presented. One technique identified as the Parallel Seismic Survey (PSS) is based on analysis of seismic refraction waves generated in the pile or drilled shaft. The refracted waves are recorded by a vertical array of hydrophones in a cased hole about 100 mm (4in) inside diameter that has been inserted vertically into the subsurface adjacent to the foundation. This refraction-based method is especially efficient at measuring the thickness of the scour zone when the scour zone has been filled with silt or loose sand after the flood surge has passed. The zone of silt or loose sand acts as an acoustical muffler and strongly attenuates the seismic energy transmitted to each hydrophone when the refracted waves pass through the scour zone. The attenuation of seismic energy through competent soil is much less than that of the silt or loose sand. The effect of this relative difference in seismic energy attenuation between the soil-filled scour zone and the competent soil below the scour zone is quite striking and the transition from transmission through the scour zone to transmission through competent soil is easily identified in the data.

A simple extension of this technique allows the depth to the bottom of the foundation to be determined. If the depth of the cased hole is 3 to 5 m (10 to 15 ft.) deeper than the maximum expected length of the pile or drilled shaft, then the resulting data also provide the depth of the pile or shaft (hereafter called "pile") toe. The extension is to record the seismic waves to a depth below the bottom of the pile where the refraction wave converts to a diffraction wave radiating from the bottom of the pile. 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 pile. A field test of the PSS technique has successfully detected both the thickness of a soil-filled scour and the length of a model foundation in one survey. (Davies, *et. al., 2000;* Mercado and O'Neill, 2000).

A second technique, the Reverse Parallel Seismic Survey (RPSS) is designed to determine the depths of individual piles in a pile group (or drilled shafts in a drilled shaft group). It is based on the fact that the travel time for an elastic wave is the same if the source and detector are interchanged. This is a direct consequence of Snell's Law, and is known as the theory of reciprocity. The application of this theory to the PSS geometry is to place individual geophones near the top of each pile in a pile group. The seismic source is inserted down the instrument access hole and the survey conducted from a depth about 3 to 5 m (10 to 15 ft.) below the maximum expected depth of the piles upward to near the surface. Once the survey has been conducted, the same data analysis and criteria for depth of scour and depth to pile toes applies as for the PSS technique.

A third technique, 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 8 to 12 mm (1/4 to 1/2 in) diameter) are sealed into the wall of a very strong steel pipe (such as 10 mm, (4 in) or larger diameter drill stem pipe) and inserted 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, being braced against the pile footing if necessary, 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 drilled shafts. 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 Beaumont-Montgomery contact is at a depth of about 7.5 m (24.6 ft) at the test site.

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 most real bridges 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 drilled shafts, termed "piers" in the figure, and cased boreholes. Figure 1(b) is an end view of the pond at a shaft 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 2 is a photograph of the pond while the PSS experiment was in progress. The engineer is lowering the hydrophone array into the instrument access tube. The cylindrical shafts 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 shafts 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 shafts 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 undisturbed soil but no information was taken as to the quality of the cement bonds. A work platform was constructed to connect the bank to the shafts and to provide access to the boreholes.

