

Likely sensitivity of bottlenose dolphins to pile-driving noise

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Abstract

Pile driver-generated noise has the potential to affect dolphin populations adversely as it is detectable up to 40 km from the source. At 9 kHz, this noise is capable of masking strong vocalisations within 10–15 km and weak vocalisations up to approximately 40 km. The masking radius reduces as the frequency increases: 6 km at 50 kHz and 1.2 km at 115 kHz. The impacts of masking are expected to be limited by the intermittent nature of pile driver noise, the dolphin's directional hearing, their ability to adjust vocalisation amplitude and frequency, and the structured content of their signals. Behavioural modifications have been observed in response to underwater sounds, including those produced by pile drivers, although in the latter case this may have been due to redistribution of prey species. A range of mitigation measures are proposed that are aimed at reducing the impact of pile driver noise on dolphin populations.

Introduction

Bottlenose dolphins (*Tursiops truncatus*) are widely distributed in warm and temperate waters throughout the world. There are resident groups inshore in the following coastal areas of Western Europe: Moray Firth, Scotland, Cardigan Bay, Wales, Cornwall/Devon, Dorset/Hampshire, North and West France, North-West Spain, Ireland – Shannon estuary and along the south-west coast (Evans 1992; Hammond *et al.* 1995; Rogan *et al.* 2000; Reid *et al.* 2003). Sightings at most UK coastal sites are greatest between July and October (with a secondary peak in some areas between March and April) (Evans 1992; Reid *et al.* 2003). These records do not necessarily reflect seasonal variations in distribution however, as sightings in the summer months are favoured by calmer seas and higher numbers of observers.

Populations are sufficiently small to warrant listing under Annex II of the Habitats Directive as a species whose conservation requires the designation of Special Areas of Conservation. Bottlenose dolphin populations attract considerable interest from both local residents and tourists and this interest can contribute significantly to the local economy (Hughes 2001).

Pile driving associated with construction work close to or within the sea appears to have the potential to modify dolphin behaviour, health and population densities, and this has caused concern at a number of UK locations. The response thresholds of cetaceans are usually the lowest for pulsed sounds, and pile driving is one of the loudest

sources of this type of noise (Richardson & Würsig 1996). This paper reports on the possible impact that pile-driving activity might have on bottlenose dolphin populations.

Importance of sound to bottlenose dolphins

For all cetaceans, including bottlenose dolphins, sound serves three main functions: (1) it provides information about their environment, (2) it is used for communication and (3) it enables the remote detection of prey. The sounds generated by these animals often extend beyond the range audible to the human ear (Table 1).

Dolphins produce loud bursts of echolocatory clicks (15–130 kHz) that are designed to function at relatively close range (rarely beyond a few kilometres), and are therefore likely to function primarily for local exploration and the detection and capture of prey. With low ambient noise or during confinement, these pulses are often between 20 and 60 kHz (Kamminga & van Velden 1987). With higher ambient noise, or when detecting more distant targets, higher amplitude pulses between 100 and 130 kHz may be generated (Au *et al.* 1974). It has been suggested that pure tone whistles are used to maintain group cohesion over large distances and may be used to contact separate groups (Janik 1997, 2000; Janik & Slater 1998). The distances at which these whistles appear to be effective (i.e. their active space) range from 14 to 25 km. Janik (2000) estimated that the radius of the active space

Table 1 Dolphin vocalisations (Au *et al.* 1974; Evans 1987; Richardson *et al.* 1995)

| Sound type | Frequency range (kHz) | Dominant frequencies (kHz) | Source level (dB re 1 μ Pa at 1 m) |
|------------|-----------------------|----------------------------|--|
| Barks | 0.20–16.0 | | |
| Whistles | 0.80–24.0 | 3.5–14.5 | 125–173 |
| Clicks | 0.10–300 | 15.0–130 | 218–228 |

