RECORDING AND ANALYZING UNDERWATER NOISE DURING PILE DRIVING FOR BRIDGE CONSTRUCTION

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ABSTRACT

Underwater sound generated by pile driving was recorded during the Hong Kong-Zhuhai-Macau Bridge (China) construction in 2014. The important parameters on the source level, the transmission loss, the time-frequency characteristics and the method of the noise measurement were introduced in this paper. Signal analysis showed the waveform of pile driving resembles a series of short pulses, composed of many different frequencies with main frequency energy distribution from 100Hz to 2kHz; the maximum value occurs at about 200Hz. The best-fit shallow water sound propagation model gave a root-mean-square source level of 208.2dB re 1μPa at 1m, a transmission spreading coefficient of 17.76, and an absorption coefficient of 0.015dB/m. The value of transmission loss is in good agreement with the results calculated by the Marsh and Schulkin (M&S) semi-empirical expressions above 1kHz, but is higher than the M&S results under 1kHz, which may be due to the muddy seabed and turbid sea water in our study area. Although it is difficult to compare our research results with other studies as there is a lack of details on monitoring conditions (including pile size, hammer energy, environmental background etc.), this paper provides a new method for underwater noise monitoring and analysis for pile driving in shallow water.

INTRODUCTION

The Hong Kong-Zhuhai-Macau Bridge (HZMB) is currently being built over the waters of Pearl River Estuary (PRE) in Southern China. Upon completion in 2019, the 48-kilometer-long bridge will provide a significant boost to the economy in the region. There is, however, growing concern for two species of marine mammal that reside in these waters, namely Indo-Pacific humpback dolphins (*Sousa Chinensis*) and Finless Porpoise (*Neophocaena Phocaenoides*) [1, 2]. The underwater noise generated by pile driving into the seabed during the bridge construction can affect the ability of these marine mammals to locate their prey and communicate with each other. It is believed that the noise may even result in physical damage to their tissues and organs, which can be potentially fatal [3].

In the marine environment, pile driving produces some of the most intense anthropogenic noises [4]. Both vibratory and impact pile drivers

are widely used during the HZMB pier construction. The vibratory pile driving is used in soft substrates at the beginning of pile driving, so its sound level is lower than the impact pile driving. In hard stratum, the impact pile drivers are used, which produce transient discontinuous sound waves (called pulses). A stress wave in the pile propagates downward due to the hammer striking the pile. This wave couples with the water and substrate, radiating sound energy into the medium [5].

Knowledge of the source level and transmission loss from impact pile driving during bridge construction will allow the prediction of how far the man-made noise could affect the marine mammals. This process depends on many factors, such as the type of pile, the hammer size, characteristics of the water, the sediment and so on [6]. Although much research has been done on the underwater noise of impact pile driving, there are still no unified methods and conclusions. In this study, we recorded and analysed the underwater noise of impact pile

driving during HZMB construction.

METHODS

Equipment and field procedures

Six steel pipe piles (two rows and three columns) were driven for each pier of HZMB, and the new bridge would require thousands of the piles. We recorded the pile driving noise of the first two piles at pier 101 (CB04 Tenders, 2014.05.03), see Figure 1. The pier 101 is at N 22°15.953', E 113°41.227'. The outer diameter of the pile is 2m and wall thickness is about 2.5mm. The pile length is 73m and the pile was driven to about 60m below the seafloor. The pile was driven by a hydraulic impact hammer MHU-800 (17m length, 110t weight, 800kJ maximum energy).

Figure 1 (a) Photo of pile driving platform (left) and monitoring boat (background right), (b) The photo of HZMB pier 101, which shows the final distribution of the six steel pipe piles.

Two sets of different acoustic loggers were used to record the underwater noise from the pile driving.

(1) Three hydrophones model 8105 (Brüel & Kjær Inc. from Denmark, voltage sensitivity 55.6 μ V/Pa, 46.6 μ V/Pa, 47.5 μ V/Pa respectively) connected to multi-analysis platform Pulse (Brüel & Kjær Inc. from Denmark).