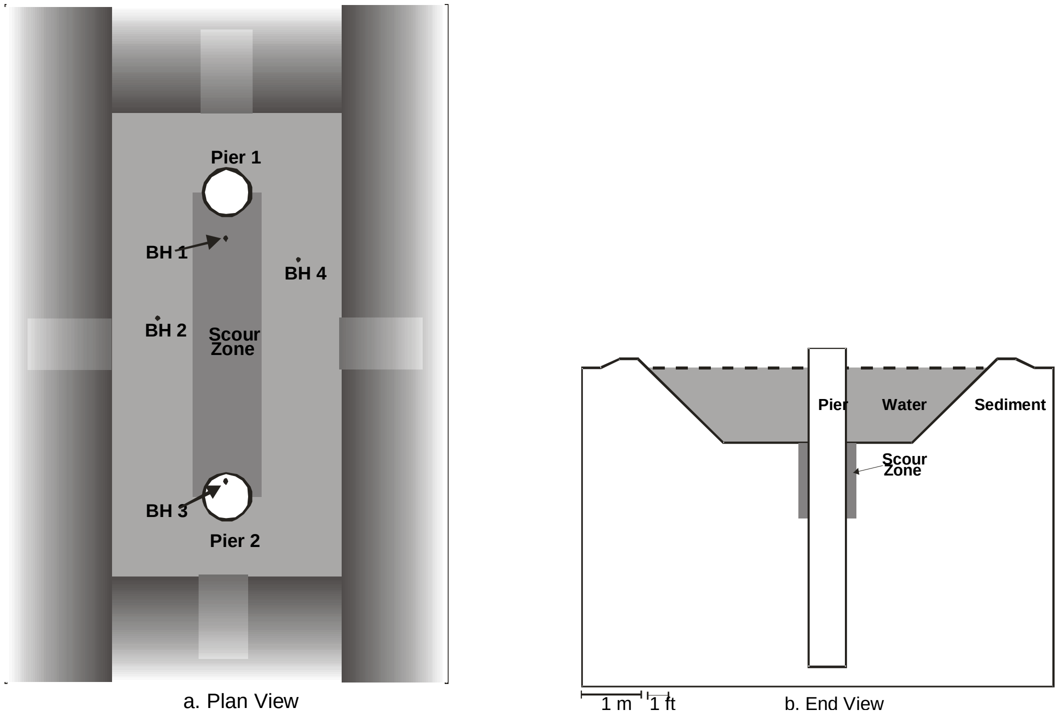

Figure 1: *Schematic display of the test site pond. Figure 1(a) is a plan view showing the pond structure and the* location *of the shafts, cased boreholes, and the scour zone. Figure 1 (b) is an end view at a shaft location.*

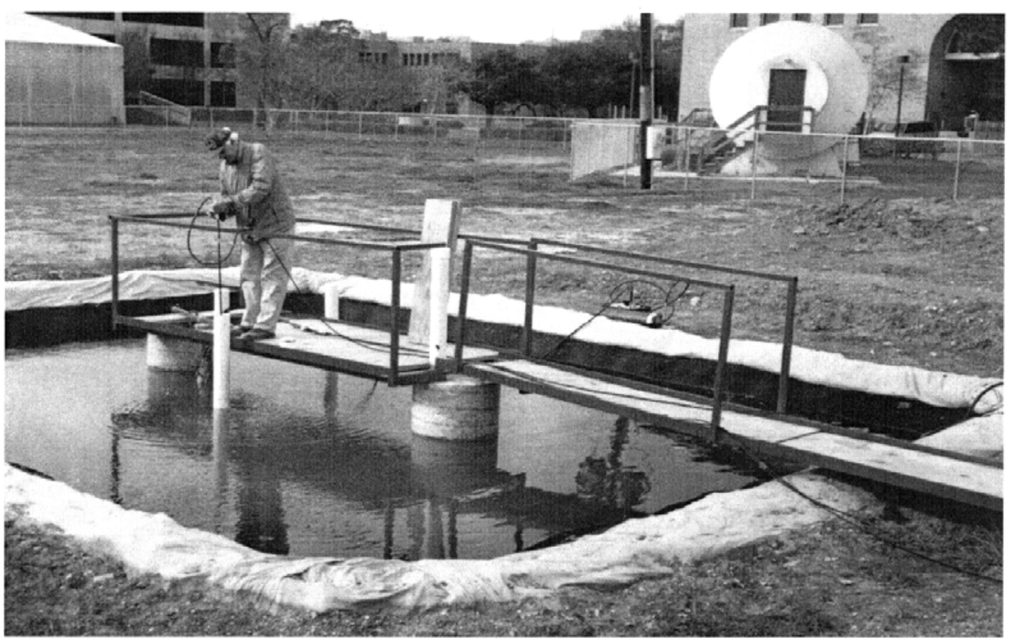

Figure 2: Test site for the Parallel Seismic Survey at the University of Houston NGES. The engineer is lowering the hydrophone array into the instrument access tube.

