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Seismic Methods to Identify Scour Depth Around Deep Bridge Foundations

By

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ABSTRACT

Two methods to detect scour around bridge piers that are based on principles of seismology are described. The first method, the parallel seismic survey, requires that a string of hydrophones be placed in a water-filled casing external to the pier being monitored. A seismic event is produced by a hammer blow to the top of the pier. Clear indications of scour were observed in a controlled field experiment. When a multi-component foundation, such as a group of piles, is to be monitored, a reverse parallel seismic survey is suggested in which the seismic events are produced at various depths in the water and the signals recorded at the tops of the piles. While these methods can be applied after a flood has subsided, they are probably not robust enough to withstand the action of a major flood. Therefore, a second method is described in which the sensing elements (hydrophones) are placed in a tube within the foundation to protect them during a flood. With this method the seismic source is an air gun that is placed in the water near the pier being monitored and which can be activated during a flood. The results from this test, the pier-interior scour detection system survey, are not as clear as those from the parallel seismic survey; nonetheless, field experiments indicate that a scour zone can be detected.

INTRODUCTION

In bridge management it is essential that departments of transportation know whether a bridge's foundation has been compromised by scouring of the soil surrounding the foundation. Although scour may sometimes reduce axial pile capacity by a small amount, a relatively small depth of scour can have a large negative impact on the stiffness and capacity of laterally loaded piles or drilled shafts. It is therefore desirable that the bridge owner have knowledge of the amount of scour around both abutments and central piers at all times. This paper describes two seismic techniques for identifying scour

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around bridge piers that may be useful in this effort and summarizes large-scale tests in which these techniques have been used experimentally. At present, depth of scour information is usually obtained using human divers. The techniques described here make it unnecessary for divers to inspect the foundations.

The seismic techniques are (1) the parallel seismic survey (PSS), which has been used successfully to identify depths of foundations (Olson et al., 1998; Mercado and O'Neill, 2000), and (2) the pier-interior scour detection system (PISDS), which has a potential advantage over the PSS because in can be operated in real time under severe flood conditions (Davies et al., 2001). In the former method it is necessary to install a cased borehole through the water and into the soil away from the pier being studied. However, it is likely that a stand-alone casing would be destroyed during a flood, meaning that the PSS should be performed only after the flood has subsided and the casing installed. The PISDS, in contrast, uses a pile or drilled shaft that is part of the foundation as its housing and so will survive for as long as the pier itself survives (Davies et al., 2002). The current paper briefly describes the two systems and gives results of deployment of both at a well-controlled test site.

TEST SITE

A facility to test scour detection systems was constructed at the National Geotechnical Experimentation Site at the University of Houston (Maher and O'Neill, 1983; O'Neill, 2000). The soil formation at the surface and extending to a depth of at least eight meters is the Beaumont formation, consisting of mostly overconsolidated, plastic clay with occasional sand seams and partings. A test pond was excavated within the site. A schematic of this test pond is shown in Fig. 1. The sides of the pond were lined with geotextiles to mitigate sloughing of the walls, which were cut on a 1:1 slope. The depth of water was approximately 1.5 m (5 ft). Two drilled shafts, termed "piers" here, 0.61 m in diameter and 5.2 m long, were constructed in the pond as indicated in Fig. 1. The three locations denoted "BH-1, BH-2, and BH-4" are locations at which PVC casings had been pushed into small-diameter boreholes and grouted to the soil at the bottom of the pond at some distance from the drilled shafts. The location marked "BH-3" consisted of a PVC pipe that had been cast into Pier 2. All PVC pipes extended approximately 7.8 m below the natural ground surface, except for BH-3, where the casing extended only to the toe of the pier. The experiments that are described were performed first with a no-scour condition (flat bottomed pond) and then with a simulated scour condition, in which, after emptying the pond, 1.2 m (4 ft) of soil around each pier and throughout the zone between the piers was hand excavated to simulate a scour event. The sides of this scour excavation were cut vertically. Upon completion of excavation in the scour zone, the pond was re-filled with water. After several days of exposure of the soil to the ponded water the water was removed, at which time it was observed that the sides of the scour excavation had sloughed irregularly into the excavation. This condition was assumed to represent the state of clay soil after a scour event (scour hole backfilled with loose sediments).

