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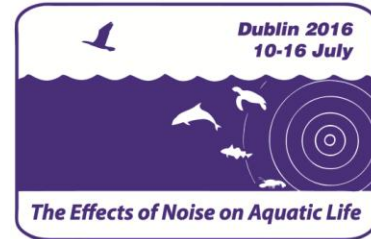Proceedings of Meetings on Acoustics **27**, 010029010029 (2017); 10.1121/2.0000324

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Relationships of sound pressure and particle velocity during pile driving in a flooded dock

Maria Ceraulo
Department of Pure and Applied Sciences, University of Urbino, Urbino, Italy; maria.ceraulo@iamc.cnr.it

Rick Bruintjes
Biosciences, College of Life and Environmental Sciences, University of Exeter, Stocker Road, Exeter EX4 4QD, UK;rbruintjes@yahoo.com

Thomas Benson and **Kate Rossington**
HR Wallingford, Howbery Park, Wallingford, UK;T.Benson@hrwallingford.com; K.Rossington@hrwallingford.com

Almo Farina
Department of Pure and Applied Sciences, University of Urbino, Urbino, Italy; almo.farina@uniurb.it

Giuseppa Buscaino
Institute for Coastal Marine Environment , National Research Council, TorrettaGranitola, Campobello di Mazara (TP), Italy; giuseppa.buscaino@cnr.it

Underwater sound is characterized by two different components, directional particle motion and scalar pressure waves. Here, we studied sound pressure and particle motion during experimental pile driving in a confined industrial-sized shipbuilding dock. The pile driving noise was generated by a 200 kg hammer striking a 7.5m steel pile. Noise data were collected using a hydrophone and a 3-axis accelerometer along 27 equally spaced locations. The results show that the relationship between the two components is approximately linear, as theory suggests, but the recorded values of particle velocity are generally larger than expected, particularly for the z-axis velocity which is shown to have a magnitude of 1 to 10 times (average 3.5) that of the theoretical velocity for a plane wave at the same sound pressure.Moreover, sound pressure and particle motion showed a different frequency distribution. For sound pressure, a shallow water cut-off frequency below approximately 400 Hz was observed in the power spectrum, which was not observed for particle velocity. This could be due to ground roll waves, but also wind induced waves and vibration on the cable could cause an increase in the low frequency vertical velocities.

1. INTRODUCTION AND OBJECTIVES

Underwater sound is characterized by two different components, directional particle motion and scalar pressure waves. As an acoustic wave propagates through water, it causes a fluctuation in the scalar sound pressure which can be measured using a hydrophone as the difference between the instantaneous pressure at a point in the presence of the acoustic wave and the static pressure of the medium. Particle motion, on the other hand, is a vector measure described as directional particle displacement, velocity or acceleration and is measured using directional accelerometers. All fish and marine invertebrates have sensory systems that allow them to perceive particle motion (Fay 1984). Many marine animals also have specially developed organs that permit them to detect sound pressure. When organisms possess both these sensory systems for sound detection, they will perceive the two components of sound with different sensitivities (Offutt 1973; Popper 2011; Radford et al. 2012). Understanding the differences between how sound pressure and particle motion propagate through the water in the marine environment is therefore important in order to fully understanding how sound may affect the creatures living there.

Until recently, a lack of availability of affordable particle motion sensors has meant that theoretical relationships have tended to be used by researchers to estimate particle velocity from measurements of sound pressure made both in laboratory water tanks and in the field (Picciulin et al. 2010, Filiciotto et al. 2016, Nedelec 2016). Theory states that, in open water, sound pressure and particle velocity are linearly related (Harris 1964, Chapman and Hawkins 1973). However this direct relationship is only valid when assuming that sound propagates as a plane wave; an assumption that is not met in enclosed tanks, in shelf seas or shallow bodies. Shelf seas and shallow water bodies provide essential habitats for a wide range of socio-economically important fish and invertebrate species (Biagi et al., 1998), however the relationships between sound pressure and particle motion in these locations are still largely unknown.

To address this, recent work by Hazelwood and Macey (2016) has focused on the problem by taking measurements of sound pressure and particle motion on the bed of a shallow enclosed dock during simulated pile driving. In their experiment they showed that the pile driving generated relatively slow moving 'ground roll' waves that propagated through the sediment-water interface and had a significant effect on the vertical component of particle velocity away from the sound source. Their results showed that the vertical particle velocity could be of the order 20 dB higher than the particle velocity calculated from theory.

