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FINAL REPORT

Noise Field Characterization in the Habitat of the East Taiwan Strait Indo-Pacific Humpback Dolphin during the Pile Driving Activity of Demonstration Offshore Wind Farm

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INTRODUCTION

The Eastern Taiwan Strait (ETS) population of Indo-Pacific humpback dolphin (*Sousa chinensis*) is listed critically endangered in the Red List of Threatened Species by the International Union for Conservation of Nature, due to its small population size and narrow distribution (Reeves et al., 2008). The range of the ETS Indo-Pacific humpback dolphin is limited to within 3 km from shore in waters of depth less than 15m off the west coast of Taiwan, along an approximately 200 km stretch of coastline between Longfeng Fishing Port in Miaoli and Jiangjun Port in Tainan (Chou, 2012). Since 2008 its estimated population has declined from 75 to 64 individuals (Kuo, 2013). A number of threats and environmental stressors that contribute to the decline of this population have been suggested. These include coastal development, habitat degradation, fisheries impacts, and underwater noise from shipping activities (Ross et al., 2010). In addition, the humpback dolphin habitats off the coast of Miaoli and Changhua are sites selected for future wind farms (Fig. 1), which include the installation of 34 (Miaoli) and 28 (Changhua) wind turbines before 2020. The proposed offshore wind farm projects are very close to the Major Wildlife Habitat of humpback dolphins (Fig. 1), therefore, the noise impact of pile driving on this critically endangered population could be serious.

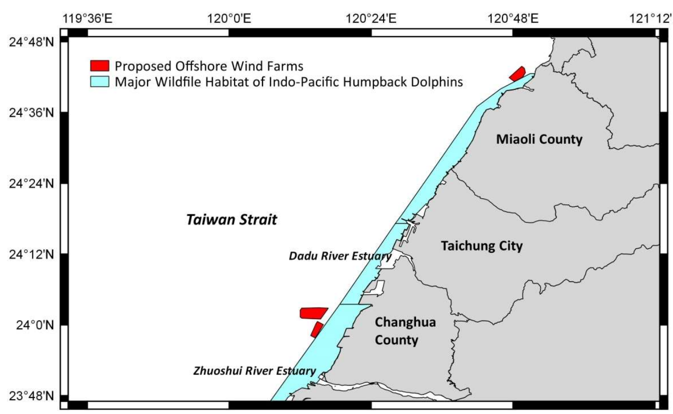

Figure 1. Map of the Major Wildlife Habitat of Indo-Pacific humpback dolphins and the three proposed offshore wind farms in western Taiwan waters.

Vessel noises are known to increase overall ambient noise levels (Urick, 1983). A recent study on the dynamics of the soundscape of the ETS Indo-Pacific humpback dolphin habitat showed that croaker choruses were the dominant source within the dolphin's hearing and vocal frequency ranges, but not vessel noises because their much lower frequencies (150-300 Hz) (Guan et al., 2015a) are well below the most sensitive hearing ranges as measured for other dolphin species. The vessel noises ETS Indo-pacific white dolphins face are different from those reported in other region with large numbers of small outboard engine boats, of which dominant frequency is in higher frequency regime (e.g., Wang et al., 2016). Therefore, under the current baseline conditions, noises from cargo ships transiting the vicinity of the humpback dolphin habitat are not likely to affect the dolphins due to its low received levels and low frequency content (Guan et al. 2015a). However, with the upcoming in-water pile driving and other activities related to the wind farm construction, the soundscape of the ETS Indo-Pacific humpback dolphin is expected to change dramatically.

Intense noises from impact pile driving have shown to cause temporary hearing threshold shift (TTS) to marine mammals at close range (Kastelein et al., 2015). At a distance that is considered safe from TTS, noises from both impact and vibratory pile driving are still at high levels (Erbe, 2009; Dahl et al., 2015) that could induce behavioral disturbances to marine mammals (Kastelein et al., 2013). Furthermore, the increase in background sound levels and the shift of soundscape dynamics from anthropogenic noise input associated with the construction activities could lead to other adverse effects (e.g., acoustic masking) to marine mammals. Unfortunately, there are no in situ measurements on noise sources from these potential activities that can be used for a site-specific environmental impact analysis in the case of the ETS Indo-Pacific humpback dolphin, and there is no study planned to measure these sources before the full scale wind farm construction starts in 2017. Therefore, we consider it urgent to collect these data during the 2016 demonstration wind turbines construction and conduct research on potential impacts on the soundscape of the humpback dolphin.

The objectives of this study were to (1) characterize the sound field during demonstration pile driving and associated activities in the humpback dolphin habitat, including distances associated with various received sound levels and inter-pulse sound field; (2) identifying dominant anthropogenic sound sources in the dolphin habitat during the construction of demonstration wind turbines and associated activities; and (3) examining the implications of the sound field from wind turbine construction and associated activities in relation to humpback dolphins' hearing and communication, including loss of communication space and masking. The results from this study provide foundational information and conservation recommendations for an environmental impact analysis for the full scale wind farm construction in 2018.

Since this research proposal was developed, the National Marine Fisheries Service (NMFS) released a regulatory guidance on assessing auditory injury on marine mammals from underwater noises (NMFS, 2016). The guidance is based on the U.S. Navy's impact assessment report (Finneran, 2016), in which marine mammal species are divided into six hearing groups based on their auditory sensitivity towards different frequency bands and provides several levels of auditory impact thresholds based on exposure to noise at different received levels. Hearing impairments addressed in the report include temporal hearing threshold shift (TTS), which is the temporary (and recoverable) reduction of hearing sensitivity at certain frequencies after noise exposure, and permanent hearing threshold shift (PTS), which is the permanent (and non-recoverable) reduction of hearing sensitivity at certain frequencies after noise exposure. In addition, dual criteria are used to assess the onset of the threshold shift: a pressure-based peak sound pressure level (SPL_{pk}) and an energy exposure-based sound exposure (SEL) metric. For the SEL metric, a frequency weighting function is incorporated to address hearing sensitivity. The NMFS guidance does not define TTS in its exposure guidance, while for the SEL metric for PTS, it uses a 24-hour cumulative energy exposure with the Navy's frequency weighting function.