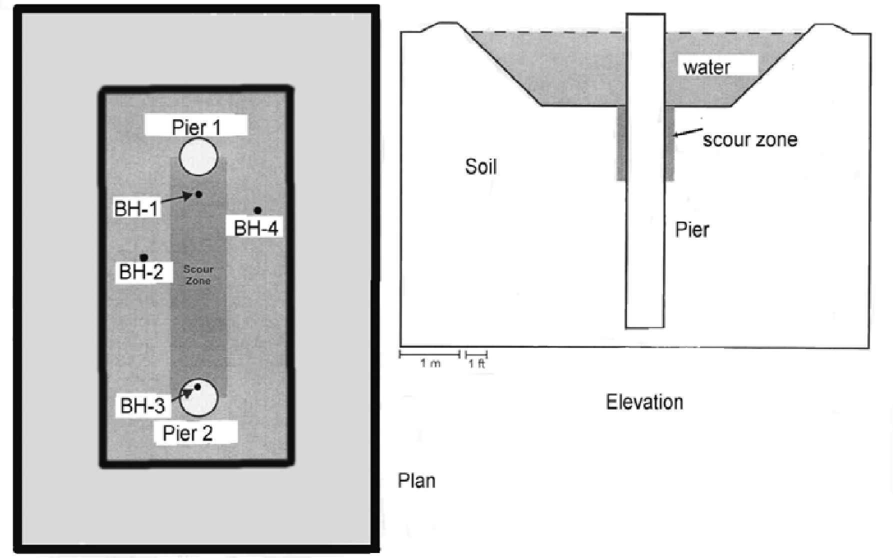

Fig. 1. Schematic of Test Pond

PSS MONITORING

A set of unclamped hydrophones was placed in tubes BH-1, BH-2 and BH-4, which had been filled with water. The hydrophones were Mark Products Model P-44 hydrophones, sensitivity of 14 μvolts per μbar pressure, which were spaced 0.305 m apart vertically. An Oyo Geospace Model DAS-1 digital data acquisition system was used to acquire data from the hydrophones at a digitizing rate of 62.5 μsec per sample. The recorded data were filtered with a broadband filter passing signals between 3 and 4000 Hz. The detection process began with tapping the head of Pier 1 with a steel hammer while the hydrophones were being monitored. Seismic waves in the soil surrounding the test pier were created through refraction. These waves were subsequently picked up by the hydrophones.

Figure 2 shows the results of a PSS test for a scour condition with the array of hydrophones placed in tube BH-1, 0.61 m from the face of Pier 1 and in line with the center of the scour trench, where there was a minimum of sloughed soil. The data in Fig. 2 are unfiltered (other than indicated above) and are typical of PSS data for a drilled shaft embedded completely in soil. The linear first-break pattern occurs down to the depth of the toe of the pier (Line AB). Below the toe of the pier the first-break arrival times exhibit a marked change (Line CD). The intersection of Lines AB and CD define the depth of the toe, which is the usual interpretation of PSS data. No scour zone can be clearly identified.

The detection of a scour zone is predicated on the principle that the soft infilled soil within the scour zone will attenuate the energy of the seismic (P-) waves refracted from the pier. To investigate this effect, the experiment was repeated with the array of hydrophones located in borehole BH-4. The results are shown in Fig. 3b and compared with a similar test for no-scour conditions in Fig. 3a, where the hydrophones were in BH-1 (equivalent to Fig. 2 but for the no-scour condition). The structural configuration of the scour trench at BH-4 at the time of that test is shown on the left-hand panel of Fig. 3b. It is seen that a considerable amount of sloughed material was located between the hammer source on the pier and BH-4. A marked attenuation in the amplitude of the seismic events can be observed for those hydrophones located adjacent to the scour zone. The depth of the scour zone can be identified clearly by plotting the amplitude of the signal versus depth. Marked changes occur at the elevations of the top and bottom of the scour zone (Mercado and O'Neill, 2001).