Based on the depths described above, it would seem that the shafts 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 shafts and boreholes. Following experiments with no-scour, a scour zone was excavated between the shafts as shown in Figure 1(a). After excavation, the scour zone consisted of a vertically sided trench .9 m (3 ft) wide and 1.2 m (4 ft) in depth below the original bottom of the pond. This trench was centered about the centerline between Shaft 1 and Shaft 2, and extended between them. 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 very soft clay. The bottom topography after the occurrence of the wall collapse was mapped by taking a grid of elevation 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 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. These instruments are standard geophysical seismic instruments available off-the-shelf with worldwide usage.

The field-use of these seismic instruments to run either a PSS or RPSS has the advantage that they are portable, and can be taken from site to site. Thus, one set of instruments can be used to monitor multiple sites. The only part of the survey that is left behind is the casing within the borehole.

The PSS Technique

Two 61 cm diameter, 5.2 m (24 in diameter, 17 ft) long shafts were constructed. The depth of the pit before excavating the scour zone was 1.5 m (5 ft). Adjacent to Shaft 1, and .61 m (24 in) away, a 10.1 cm (4 in) diameter, 7.9 m (26 ft) deep hole was drilled and lined with PVC pipe. A refraction wave was generated in the shaft by striking the top of the shaft with a hammer. The refraction wave was recorded at .3 m (1ft) intervals in the PVC pipe. The pit was emptied and a 1.2 m (4 ft) deep scour zone was hand-dug around the shaft, then filled with soft soil created by slumping and softening of the trench sides. This placed the bottom of the scour zone at a depth of 2.75 m (9 ft). The refraction experiment was repeated, and the data were analyzed.

The PSS Technique-Scour Detection Mode.

Figure 3 shows the observed data from a Shaft 1 test where the soft clay had 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 shaft. The important acoustic properties of the very soft clay 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.

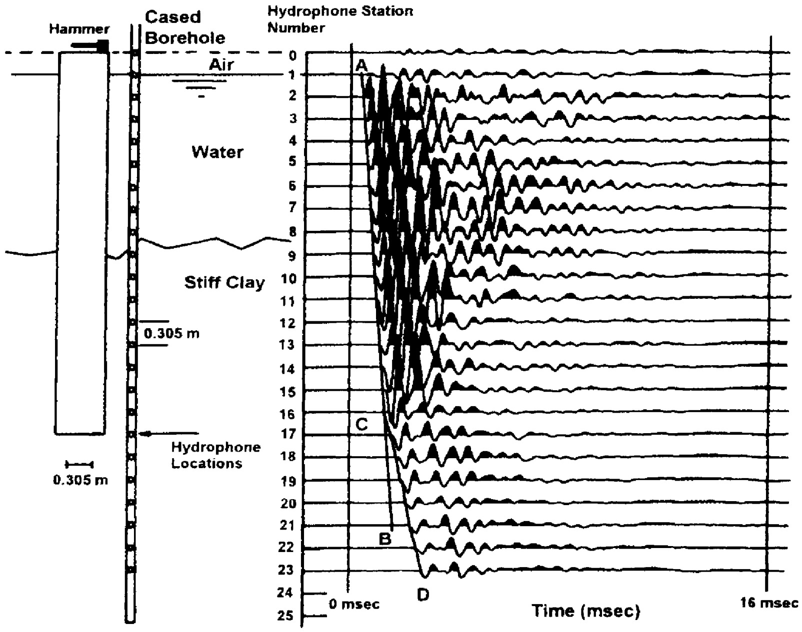

Figure 3: No-scour case. Data not filtered. Note the uniform data amplitudes across the water-sediment interface. The linear refraction *first-arrival pattern A-B changes to the hyperbolic first-break pattern C-D at C, which occurs at the base of the shaft.*

Figure 4 shows the seismic data under the condition that the scour zone has been partially filled with very soft clay that has slumped in from the sides of the trench. The anomalously low amplitude of the seismic data at recording depths 1.8 m (6 ft) through 2.75 m (9 ft) is a consequence of the strong energy attenuating nature of the soft clay infill compared to water above and competent soil below the soft clay-filled scour hole.