In NMFS noise exposure guidance, the Indo-Pacific humpback dolphin is classified as a mid-frequency cetacean species. The TTS onset thresholds for mid-frequency cetacean when exposed to impulse sounds are 179 dB re 1 μPa^2-s (SEL) and 224 dB re 1 μPa (SPL_{pk}), and the PTS onset thresholds are 185 dB re 1 μPa^2-s (SEL) and 230 dB re 1 μPa (SPL_{pk}). To further analyze the potential noise impacts to the Indo-Pacific humpback dolphin, received levels at various distances from the source were computed in accordance to NMFS' noise exposure guidance.

METHODS

I. Pile Driving Activities and Locations

In September 2016, two demonstration monopiles were installed by impact pile driving off the coast of Miaoli (Turbines #21 and #28, Fig. 2). These monopiles are both made of steel piles of 5.8 meters diameters, and the lengths are 65.18 m for #21 and 73.78 m for #28. The monopile for Turbine #21 is located at 24°41’35.75”N, 120°49’1.54”E, approximately 2 km from shore; and the monopile for Turbine #28 is located at 24°41’27.45”N, 120°48’24.2”E, also approximately 2 km from shore. The substrate of both pile driving sites are sand.

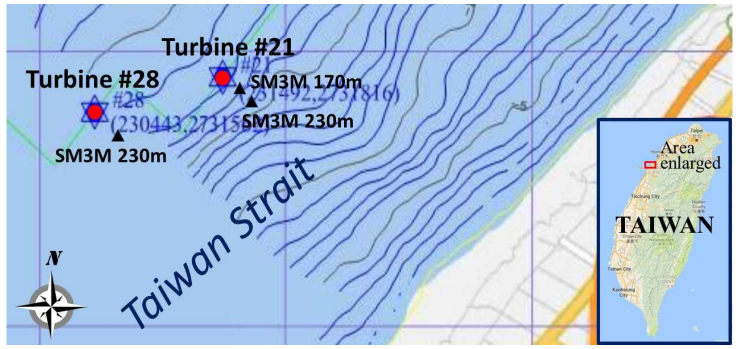

Figure 2. Map of the demonstration pile driving sites for the two wind turbine monopiles and locations where SM3Ms were deployed for ambient and pile driving noise measurements off Miaoli in the west coast of Taiwan.

Pile driving for Turbine #21 started at 20:20 on 3 September 2016 and completed at 10:10 the next morning. Pile driving was conducted intermittently throughout this period. Pile driving started with trial strikes with a total of 431 strikes during the first hour. By midnight it logged 1,826 strikes. Pile driving paused between midnight and 04:00. Pile driving resumed at 04:00 but stopped 30 minutes later after 409 strikes. Pile driving resumed again at 08:00 and continued until finish at 10:10 with a total of 2,522 strikes. The entire pile driving took approximately 14 hours with a total of 4,757 strikes with 1.9 hours of actual pile driving.

Table I. Specification of the SM3M bottom-mounted acoustic recorders used for ambient noise and pile driving noise recording.

Dimension & weight	Diameter: 16.5 cm; length: 79.4 cm; weight: 9.5 kg
Power	32 AAA batteries
Acoustic channels	2
Sampling rate	44.1 kHz
Data storage	8-128GBSDHC or 512GBSDXC at 16 bits
Max. depth	150 m
Hydrophone sensitivity	Nominal: -165 dB re 1 V/μPa High-sensitivity: -240 dB re 1 V/μPa
Gain	0 – 12 dB
Data format	.wav

Pile driving for Turbine #28 started at 12:30 on 7 September 2016. Pile driving was also conducted intermittently throughout this period, but it took less time compared to pile driving for Turbine #21. A total of 1,463 strikes were logged by 14:00 before pile driving was paused till 15:15. Pile driving resumed at around 15:15 and finished by 17:15. The entire pile driving took approximately 5 hours with a total of approximately 3,778 strikes with 1.4 hours of actual pile driving.

II. Acoustic Sampling

Underwater acoustic recordings were collected before, during, and after impact pile driving using one bottom-mounted digital acoustic recorder and one shipboard acoustic sensor.

The bottom-mounted acoustic recorders is the Submersible Long-term Passive Recorder SM3M by Wildlife Acoustics (Concord, MA). Each SM3Ms are equipped with two hydrophones with sensitivities of -165 dB re 1 V/µPa and -240 dB re 1 V/µPa. The system has gains between 0 and 12 dB and operates at a sampling frequency of 44.1 kHz. Detailed specifications of the bottom-mounted SM3M recording systems are shown in Table I. The SM3M recorders were secured in custom-made metal frames and were deployed on seabed (Fig. 3) for continuous recording. During the passive acoustic monitoring for pile driving of Turbine #21 and #28, one SM3M recorder was deployed at distance of 230 m from the source, respectively. Water depths where the bottom-mounted sensor was deployed were approximately 20m. Underwater background noises were also collected two days before and two days after pile driving.

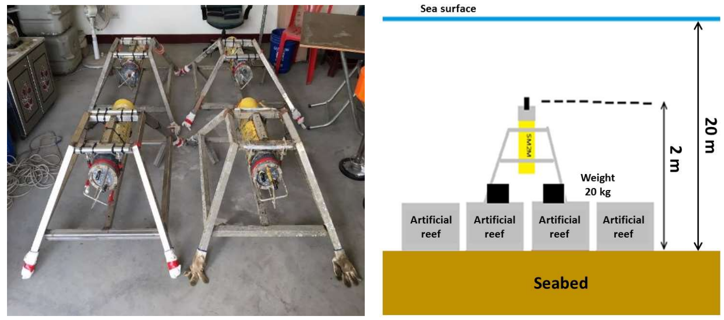

Figure 3. Two SM3M Submersible Long-term Passive Recorders fixed on metal frames (left) and a schematic diagram of deployment (right).

For shipboard passive acoustic monitoring, a Brüel & Kjær (B&K) Hydrophone Types 8103 with a NI USB-4431 DAQ AD converter were used. The hydrophone was calibrated using a B&K Pistonphone Type 4228 before data collection. Acoustic data were recorded directly onto a laptop computer using LabVIEW software. Figure 4 shows the equipment used for shipboard passive acoustic monitoring. Shipboard acoustic data collection was conducted during active pile driving at distances of 750 m, 1,250 m, and 3,000 m from the source. During the data collection, the hydrophone was lowered from the side of the research vessel to approximately 5 m under the surface. Table II shows the time and location of shipboard measurements that were taken during the pile driving activities of Turbine #21. This procedure was also conducted during the pile driving of Turbine #28.