The objective of this work is to evaluate and compare direct measurements of sound pressure level (SPL) and particle velocity generated by experimental pile driving in an industrial-sized confined space. The work builds on the previous work of Hazelwood and Macey (2016), but here the focus is to try to establish the relationship between sound pressure and particle velocity from measurements taken above the bed, rather than on the bed, in order to reduce the influence of ground roll. Comparisons are made in terms of the single strike Sound Exposure Level [SEL] for a series of pile strikes and in terms of their power spectral density (PSD) measured on third-octave bands.

2. MATERIAL AND METHODS

A. DATA COLLECTION

Recordings of pressure and particle velocity were carried out during experimental pile driving conducted in a confined industrial-sized flooded shipbuilding dock(dimensions: 92 x 18 with an average water depth of 2.5 m) that incorporated a simulated seabed layer (approximately 3.5 m thick). The simulated seabed sloped slightly, which corresponded to a 2.5 to 3.5 m water depth (Bruintjes et al. in review). Pile driving was generated by a 200 kg hammer (~1.6 kJ hammer energy) striking a 7.5m long, 0.17 m diameter, steel pile that rested on the simulated seabed. To ensure a stable position of the pile and similar acoustic conditions during subsequent pile driving, a steel plate (151 x 164 x 1.4 cm) was welded at 50 cm from the base of the pile. At the deepest side of the dock a section lacked simulated seabed sediment to facilitate draining (Figure 1). The pile driver strike rate was 10 strikes per minute.

Separate trials were carried out with the pile located at two different locations in the dock (deep and shallow; Figure 1).During each trial, simultaneous recordings of sound pressure level and particle velocity were collected along nine equally spaced transects within the dock, providing a total of 27 (9 x 3) measurement points, which was repeated at a depth of 1 m and 1.8 m (Figure1).
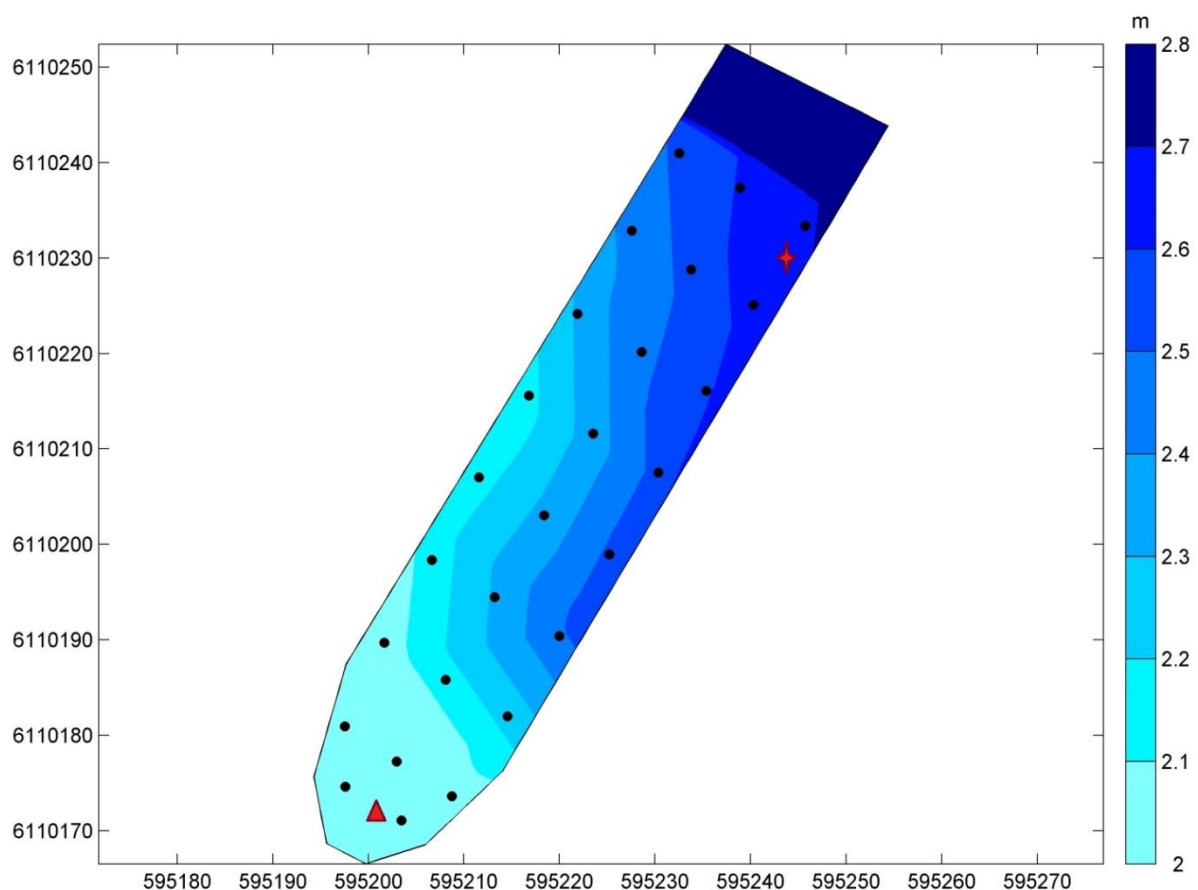
Figure 1.   Map of the shipbuilding dock. Red triangle indicates the location of the pile in the shallow side of the dock and red star indicates the location of the pile in the deep side of the dock. Black points indicate recording locations and the blue colors represent the depth of the water column. N.B. the part lacking sediment (dark blue) was not used for sound recordings.

