SOUND PRESSURE AND PARTICLE VELOCITY MEASUREMENTS FROM MARINE PILE DRIVING WITH BUBBLE CURTAIN MITIGATION

Alex MacGillivray and Roberto Racca
JASCO Research Ltd., #2101-4464 Markham St., Victoria BC, Canada, V8Z 7X8
alex@jasco.com, rob@jasco.com

1. INTRODUCTION

In October 2005, JASCO Research Ltd (JASCO) performed measurements of underwater acoustic pressure and acoustic particle velocity near marine pile driving work at Washington State Ferries' Eagle Harbor maintenance facility, located on Bainbridge Island in Washington State. Ten steel piles, all 30 inches in diameter, were installed at the construction site in 10 metre deep water. Bubble curtain mitigation was employed by the construction contractor to reduce underwater sound levels generated by the pile driving. The goal of this study was to determine the effectiveness of the bubble curtain at reducing acoustic particle velocity levels as well as sound pressure levels, since injuries to the hearing organs of fish may be more directly related to particle motion than to pressure (Hastings and Popper, 2005).

2. THEORY

Acoustic particle velocity can be measured using the pressure gradient method, as described for example by Fahy (1977). Euler's linearized momentum equation can be used to show that the acoustic particle velocity is related to the time integral of the acoustic pressure gradient:

$$\mathbf{v} = -\int \nabla p / \rho_0 dt \qquad (1)$$

where **v** is the vector particle velocity, ρ_0 is the fluid density and p is the acoustic pressure. Experimentally, the pressure gradient may be measured from the differential pressure between two closely spaced hydrophones:

$$\frac{\partial p}{\partial x} = -\rho_0 \frac{\partial v_x}{\partial t} \cong \frac{p(x+h/2) - p(x-h/2)}{h} \qquad (2)$$

where p is acoustic pressure, v_x is the component of velocity along a single axis and h is the hydrophone spacing. The finite difference approximation of Equation 2 depends on the condition that hydrophone separation h be small relative to the acoustic wavelength; consequently there is an upper frequency limit for the practical application of this formula. It may be demonstrated that the amplitude error, in decibels, due to this finite-difference approximation is less than the quantity:

$$\varepsilon = 20\log_{10}\left(\frac{k_x h}{2\sin(k_x h/2)}\right) \qquad (3)$$

where $k_x = 2\pi f/c$ is the acoustic wavenumber, f is the frequency of sound and c is the speed of sound in water.

3. METHODS

Apparatus

Acoustic particle velocity from pile driving was measured by the pressure gradient method using a custom built, multi-component hydroacoustic sensor designed by JASCO. The pressure gradient sensor was composed of a pyramidal frame supporting four Reson TC4043 hydrophones and a JASCO AIM attitude/depth sensor. The hydrophones were cross-calibrated before and after the field measurements using a swept reference signal (from 100 Hz to 2 kHz) from an underwater loudspeaker. A schematic diagram of the pressure gradient measurement system is shown in Figure 1.

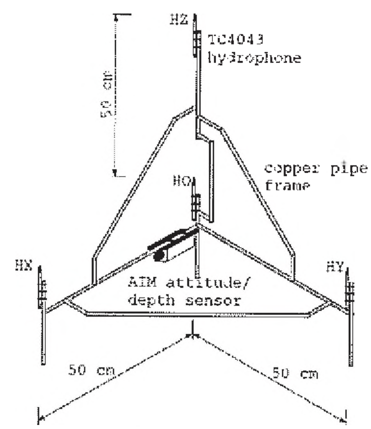

Fig. 1. Schematic diagram of the pressure gradient sensor shown in isometric projection. Four Reson TC4043 hydrophones are located at the positions indicated HO (origin) HX (X-axis) HY (Y-axis) and HZ (Z-axis). The AIM attitude/depth sensor is oriented in the X-direction. The axial hydrophones HX, HY and HZ are all located 50 cm from the origin hydrophone HO.

Pressure signals from the four hydrophones were sampled at 25 kHz per channel, with 16-bit resolution, using a laptop PC based digital acquisition system. Custom software, written using the data analysis language IDL (Research Systems, Inc.), was used to compute three acoustic particle velocity traces from the time integral of the pressure gradient between the hydrophones, according to Equation 2.

The differential pressure traces were low-pass filtered at 1330 Hz to limit errors in the differential pressure calculation caused by aliasing of higher frequencies — 1330 Hz corresponds to the 3 dB error point in the finite difference approximation according to Equation 3. The traces were also high-pass filtered at 15 Hz to remove cumulative integration errors in the particle velocity calculation. High-pass filtering is required because the integral operator in Equation 1 effectively multiplies the power spectrum of the differential pressure by the inverse of frequency, causing preferential amplification of low frequency noise.