(2) One hydrophone model 8104 (Brüel & Kjær Inc. from Denmark, voltage sensitivity 47.5 μ V/Pa) was connected by a 10m cable to a data acquisition board model 6062E (National Instruments Inc. from the US, 12-bit resolution).

In order to make sure the recording was accurate, both data acquisition systems and hydrophones were calibrated. The hydrophone frequency response from 10Hz to 10kHz is flat, which is suitable to the frequency of the noise from pile driving operations. Both loggers were configured with a sampling rate at 65536Hz, to allow analysis up to 32768Hz. Anti-heavy buoy was used to ensure that flow noise over the hydrophone would not influence the measurement.

Each measurement distance and location was identified by GPS and laser rangefinders, and the relative error was less than 5%. Wind direction and force was south east, Beaufort force 4 and sea state about 2. Previous geophysical studies showed that the seabed of the pile driving site is nearly flat, and the water depth can vary from about 4m to 7m mainly depending on the tide [7]. When we performed the measurement, the local water depth was about 6m. The sediment mostly in the piling area contains mud after sampling cores. The sound speed profile (SSP) was measured many times near the piling site and a typical curve is shown in Figure 2. SSP varies slightly in different depths, and the shift is less than 0.5m/s. Because the wind blows across the surface above, the sound speed first increases with the hydrostatic pressure in isothermal water and then falls with the temperature decrease. So this shallow water contains a weak mixed layer at the depth of 1m or so, where maximum value of sound speed occurs.

Figure 2. Sound speed profile (SSP) of the studied water was measured by HY1200 (Haiying Inc., from China) near the construction site and the maximum of the sound speed was marked in the textbox.

Measurement process

Both fixed position monitoring and floating recording methods were used in our research. The

process is shown in Figure 3. There was a pile carrier at the side of the pile driving ship. E and F on the pile carrier were regarded as the fixed positions, and $P_1E=50m$, $P_1F=100m$. The B&K Pulse shown in equipment (1) was provided at point E and three hydrophones were deployed at 1m, 4m and 5m depth from the sea surface respectively.

Figure 3. Measurement process.

Boat-M was mobile, which was used to move from location to location. We measured pile P1 at the distance of $P_1A=1000m$ and $P_1B=300m$ from the pile front, while pile P2 at the distance of $P_2C=200m$ and $P_2D=500m$. Both Boat-M and point F were provided with NI 6062E shown in equipment (2) and placed the hydrophone at 4m depth from the surface. For each recording site, underwater noise from pile driving was recorded in no less than 3 minutes.

Sound propagation model

Sound propagation as a function of distance is described by the sonar equation:

$$RL = SL - TL \quad (1)$$

Where RL (received level) is the SPL (sound pressure level) at a certain distance from the source, SL (source level) represents the SPL at 1m from the source, and TL (transmission loss) can be calculated by the equation:

$$TL = N \log_{10}(r) + \alpha r \quad (2)$$

Where N is spreading loss coefficient and α is absorption coefficient in dB/km. Plug (2) into (1) and use Curve Fitting Tools in Matlab (2013b, Mathworks Inc. from the US) to calculate TL, then N and SL can be calculated [8].

RESULTS

Time domain characteristics

It took about 2 hours to finish each pile-drive process, including about 40 minutes impact pile driving. The underwater noise from impact pile driving behaves as a series of pulses, each pulse representing a strike on the pile. Figure 4 illustrates a typical pressure time history for a 0.3s period of pile driving.

Figure 4. Time domain waveform for one pulse of pile driving at distance of 50m.

The time history was recorded at the distance of 50m from the pile driving, at the depth of 4m. There is one individual strike in the period, in which the sound pressure rises very rapidly to a maximum positive pressure (about 2.5kPa), and a negative value of just over the same value. There follows a period of decaying oscillatory pressure. The strike duration is about 0.2s. The peak pressure level of this wave is about 188 dB re 1 μ Pa.