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 soft soil-filled depth range, 1.8 to 2.75 m (6 to 9 ft).

In general, visual inspection of the filtered data adequately identifies the extent of the scour zone. To quantify the effect of the infill soil attenuation on the data, 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 data over a fixed time gate from 0.0 to 18.0 ms as a function of depth. The anomalous energy zone caused by the soft clay-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 ± .3 m (1 ft).

The PSS Technique-Depth of Foundation Mode.

The refraction wave changes to a diffraction mode of travel geometry below the bottom of the shaft. 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 shaft to within .3 m (1 ft).

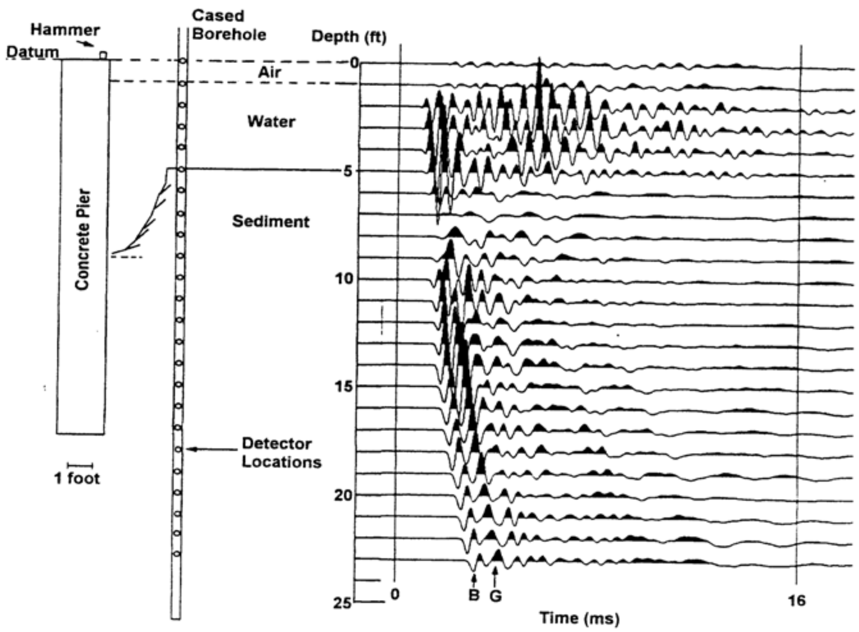

Figure 4: Scour case. Data *not filtered. Note the strong attenuation of data amplitudes where the seismic energy traverses the soft clay-filled scour zone.*