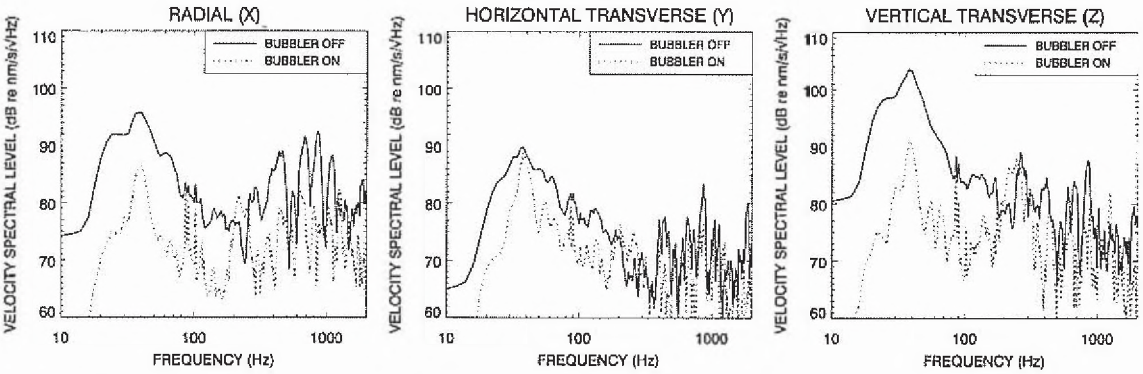

Fig. 2. Average X, Y and Z velocity spectral levels for inactive bubble curtain (solid line) and active bubble curtain (dotted line). The velocity sensor was oriented with the X-axis towards direction of the pile-driving and the Z-axis pointing vertically.

Measurements

Measurements were obtained during the installation of eight cylindrical steel piles next to a pier at the ferries maintenance facility. The outside diameter of the piles was 30 in. and the wall thickness was 1 in.; the length ranged from 75 ft. to 80 ft. and the weight per unit length was 311 lbs/foot. A Delmag 62 single-action diesel impact hammer with a 14,600 lbs hammer piston was used to drive the piles into the substrate. The bubble curtain apparatus consisted of a 1 in. thick cylindrical PVC sleeve, 44 ft. long and 47 in. outside diameter, that was lowered over each pile before hammering. Air was injected through two internally mounted aerating tubes, one located at the base of the sleeve and the other 10 ft. above the base. An air compressor supplied the aerating tubes at a rate of 300-350 CFM (cubic feet per minute).

The nominal water depth at the site was 10 meters and the acoustic sensor was deployed mid water column at a depth of 5 meters. Sound pressure and particle velocity waveforms were measured at horizontal ranges from 9 to 19 meters from the pile driving. For some of the measurements the air curtain apparatus was purposely left inactive (sleeve in position but with no air supply) to allow comparative measurements to be taken.

4. RESULTS

Figure 2 shows average X, Y and Z velocity spectral levels for hammering of a single pile with the bubble curtain active (12 strikes) and inactive (15 strikes) respectively. Above 100 Hz, maximum velocity spectral levels were observed on the radial (X-axis) velocity trace, which was oriented towards the direction of the pile driving. Below 100 Hz, maximum velocity spectral levels were observed on the vertical (Z-axis) trace; this was due to the low frequency vertical particle displacement caused by the downward movement of the pile upon impact of the pile driving hammer.

Table 1. Average acoustic particle velocity and sound pressure levels measured at 10 metres range.

Level	Curtain ON	Curtain OFF
Peak velocity	129.1 dB//nm/s	140.5 dB//nm/s
RMS velocity	117.3 dB//nm/s	129.4 dB//nm/s
Pulse length	141.9 ms	61.7 ms
Peak pressure	194.4 dB//μPa	204.2 dB//μPa
RMS pressure	183.3 dB//μPa	192.6 dB//μPa
Pulse length	49.3 ms	38.1 ms

Table 1 shows the average peak and 90% RMS particle velocity and sound pressure levels measured from hammering of a single pile at 10 metres range. Average measurements from hammering of three different piles at different ranges showed that the active bubble curtain reduced peak velocity levels by 11.4 dB and 90% RMS velocity levels by 12.1 dB. Similarly, the active bubble curtain reduced peak pressure levels by 9.1 dB and 90% RMS pressure levels by 8.6 dB. Thus the bubble curtain proved effective in mitigating both sound pressure and particle velocity levels generated by the pile driving.

REFERENCES

Fahy, F. J. (1977). Measurement of acoustic intensity using the cross-spectral density of two microphone signals. J. Acoust. Soc. Am. 62, pp. 1057–1059.

Hastings, M. C. and Popper, A. N. (2005). Effects of sound on fish. California Department of Transportation Contract 43A0139 Task Order, 1.

ACKNOWLEDGEMENTS

This study was sponsored by the Washington State Department of Transportation. In particular, the authors would like to acknowledge the cooperation and support of Jim Laughlin of Washington State Department of Transportation and Ellie Ziegler of Washington State Ferries.