Figure 4. Instrument used for shipboard passive acoustic monitoring: B&K 8103 hydrophone (left); B&K 4228 pistonphone (middle); and NI USB-4431 DAQ AD converter.

Table II. Location and time shipboard underwater recordings were made during pile driving for Turbine #21 on September 3 and 4, 2016.

Recording date & time	Direction and distance to pile	Latitude	Longitude
03SEP16, 20:35-2052	750m Northwest	120º48.730'E	24º41.900'N
03SEP16, 21:01-21:10	750m Northeast	120º49.086'E	24º42.000'N
03SEP16, 21:22-21:52	3,000m Northeast	120º49.268'E	24º43.206'N
03SEP16, 22:07-22:21	3,000m Northwest	120º47.843'E	24º42.810'N
03SEP16, 22:54-23:07	1,250m Southeast	120º49.359'E	24º41.326'N
03SEP16, 23:18-23:48	750m Southwest	120º47.330'E	24º40.933'N
04SEP16, 00:00-00:06	3,000m Southwest	120º47.323'E	24º41.000'N

III. Acoustic Data Analyses

Acoustic data analyses were conducted using custom developed MATLAB® (MathWorks, Natick, MA) algorithms. Broadband (10 Hz – 20 kHz) peak sound pressure levels (SPL_{peak}) and root-mean-square (rms) sound pressure levels (SPL_{rms}) that contain 90% of a single strike acoustic energy were computed. The broadband frequency range selected and SPM_{rms} integration time are based on recommendations from a guidance memo from the U.S. National Marine Fisheries Service (NMFS, 2012).

Pile driving source level is back-calculated using a hybrid sonar equation that incorporates depth dependent spherical and cylindrical spreading transmission loss (Urick, 1983)

$$TL = 20\log_{10} H + 10\log_{10}(R - H) \tag{1}$$

where *TL* is transmission loss in dB, *H* is water depth at the source, and *R* is the horizontal range from the source. The *TL* is also calculated using PE numerical simulation, and the result is similar to the result obtained with Eq. (1) in this location. A comparison of transmission loss between the PE simulation and measurements based on Eq. (1) is provided in Table III.

Table III: Transmission loss at measured stations and simulated with PE and Eq. 1

Recording date & time	Direction and distance to pile	TL by PE	TL by Eq. (1)
03SEP16, 20:35-2052	750m Northwest	43 dB	48.8 dB
03SEP16, 21:01-21:10	750m Northeast	42 dB	48.8 dB
03SEP16, 21:22-21:52	3,000m Northeast	51 dB	54.8 dB
03SEP16, 22:07-22:21	3,000m Northwest	55 dB	54.8 dB
03SEP16, 22:54-23:07	1,250m Southeast	43 dB	51.0 dB
03SEP16, 23:18-23:48	750m Southwest	53 dB	48.8 dB
04SEP16, 00:00-00:06	3,000m Southwest	53 dB	54.8 dB

A recent marine mammal noise exposure guidance released by NMFS divides marine mammal species under its jurisdiction into six hearing groups based on their hearing sensitivities (NMFS, 2016). The ETS Indo-Pacific humpback dolphin is designated as a mid-frequency cetacean species within the marine mammal hearing group. The guidance also calls for frequency weighting function developed by Finneran (2016) to be used to assess potential hearing impacts to marine mammals of different hearing groups. Therefore, single strike sound exposure levels (SEL_{ss}) based on the marine mammal weighting function developed by Finneran (2016) for mid-frequency cetaceans were calculated using the following equation.

$$W(f) = C + 10\log_{10}\left\{\frac{(f/f_1)^{2a}}{\left[1+(f/f_1)^2\right]^a\left[1+(f/f_2)^2\right]^b}\right\} \tag{2}$$

where $a = 1.6$, $b = 2$, $f_1 = 8.8$ kHz, $f_2 = 110$ kHz, and $C = 1.20$ dB for mid-frequency cetaceans.

Furthermore, spectrograms of recordings during pile driving were produced using fast Fourier transform (FFT) of 1 sec window size, 90% overlap, and a Hanning window.

In addition, 24-hour cumulative sound exposure levels for mid-frequency cetaceans $SEL_{MF,24h}$ were also computed using equation

$$SEL_{\mathrm{MF,24h}} = SEL_{\mathrm{MF,s-s}} + 10\log_{10}(N) \qquad (3)$$

where $SEL_{\mathrm{MF,s\text{-}s}}$ is the single strike SEL of mid-frequency cetacean based on Eq.(2), and N is the number of impact pile strikes. This metric is also based on NMFS 2016 noise exposure guidance for assessing hearing impacts on marine mammals (NMFS 2016).

Finally, for pile driving sound, 1/3-octave-band spectral levels of the broad frequency band at two of the pile driving time (3 September, 20:49, and 4 September, 08:45) were calculated from recordings made by two SM3M sensors.

Inter-pulse sound field were calculated for sound acoustic pressure 100 ms after a pulse to 500 ms before the following pulse.

RESULTS

I. Noise Levels from Direct Pulses

Representative waveforms, SPL plots, and spectrograms from bottom-mounted SM3M sensor monitoring during pile driving for Turbine #21 at distances 170 and 230 m from the source are shown in Figs. 5 and 6. Representative waveforms, respectively, SPL plots, and spectrograms for Turbine #28 at a distance 230 m from the source is shown in Fig 7. These results show that SPL_{rms} for impact pile driving at distance of 230 m ranged from 184-187 dB re 1 μPa, with peak sound pressure level (SPL_{pk}) from 202-204 dB re 1 μPa, and peak-to-peak SPL ($SPL_{pk\text{-}pk}$) from 208-210 dB re 1 μPa. The mean value for mid-frequency cetacean weighted $SEL_{\mathrm{MF,s\text{-}s}}$ at 230m for Turbine #21 pile driving is 159 dB re 1 μPa^2-s. The mean value for mid-frequency cetacean weighted $SEL_{\mathrm{MF,s\text{-}s}}$ at 230 m for Turbine #28 pile driving is 155 dB re 1 μPa^2-s. The back-calculated SPL_{rms} using the PE model is approximately 196-200 dB re 1 μPa at 10 m. The back-calculated source level for SPL_{rms} using the PE model is approximately 196-200 dB re 1 μPa at 10 m. The back-calculated source level for the unweighted $SEL_{s\text{-}s}$ is approximately 189 dB re 1 μPa^2-s at 10 m. The source levels for SPL_{pk} and $SPL_{pk\text{-}pk}$ cannot be back-calculated because acoustic propagation is frequency-dependent and is more complicated than simply incorporating transmission loss.