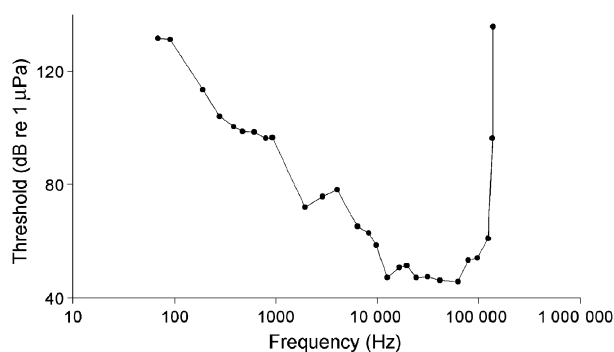
of unmodulated bottlenose dolphin whistles between 3.5 and 10 kHz, produced at maximum source level, was between 20 and 25 km in calm seas in the Moray Firth. The active space reduced to 1.5–4 km for whistles of 12 kHz. The significance of these measurements remains to be determined because it is not known to what extent the size of these active spaces is relevant to dolphin social behaviour (Janik 2000).

The auditory sensitivities of bottlenose dolphins are greatest at very high frequencies (15–130 kHz), where the hearing threshold is in the range 40–80 dB (Fig. 1). Hearing is progressively less sensitive as the frequency decreases, falling to approximately 130 dB for 100 Hz sounds (Lawson *et al.* 2001).

Sound localisation is an important aspect of hearing. In land mammals, two cues are important for localising sound: differences in arrival time (interaural time) and differences in sound level (interaural intensity). Binaural hearing studies are relatively rare for marine mammals, but the consensus from research on odontocetes is that binaural cues are important for underwater localisation (Renaud & Popper 1975; Moore *et al.* 1995). Odontocetes apparently have very good frequency discrimination; bottlenose dolphins can discriminate frequencies differing by 0.2–0.8% between 2 and 130 kHz (Thompson & Herman 1975).

Sound generated by pile driving

When quoting a sound level, it is important to give the range of frequencies (band) over which the level was

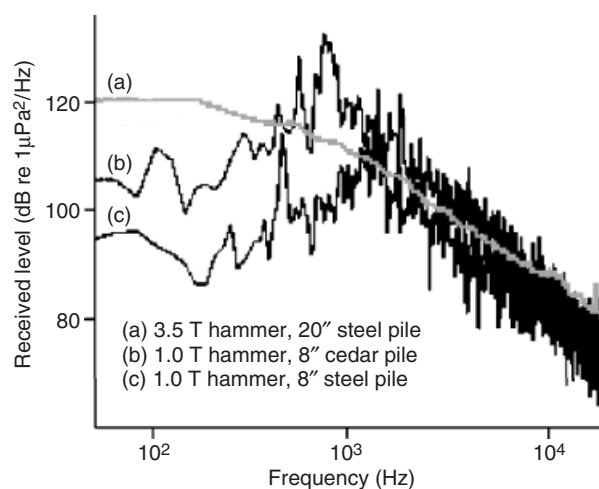
**Fig. 1.** Hearing thresholds of a bottlenose dolphin (Johnson 1967).

measured. Spectral density levels (dB re 1 μ Pa²/Hz) represent the mean square sound pressure in each 1 Hz band. Levels are often measured over an octave band (an octave is a factor of 2 in frequency) that represents the integral of the density spectrum over the bandwidth of the 1-octave band. When dealing with mammalian hearing, sound levels are often given for 1/3-octave bands (the sum of the sound power within all 1 Hz bands within the 1/3 octave) because the effective filter bandwidth in these animals is approximately 1/3 of an octave (Richardson *et al.* 1995).

Impulsive hammering can be loud: levels as high as 131–135 dB re 1 μ Pa were measured 1 km from a hammer used for pipe installation (Richardson *et al.* 1995). Blackwell *et al.* (2003) measured sounds generated by impact driving conductor and insulator pipes for oil and gas wells. Individual pile-driving pulses generated a mean underwater broadband level of 151 dB re 1 μ Pa.

