Overview and Summary of Recent Research into the Potential Effects of Pile Driving on Cetaceans

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ABSTRACT

In recent years there has been a greater focus on the potential for anthropogenic sounds from renewable energy developments (e.g. wind farms) to impact marine mammals. Sounds produced during the construction phase are likely to be the most intense due to foundation laying activities like pile driving. The most common technique of driving piles is impact pile driving, which also produces the highest level impulse sounds, followed by vibratory pile driving which produces lower level, more continuous sounds. A variety of techniques exist to reduce or mitigate against impacts from the high levels of sound produced including bubble curtains, ramp-ups, cushion blocks, cofferdams, or temporary noise attenuation piles. To date, there have been a number of publications hypothesizing as to potential effects of these sounds, but only a few publications empirically measured responses to pile driving noise, most notably showing reduced acoustic activity to varying degrees from harbor porpoises.

INTRODUCTION

Cetaceans use underwater sound as a primary means of communication and assessing their environment. They must integrate information and resources over large spatial and temporal scales (Lockyer, 1984, Boyd et al., 1999). Mates and conspecifics may be widely dispersed. Food resources can be patchy and separated by great distances. While light is attenuated rapidly in water, limiting the effectiveness of vision to distances of a few meters, sound is a highly efficient means of sending information over long distances (Tyack, 1998). The ability of sound to travel great distances through water also highlights the fact that anthropogenic noise sources can potentially have impacts over vast areas of the ocean.

There has been a greater focus in recent years on marine renewable energy development, most notably in production of offshore wind farms (e.g. Simmonds et al., 2010; Dolman et al., 2007; Madsen et al., 2006; Bailey et al., 2010) and the potential for sounds produced by these developments to affect marine mammals. While offshore wind farms may create moderate levels of chronic noise during their day to day operation (Hildebrand, 2009; Dolman et al., 2007), their initial construction generally utilizes pile driving which has led to greater attention towards the impacts of these acute, high source level (i.e., impact pile driving) sounds on the surrounding environment (Bailey et al., 2010; Madsen et al., 2006). Outside of explosives and seismic air-gun arrays, impact pile driving has the potential to produce some of the loudest anthropogenic impulsive sounds to enter the marine environment (Caltrans, 2009; Hildebrand, 2009). Additionally, these sounds are predominantly low frequency and have the potential to travel great distances depending on sound propagation conditions.

Here, we present a brief overview of the various pile driving and noise mitigation techniques, as well as a short summary of the findings of the most recent literature describing potential impacts of pile driving sounds on marine mammals.

PILE DRIVING TECHNIQUES

There are generally two types of pile drivers that are most commonly used: impact hammer, and vibratory.

Impact pile driving is the most commonly used method where a heavy weight is lifted (through hydraulic, steam or diesel power) and dropped against the top of the pile, driving it into the substrate. This type of pile driving typically leads to the highest noise levels of any of the methods as impulsive acoustic energy is created upon impact, and radiates from the impact site through multiple paths. Noise increases with pile size (diameter and wall thickness), hammer energy, and ground hardness (Erbe, 2010). The different pile material leads to variable source levels produced, with large diameter steel piles producing the highest levels of noise when driven by an impact hammer (Caltrans, 2009).

Vibratory pile driving is another commonly used method which has lower peak sound pressures associated with it compared to impact pile driving and creates a more continuous lower level of sound (Spence et al., 2007). Vibratory hammers sit on top of the pile, and use as series of oscillating weights to continuously transfer vertical vibrations into the pile at a specific frequency, while horizontal vibrations cancel out (Erbe, 2010). The driving frequency is typically on the order of 10-60 Hz (Spence et al., 2007) causing the sediment surrounding the pile to liquefy and allow pile penetration (Caltrans, 2009).

Press-in, or push pile driving is a newer technology that is not as commonly used as either impact or vibratory pile driving, but the noise and vibration levels emitted by this method are largely reduced over both these two methods (White et al., 2002) making it worthy of mention here. Press-in pile driving uses hydraulic rams to force a pile into the ground using the static force provided by attaching the machine, a ‘Silent Piler’ to previously driven piles (Finlay et al., 2001).

While both vibratory and press-in driving emit lower levels of noise than impact pile driving, there is a cost increase associated with these methods, and certain situations prevent their use (e.g. sediment conditions or need for proven load bearing requirements of the pile) (Caltrans, 2009; Spence et al., 2007). There are a variety of others methods that can be used to install piles (e.g., oscillatory, suction, pre-drilling) which have varying noise signatures, but currently they are not used on a regular basis (Spence et al. 2007; HDR Alaska, Inc. 2011).