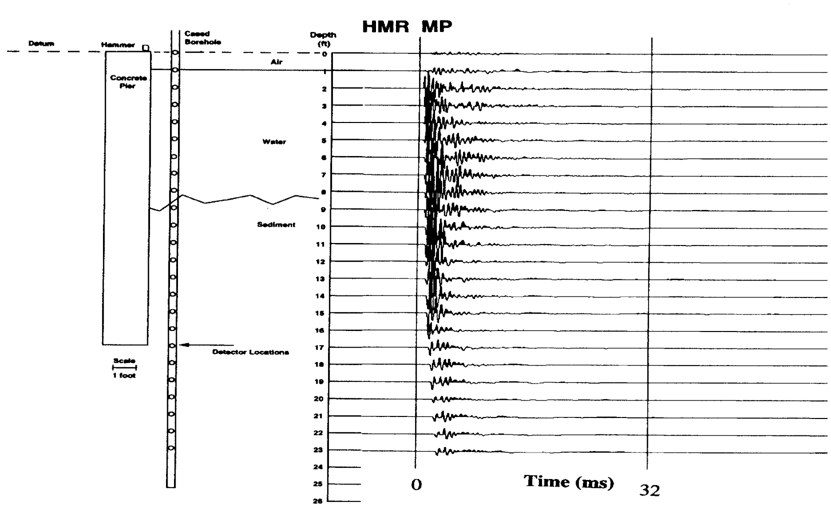

Figure 5(a): No-scour case. Seismic data after digital filtering with a strong low-cut filter. Note the uniform amplitudes across *the water-sediment interface*

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) is rather easily seen in Figure 3 (and also Figures 4, 5(a) and 5(b)). This point corresponds to 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 interpretation also can be confirmed through a simple migration process for the diffracted waves as follows, which is illustrated in Figure 7.

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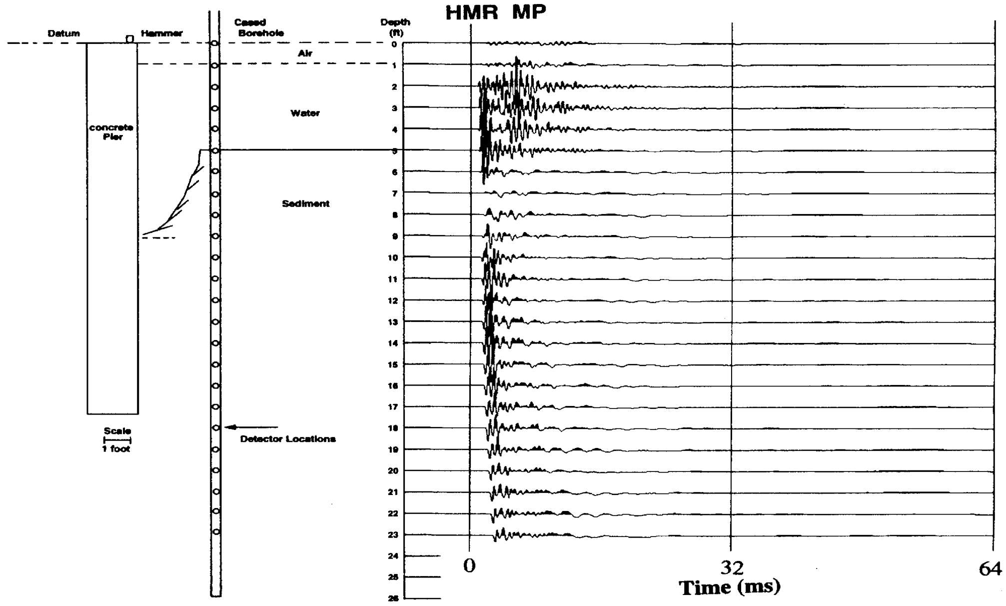

Figure 5(b): Scour case. Seismic *data after digital filtering with a strong low-cut filter. Note the severe energy attenuation of data transmitted through the soft clay-filled scour zone.*