S. Vagle (pers. comm.) recorded sound pressure levels from four projects in which 1–3.5 t drop hammers were used to drive either steel or wood piles into underwater substrates consisting of mud, clay, gravel or a combination of these. Sound pressure levels were measured over the frequency range of 50–22 000 Hz and were expressed as mean square pressure per unit frequency (dB re 1 μ Pa²/Hz at 1 m) representing the sound power in each 1 Hz band, after adjustment for spreading loss (see below). Pressure levels recorded at 1 kHz ranged from 100 to 130 dB re 1 μ Pa²/Hz, progressively falling as the sampling frequency increased (Fig. 2).

Würsig *et al.* (2000) measured the sound levels, in 1-octave bands (representing the sum of the sound pressures within each band), of pulses generated by a pile driver located between 250 and 1000 m from the receiver.

**Fig. 2.** Spectral density levels produced by various pile drivers (S. Vagle pers. comm.).

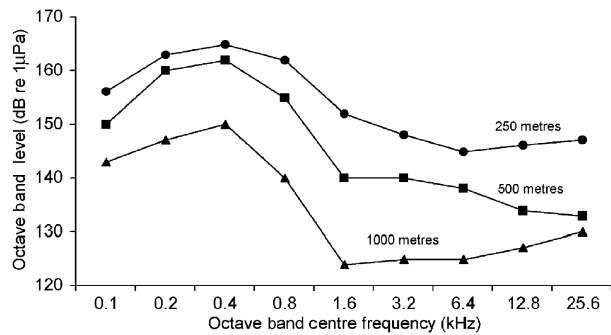


Fig. 3. One-octave band levels produced by a 6 t diesel hammer (Würsig *et al.* 2000).

The driver consisted of a 6 t diesel hammer that fell by gravity about 1.0–1.5 m during each stroke, detonating a fuel–air mixture to drive down the piling. Maximum blows delivered corresponded to approximately 90 kJ of energy during a 40 ms period. Pulse levels at a depth of 8 m and a distance of 250 m from the source showed a frequency profile similar to those obtained by S. Vagle (pers. comm.) and were highest for centre frequencies 200–800 Hz (approximately 162 dB 1-octave band level), progressively falling to approximately 146 dB for frequencies 12.8–25.6 kHz (Fig. 3). Converting these values to spectral density levels and adjusting for loss over distance (see below) give levels at 1 m of 165 dB re 1 $\mu\text{Pa}^2/\text{Hz}$ at 200–800 Hz falling to approximately 130 dB re 1 $\mu\text{Pa}^2/\text{Hz}$ at 12.8–25.6 kHz.

Detection of background noise

Sound intensities generated by a piling hammer or dolphin vocalisation will decrease with distance (R , km) from the source as a result of spreading and absorption. Spreading losses (dB) are independent of frequency but dependent on depth: $20 \log R$ for deep and $10 \log R$ for stratified or shallow (<200 m) coastal waters (Richardson *et al.* 1995). Spherical spreading usually persists from the source out to a range approximately equal to the depth of water, after which cylindrical spreading occurs. In the current context, where water is expected to be relatively shallow, transmission loss (TL) from the source to the receiver has been estimated using the following equation (Richardson *et al.* 1995):

$$\text{TL} = 10 \log(1000 R) + \alpha R$$

where α = absorption coefficient (dB/km) = $0.036(\text{frequency, kHz})^{1.5}$.

