Acoustic Radiation from a Submerged Pile during Pile Driving

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Abstract- **Pile driving with an impact hammer is inherently a transient process and can produce very high sound levels. It is shown that the underwater noise during pile driving is due to a radial expansion of the pile that propagates along the pile after impact. This structural wave produces a wave front cone in the water, and a downward moving wave that continues into the sediment. An upward moving wave front is produced in the sediment after the first reflection of the structural wave, which is subsequently transmitted into the water. This process is repeated to produce an acoustic field that consists of wave fronts with alternating positive and negative angles. Good agreement in the estimate of the angles was obtained between a finite element wave propagation model and measurements taken during a full scale pile driving study.**

I. Introduction

Pile driving in water produces extremely high sound levels in the surrounding environment in air and underwater. Underwater sound levels as high as 220 dB re 1 µPa are not uncommon 10 meters away from a steel pile as it is driven into the sediment with an impact hammer.

Reported impacts on wildlife around the construction site include fish mortality associated to barotrauma, hearing impacts in both fish and marine mammals, and bird habitat disturbance. Pile driving in water is therefore a highly regulated construction process and can only be undertaken at certain time periods during the year. The regulations are now strict enough that they can severely delay or prevent major construction projects.

There is thus significant interest in reducing underwater noise from pile driving either by attenuating the radiated noise or by decreasing noise radiation from the pile [1, 2]. As a first step in this process it is necessary to understand the dynamics of the pile and the coupling with the water as the pile is being driven into the sediment. The process is a highly transient one in that every strike causes the propagation of deformation waves down the pile. To gain an understanding of the sound generating mechanism we have conducted a detailed transient wave propagation analysis of a submerged pile using finite element techniques. The conclusions drawn from the simulation are largely verified by a comparison with measured data obtained during a full scale pile driving test carried out by the University of Washington, the Washington State Dept of Transportation (WSDOT), and Washington State Ferries (WSF) at Vashon Island ferry terminal in November 2009.

II. Finite Element Model

To investigate the acoustic radiation due to a pile strike we created an axisymmetric finite element model of a 30 inch radius, 30.2 m long hollow steel pile with a wall thickness of one inch submerged in 12.5 meters of water and driven 10 meters into the sediment. The radius of the water and sediment domain was 10 meters (see Fig. 1). Perfectly matched boundary conditions were used to prevent reflections from the boundaries that truncate the water and sediment domains. The pile was fluid loaded via interaction between the water/sediment. All domains were meshed using quadratic Lagrange elements.

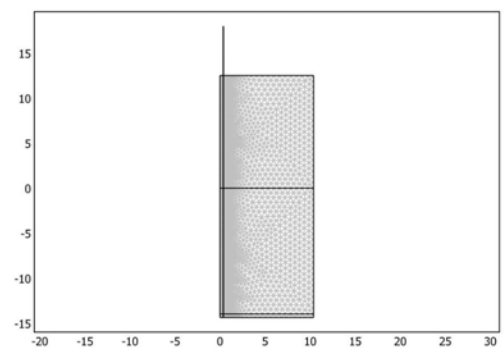


Figure 1. Geometry for axisymmetric finite element model

The pile was impacted with a pile hammer with a mass of 6,200 kg that was raised to a height of 1.73 meters above the top of the pile. The velocity at impact was 7.5 m/s, and the impact pressure as a function of time after impact was examined using finite element analysis and approximated as