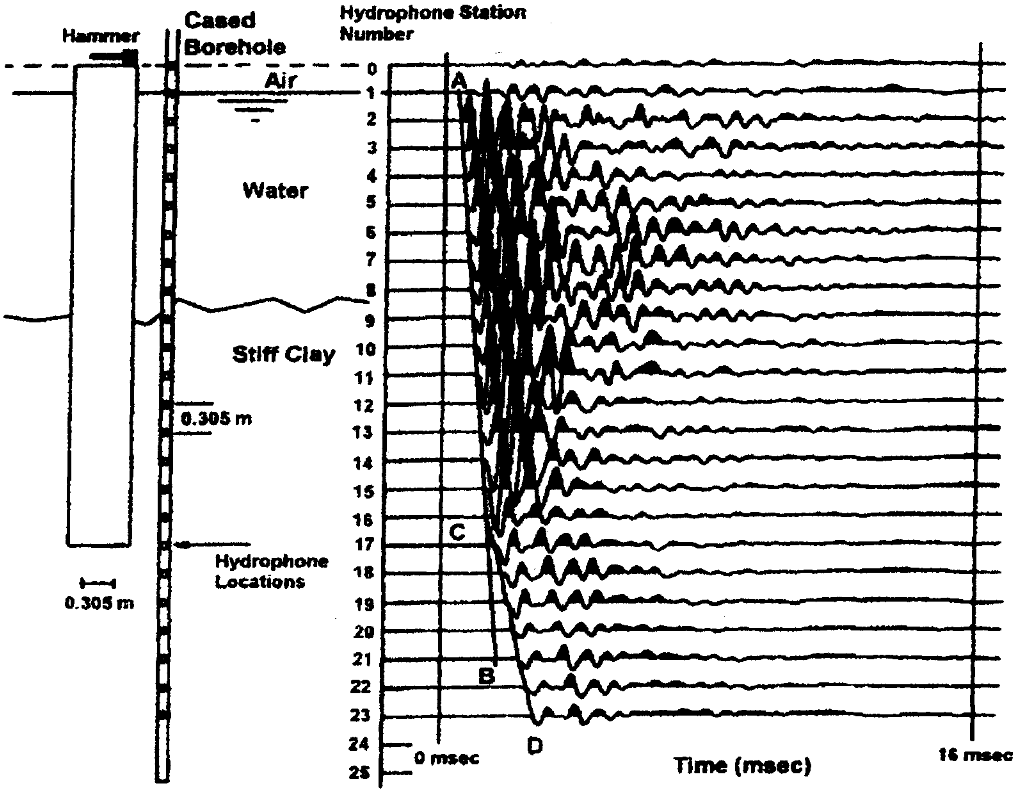

Figure 2. First Wave Arrivals from Pier 1 in BH-1 for the Scour Case, PSS

The data suggest that the PSS is a technique that can take advantage of the reduced seismic wave velocities of infilled soil to detect scour either after a flood event has passed or, possibly, during a flood event if the access tube can be protected from hydraulic forces and debris impact. However, research should continue toward the goal of developing a seismic system as reliable as the PSS but better able to withstand the flood environment.