In order to be perceived, pile driver levels need to be above both the ambient noise and the hearing threshold. It is generally assumed that a sound is just detectable when its received level equals the level of

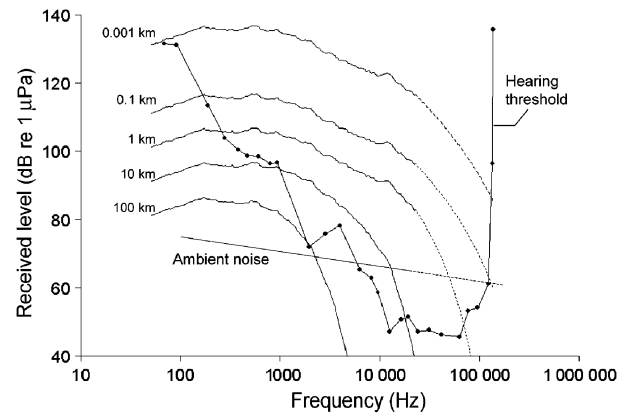


Fig. 4. Predicted 1/3-octave pile driver noise level spectra.

background noise in the same 1/3-octave band (Richardson *et al.* 1995). The predicted attenuation of pile driver noise spectra is shown in Fig. 4, together with hearing threshold and ambient noise (sea state 0) levels. In this figure, pile driver sound levels given in Fig. 2(a) and ambient noise are shown on a 1/3-octave basis at a range of distances from the source. In this example, pile driver-generated noise is detectable over the range of dolphin hearing up to a distance exceeding 10 km from the source. Values shown by dashed lines in Fig. 4 represent extrapolation of existing values to frequencies above 22 kHz. These values must therefore be treated as speculative.

Masking by background noise

The ability of dolphins to detect signals embedded in noise is measured using two parameters: masking band (MB) and critical ratio (CR). MB defines the frequency range able to mask a pure tone. Noise at frequencies outside the MB will have little effect on the detection of the tone. CR is a comparison of the signal power required for target detection versus noise power. MBs tend to be a constant function of the CR throughout an animal's functional hearing range.

Based on CR and masking bandwidth data, odontocetes, including bottlenose dolphins, are better than most mammals at detecting signals in noise. Johnson (1968) estimated masking bandwidths from the CRs of bottlenose dolphins. Between 5 and 100 kHz, MBs appeared to be less than 1/6-octave width and rose to approximately 1/3-octave width at 150 kHz.

Pile driver noise has the potential to mask dolphin vocalisations over a significant distance. Both these sounds will attenuate over distance, and masking will be determined by their levels relative to each other. Figure 5 shows estimated TLs for pile driver noise and dolphin