$$p(t)= -2.7\ 10^8\ exp(-t/0.004)\ \text{Pa}\ . \qquad (1)$$

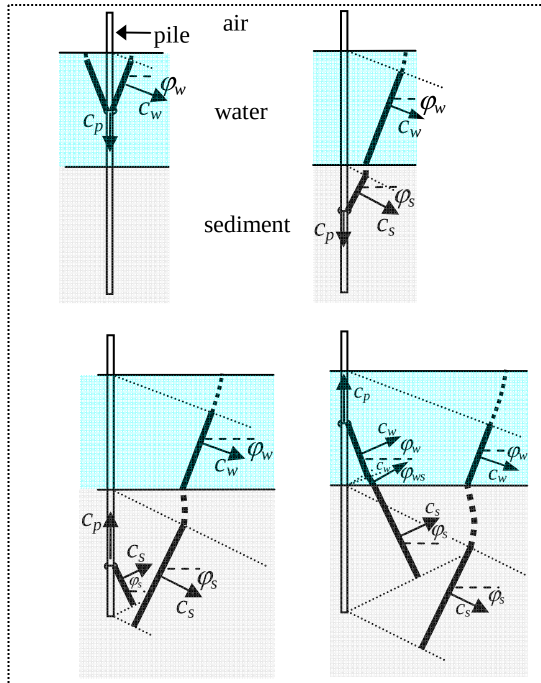
The acoustic medium was modeled as a fluid using measured water sound speed at the Vashon site, c_w, and estimated sediment sound speed, c_s, of 1485 m/s and 1625 m/s, respectfully. The sediment speed was estimated using coring data metrics obtained at the site, which characterized by fine sand, and applied to empirical equations in [3, 4].

III. Finite Element Results

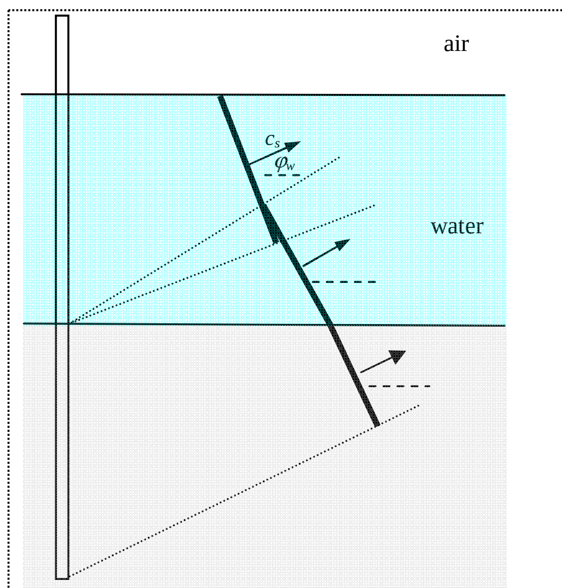
The primary source of underwater sound originating from pile driving is associated with compression of the pile. The compression wave in the pile due to the hammer strike produces an associated radial displacement motion due to the effect of Poisson's ratio of steel (0.33) . This radial displacement in the pile propagates downwards with the longitudinal wave with wave speed of c_p = 4,840 m/s when the pile is surrounded by water. Since the wave speed of this radial displacement wave is higher than the speed of sound in the water the rapidly downward propagating wave produces an acoustic field in the water in the shape of an axisymmetric cone with apex traveling along with the pile deformation wave front as is illustrated in Figure 2. This Mach cone is formed with cone angle of $\varphi_w = \sin^{-1}(c_p / c_w) = 17.9^\circ$. Note that this is angle that formed between the vertically-oriented pile and the wave front associated with the Mach cone; it is measured on vertical line array (VLA) as discussed in Sec. IV, and here it will be manifested as a vertical arrival angle with reference to horizontal. This angle only depends on the two wave speeds and is independent of the distance from the pile. The Mach cone angle changes from φ_w to $\varphi_s = \sin^{-1}(c_p / c_s) = 18.7^\circ$ as the pile bulge wave enters sediment. Note that the pile bulge wave speed in the sediment is slightly lower due to the higher mass loading of the sediment and is equal to c_p = 4,815 m/s.

As the wave in the pile reaches the pile terminal end it is reflected upwards. This upward traveling wave in turn produces a Mach cone of angle φ_s (defined as negative with respect to horizontal) that is traveling up instead of down. The sound field associated with this cone propagates up through the sediment and penetrates into the water. Due to the change in the speed of sound going from sediment to water the angle of the wave front that originates in the sediment changes from φ_s to φ_{sw} = -29.0° following Snell's law. Ultimately, two upward moving wave fronts occur as shown in the schematics in Figs. 2 and 3. One with angle φ_{sw} and one with angle φ_w, the latter is produced directly by the upward moving pile wave front in the water. (Other features of propagation such as diffraction and multiple reflections are not depicted in these simplified illustrations.)