MITIGATION OF PILE DRIVING SOUNDS

There are several techniques that can be used to mitigate against potential negative effects from pile driving. For example, time-area avoidance measures can be used to reduce overlap between the activity and species of interest (e.g., salmonids, Caltrans, 2009). Additionally, many European pile driving activities have used active acoustics (acoustic mitigation devices) to deter animals from the activity site (e.g., Gordon et al., 2007, Kastelein et al., 2010).

When it comes to addressing the sound source, there are several techniques that can be used to reduce the underwater sound generated from pile driving activities. These include the following:

- Bubble curtains (confined/unconfined): Placing air bubbles around a pile (bubbles can be confined or unconfined) can act as a means to prevent sound propagation based on the differences in density between air and water (Reyff, 2009). Up to a 15 dB reduction can be achieved (Caltrans, 2009).
- Ramp-up/Soft start: Gradually increasing hammer energy level over time. The goal with this technique is to allow animals in the vicinity to experience a reduced level of sound and evacuate the area before maximum levels are achieved (Robinson et al., 2007). The effectiveness of this technique has yet to be determined.
- Cushion blocks/Caps: Materials (wood, micarta, nylon) placed atop piles during impact pile driving activities to reduce source levels. Typically sound reduction can range from 4 to up to 26 dB (Caltrans, 2009).
- Cofferdams: Structures used to isolate submerged pile from water column. Those that are dewatered (creating an air-filled space between pile and surrounding water) are more effective than those that are not (Caltrans, 2009).

- Temporary noise attenuation pile (TNAP) design: Hollow walled (air-filled) steel pile casing or foam-lined steel casing placed around the pile being driven. Levels can be reduced by 8 to 14 dB (Laughlin, 2010).

RECENT STUDIES OF POTENTIAL EFFECTS ON CETACEANS

Potential impact zones

A few earlier papers conducted desktop exercises of the potential impacts of pile driving activity. David (2006) used previously reported sound levels and frequencies produced by pile driving to predict received levels and assess potential impacts on bottlenose dolphins. Using generic transmission loss calculations, the author suggests that typical impact pile driver noise could be expected to be perceived by populations over 10km from the source, and loud pile driving noise has the potential to mask whistles at distances up to 40km and echolocation clicks up to 6 km. The impacts of masking would be expected to be limited by the directional hearing of dolphins and by the intermittent nature of the pile driver noise.

Madsen et al. (2006) conducted a review of existing literature at the time, and modeled and assessed zones of impact from different activities associated with wind farms on four species of marine mammals (harbor porpoise, bottlenose dolphin, harbor seal, northern right whale). In contrast to David (2006), these authors discount the likelihood of masking effects from impact pile driving sounds due to the short duration and low duty cycle (duration of individual signals relative to repetition interval of signals). However, they suggest behavioral disruptions could potentially be caused over large areas of many kilometers, and that hearing impairment (temporary or permanent threshold shifts), could potentially occur over ranges of 700m to 2km.

More recently, empirical measurements were made of the sound field surrounding the installation of two 5MW wind turbines of NE Scotland with the use of impact pile driving. The turbines were in relatively deep water (>40m), 25 km from a Conservation area with a protected population of bottlenose dolphins. Pile driving noise at ranges from 0.1 to 80km were measured and ranged from peak to peak broadband levels of 205 dB re 1µPa, to being indistinguishable from background noise. Noise levels across frequencies were detectable above background levels to about 70km. Noise levels were related to suggested noise exposure criteria for the bottlenose dolphin, harbor porpoise, minke whale, and harbor and grey seals. Based on updated hearing impairment thresholds, these measurements suggest no risk of hearing impairment at distances greater than 100m, but the limited understanding of hearing and behavioral response thresholds makes it difficult to effectively assess impacts at larger ranges from the source (Bailey et al., 2010).

Harbor porpoise (*Phocoena phocoena*) data

Carstensen et al. (2006) investigated the effect of impact pile-driving on harbor porpoises during the 2002-03 construction the Nysted windfarm in shallow water (6-9m) off Denmark by means of passive acoustic porpoise detectors (T-PODs) monitoring porpoise echolocation activity. Six T-POD monitoring stations were equally distributed between the construction area and a nearby reference area. A large increase in mean waiting times, the period between 2 consecutive encounters of echolocation activity, was seen, increasing from 6 h in the baseline period to 3 days in the wind farm area during the construction. This increase was 6 times larger than changes observed in the reference area. The authors suggest that, assuming echolocation activity is related to harbor porpoise density, their habitat-use changed substantially, with the porpoises leaving the construction area of the offshore wind farm. It should be noted that there is no description of received levels from the pile driving activity so it is impossible to associate response with sound levels.