The SEL of pressure measurements were recorded using a hydrophone (*High Tech, Inc.* model HTI-96-MIN with a sensitivity of -165 dB re 1V/μPa in the range of 2-Hz to 30-kHz). For particle velocity, a 3-axis particle motion sensor (*GeoSpectrum Technologies* model M20-PVL with a sensitivity of -87 dB/V re 1 m/s at 10 Hz, -66 dB/V re 1 m/s at 100 Hz and -42 dB/V re 1m/s at 1000 Hz) was used. Both sensors were connected to a Roland BOSS BR-800 4-channel digital sound recorder.

The hydrophone and accelerometers were deployed via a rope and pulley system with the instruments hanging at a fixed depth in the water column. This meant that the accelerometers were decoupled from the seabed and hence less likely to receive a 'ground roll' signal. However, the method of deployment was prone to additional noise being introduced from wind induced vibration and care needed to be taken to remove bad data from the recordings (described in the following section).

B. DATA ANALYSIS

Calibrated data of pressure and particle velocity for each recorded pile strike were analysed using paPAM software (version 0.87 developed by Nedelec et al., 2016) which was modified to automatically detect and process all the individual pile strikes. The calibration process took into account the sensitivity response of the particle motion sensor which was not constant across the frequency spectrum.

The recordings from each experiment were analysed to obtain the following parameters:

   A. single strike Sound Exposure Level for pressure [SEL_h] (dB re 1 μPa)

   B. single strike Sound Exposure Level for 3 axis particle velocity [$SEL_{x,y,z}$] (dB re 1 nm/s)

   C. single strike third-octave band Pressure Spectral Density of pressure [PSD_h] (dB re 1 μPa) with center frequencies of 100 Hz, 125 Hz, 160 Hz, 200 Hz, 250 Hz, 315 Hz, 400 Hz, 500 Hz, 630 Hz, 800 Hz, 1000 Hz, 1250 Hz, 1600 Hz, 2000 Hz and 2500 Hz.

   D. single strike third-octave band Pressure Spectral Density of 3 axis particle velocity (dB re 1 nm/s) [$PSD_{x,y,z}$] with center frequencies of 100 Hz, 125 Hz, 160 Hz, 200 Hz, 250 Hz, 315 Hz, 400 Hz, 500 Hz, 630 Hz, 800 Hz, 1000 Hz, 1250 Hz, 1600 Hz, 2000 Hz and 2500 Hz.

The 3-axis particle velocity data ($SEL_{x,y,z}$ and single strike $PSD_{x,y,z}$ for each third-octave band) were combined to give scalar values following the formula:

$$SEL_{xyz} = 20 log_{10} \sqrt{10^{(\frac{SEL_x}{20})^2} + 10^{(\frac{SEL_y}{20})^2} + 10^{(\frac{SEL_z}{20})^2}} \qquad (1)$$

$$PSD_{xyz} = 20 log_{10} \sqrt{10^{(\frac{PSD_x}{20})^2} + 10^{(\frac{PSD_y}{20})^2} + 10^{(\frac{PSD_z}{20})^2}} \qquad (2)$$

where SEL_x, SEL_y and SEL_z are the values of Sound Exposure Level for each direction, and PSD_x, PSD_y and PSD_z are the values of Sound Pressure Density for each direction for each third octave band.

During windy periods the measured vertical (z-axis) velocity became very large relative to the x- and y-axis velocities due to wind induced vibration in the rope and was observed to be constantly high even between the pile strikes. The data recordings were therefore visually inspected to assess the level of vertical (z-axis) particle velocity relative to the sound pressure and x- and y- axis velocities and any periods of bad data were discarded.