Figure 4 shows an axisymmetric surface plot of the total acoustic pressure at four different time steps. (The pile is to the left.) The four frames compare nominally with the wave front illustrations in Fig. 2. The axial stress wave in the pile produced by the hammer impact does not produce a simple step change in the radial motion of the pile wall as illustrated in Fig. 2 but sets up radial oscillation of the wall after the initial wave has passed through. An axisymmetric impact force will lead to an axisymmetric radial displacement oscillation as seen in Fig. 4. The figure shows the initial Mach cones, for which wave fronts are shown in Fig. 2, followed by the alternating pressure due to oscillations of the pile wall.



gure 2. Illustration of the primary wave fronts associated with the Mach ne generated by the pile compression wave



igure 3. Illustration showing only the first upward traveling wave front.

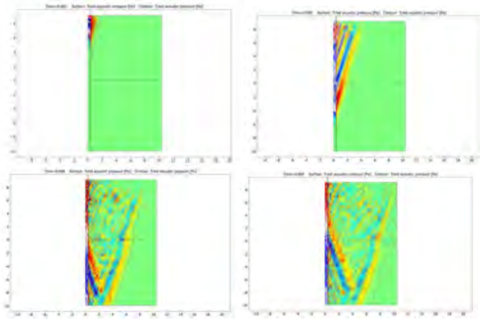


Figure 4. Finite element simulation showing the axisymmetric sound field generated in the surrounding water and sediment at 3, 5, 8 and 9 ms (left to right, top to bottom) after impact of a pile.

IV. Comparisons With Measured Data

An experiment to measure underwater noise from pile driving was conducted at the WSF Vashon Island ferry terminal in November 2009 as part of planned construction project. The piles (Fig. 5) were approximately 30.2 m long and were set in 10.5 to 12 m of water depending on tidal range. The underwater sound was monitored using a vertical line array (VLA) consisting of 9 hydrophones (ITC 1042) with spacing 0.7 m, with lowest hydrophone placed 2 m from the bottom (Fig. 6). The array was set such that the distance from the piles ranged from 8 to 12 m.

igure 5. Photograph of 6,200 kg impact hammer being placed in position for ile driving at the Vashon Island ferry terminal.

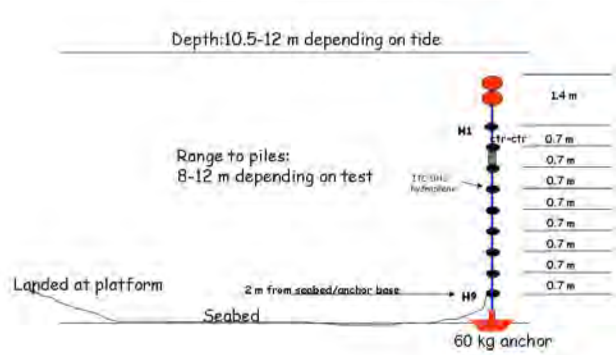


Figure 6. Vertical line array used to measure acoustic radiation from pile driving.

Figure 7 shows the pressure time series recorded by two hydrophones on the VLA, one 2 m off the bottom and the other 5.5 m. For this particular test the VLA was 8 m from the pile as it was being driven into the sediment with the hammer shown in Fig. 5. Key features of the data are as follows:

1. The first and highest amplitude arrival is a negative pressure wave of order 10-100 kPa.

2. The main pulse duration is ~20 ms over which there are fluctuations of 10 dB, during the next 40 ms the level is reduced by 20 dB.

3. There are clearly observable time lags between measurements made at different heights off the bottom. These time lags can be associated with the vertical arrival angle.

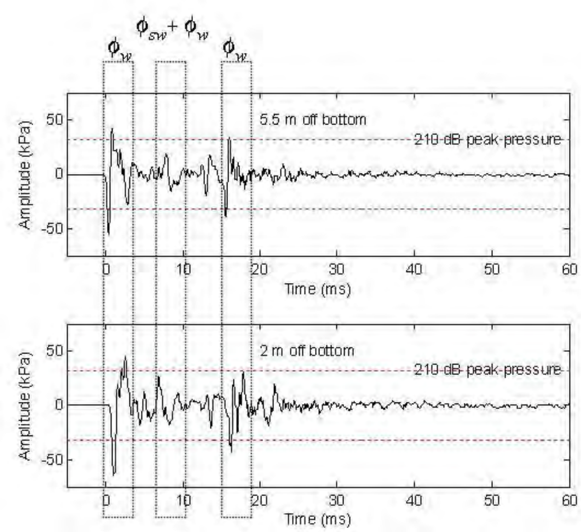


Figure 7. Pressure time series of underwater noise from pile impact at range 8 m at two different heights above the seabed. Boxes indicate segments associated with different vertical arrival angles and are discussed further below.