Representative waveforms and spectrograms from shipboard monitoring during pile driving for Turbine #21 at distances 750, 1,250, and 3,000 m from the source are shown in Figs. 8, 9, and 10, respectively. Results show that SPL_{rms} at 750, 1,250, and 3,000 m were approximately 160-165, 160, and 155 dB re 1 μPa, respectively. The mean value for mid-frequency cetacean weighted $SEL_{\mathrm{MF,s\text{-}s}}$ at 750 m is 141 dB re 1 μPa^2-s. The back-calculated source level using shipboard data showed a source levels around 209-214 dB re 1 μPa at 1 m.

Using Eq. (3), the $SEL_{\mathrm{MF,24h}}$ were calculated based on recordings obtained from Turbine #21 pile driving at 230m by SM3M sensor and at 750 m by shipboard sensor. Results show that the $SEL_{\mathrm{MF,24h}}$ at these two locations are 197 and 178 dB re 1 μPa^2 (24 hours), respectively. The $SEL_{\mathrm{MF,24h}}$ for Turbine #28 pile driving at 230m is 192 dB re 1 μPa^2 (24 hours). A summary of the measured and computed sound levels for Turbine #21 are shown in Table IV.

One-third-octave-band spectral levels of pile driving noise recorded at 20:40 on 3 September and 08:45 on 4 September 2016 by SM3M deployed 230 m from the source are shown in Fig. 11. The results show that pile driving noises at these two time periods are comparable for each location, with dominant frequency around 100-300 Hz. The higher spectral levels on 4 September 2016 was due to the hammer operating at full power, while on 3 September it was operated at a lower power during ramp-up.

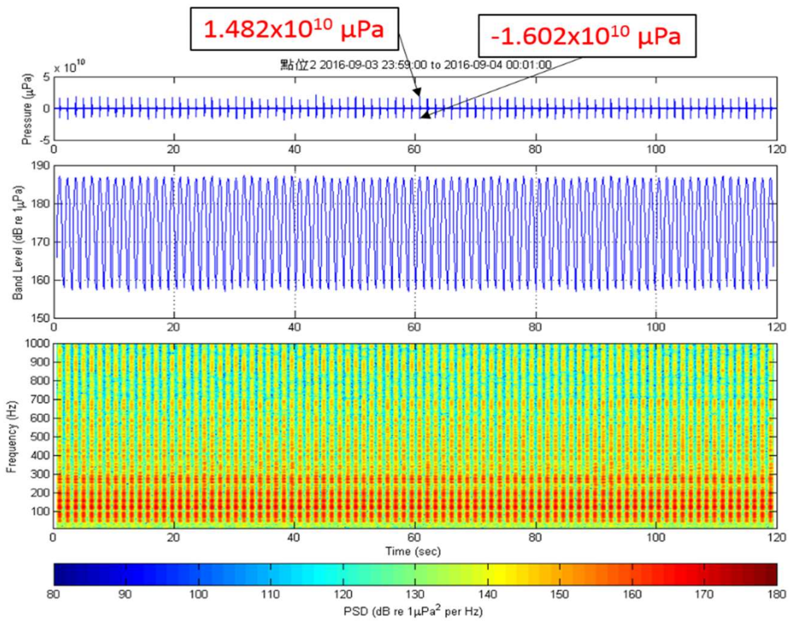

Figure 6. Waveform (top), SPL plot (middle), and spectrogram (bottom) during pile driving for Turbine #21 at 23:59 on 3 September 2016, recorded from bottom-mounted SM3M sensor deployed at 230 m southeast of the source.

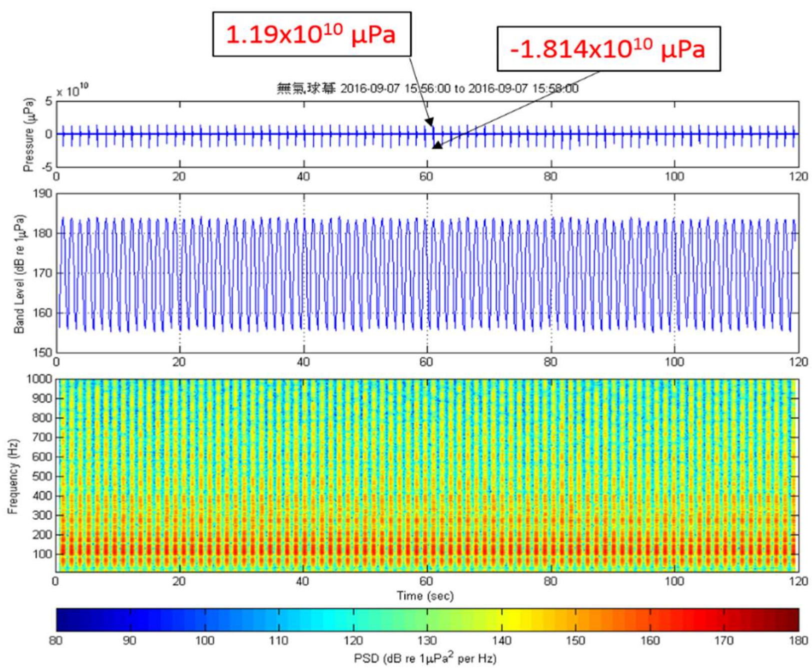

Figure 7. Waveform (top), SPL plot (middle), and spectrogram (bottom) during pile driving for Turbine #28 at 15:56 on 7 September 2016, recorded from bottom-mounted SM3M sensor deployed at 230 m southeast of the source.