3. RESULTS

Out of a total of 1214 pile driving strikes recorded, only 371 were deemed to be free from wind induced noise. Of these, 116 strikes were during pile driving in the deep location and 255 strikes during pile driving in the shallow location (Figure 1). Figure 2 shows spatial maps of SEL_h (A and C) and SEL_{xyz} (B and D) at 1 m below the surface for pile driving at both locations.
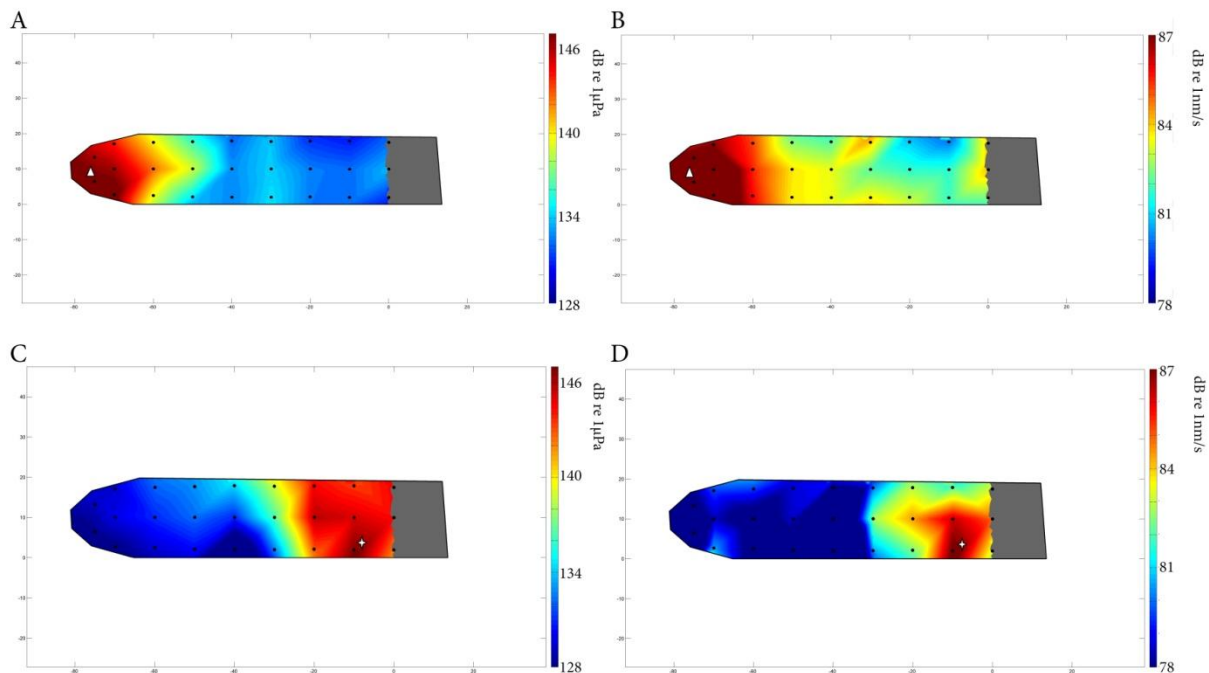
Figure 2. Spatial maps of SEL_h (A, C) and SEL_{xyz} (B, D) during pile driving at both of driving locations (white triangles indicate the location of the pile in the shallow side and white stars indicate the location of the pile in the deep side of the dock). N.B. the grey part was lacking sediment and it did not use for sound recordings.