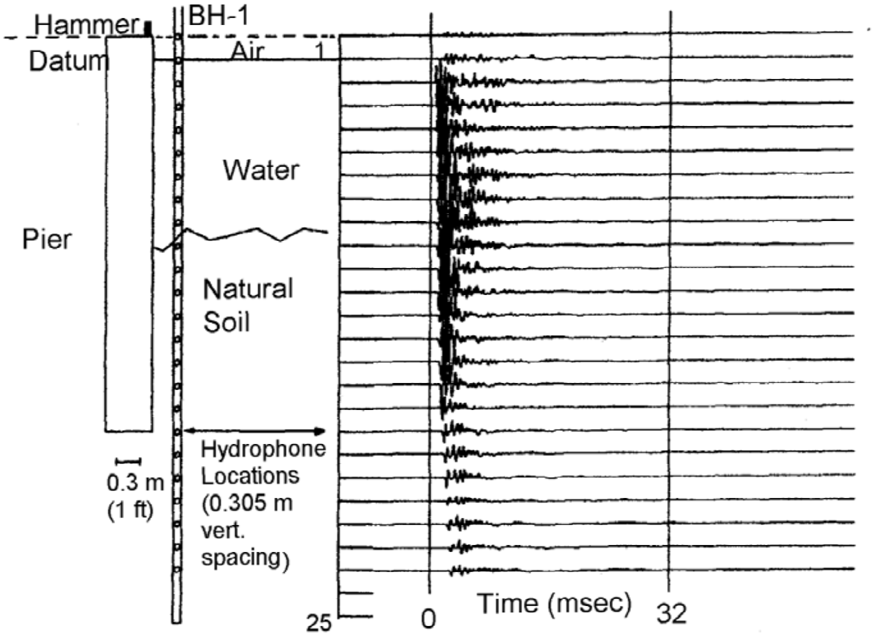

Figure 3a. Plot of PSS Signals in BH-1, No-Scour Condition

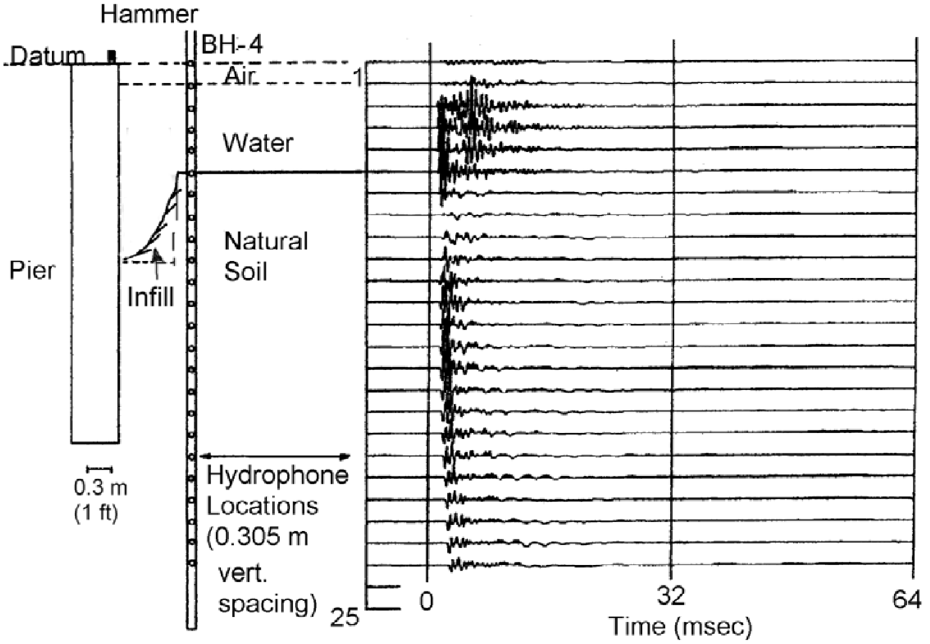

Figure 3b. Plot of PSS Signals in BH-4, Scour Condition

PILE GROUPS: REVERSE PSS TECHNIQUE

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. 4 is an arrangement in which the source (perhaps an air gun) is placed at several positions vertically along a track (perhaps a pipe driven into the sediments like a pile), filled with water, in a post-flooding situation. For the lower locations of the source, the 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 selected piles in the exterior of the group (Fig. 4). As the source moves closer to the surface the ray paths finally intersect the individual piles at the critical angle to convert to refraction waves, which also travel up the pile to excite the geophones. By reciprocity, the first break pattern recorded at each geophone will duplicate the first break patterns for the case where the source is located at the top of the pile and the receivers (hydrophones) are at various depths exterior to the pile (the standard PSS procedure). While this technique has yet to be field-tested by the authors, it should provide usable information if it is possible to vary the energy of the source to suit the geometry of the pile group and the attenuation characteristics of the soil at the site.