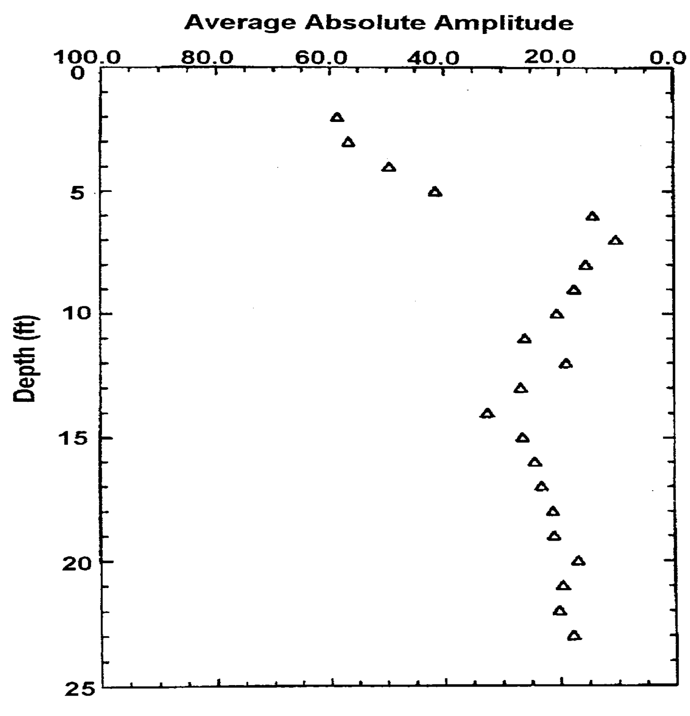

Figure 6: Plot of Average Absolute Amplitude versus depth of filtered seismic data in figure 5(b). Note the strong energy anomaly coinciding with the infilled scour zone.

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.

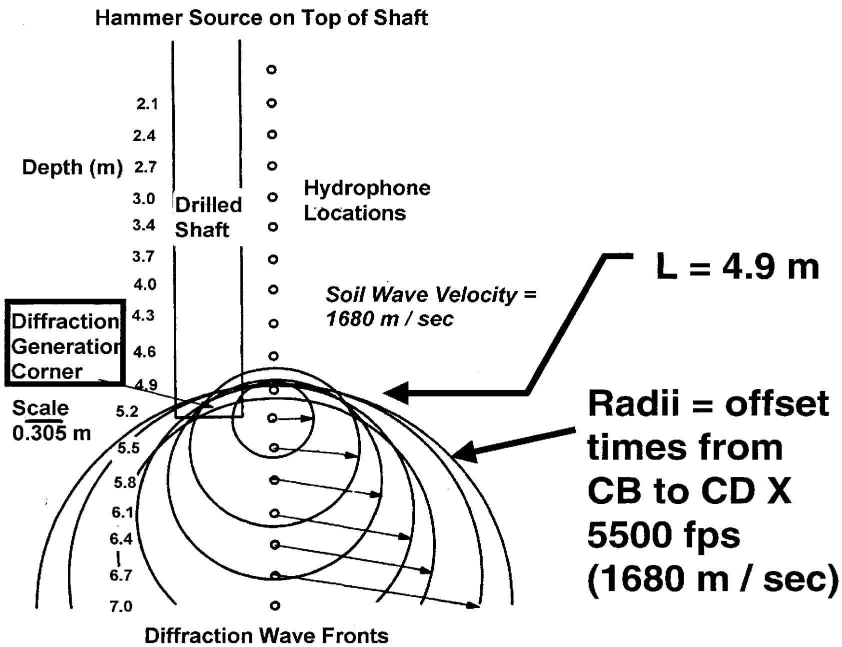

Figure 7: Simple migration technique to locate the diffracting source, which is where the migration circles intersect.

The RPSS Technique

The PSS technique can be simply modified to determine the depth of scour and individual pile length 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 clay or loose sand layer, and into the competent soil below the level of scour (soil-filled). To generalize the example, the middle pile is assumed shorter than the others.

The PSS method is valid for single piles or drilled shafts, which constitute the foundation elements for many bridges. However, when the foundation is a group of piles, the method becomes less useful. To address this problem, a variation of the PSS method might be suitable for pile groups (Mercado and McDonald, 2002).

Shown schematically in Fig. 8 is an arrangement in which the source (for example an air gun) is activated at regularly spaced intervals up a vertical cased water-filled borehole or pipe driven into the sediments at the bottom of a river or bay. For the deeper locations of the source, the elastic waves created by the source strike the bottoms of the piles and propagate up the piles with the P-wave velocity of the pile material.