Figure 3 shows the SEL_h versus each of the vector components SEL_x, SEL_y, and SEL_z for all recordings during pile driving at the shallow (A) and deep (B) locations.
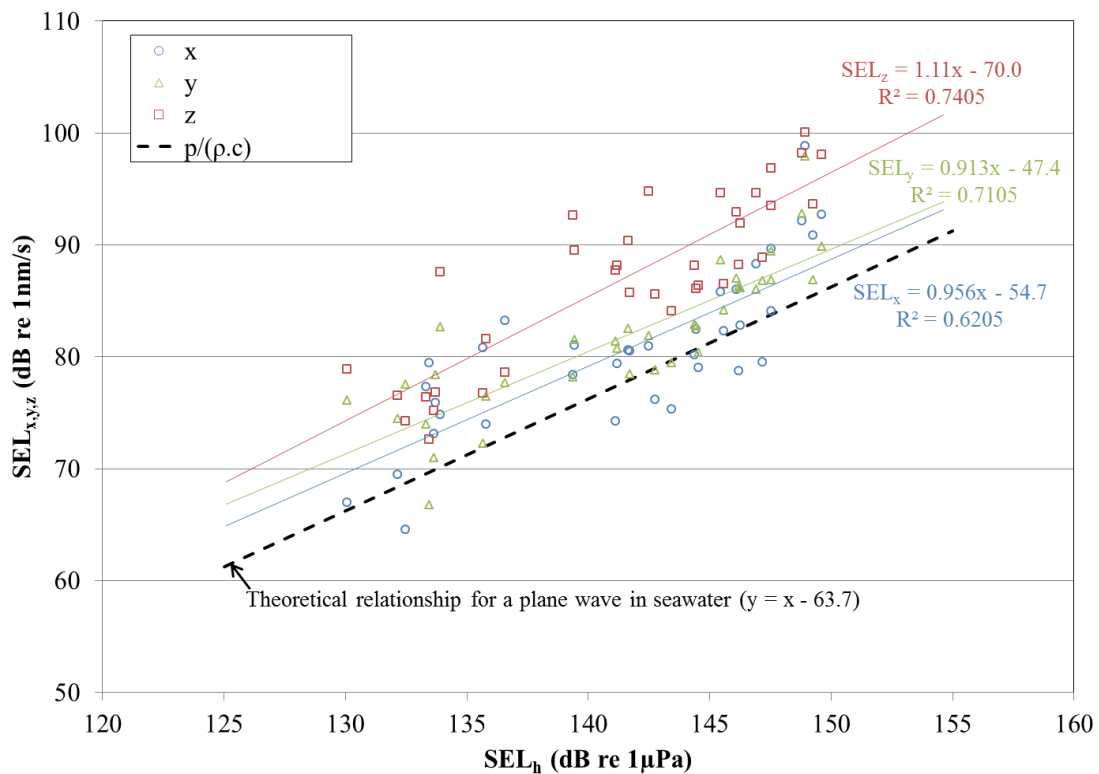

Figure 3. Scatterplot and regression lines of strike averaged SEL_h and $SEL_{x,y,z}$ at each measurement during pile driving considering both pile locations together

Significant correlations between SEL_h and each particle velocity vector component ($SEL_{x,y,z}$) were found (Table 1).

Table.1. Pearson's correlation results between SEL_h and $SEL_{x,y,z}$ for each pile locations

Pile Location			SEL_x	SEL_y	SEL_z
Deep	SEL_h	ρ	.935	.953	.766
		p	<0.001	<0.001	<0.001
		N	19	19	19
Shallow	SEL_h	ρ	.858	.875	.928
		p	<0.001	<0.001	<0.001
		N	23	23	23

Our results show that during pile driving the average SEL_h measured at a distance of 2 m from the pile driving sound source was 152 dB re 1μPa. This reduced to an SEL_h of 135 dB re 1μPa at 30 m from the pile. The reduction in sound pressure with distance is plotted in Figure 4 and a logarithmic fit to the sound pressure data show that the sound is reducing with a slope of -11.9 which is therefore close to pure cylindrical spreading (slope = 10). Also included in Figure 4 is a plot of SEL_{xyz} versus distance which has a very similar logarithmically fitted slope of -11.8. Values of SEL_{xyz} (i.e. scalar particle velocity) during pile driving were on

average 102 dB re 1nm/sat a distance of 2 m from the acoustic source, reducing to 86 dB re 1nm/s at 30 m from the pile driving source.
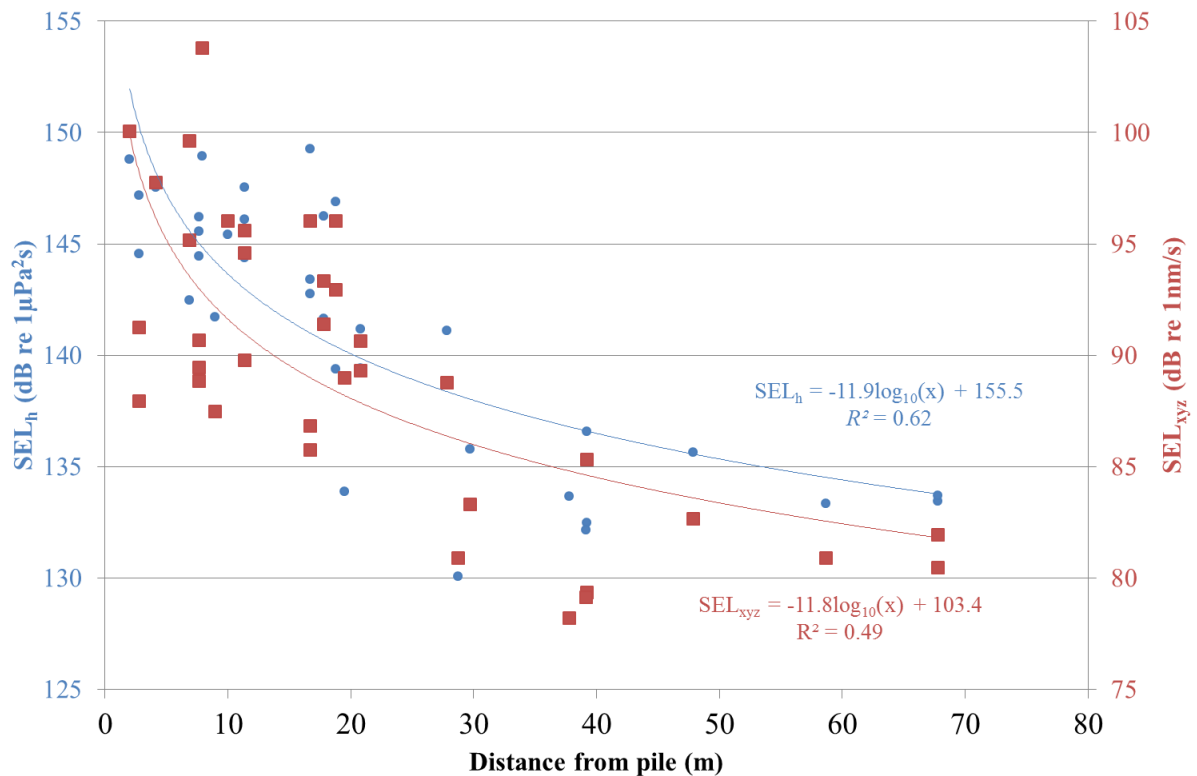
Figure 3. *SEL$_h$ (blue circles) and SEL$_{xyz}$ (red squares) during pile driving versus distance from the pile driving source (considering both pile locations together).*