During the impact pile driving installation of steel (4m diameter) piles for the foundation of wind turbines in the shallow waters (~6m) at Horns Reef, North Sea the acoustic behavior of harbor porpoises was monitored through the use of Timed Porpoise Detectors (T-PODS). These units, placed in 3 locations out to 21km from the site, automatically detect and record the time of occurrence of detected clicks. Received sound pressure levels of the pile driving sounds were also measured at 4 locations leading to a back-calculated source level of 235dB re 1µPa (peak to peak), though levels were likely considerably lower than this close to the foundation. Recorded acoustic activity of harbor porpoises decreased after pile driving events with time between “encounters” (clusters of echolocation events recorded on T-PODS) increasing to 7.5 hours after pile driving events, compared to 5.9 hours on average during the construction period as a whole. The effect was noted out to the limits of the area monitored, at a range of 21km (Tougaard et al., 2009).

Somewhat more equivocal results were recently published (Thompson et al., 2010) assessing the measured reactions of cetaceans to the installation of the wind turbines described above (Bailey et al., 2010 in Potential Impact Zones section). T-PODs were used, and detections of porpoises were compared to data collected the following year as a control, and also by comparing the echolocation event intervals after pile driving activity with intervals when pile driving was not occurring. While the analysis of waiting times until a porpoise detection suggested no strong response to the first of two piling events, the waiting times following the second piling event were exceptionally long. This overall period of 2– 3 relatively silent days was similar in magnitude to the observed responses in the Carstensen et al. (2006) study. There was also some indication of a disturbance response when comparing data from 2006 and 2007. Porpoises were detected on most days in both years, but the number of hours that they were detected in each day during July and August was significantly lower in 2006, when the core engineering work was carried out. The authors however, are careful to point out that the evidence for disturbance is not particularly strong, and the apparent changes seen may simply have resulted from the study design, small sample size and other chance or biological factors (Thompson et al., 2010).

Most recently, during the 2008 impact pile driving installation of foundations at the Horns Rev II wind farm in the North Sea, Brandt et al., (2011), monitored porpoise acoustic activity through the use of T-PODS at ranges of ~2-21km from the pile driving activity. Porpoise acoustic activity was absent at the closest locations for the first hour, and remained lower than normal for 24-72 hours after pile driving. The period of reduced acoustic activity gradually decreased with distance with a negative effect detectable to 17.8km. At the most distant T-POD at 22km, porpoise activity increased for about 30 hours following pile driving, suggesting animals moving away from the construction site may have caused the temporary increase in acoustic activity. Overall, porpoise activity, and possibly abundance were reduced over the 5 month construction period compared to a baseline period prior to the start of construction. Finally, the authors made noise level measurements at 2 locations ~700 and ~2300m from the activity. Based upon these measurements, they suggested hearing impairment (e.g. temporary threshold shift) at these ranges was a reasonable possibility, given the harbor porpoise’s apparent sensitivity to noise exposure.

Finally, as the most common measured effect has been a reduction in acoustic activity, it is important to note that without concurrent visual observations, it is impossible to distinguish whether the absence of recorded clicks following a pile-driving event indicates that porpoises left the area or that they merely changed vocal behavior (i.e. ceased clicking).

Indo-Pacific humpback dolphin (*Sousa chinensis*) data
In association with impact pile driving activity off western Hong Kong (construction of an aviation fuel receiving facility), Würsig et al., (2000) reported that generally no overt behavioral changes (i.e., no difference in re-orientations between surfacing) were seen but speed of travel increased during pile driving compared to other periods (i.e., twice as high). It should be noted that air bubble curtains were used during this activity.

Beluga whale (*Delphinapterus leucas*) data
Belugas have been monitored (shore-based) as part of the pile driving (i.e., impact and vibratory) and construction activities associated with the Port of Anchorage Marine Terminal Redevelopment (MTR) Project. It has been reported that “No immediate negative behaviors (e.g., abrupt behavioral changes, rapid descents) were observed in response to pile driving or other MTR in-water construction activities. However, there is preliminary evidence that beluga whales have altered habitat use patterns in Knik Arm by avoiding the area in and around the MTR Project footprint and increasing use of the mid-channel and western shoreline” (ICRC, 2011). Specifically, there was a reduced proportion of sightings within and adjacent to MTR Project footprint in 2010 compared to 2009 and 2008 (i.e., 21% in 2010, 46% in 2009, and 64% in 2008).

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