These waves excite geophones attached to the tops of the piles in the group (Figure 8). As the source moves closer to the surface, the elastic wave ray paths intersect the individual piles at the critical angle and convert to refraction waves. The refraction waves travel up the pile to excite the geophones.

By reciprocity, the first break pattern recorded at each geophone will duplicate the first break pattern as if the source were located at the top of the pile and the receivers (hydrophones) were at various depths in a vertical borehole adjacent to the pile (the standard PSS procedure). The propagation paths and travel times are identical for pile-head source to downhole-receiver, and the reversed path of downhole source and pile-head receiver. The energy received at the receivers from both PSS and RPSS configurations will be similarly affected by the presence of a strongly energy attenuating soft-soil-

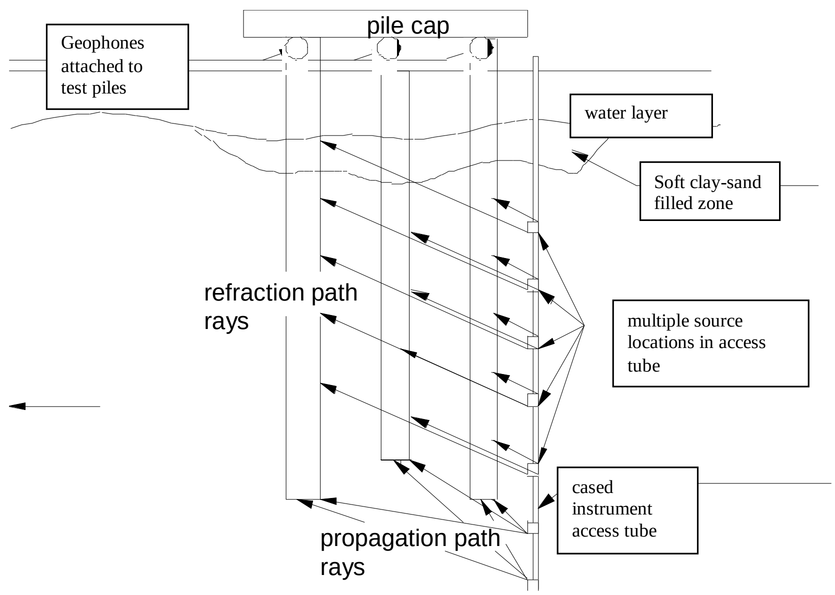

Figure 8: Sketch of PSS reversed *source-detector geometry and ray paths to determine both depth of scour and depth of foundation in a multiple-pile group*.

filled scour zone (if present). The final result is that the data will be the same as if each individual pile was tested by the PSS technique. The data from each individual pile will measure both the depth of scour (if any) and the depth to the toe of the pile. Hence, even the short pile in the group sketched in Figure 8 will be identified, its length measured, and the depth of any soft soil-filled scour zone also measured.

The geophysics industry calls surveys of this type "up-hole surveys" which are routinely performed to quantify the near-surface geology 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 the data analyzed 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 associate this transition with the toes of the individual piles. The analysis of the energy received as a function of depth to measure the depths of infilled scour zones is straightforward and identical to the methodology used to analyze the depth of scour from a PSS.

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 have no 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 very soft clay or loose sand vs. against competent, undisturbed soil. The design concept is illustrated in Figure 9.