The spatial pattern of the measured sound levels within the dock show a dip in sound level at between 30-40 m from the sound source which could be consistent with phase interference caused by reflections from the dock side-walls, both for sound pressure and particle motion.

Sound pressure and particle velocity showed a different frequency distribution. For sound pressure, a shallow water cut-off frequency was observed. During pile driving in the deep part of the dock, the frequency cut-off for the pressure was below approximately 300 Hz; during pile driving in the shallow part of the dock, the frequency cut-off for the pressure was below approximately 400 Hz. The frequency cut-off was independent from the distance from the sound source (Figure 5). A similar reduction in intensity at low frequencies was not observed for particle velocity (Figure 5).
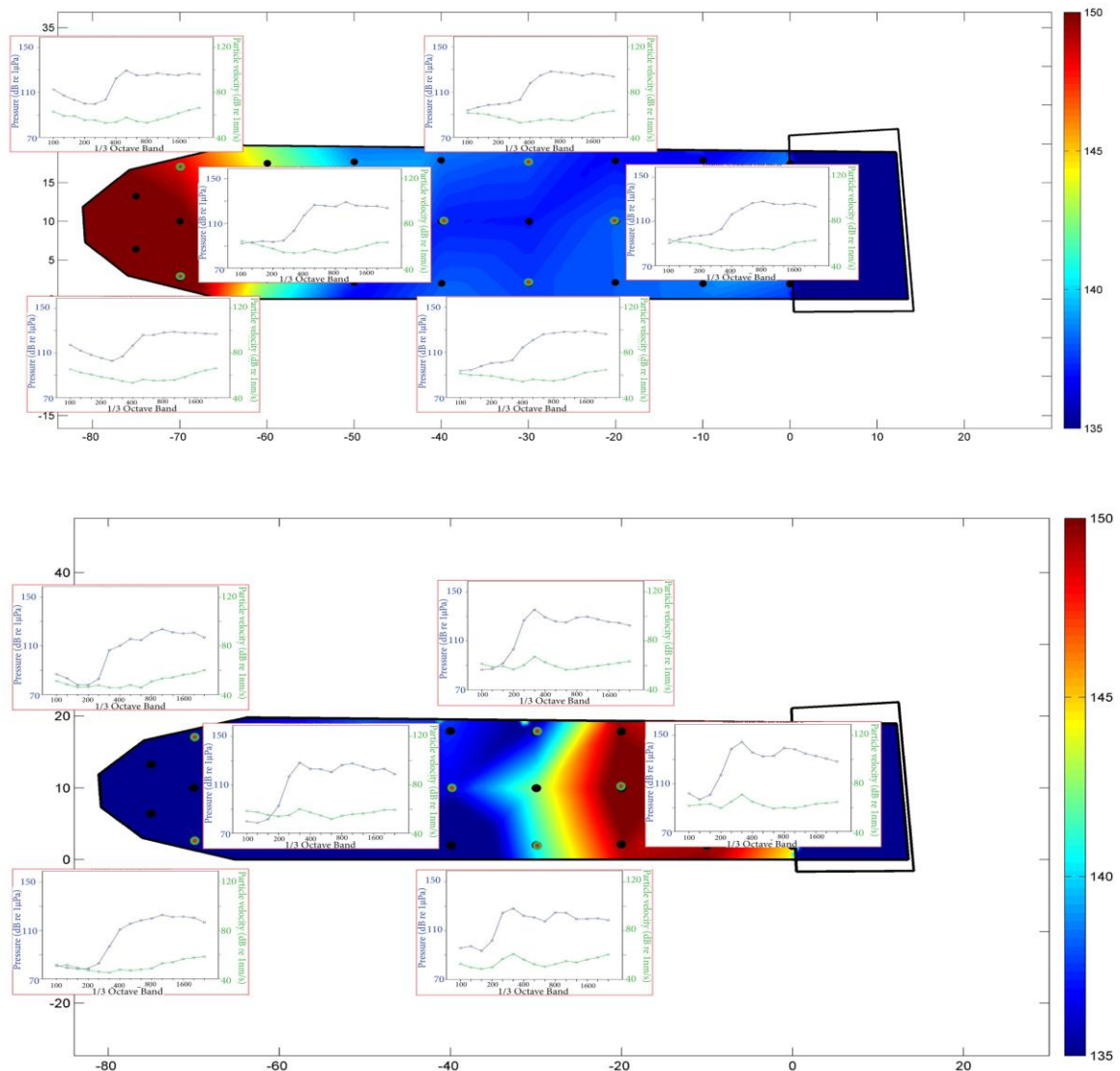
Figure 5.   Average values of single strike third-octave band PSD for SPL pressure(blue line) and particle velocity (green line) for several recording points during pile driving at the two pile driving locations (Shallow and deep ends).