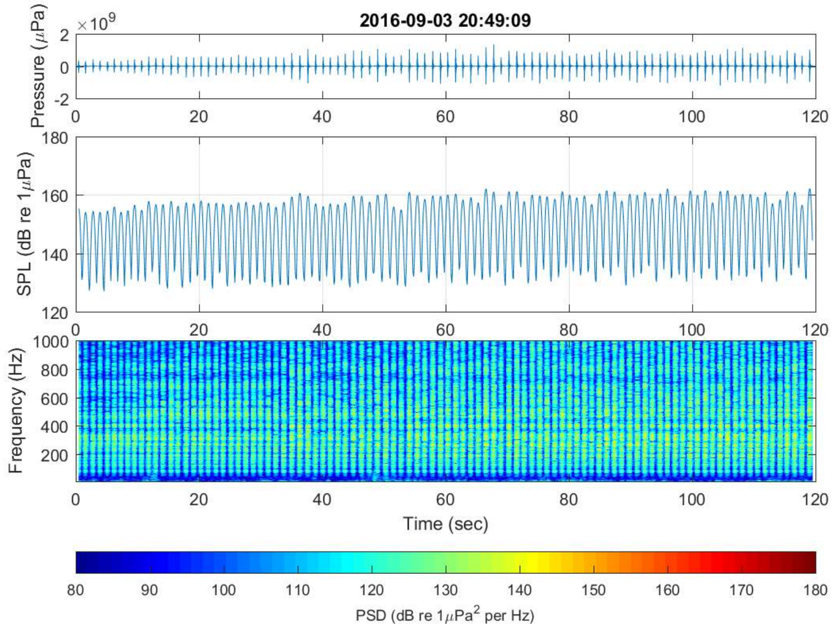

Figure 8. Waveform (top), SPL plot (middle), and spectrogram (bottom) during pile driving for Turbine #21 at 20:49 on 3 September 2016, recorded from shipboard hydrophone at 750 m northwest of the source.

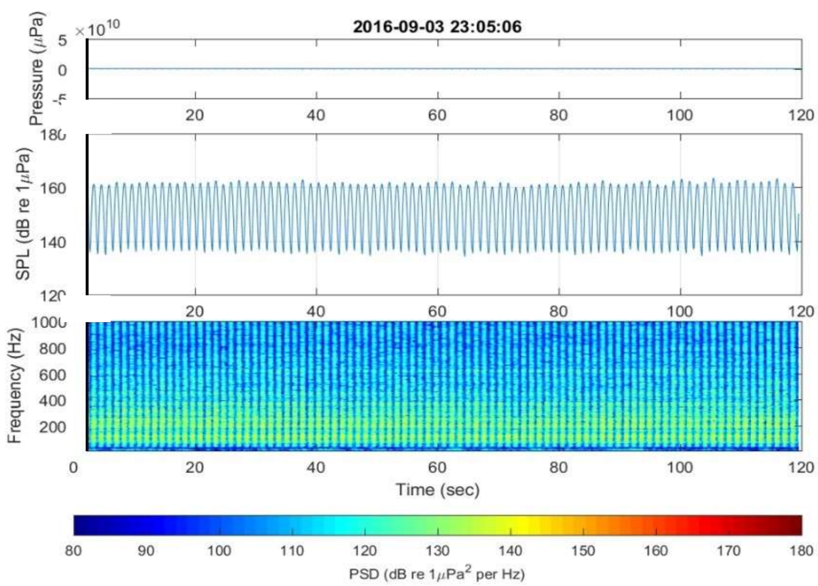

Figure 9. Waveform (top), SPL plot (middle), and spectrogram (bottom) during pile driving for Turbine #21 at 23:05 on 3 September 2016, recorded from shipboard hydrophone at 1,250 m southeast of the source.

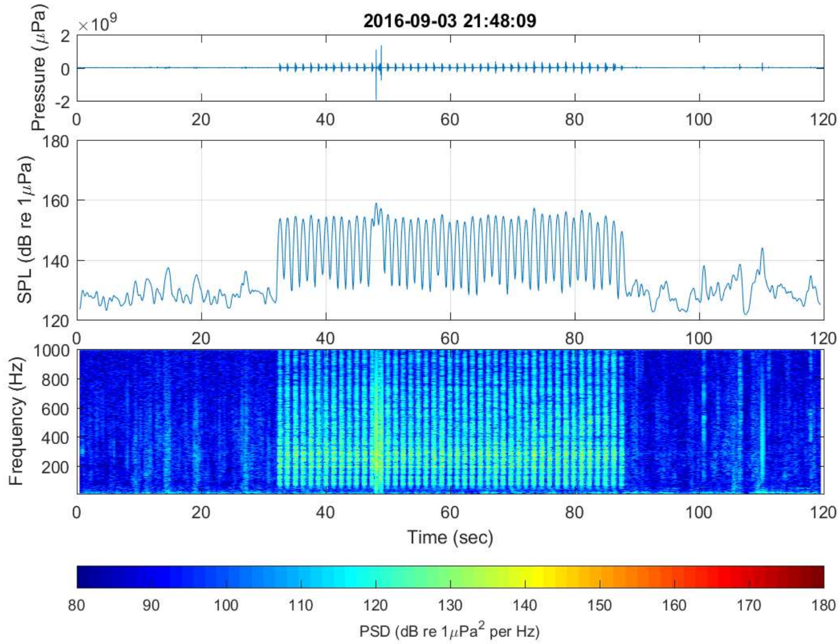

Figure 10. Waveform (top), SPL plot (middle), and spectrogram (bottom) during pile driving for Turbine #21 at 21:48 on 3 September 2016, recorded from shipboard hydrophone at 3,000 m southeast of the source.