Noise recordings were made at 200m, 300m, 500m, and 1000m distance from the pile (Figure 3). Figure 5 shows three individual pile driving strikes (about 3.1s) at the four monitoring sites. As the distance from the pile increases, the sound pressure decreases from 1kPa to 100pa and the waveform duration increases.

By endpoint detection of double-thresholding, the time interval between two pulses is 1.7s or so ($sd=0.093$), depending on the required penetration depth of the pile and the seabed, so there were more than 1200 individual pile driving strikes for each pile. K=300 strikes with high quality (strikes without transients or other spurious data by visual check for time history) at each distance were chosen to be analyzed, and results are summarized in Table 1.

All sound levels, including peak levels (SPL_{peak}), root-mean-square levels (SPL_{rms}), and sound exposure levels (SEL), were computed on a linear scale before converting to dB units. Peak levels are the highest, followed by rms levels, and sound exposure levels are the lowest.

Figure 5. Time domain waveform for three pile driving pulses at distance of (a)200m, (b)300m, (c)500m, (d)1000m

Table 1. Noise level summary at different distances, including maximum, mean and minimum for SPL_{peak} , SPL_{rms} and SEL. K=300

pile NO.	start time	distance (m)	SPL_{peak} (dB)			SPL_{rms} (dB)			SEL (dB)		
			min	mean	max	min	mean	max	min	mean	max
101-P1	14:14	1000	157.1	166.2	171.2	132.0	139.6	143.3	131.6	133.1	135.1
	15:30	300	173.4	180.0	190.6	146.2	156.7	160.6	145.9	149.2	151.1
101-P2	17:38	500	170.7	179.0	183.7	149.1	154.8	172.4	147.5	149.7	166.4
	18:13	200	169.2	187.1	190.6	149.7	165.8	173.7	145.2	154.4	167.5

Frequency domain characteristics

Figure 6 illustrates the 1/3-octave band PSD of pile driving noise at fixed positions E and F over a period of 2 minutes (about 50 pulses), and 2 minutes background noise recorded at 1km when no pile driving was occurring. It can be seen that most of the energy of the noise is between 100Hz and 2 kHz. In the whole frequency band the levels of piling noise are appreciably higher than the background noise.

A spectra comparison at different depths is shown in Figure 7. The pile driving noise was recorded at the same distance of 50m (namely site E), and about 200 piling stroke pulses at the three depths (1m, 4m and 5m) simultaneously were chosen to be analyzed. The curves are almost the same over 600Hz. The spectral levels of 4m and 5m are generally in the order of 10dB above those of 1m

over a narrow frequency range from 60- 600Hz, and all of these three spectra have a peak level at about 200Hz, which may be related to the natural frequency of the pile and pile driving platform.

Figure 6. 1/3-octave band PSD of pile driving noise at fixed positions E and F, and a background noise recorded at 1km when no pile driving was occurring. Recording of the background noise were made with a Brüel & Kjær 8104 hydrophone, sampling at 65536Hz, deployed at a depth of 4m.

Figure 7. 1/3-octave band PSD of pile driving noise at the fixed position E, and the hydrophones were deployed at 1m, 4m and 5m depth.

The PSD of floating recording pile driving noise are shown in Figure 8. The 300 strikes as described in the previous section were analyzed. It can be seen that the frequency content falls as the distance from the pile increases. At 1000m, the levels have decreased significantly. High frequencies were rapidly attenuated with distance.

Figure 8. 1/3-octave band PSD of pile driving noise at 200m, 300m, 500m and 1000m distances from the pile being driven.