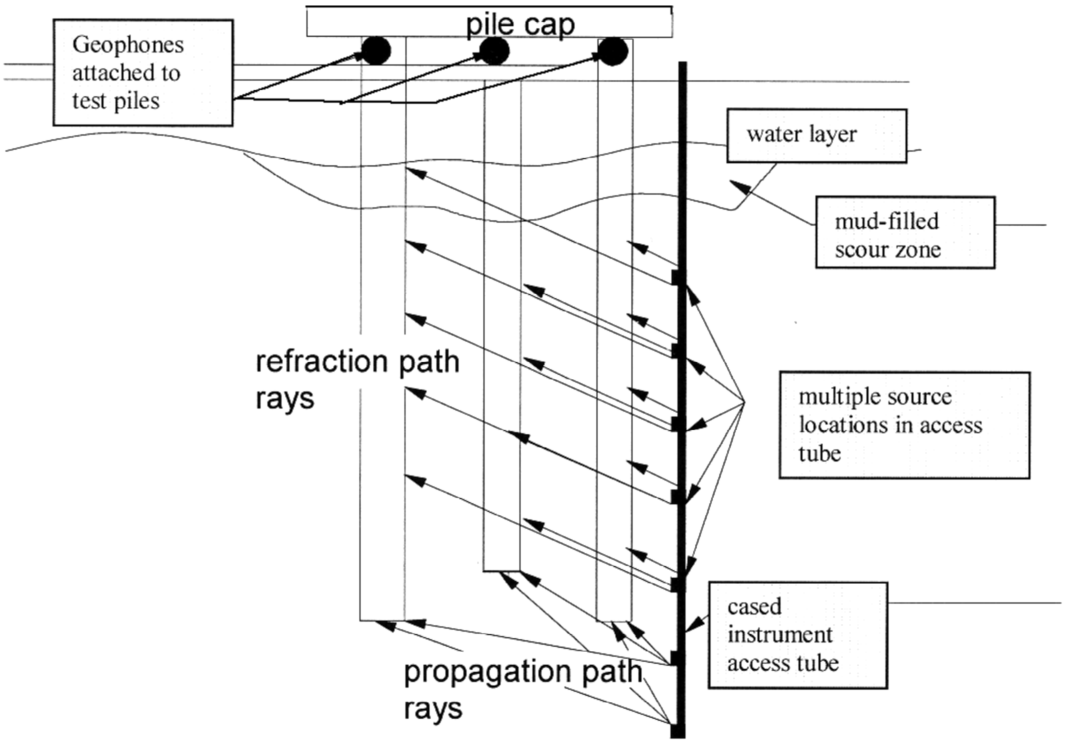

Figure 4. PSS Reverse Source-Detector Geometry for Investigation of Scour Around Pile Groups (Mercado and McDonald, 2002)

PISDS MONITORING

Although the PSS can be useful under certain circumstances in remotely gauging the depth of scour around a foundation within a body of water, a more physically robust detector will usually be needed in order to observe scour development in real time. One way of making a detector more robust would be for it to be located within an active foundation element, such as a pile or drilled shaft, or within a special drilled shaft or pile constructed for the express purpose of protecting the detector. It is possible, however, that the presence of a concrete shaft or steel pipe around a cased receiver hole might reduce the quality of the seismic data recorded within the cased hole. The "pier-interior scour detection system," or PISDS, nonetheless uses a pier-interior cased hole to house hydrophones. The feasibility of this system was investigated at the same site at which the PSS system data in the previous section were acquired.

The PISDS uses unclamped hydrophones within a water-filled casing, in a manner similar to the PSS. The data acquisition system is also the same as that used for the PSS. The seismic sources were a hammer, per the PSS, and an air gun. The air gun was a Bolt Technology Model DHS 500 gun with an 82 cm^3 firing chamber. In most cases it operated at a chamber pressure of 6900 kPa, with air as the gun gas. The hammer source was a 0.7 kg steel hammer.

The air gun was placed in the water at a designated depth and distance from Pier 2 (shot point). The trigger for the air gun also started the digital recording of the hydrophone traces. For the hammer-source tests, the hammer was struck directly atop Pier 2 with the hydrophone detectors housed within BH-3, inside Pier 2.

HAMMER SOURCE EXPERIMENTS. In theory the first wave arrivals in the hydrophones should be the P-waves generated in the pier by the hammer strike. These are then followed by later waves generated by other seismic events, including, perhaps, events associated with the scour zone. Hammer source tests were conducted on Pier 2, and the first arrival times did indeed correlate with direct P-wave propagation in the pier for a wave velocity of 4420 m/s, which was independently verified by Davies et al., 2001. This fact indicated that the pier-interior geophones could be of potential use in detecting P-wave propagation velocity within the pier and thereby in detecting scour zones.

OFFSET TESTS. The next step in investigating the PISDS method was to see if pier interior hydrophones and pier exterior hydrophones could give comparable data, it having been shown in the PSS tests that pier-exterior hydrophones within a borehole can detect scour zones. This step was performed using the air gun as a source and placing the detector system (hydrophone string) in BH-3, a pier-interior cased hole, and in BH-1, a pier-exterior cased hole. The air gun was placed in the water at a depth of 0.3 m and a distance of 1.5 m form BH-3. The experiment was repeated with the air gun at a depth of 0.3 m and 1.5 m away from BH-1 (with the air gun, BH-1 and Pier 1 all in the same vertical plane). The results of these tests are shown in Fig. 5 for the scour condition, where there was a minimum of infill material.