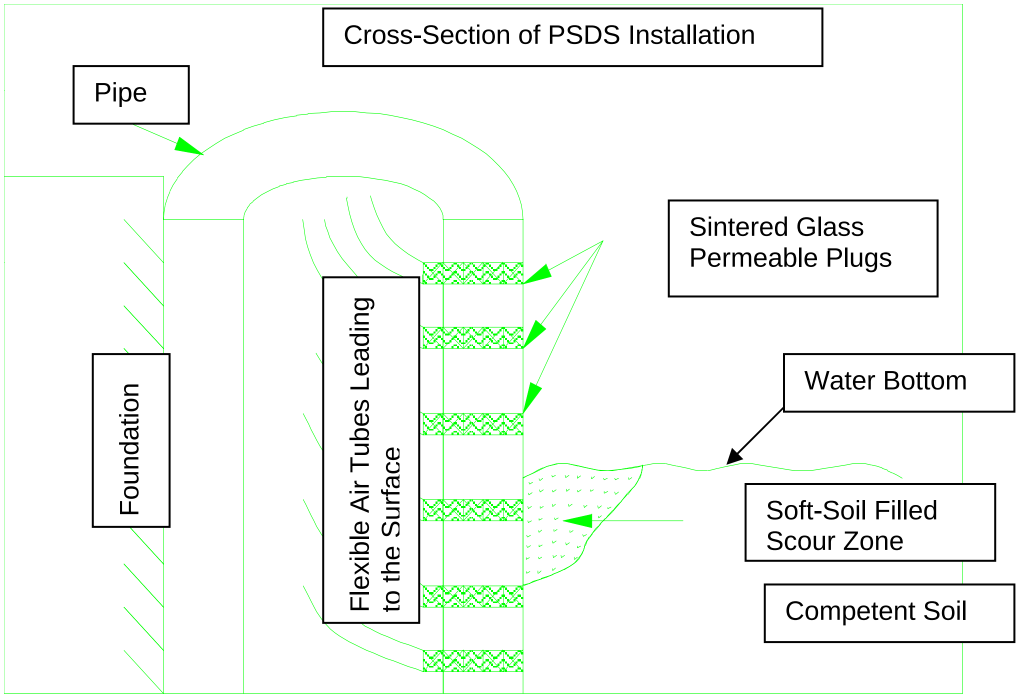

Figure 9: Sketch of PSDS pipe showing the vertical array of porous plugs with flexible tubes leading to the surface through the pipe interior. Porous plugs with their exterior surfaces in contact with the water or loose infill soil will bleed off excess test pressure at a measurably different rate than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

Figure 9 is a cross-sectional view of the pipe driven vertically into the river bottom against, or near, a pile or shaft. 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, driving the pipe into competent soil will create a seal to the plug after sufficient time has passed to allow reconsolidation of the soil around the pipe. 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 or infill soil (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 silt-sized soil particles to enter and clog the plug.

Summary

The PSS Technique

Advantage of the PSS technique is its ability to simultaneously determine the extent of a soft clay- or loose sand- filled scour zone, and verify the depth to the toe of the pile or drilled shaft from one survey. 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.

The RPSS Technique

Advantage of the RPSS technique is its ability both to determine the extent of a mud-filled scour zone, and verify the depth to the toes of individual piles in pile groups. The RPSS technique also 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.

While the RPSS technique has yet to be field-tested by the authors, based on their experience with the PSS, and the soundness of the physical principles on which it is based, it should provide the same information for depth of scour and depth of foundation.

Field Instrumentation and Deployment

No instrumentation is left at the test site for either the PSS or RPSS, so vandalism is not a problem. The instrument access hole is adjacent to the pile group. (We have successfully obtained data with the access hole 1.5 m (5 ft) from the piles for a PSS, 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 commercially available seismic equipment developed to conduct geophysical surveys, VSP and Tomographic surveys is needed to conduct either a PSS or RPSS.

The PSDS Technique

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 considered necessary, and further protected 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.

Field Instrumentation and Deployment

The pipe containing the porous plugs with air tubes leading to the surface is permanently installed at a bridge site. A rugged, tamper-proof box could be permanently attached to the top of the pipe to safeguard the air hoses from vandals during non-flood periods. When in operation to monitor scour during a flood event, the instrumentation to test the bleed-off rate of the multiple porous plugs could be mounted off the bridge for safety. Long air hoses would link the instrumentation to the air hoses stored atop the pipe. A telecommunications link could transmit bleed-off vs. depth data to a central site for real time monitoring. Some type of portable structure would be required on-site at the bridge to protect this instrumentation from weather and vandalism during the scour-monitoring period.

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