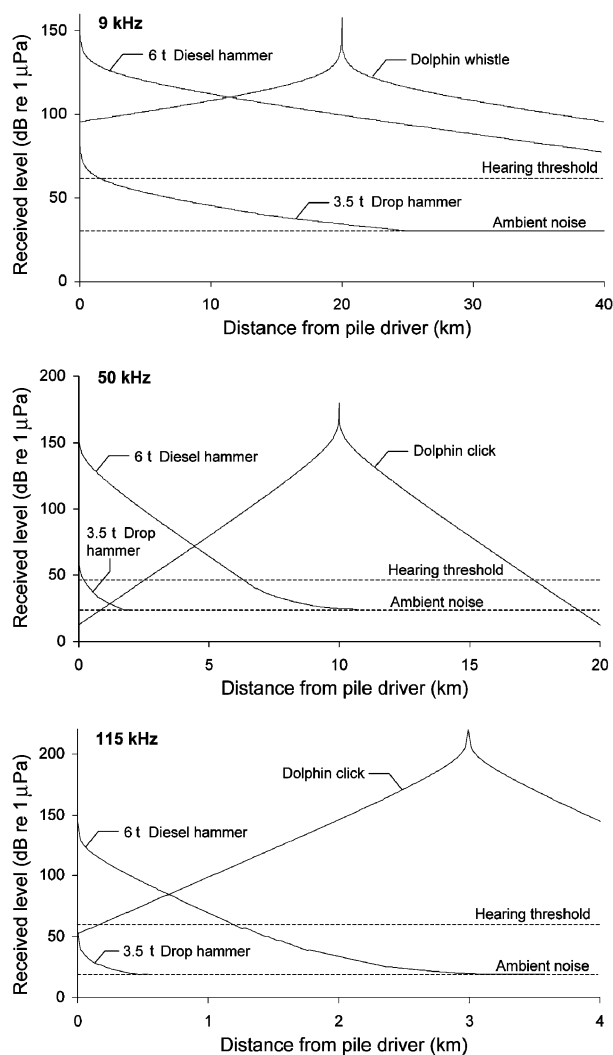


Fig. 5. Attenuation of sound over distance at 9, 50 and 115 kHz.

vocalisations for sea state 0, where ambient noise is lowest. Three vocalisation frequencies are shown: 9 kHz, representing the mean frequency of dolphin whistles (Janik 2000), and 50 and 115 kHz, representing, respectively, the mean frequencies of low- and high-amplitude echolocatory clicks (Au *et al.* 1974; Evans 1987; Kammin & van Velden 1987; Richardson *et al.* 1995).

Vocalisations above the hearing threshold will be audible unless below the total background noise (consisting of ambient plus pile driver noise) in the MB surrounding the call frequency. Figure 5 shows the sum of ambient (sea state 0) and pile driver noise levels for pile drivers illustrated in Figs 2(a) and 3. The figure also shows hearing threshold and ambient noise levels as dashed horizontal lines. The pile drivers are positioned at distance zero and the vocalising dolphin at an arbitrary distance along a straight line. One can imagine moving the dolphin

position to the left and right in order to explore the masking effects of background noise at different distances. Pile driver and ambient noise are measured in the MB surrounding the vocalisation frequency. Masking bandwidths are taken from estimations made from CRs, with values just below 1/6-octave width (Johnson 1968). Thus, pile driver pressure level (dB re 1 μPa) = spectrum noise level (dB re 1 $\mu\text{Pa}^2/\text{Hz}$ at 1 m) + 10 log(masking bandwidth).

Pressure levels for 50 and 115 kHz were estimated by extrapolation of the trends shown in Figs 2(a) and 3. These values must be considered highly speculative, particularly for 115 kHz, although inaccuracies in this frequency range are mitigated by the fact that such high frequencies attenuate relatively rapidly over distance.

According to Fig. 5, 9 kHz whistles would be audible by dolphins well in excess of 20 km from the source individual. Ranges for 50 and 115 kHz clicks are approximately 2 and 3 km, respectively. Masking is predicted when noise levels are above the received vocalisation level and hearing threshold. It is clear that the two types of pile driver differ significantly in the level of masking produced. The 3.5 t drop hammer would mask only weak vocalisations with a maximum masking radius of 1.3 km at 9 kHz, 0.2 km at 50 kHz and 0 km at 115 kHz. The 6 t diesel hammer appears to be capable of masking weak 9 kHz vocalisations over 40 km away and relatively strong calls within a radius of 10–15 km. Echolocatory clicks could be masked by this hammer at distances up to 6 and 1.2 km for 50 and 115 kHz sounds, respectively. These estimates are based on theoretical TLs in a homogeneous environment. In practice, they are likely to be higher owing to physical obstacles, water currents and variations in water depth.

As CRs and masking bandwidths are determined using continuous masking sound sources and the sound generated by pile drivers is intermittent and pulsatile, these zones of potential masking indicate that vocalisations are interrupted rather than hidden. The impacts of masking on dolphin vocalisations may be reduced because (i) dolphin hearing is directional and (ii) masking effects on echolocation are much reduced if the noise does not emanate from the direction of the target (Au & Moore 1984; Richardson *et al.* 1995). There is evidence that bottlenose dolphins can shift the dominant frequency of their echolocation frequencies away from masking noise frequencies and that they can increase the output level of these signals to counteract masking effects (Au *et al.* 1974; Moore & Pawloski 1990; Romanenko & Kitain 1992). The structured content of echolocation signals might resist masking to some extent because their frequency content and temporal characteristics differ from those of the background noise.