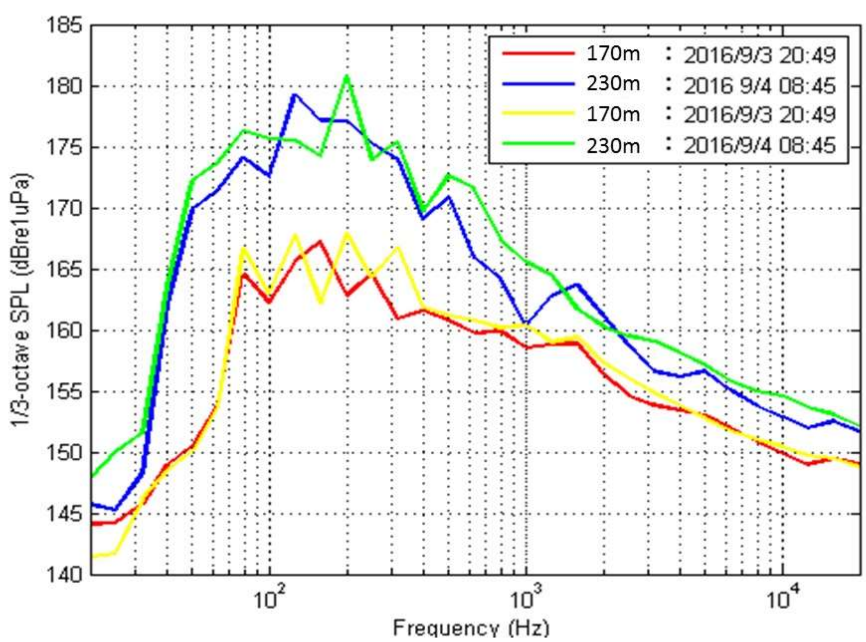

Figure 11. One-third-octave-band spectral level of pile driving noise recorded at 20:49 on 3 September and 08:45 on 4 September 2016 by SM3M sensors at 170 and 230 m from the source.

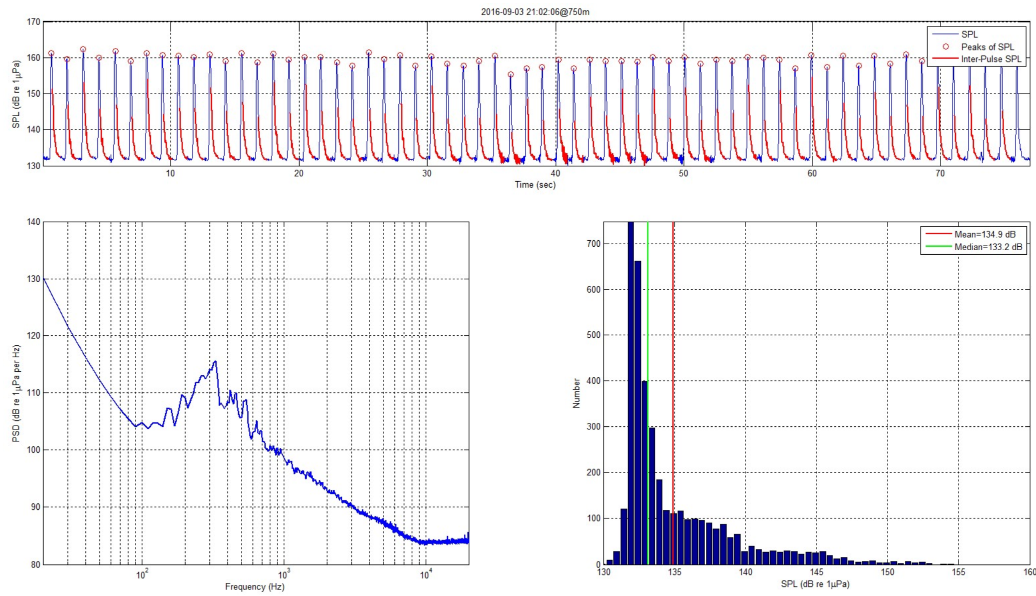

Figure 12. An example of SPLs (top), mean spectra (bottom left), and inter-pulse sound level distribution (bottom right) of pile driving measured at 750 m on 3 September 2016, around 21:02.

Table IV. Summary of received noise levels at different distances by SM3M sensor and shipboard hydrophone, in comparison with NMFS (2016) and the U.S. Navy (Finneran, 2016) marine mammal harassment criteria.

Sensor & Distance	SPL_{rms} (unweighted, dB re 1 µPa)	SEL_{ss} (unweighted, dB re 1 µPa^2-s)	SPL_{pk} (unweighted, dB re 1 µPa)	SEL_{MF} (dB re 1 µPa^2-s)[1]
SM3M at 230m	183-187	176-180	200-204	197
Shipboard at 750m	173-<u>177</u>	166	185-<u>189</u>	<u>178</u>
Shipboard at 1,250m	169	162	180	<u>162</u>
Shipboard at 1,500m	<u>166</u>	<u>163</u>	<u>179</u>	<u>160</u>
Shipboard at 3,000m	163	160	176	<u>157</u>
※ NMFS criteria	Behavioral harassment: 160		PTS[2]: 230	PTS[2]: 185
※ U.S. Navy criteria			TTS[3]: 224; PTS[2]: 230	TTS[3]: 170; PTS[2]: 185

* Underlined values are calculated

[1]The NMFS' SEL metric is based on sound exposure level during a 24-hour period, while the Navy's does not specify exposure duration.

[2]PTS: permanent hearing threshold shift. PTS is considered as an auditory injury.

[3]TTS: temporal hearing threshold shift. TTS is not considered as an injury.

II. Pile Driving Inter-pulse Noise Levels

Mean broadband inter-pulse sound levels are 134, 135, and 133 dB re 1 µPa at distances 750, 1,250, and 3,000 m from the pile, respectively. The median broadband inter-pulse sound levels at theses distances are 133, 133, and 132 dB re 1 µPa, respectively. Examples of SPL plots, spectra, and broadband inter-pulse sound level distribution histograms at 750, 1,250, and 3,000 m are shown in Figs. 12 to 14.