Source level and propagation model

We used the mean SPL_{rms} at four different distances from the pile to estimate the source noise level and propagation model with formula (1) and (2). The surrounding water in which piles are placed is only a few metres deep, hence sound loss will be individually or cumulatively affected by the sediment and overlying water. So absorption losses cannot be ignored when we analyze sound propagation in the shallow. Using rms noise measured during impact pile driving for HZMB construction works, a best-fit regression model is given as:

$$RL = 208.2 - 17.76 \log_{10}(R) - 0.015R \quad (3)$$

The results can be displayed as Figure 9. It may be seen that the fitted curve is more like a straight line at distances within 300m or so and then it dives down away from the straight line. This indicates that the levels predicted at long ranges are considerably reduced.

Figure 9. Propagation model fitted to root-mean-square noise at four distances during pile driving operations.

As for the short ranges, the sound propagation is complex. Seeing Figure 6, it is incorrectly thought that the sound energy weakens linearly with

the distance. Based on formula (3), the SPL_{rms} at 50m and 100m can be extrapolated. These values can then be compared to the measurements at locations E and F. The results in Table 2 illustrate that nonlinear attenuation pulses appeared at the near field (not the sound field). It is noteworthy that the sites E and F are not on the same measurement line with sites A, B, C and D. Because of different bathymetry, seabed etc., the sound propagation is influenced by the water sound channel of different directions.

Table 2. Compared SPL_{rms} from extrapolated values from the propagation model and measured values at distances of 50m and 100m

distance (m)	extrapolated value (dB)	measured value (dB)
50	177.3	171.0
100	171.2	162.2

DISCUSSION

Examples of comparisons with other studies

Lots of impact pile driving measurements and analyzes have been done in the past [5, 6, 7, 9, 10, 14, 15], but are lacking the details of the pile driving process and/or using different equipment or software, which makes the results difficult to compare with each other. We have tried to select the piling studies with as much details as possible to describe the pile driving conditions for HZMB construction (Table 3).

In [9], SPL_{rms} of 194dB and 175dB were observed at ranges of 57m and 1850m respectively during the pile driving of a 2m diameter, 65m long test pile, using a 800kJ hydraulic hammer. Our results are SPL_{rms} of 188dB and 140dB at 50m and 1000m respectively. Although the pile driving conditions of Robinson, et al. including stroke energy and pile size are very similar with our studies, their results of SPL_{rms} are significantly higher than ours. That is caused by different conditions, for example the sediment mainly contains chalk seabed,

the pile driving operation occurs in the 8m to 15m deep UK coastal water.

In [10], hollow steel piles (2.4m outer diameter), hydraulic piston hammer (900kJ maximum energy) driven, can produce $SPL_{peak}=207dB$ at 108m and $SPL_{peak}=191dB$ at 358m. While we recorded mean $SPL_{peak}=193dB$ at 100m and mean $SPL_{peak}=180dB$ at 300m. Here, our measurement ranges (200m and 300m) are between 108m and 358m. The pile size of Reyff is larger and the hammer was heavier than ours during the HZMB construction. This indicates that the pile size and blow energy may play an important role in making underwater noise.

Table 3. Comparison with other studies

	SPL_{rms}	SPL_{peak}
Robinson, et al. [9]	194dB@57m, 175dB@1850m	—
Reyff [10]	—	207dB@108m, 191dB@358m
This study	188dB@50m, 140dB@1000m	193dB@100m, 180dB@300m

The two examples above suggest that it is hard to compare the pile driving noise for different projects, because the piling conditions are not identical. The results of this study may be only meaningful to the same pile driving operation as the HZMB. However, the new monitoring and analyzing method for underwater noise in shallow water will have some promotional practical values for pile driving in marine and offshore engineering construction.

Transmission loss

In travelling through the sea, an underwater sound signal becomes delayed, distorted and weakened [8]. The measured data directly fits the above propagation model. The model indicates a rms source level of 208.2 dB re 1μPa at 1m, for the impact pile driving operation during the HZMB project, with a geometric spreading loss factor of 17.76 and an absorption coefficient of 0.015 dB/m.

Spreading loss: the pile driving pulse becomes elongated by multipath effects and spreads out with

time as it travels in range [8]. Considering the close coupling between bottom loss and sound energy in the overlying water, the sound cannot cross the upper and lower bounds in this very shallow water. The kind of spreading is called cylindrical spreading.