Observed effects of loud noises on dolphins

Pile driver noise can therefore be perceived by dolphins over a considerable distance and it may have some effect on their ability to detect vocalisations, but what impacts could pile driver noise have on dolphin physiology and behaviour? The threshold peak impulse sound pressure for direct physical trauma in marine mammals, birds and fish is generally considered to be > 200 dB (McCauley 1994; Richardson *et al.* 1995; Evans & Nice 1996; Gordon *et al.* 2003). This being the case, dolphins would not be expected to experience permanent hearing impairment from sound pressures generated by pile-driving activity, even when very close to the source. Effects on behaviour are more likely. As well as masking of communication and echolocation signals, pile driver noise could interfere with environmental sounds that animals listen to, for example the sound of surf or prey species. In addition, underwater noise could startle or displace animals.

Würsig *et al.* (2000) recorded the impact of pile driving into the seabed, in 6–8 m depths of water, on hump-backed dolphin behaviour. No overt behavioural changes were observed in response to the pile-driving activities, but the animals' speed of travel increased and some dolphins remained within the vicinity while others temporarily abandoned the area. Dolphin numbers returned close to normal once pile driving had ceased. The authors concluded that it was not possible to determine whether this temporary displacement from the area was due to a direct effect of the pile driving or indirect factors such as changes in prey distribution. Mullin *et al.* (1989) have reported displacement of bottlenose dolphins near oil production platforms at relatively shallow depths and attraction at deeper levels. Again, changes in prey distribution may have been responsible for this movement, although these were not investigated.

In an effort to reduce by-catches of bottlenose dolphins along the east coast of the United States, the potential for acoustic alarms to deter these animals was assessed by Cox *et al.* (2004). These alarms, or pingers, proved to be moderately effective in reducing by-catches of other small cetaceans by commercial gillnets in some cases. This study found that there was no significant change in dolphin numbers around the gillnet when the alarms were turned on. Bottlenose dolphins do, however, appear to be repelled by noise pulses obtained by striking an iron pipe held in the water (Mhenni 1993). An analysis of the sounds generated by similar 'bang pipes' showed that they produced frequencies in the range of 0.2–5.2 kHz and were capable of generating levels over 170 dB re 1 μ Pa (Akamatsu *et al.* 1993). No significant reactions to the playback of 800–900 Hz signals in excess of 120 dB re 1 μ Pa

were observed in bottlenose dolphins, but this is probably a reflection of their low sensitivity at these frequencies (Tyack *et al.* 1993).

Seismic surveys, such as those conducted during exploration for oil and gas, involve the production of some of the most intense man-made noises (200–250 dB re 1 μ Pa at 1 m) and often cover extensive areas for extended periods of time (Gordon *et al.* 2003). The frequency distributions of noise generated by airgun arrays used in seismic exploration are similar to those produced by pile drivers (Richardson *et al.* 1995). Early studies carried out during phases of seismic exploration in the southern Irish Sea suggested changes in bottlenose dolphin behaviour at the beginning of the seismic survey, but failed to demonstrate causal effects (Baines 1993; Evans & Nice 1996). In a study of the effects of seismic surveying on marine mammals in UK waters, the sighting rates of bottlenose dolphins were unaffected by the activity of both large airgun arrays and site surveys (Stone 2003). The bottlenose dolphin population in the Moray Firth, Scotland, has been exposed to seismic surveying activity within the area. This population has not been grossly displaced by these activities, although it may have been negatively impacted (Turnpenny & Nedwell 1994; Evans & Nice 1996).