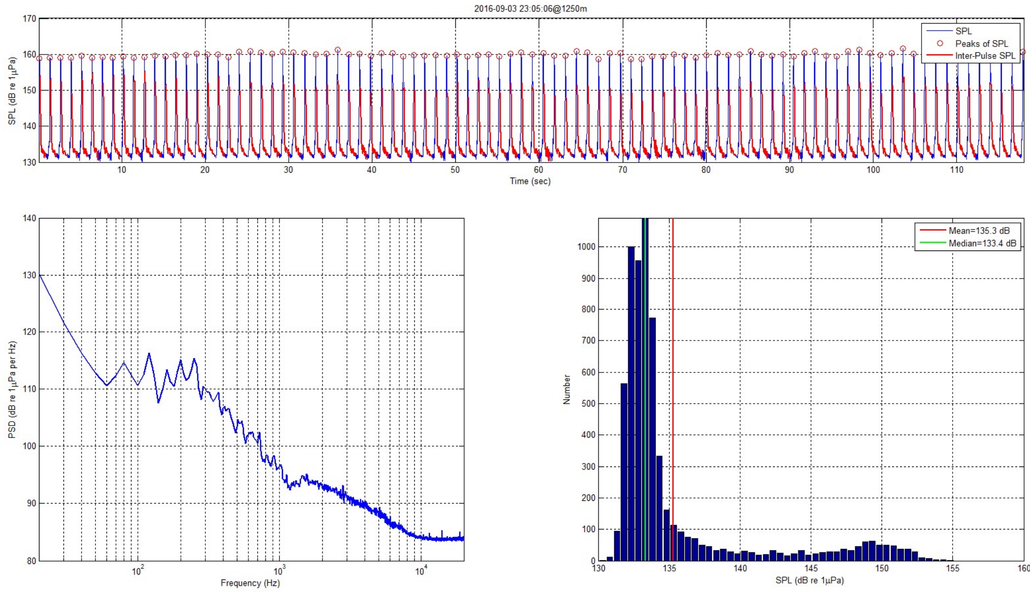

Figure 13. An example of SPLs (top), mean spectra (bottom left), and inter-pulse sound level distribution (bottom right) of pile driving measured at 1,250 m on 3 September 2016, around 23:05.

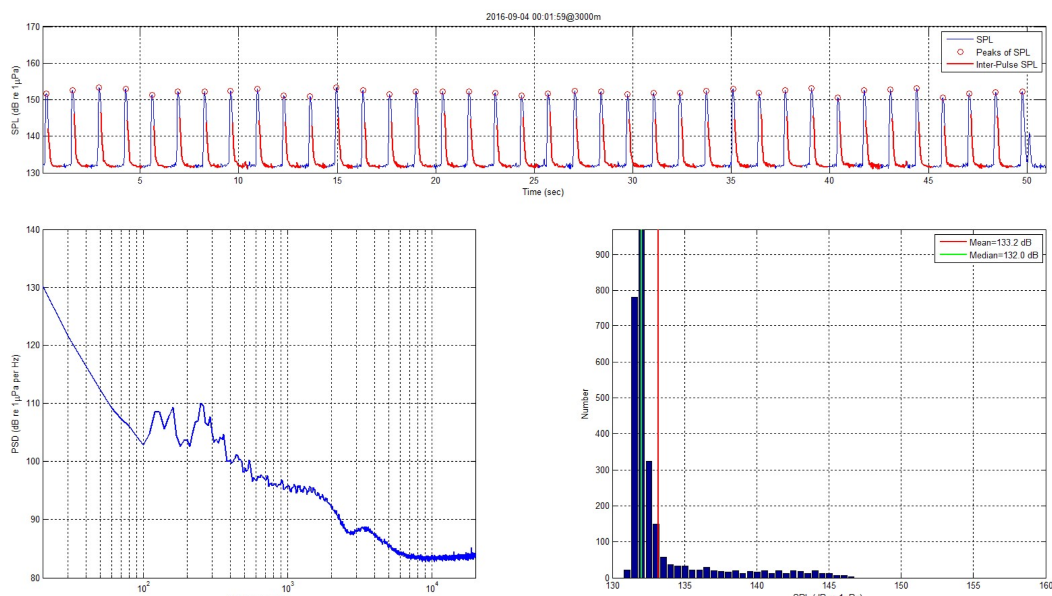

Figure 14. An example of SPLs (top), mean spectra (bottom left), and inter-pulse sound level distribution (bottom right) of pile driving measured at 3,000 m on 4 September 2016, around 00:01.

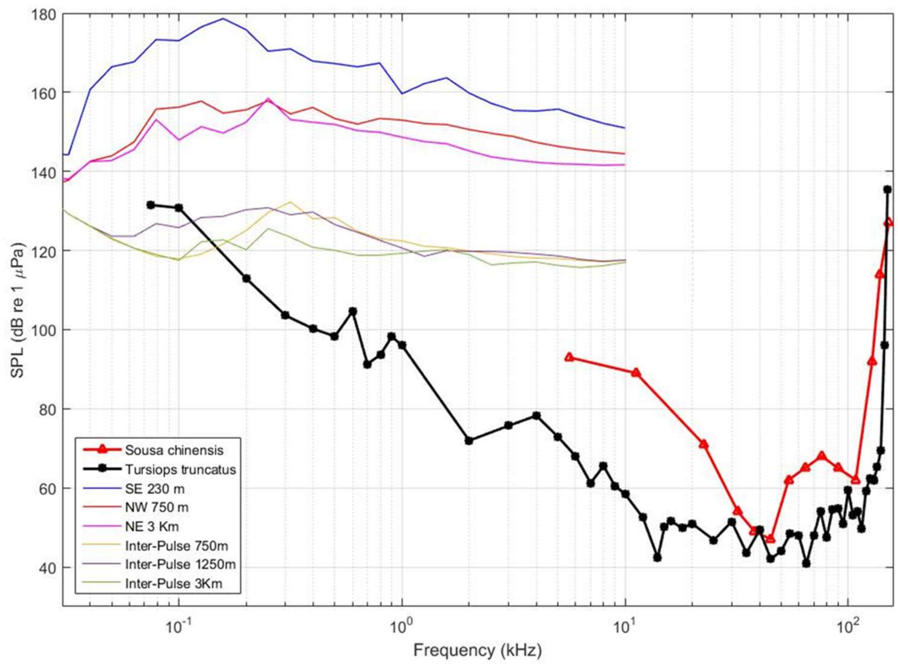

Figure 15. Power spectrum density (PSD) of pile driving noise and the associated inter-pulse sound levels at different distances from the source superimposed with published audiograms of a Indo-Pacific humpback dolphin, a bottlenose dolphin, and PSD and OTO of a vessel passage. The blue shaded area indicates the Indo-Pacific humpback dolphin whistle frequency band of 3-6 kHz.