The different frequency distribution of the two components is evident when considering the averaged PSD values of pressure and velocity for each 1/3 octave bands (Table 2). Considering the different cut-off frequency for pile driving at the different pile driving locations, the averaged values of particle velocity below the frequency cut-off were comparable to the averages ones measured above the frequency cut-off.

Table 2. Mean and standard deviation of pressure and particle velocity PSD calculated for 1/3 octave bands.

	Pile Location: deep end of the dock														
	100 Hz	**125 Hz**	**160 Hz**	**200 Hz**	**250 Hz**	**315 Hz**	**400 Hz**	**500 Hz**	**630 Hz**	**800 Hz**	**1000 Hz**	**1250 Hz**	**1600 Hz**	**2000 Hz**	**2500 Hz**
Mean PSD_h (dB re 1µPa)	95.5	92.1	92.2	98.9	115.9	126.1	124.7	123.8	123.6	127.4	128.3	125.6	124.9	124.6	121.8
St. Dev. PSD_h (dB re 1µPa)	12.8	13.4	14.9	17.3	20.9	14.2	9.0	6.8	7.4	6.4	4.9	5.1	4.8	4.1	4.3
Mean PSD_{xyz} (dB re 1nm/s)	62.5	60.1	58.8	57.9	61.3	64.0	60.1	58.3	56.1	57.8	58.5	59.3	71.4	72.9	72.8
St. Dev. PSD_{xyz} (dB re 1nm/s)	6.7	6.7	6.8	6.5	9.0	8.6	6.1	5.2	5.5	4.1	2.9	3.4	3.4	3.3	3.2
	Pile Location: shallow end of the dock														
Mean PSD_h (dB re 1µPa)	99.6	99.0	99.1	98.6	99.4	104.3	117.1	124.4	124.5	125.7	127.6	126.0	126.6	125.9	124.9
St. Dev. PSD_h (dB re 1µPa)	14.3	12.9	11.5	11.3	10.5	7.8	6.6	5.5	5.3	4.6	3.8	3.9	2.8	2.8	3.1
Mean PSD_{xyz} (dB re 1nm/s)	66.4	64.7	62.4	60.5	58.6	57.0	56.8	58.6	56.8	55.9	57.0	59.0	62.0	63.8	65.0
St. Dev. PSD_{xyz} (dB re 1nm/s)	5.6	5.0	4.6	4.1	4.0	3.9	3.1	3.6	3.0	2.9	2.3	2.9	1.7	1.8	2.1

Possible reasons for the relatively large values of particle velocity at the low frequencies could be due to the presence of ground roll waves or noise induced by wind induced waves and/or vibrations of the instrument cables. This is highlighted by the fact that the vertical velocities are by far the largest as shown in Figure 3. To highlight this further, the maximum, minimum and mean relative magnitudes of the measured particle velocity to the theoretical particle velocity compared with that for a theoretical plane wave are shown in Table 3.