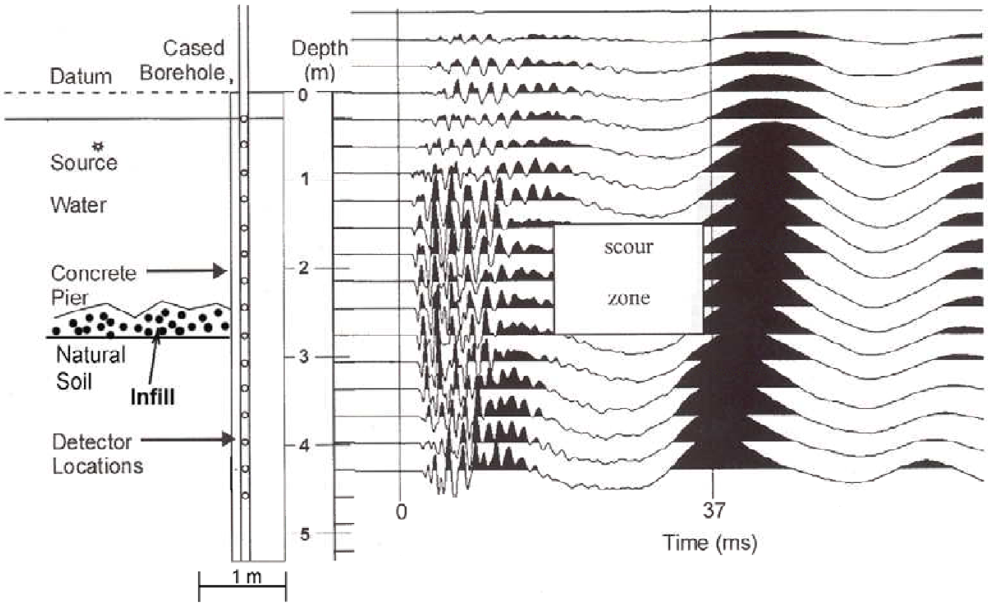

Figure 5a. Results of Offset Test for Pier-Interior Cased Hole (BH-3)

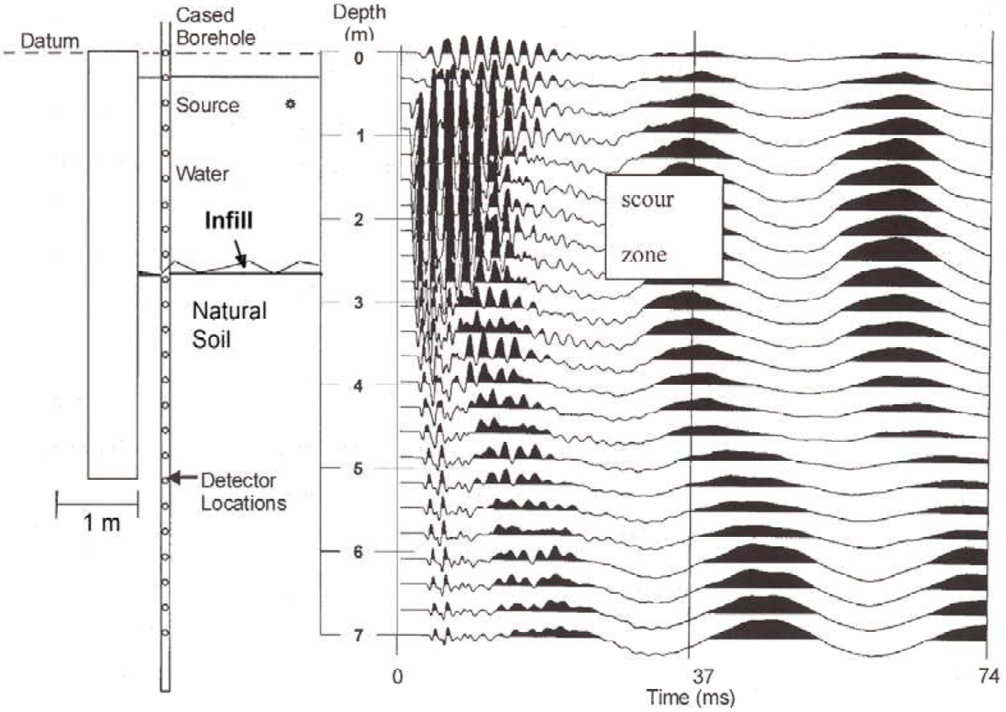

Figure 5b. Results of Offset Test for Pier-Exterior Cased Hole (BH-1)