Mitigation measures

The effects of pile driving on bottlenose dolphins may be reduced by adopting certain mitigation measures. If possible, operations should be avoided when dolphins are calving as lactating females and young calves are likely to be particularly vulnerable. Calving has been reported in all seasons but occurs predominantly in the warmer months (Connor *et al.* 2000). In Cardigan Bay, Wales, newborn calves have been observed between May and September (Grellier *et al.* 1995). The area of sea surrounding the pile-driving operations should be scanned for dolphin populations; this could include the use of hydrophones, which would be particularly useful in bad weather. It is recommended that this is performed by trained observers and that records are maintained of animals and their behaviour. The Joint Nature Conservation Committee (JNCC) guidelines recommend that an exclusion zone of 500 m radius should be monitored for at least 30 min before the start of piling (Joint Nature Conservation Committee 2004). If dolphins are observed in the exclusion zone, marine works should be delayed until they have left the area. If dolphins enter the exclusion zone after piling has commenced, marine works should cease until they have left. JNCC guidelines also recommend the adoption of a 'soft start'; using a low-energy start to the operations would give dolphins an opportunity to leave the area (Joint Nature Conservation Committee 2004). Alternatively, a ramped warning signal

could be given by banging on a steel pipe with progressively increasing force. However, at this time, there is no real evidence to indicate that this practice is effective; indeed, the noise may attract dolphins to the area. Monitoring the effectiveness of 'soft starts' by pile-driving operators should be encouraged in order to resolve this question. If possible, onshore piling should be restricted to low tide and sequenced so that no plant, including the piling hammer, will operate within the water. Offshore piling and related equipment should be acoustically decoupled from the hull of the piling vessel.

Some attenuation of pile driver noise has been achieved by surrounding piles with an air bubble curtain. Würsig *et al.* (2000) achieved a 3–5 dB attenuation of broadband pulse levels using an air bubble curtain positioned within a 25 m radius of the pile. The largest reductions in sound levels (8–20 dB) were achieved over a frequency range of 400–6400 Hz. Similar levels of attenuation have been reported by Longmuir & Lively (2001) using an air bubble curtain generated by placing manifolds around the pile at 7 m intervals, and by S. Vagle (pers. comm.) using a single ring around the base of the pile. Such measures could have a significant effect on the impact of pile driving on bottlenose dolphin behaviour as these frequencies are used for much of their whistling communication over relatively long distances. Higher levels of attenuation might be produced by proprietary equipment that contains the air bubbles within a material curtain or solid pipe; such equipment would also be more resistant to strong currents.

These mitigation measures should go some way towards limiting the impact of pile-driving activities on bottlenose dolphin populations. However, it is clear that further research into this area, and the reactions of marine mammals to industrial noise in general, is warranted. This is particularly so, given the increase in offshore industry related to the construction of wind farms.

Conclusions

(1) Underwater energy levels from piling operations are not expected to exceed 165 dB re $1 \mu\text{Pa}^2/\text{Hz}$ at 1 m from the source over the highest energy frequency range of 20 Hz to 1 kHz. Typical levels in this band are likely to be 100–130 dB re $1 \mu\text{Pa}^2/\text{Hz}$ at 1 m.

(2) Typical pile driver noise is expected to be perceived by populations over 10 km from the source, and loud sources will have the potential to mask whistles at distances up to 40 km and echolocatory clicks up to 6 km. The impacts of masking are expected to be limited by the directional hearing of dolphins and by the intermittent nature of the pile driver noise.

(3) Behavioural studies indicate a temporary displacement from the area where pile drivers are operating. The

causes are unknown, but possibilities include a reaction to the piling noise and dispersal of prey species.

(4) It is possible that the noise generated by pile driving up to distances of 40 km away could interfere with dolphin communication, echolocation and breeding. The impact would be significant if animals were scared away for an extended period, or if foraging, mating or nursing were impeded.

(5) The impacts of pile driver noise could be reduced by avoiding operations during the calving season, when dolphins can be detected in a 500 m exclusion zone and by the adoption of a soft-start procedure, ramped warning signals and bubble curtains.

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