Table 3 Ratio of the measured particle velocity versus that of a theoretical plane wave

Velocity component	Max ratio	Min ratio	Mean ratio
x-axis	1.5	0.6	4.8
y-axis	1.7	0.7	4.3
z-axis	3.5	1.2	9.9

4. DISCUSSION

In this study, measurements were taken to try to determine the relationship between sound pressure and particle velocity in a very shallow and enclosed environment. The results show

that the relationship between the two components is approximately linear, as theory suggests, but the recorded values of particle velocity are generally larger than expected, particularly for the z-axis velocity which is shown to have a magnitude of 1 to 10 times (average 3.5) that of the theoretical velocity for a plane wave at the same sound pressure (See Table 3). The horizontal (x and y) components of velocity were both between 0.6 and 4.8 (average 1.6) times the velocity predicted for a plane wave.

The large vertical velocities were predominantly at low frequencies (<400Hz) at which sound pressure was reduced due to low-frequency cut-off caused by the shallow depths. This might therefore be accounted for by the presence of ground roll waves as described by Hazelwood and Macey (2016). However, the instruments in the current study were not mounted on the bed, so we expected a less pronounced ground roll, although still present in the water column to some degree. Some of the additional vertical particle velocity could be caused by wind induced water waves or vibrations in the instrument cables. During the experiment, indeed, periods of strong wind showed significant increases in the z-component of velocity, making many of the measurements unusable. Although the noisiest data were removed from the analysis it cannot be ruled out that some of the particle velocity values are affected (increased) due to the presence of low level wind induced velocities.

Therefore, for understanding the relationship between sound pressure and particle motion we suggest the strong need to obtain noise-free measurements by isolating the pile driving component in order to verify the effect of its noise on the z-axis.

3. REFERENCES

Biagi, F., Gambaccini, S. and Zazzetta, M. (**1998**)."Settlement and recruitment in fishes: The role of coastal areas," Ital. J. Zool.**65**, 269–274.

Chapman, C.J., and Hawkins, A.D. (**1973**). "A field study of hearing in the cod, *Gadus morhua* L.," J. Comp. Physiol.**85**, 147-167.

Fay, R. R. (**1984**). "The goldfish ear codes the axis of acoustic particle motion in three dimensions," Science **225**, 951–954

Filiciotto, F., Vazzana, M., Celi, M., Maccarrone, V., Ceraulo, M., Buffa, G., Arizza, V., deVincenzi, G., Grammauta, R. andBuscaino, G. (**2016**). "Underwater noise from boats: Measurement of its influence on the behaviour and biochemistry of the common prawn (*Palaemon serratus*, Pennant 1777)," J. Exp. Mar. Biol. Ecol.**478**, 24-33.

Harris, G.G. (**1964**)."Considerations on the physics of sound production by fishes,"In: *Marine bio-acoustics*, edited by W. N. Tavolga (Oxford: Pergamon Press),pp. 233-247.

Hazelwood and Macey (**2016**). "Modeling Water Motion near SeismicWaves Propagating across a Graded Seabed, as Generated byMan-Made Impacts",J. Mar. Sci. and Eng.,4, 47Lugli, M., and Fine, M.L. (**2007**). "Stream ambient noise, spectrum and propagation of sounds in the goby *Padogobius martensii*: Sound pressure and particle velocity," J.Acoust. Soc. Am.**122**, 2881-2892.

Nedelec, S.L., Campbell, J., Radford, A.N., Simpson, S.D., and Merchant, N.D. (**2016**). "Particle motion: the missing link in underwater acoustic ecology," Meth. Ecol.Evol.**7**, 836-842.

Offutt, G.C. (**1974**). "Structures for the detection of acoustic stimuli in the Atlantic codfish, *Gadus morhua*," The J.Acoust.Soc. Am. **56**, 665-671.

Picciulin, M., Sebastianutto, L., Codarin, A., Farina, A., and Ferrero, E. A. (**2010**). "In situ behavioural responses to boat noise exposure of *Gobius cruentatus* (Gmelin, 1789; fam. Gobiidae) and *Chromis chromis* (Linnaeus, 1758; fam. Pomacentridae) living in a Marine Protected Area,"J. Exp. Mar. Biol. Ecol.**386**(1), 125-132.

Popper, A.N., Salmon, M., and Horch, K.W. (**2001**). "Acoustic detection and communication by decapod crustaceans,"J. Comp. Physiol. A**187**, 83-89.

Radford, C.A., Montgomery, J.C., Caiger, P., and Higgs, D.M. (**2012**). "Pressure and particle motion detection thresholds in fish: a re-examination of salient auditory cues in teleosts,"J. Exp. Biol.**215**, 3429-3435.