One way of evaluating the data in Fig. 5 is to compare visually Figs. 5a and 5b. Over the range of detector locations, the data in Fig. 5b are of slightly higher quality than those in Fig. 5a. However, in the depth range of 1.5 to 3.7 m (scour zone and natural soil just below the scour zone), the first breaks are well defined on both data sets. At later times, after the first breaks, the two data sets differ considerably due to the presence of much stronger reflections (up-going waves) from the toe of the pier for the borehole interior case (Fig. 5a). This observation strongly suggests that data from the pier-interior borehole may be useful in scour zone detection if such detection can be performed by observing first breaks in the hydrophone traces.

A method to utilize first break times for the pier-interior borehole is to compare graphs of measured first break times with direct P-wave arrival times from a water source 0.305 m below the water surface and 1.5 m from a string of vertical hydrophones (field test condition) computed from a simple flat-layer, elastic geophysical wave propagation model (Dobrin, 1974; Davies et al., 1996). Analyses were made by considering the conditions shown in Table 1 and then by tracing the wave rays through their fastest path (through water or through water and soil) to the location of a particular hydrophone to obtain the theoretical time of first wave arrival, considering wave refraction at the

Table 1. Parameters used in flat-layer wave propagation model

Condition analyzed	**P-wave velocity (m/s)**		
	Water (0-1.5 m)	**Scour zone (1.5-2.7 m)**	**Natural soil (below either 1.5 or 2.7 m)**
A. Source in water, hydrophones in water	1525 (full depth)	Not modeled	Not modeled
B. Source in water, upper hydrophones in water, lower hydrophones in high velocity soil at a depth of 1.5 m	1525	Not modeled	1675 (below 1.5 m)
C. Source in water, upper hydrophones in water, lower hydrophones in low velocity soil at a depth of 1.5 m	1525	1070	1070 (below 2.7 m)
D. Source in water, upper hydrophones in water, lower hydrophones in high velocity soil below a depth of 2.7 m	1525	1525	1675 (below 2.7 m)

interface between the media using the principles of Snell's Law. The concrete pier itself is not considered since wave travel distance in the concrete is very small compared to wave travel distance in the water or soil. [BH-3 was on the side of Pier 2 closest to the air gun source.]

In Table 1 Condition A is for water only and is relevant only for the upper hydrophones, above the soil; Condition B represents the no-scour condition; Condition C may represent either scour with soft, sloughed sediment (infill) below a depth of 1.5 m or no-scour with a soft natural soil below the water; Condition D represents scour with no infill in the scour zone. The measurements (no-scour and scour conditions) and computed first arrival times for the conditions in Table 1 are shown for the pier-exterior borehole in Fig. 6a and for the pier-interior borehole in Fig. 6b.

INTERPRETATION. One way to interpret Fig. 6 is to consider the arrival time-hydrophone depth plot for "no-scour" conditions to be the baseline. In practice, this could be the set of readings taken shortly after a detection borehole is installed. Scour is evident, then, when the first-arrival-time measurements from a source (such as an air gun) situated at the same location as existed for the baseline readings deviates from this baseline. The depth at which the "scour" data separate from the baseline in both Figs. 6a and 6b is 1.5 (pier interior hydrophones) to 1.7 m (pier exterior hydrophones), which represents the elevation of the bottom of the test pit before simulated scour occurred.

For no-scour conditions, the data from both pier interior and pier exterior boreholes show some agreement below 1.5 m (bottom of water) with the computed values for Condition C, which simulates a low-velocity halfspace (soft soil) below water. For the scour condition from depths of about 3.0 m to 4.3 m the measurements from both pier exterior and pier interior boreholes generally agree with Condition D, in which the low-velocity soil in the scour zone has been replaced with water, or perhaps sloughed soil with very large water-filled voids.

The similarity of the comparisons in the pier interior and pier exterior boreholes is evidence that the pier interior system can be used to monitor scour outside the pier. For the pier-interior method to become practical and reliable further experiments of this type in other types of soil (specifically, cohesionless soil) need to be conducted, and signal filtering rules need to be determined for flood conditions, where water cavitation and similar phenomena can both produce background noise and attenuation of seismic waves from the source.