With the range of VLA, of length L = 5.6 m, being 8 to 12 m from pile (a known value depending on particular test) the question as whether or not the pile source is in the far field of the VLA needs to be addressed. This depends on the spatial extent of the source and the frequency; assuming a point source and frequency 500 Hz, a range of > 20 m is needed to assume a plane wave arrival.

Here, to avoid any assumptions relating to far field we examine the VLA using pairs of hydrophones, separated by 0.7 m, which largely removes any far field criteria. Figure 8 shows estimated vertical arrival angle based on correlation estimates of inter-sensor time-delay. The eight pair-wise estimates of arrival angle are plotted as function nominal depth off the bottom (i.e. the average of the two sensors involved). The colors represent three separate measurements (involving different piles), for which the range to VLA was 8 m (green) and 12 m (black and red). Three segments of data are selected to compute inter-sensor delay, with nominal time for these segments shown in Fig. 7.

According to the FEA results in Sec. III, there should be two opportunities to measure φ_w, one being the initial negative phase and the next approximately 12-14 ms later which represents a second, reflected wave originating from the top of the pile. These estimates cluster on the right side of Fig. 8 near 17.6°, a value equal to the mean of the all estimates derived from the first negative phase (solid color squares) and represented by the solid blue line, and which is remarkably close to the predicted value of 17.9° . The standard deviation of this estimate is 2.1°, which a bit higher than that predicted by the Cramer-Rao lower bound as determined by signal bandwidth, SNR and mean arrival angle. Interestingly, the next set of estimates of φ_w (open triangles) clusters about the blue line but with higher variance owing to reduced SNR. Turning now to the negative estimates shown on the left side of Fig. 7, these represent in a sense a combined estimate of $\varphi_w + \varphi_{sw}$ which would necessarily result in considerable spread.

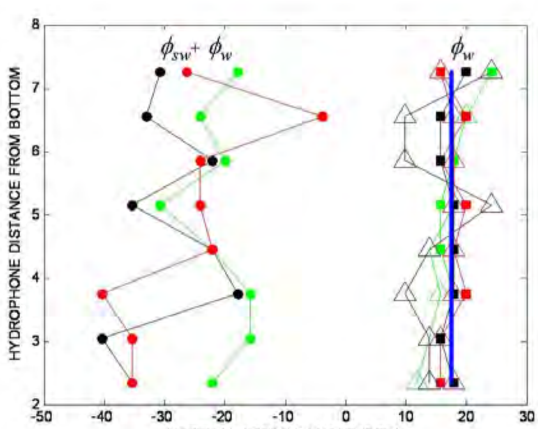


Figure 8. Estimated vertical arrival angle versus depth off the bottom for three pile driving tests, with following color code: green represents data for which the pile was at range 8 m from the VLA; black and red represent two different pile tests at 12 m range from the VLA. Square and open-triangle symbols are estimates from data nominally within time periods represented by the 1st and 3rd boxes, respectively, shown in Fig. 7; circle symbols are estimates from data nominally within the time period represented by the 2nd box in Fig. 7. See text for further explanation on variability. Solid blue line is the mean of all the square symbols.

V. CONCLUSIONS

We have shown via finite element analysis that the generation of underwater noise during pile driving is due to a radial expansion wave that propagates along the pile after impact. This structural wave produces a Mach cone in the water and the sediment. An upward moving Mach cone produced in the sediment after the first reflection of the structural wave results in a wave front that is transmitted into the water. We show that repeated reflections of the structural wave cause upward and downward moving Mach cones in the water and that the corresponding acoustic field consists of wave fronts with alternating positive and negative angles. Good agreement was obtained between a finite element wave propagation model and measurements taken during full scale pile driving in terms of angle of arrival. Furthermore, this angle appears insensitive to range for the 8 to 12 m ranges measured, which is consistent with the wave front being akin to a plane wave.

CKNOWLEDGMENT

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