Power spectral density (PSD) of pile driving noise and inter-pulse sound levels at three distances from the source are shown in Fig. 15. These noise levels are also plotted against the published audiograms of an Indo-Pacific humpback dolphin (Li et al., 2012) and a bottlenose dolphin (Johnson, 1967), and the PSD and one-third octave (OTO) spectrum of a passing vessel (Guan et al., 2015a). The majority of acoustic energies from pile driving and the associated inter-pulse sound levels are below 1 kHz, which fall under less sensitive hearing as far as frequencies are concerned. Nevertheless, pile driving pulse energies in general are about 15-70 dB over dolphin's hearing threshold up to 750 m from the source.

In addition, Fig. 15 shows that inter-pulse sound levels are higher than noise from a typical vessel passage in the area across the entire frequency spectrum. The typical Indo-Pacific humpback dolphin whistle frequency band is also included in Fig. 15 to show potential acoustic masking from impact pile driving inter-pulse sound field.

CONCLUSIONS AND DISCUSSIONS

This is the first comprehensive study on underwater noise from in-water impact pile driving activities and the associated soundscape for offshore wind farm construction in Taiwan. Measurements using bottom-mounted SM3M sensor and shipboard hydrophone at various locations show good agreements of noise attenuation over the distances. In general, SPL_{rms} ranged from 187 to 155 dB re 1 μPa as the distance moved from 230 to 3,000 m from the source, and

SPL_{pk} range from 204 to 176 dB re 1 μPa for the same distances. Transmission loss (*TL*) based solely on geometrical spreading between 230 and 3,000 m

$$TL = F \log_{10}\left(\frac{R_2}{R_1}\right) \tag{4}$$

yields a transmission loss coefficient *F* of approximately 26 for SPL_{rms} and 23 for SPL_{pk}, where R_1 and R_2 are initial and final distances of 230 and 3,000 m from the source, respectively.

Results from underwater recordings using different sensors and a simplified sonar equation yielded comparable results concerning the source levels. Back-calculated source levels using relatively closer-by (230 m) SM3M sensor provided source levels at 227-230 dB re 1 μPa at 1 m, while the shipboard hydrophones at 750, 1,250, and 3,000 m calculated the source levels to be 209-214 dB re 1 μPa at 1 m. The lower back-calculated source levels derived by the farther shipboard hydrophone are likely due to absorption and scattering of acoustic energy through longer distances that were not incorporated in the computation.

Accumulative acoustic energy exposure levels over the entire duration of pile driving based on two demonstration monopiles are 194 and 192 dB re 1 μPa^2-s for Turbines #21 and #28, respectively. The difference in $SEL_{MF,24h}$ is probably due to the combination of different single strike SELs-s (159 dB re 1 μPa^2-s for Turbine #21 vs. 155 dB re 1 μPa^2-s for Turbine #28) and the number of strikes needed to install each turbine (4,757 strikes for Turbine #21 vs. 3,700 strikes for Turbine #28). Nevertheless, it is interesting to note that the cumulative noise exposure levels when both piles were driven were s only 2 dB different.

A comparison between the U.S. Navy and NMFS noise exposure impact onset levels along with received noise levels at different distances from this study is presented in Table III. The results indicate that at a distance of 750 m, exposure to the noise from impact pile driving is unlikely to induce PTS in Indo-Pacific humpback dolphins based on both the U.S. Navy and NMFS marine mammal hearing impact guidance (Finneran, 2016; NMFS, 2016). Although the results suggest that accumulation of acoustic energy at this distance over the duration of pile driving could induce TTS in a dolphin within the 750 m zone, considering that this would require the animal to stay within the zone for hours, this is not a likely scenario.

Many studies show that marine mammals avoid areas with intense anthropogenic noise (Southall et al., 2007), and thereby avoid experiencing hearing impairment. Our results further show that at a distance of 1,500 m from the source, modeled SPL_{rms} is expected to be at 158 dB re 1 μPa, which is below NMFS noise exposure criteria for behavioral disturbance (160 dB re 1 μPa_{rms}) of mid-frequency cetaceans. However, given the narrow range of the dolphin's key habitat off the west coast of Taiwan, the areas for avoidance could be limited. Therefore, additional research on behavioral responses by the ETS Indo-Pacific humpback dolphins to the offshore windfarm construction and operation are warranted.

Similar studies on inter-pulse sound field have been conducted on short transient noises from other sources (e.g., seismic airgun: Guan et al., 2015b; 2016; simulated mid-frequency active sonar: Guan et al., 2017), which indicate elevated sound levels in between pulses. This preliminary study marks the first attempt to address potentially elevated inter-pulse sound levels during in-water impact pile driving. The PSD of the inter-pulse sound levels is up to 20 dB higher than the bottlenose dolphin's hearing threshold over the frequency range that was measured (Fig. 15). The inter-pulse sound levels are roughly 10 dB lower than the Indo-Pacific humpback dolphin's hearing threshold within the measured frequency band of 5.6 to below 10 kHz. However, the hearing sensitivity of the Indo-Pacific humpback dolphin was measured on one captive animal using the auditory evoked potential (AEP) method (Li et al., 2012). The AEP method does not work in low frequency regimes below 1 kHz, where most of the acoustic energy from pile driving is. Nevertheless, the overall broadband increase in the inter-pulse sound levels during impact pile driving that extends to at least 3 km from the source indicates that it is likely to cause acoustic masking to cetacean species, including the Indo-Pacific humpback dolphin, in their marine environment.

It is also interesting to note that below 300 Hz, the inter-pulse spectral levels at 750 m are lower than those at 1,250 m (Fig. 15), which may explain the result that the mean inter-pulse broadband level at 750 m is about 1 dB lower than that at 1,250 m. We consider this probably due to certain environmental conditions that support reverberant field effects at different ranges. Further research is needed in order to get a better insight on this phenomenon.

Overall, the results of this study contribute valuable information on impact pile driving noise levels and its associated soundscape during the construction of offshore wind turbines in other areas (such as off the U.S. coast). Received SPLs and SELs at various distances during pile driving can also provide useful information to assess potential impacts on marine mammals in the area, which would assist regulators in conducting environment impact analyses and in their decision making.

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