Finally, it is noted that the PSS and PISDS methods are protected by U. S. Patent Number 5,753,818.

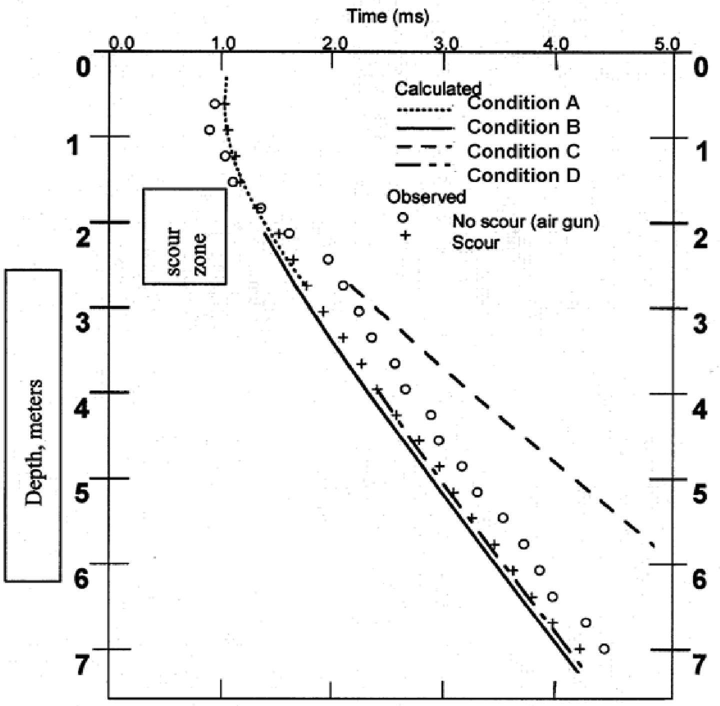

Figure 6a. Measured and Computed First Arrival Times at Hydrophone Locations, Pier-Exterior Borehole

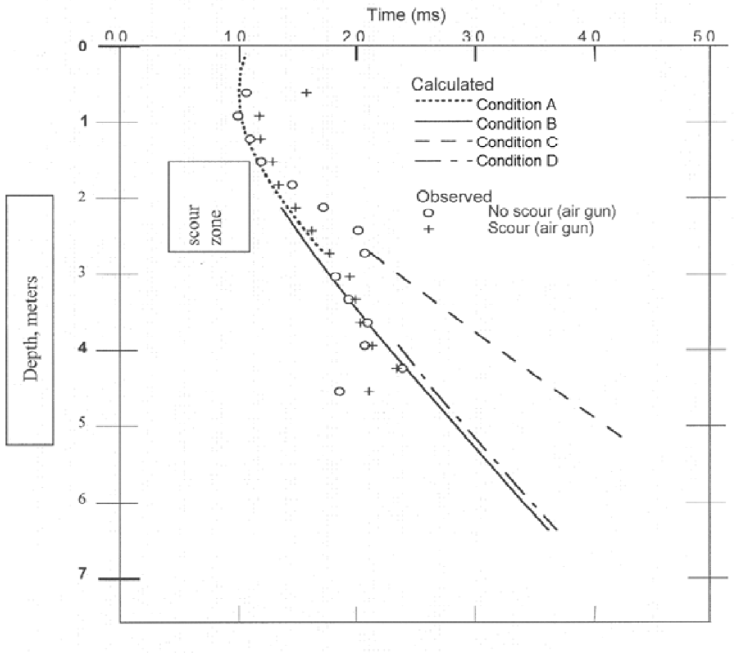

Figure 6b. Measured and Computed First Arrival Times at Hydrophone Locations, Pier-Interior Borehole

CONCLUSIONS

The following conclusions are drawn from this study.

1. The PSS method should be effective in detecting scour around single piles or drilled shafts (piers) after a flood has passed when loose infill soil appears in the scour zone.

2. The reverse-PSS method may be a useful technique in detecting scour around groups of piles after a flooding event.

3. Seismic events within water generated outside a concrete pier were detected in a cased tube cast within the pier.

4. The seismic events recorded within the pier-interior cased hole compare favorably with corresponding events recorded in a pier-exterior borehole. As a consequence, the PISDS method, which uses the pier-interior hole to protect the receiving instruments during a flood, has the potential to be used to indicate scour conditions adjacent to a pile or drilled shaft in real time during a flood.

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