Absorption loss: the acoustic energy converts into heat in the process of absorption loss. The ionic relaxation mechanism, together with shear viscosity, is the main reason causing the absorption of sound in the sea [11], which is affected by the sound frequency. By the experimental results in Figure 8 and polynomial fit technique, absorption coefficient of different frequencies can be obtained. Combined with the spreading loss at different distances, namely $17.76\log_{10}R$, we can get the TL as per formula (2) with the measured value.

Meanwhile, the semi-empirical expressions published by Marsh and Schulkin in 1962 [12] can roughly predict the TL in shallow water. A skip distance in kyd is defined as (4) for water depth and layer depth L in feet.

$$H = \left[\frac{1}{8} (D+L) \right]^{\frac{1}{2}} \quad (4)$$

Based on the bathymetry and SPP mentioned earlier, $D=6m$ and $L=1m$. After unit conversion and calculation, the skip distance of H is 1549.4m. The range R between the source and receiver that was measured in our work is less than H. Therefore, according to the M&S equation, the estimated TL can be shown as (5).

$$TL = 20\log_{10}(R) + \alpha R + 60 - k_l \quad (5)$$

Where k_l is a “near-field anomaly” depending on sea state and bottom type, and we get k_l in table lookup methods. The absorption coefficient α is calculated as proposed by Thorp, et al. [13].

At the frequencies of 0.2kHz, 0.4kHz, 0.8kHz, 1kHz, 2kHz, 4kHz, 8kHz and 10kHz, mentioned by [12], the measured and estimated TL varying with distance R can be obtained by fitting curves to measured data (Figure 10).

Figure 10. Comparison between the measured results and estimated values: TL in dB.

Table 4. Statistical comparison of measured and estimated values

statistics \ f (kHz)		0.2	0.4	0.8	1	2	4	8	10
absolute difference	max	31.697	16.104	27.987	29.689	6.516	1.192	4.348	4.322
	min	4.420	3.028	3.835	3.794	0.463	→0 ^{a)}	0.002	0.001

	(max-min)/ max	0.8606	0.8119	0.8630	0.8722	0.9290	0.9999	0.9996	0.9997
Euclid distance		641.60	328.83	564.34	596.36	118.56	21.30	68.24	68.06
correlation		0.9827	0.9903	0.9842	0.9835	0.9954	0.9984	0.9960	0.9964

a) Approaching to zero, the min of absolute difference is very tiny at 4kHz.

In order to show the comparison clearly, some statistics about curve similarity are studied (Table 4). After subtracting the ordinate values of the two curves and changing into absolute values, the difference between estimated TL and measured TL can be calculated (see the dotted red line in Figure 10). Table 4 summarizes the min, max, and normalized difference. Moreover, the similarity of the two curves is also verified by Euclid distance and correlation coefficients.

According to the absolute difference statistics and Euclid distance, it appears that the estimation values are all lower than the measured results when the frequency of the pile driving noise is not greater than 1kHz, and the measured values of TL agree well with the estimated ones at the higher frequencies. The correlation coefficients were close to 1. So the estimated and measured derivative values have the similar change tendency, namely the nearer the distance from the pile, the smaller the TL will be, and vice versa.

The comparison between our measurement and the empirical estimation reported here suggests that the measured TL of pile driving noise in the shallow water at frequencies below 1kHz is higher than the TL at high frequency. Frequencies play an essential role in calculating the TL for pile driving in the shallow water. The measurement below 1kHz is more vulnerable to marine environment, which may be due to the low-frequency noise absorbing easily in the muddy seabed and scattering loss increasing in the turbid sea water of RPE [8].

The underwater noise source generated by pile driving is a very complicated source, as it's not a monopole source. The geometrical spreading model used in our research may not provide accuracy to pile driving operations in other seas. The present authors are currently trying to find a more efficient

way such as finite element, wave-number integration etc. to deal with this issue.

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