
Jammerland Bay Nearshore A/S

# Underwater noise modelling of impact piling for 3 MW and 7 MW turbine foundations at Jammerland Bugt nearshore wind farm

JANUARY 2017

Jammerland Bay Nearshore A/S

# Underwater noise modelling of impact piling for 3 MW and 7 MW turbine foundations at Jammerland Bugt nearshore wind farm

| | |
|---|---|
| **Client** | Jammerland Bay Nearshore A/S<br>Gyngemose Parkvej 50<br>DK-2860 Søborg |
| **Consultant** | Ringstedvej 20<br>DK-4000 Roskilde |
| **Sub-consultant** | Subacoustech Environmental Ltd<br>Unit 9, Claylands Park<br>Claylands Road<br>Bishops Waltham<br>Southampton, Hampshire<br>SO32 1QD, UK |
| **Project no.** | 3621400172 |
| **Document no.** | JB-TR-003 |
| **Version no.** | 02 |
| **Prepared by** | R.J. Barham |
| **Reviewed by** | Tim Mason |
| **Approved by** | Kristian Nehring Madsen |
| **Photos** | Unless specified © Orbicon A/S |
| **Published** | January 2017 |

INDHOLDSFORTEGNELSE

# 1 INTRODUCTION

Underwater noise modelling has been undertaken with respect to impact piling for installation of foundations for offshore wind turbines at the Jammerland Bugt Offshore Wind Farm. The underwater noise modelling considered the installation of 3 MW and 7 MW turbine foundations.

## 1.1 The INSPIRE model

The INSPIRE model (currently version 3.4.3) is a semi-empirical underwater noise propagation model based around a combination of numerical modelling and actual measured data. The model provides estimates of the unweighted peak, peak-to-peak and RMS level of noise as well as various other metrics along 180 equally spaced radial transects (one every 2 degrees).

For each scenario, a criterion level can be specified allowing a contour to be drawn, within which a given effect may occur. These results are then plotted over the bathymetry data so that impact ranges can be clearly visualised and assessed as necessary.

## 1.2 Turbine details

A 3 MW and a 7 MW turbine model are being considered for the wind farm and no further details regarding the turbine foundations or installation techniques are currently available. For the purposes of noise modelling, appropriate engineering parameters have been selected based on those used or proposed either previously on Danish projects or other wind farms on a similar scale, and scaled from these parameters.

## 1.3 Modelling parameters

A soft start of 20 minutes has been included, with a gentle ramp-up in blow energy over the entire installation period; this is summarised in Table 1-1. Although large impact hammers, such as the Menck 1900S and Menck 3000S, are capable of delivering 32 blows per minute at maximum energy, the strike rate will tend to be much slower initially and so 3 seconds per blow over the whole piling period is expected to provide a reasonable average. It should be noted that all the modelling results assumed that only one piling operation will occur at any one time; i.e. there will be no simultaneous piling operations.

The following parameters are used for the underwater noise assessment, and assume a monopile installation:

### 3 MW turbine

| | |
|---|---|
| Foundation diameter | 3 metres |
| Maximum installation energy | 1200 kJ (250 kJ at soft start) |
| Average strike rate | 1 strike every 3 seconds |
| Total installation time | 2 hours |

## 7 MW turbine

| | |
|---|---|
| Foundation diameter | 6 metres |
| Maximum installation energy | 1800 kJ (350 kJ at soft start) |
| Average strike rate | 1 strike every 3 seconds |
| Total installation time | 4 hours |

Underwater noise levels from piling were modelled for locations at the north and south of the Jammerland Bugt offshore wind farm boundary; these locations are summarised in Table 1-2 and Figure 1-1. It should be noted that the turbine positions for the 3 MW and 7 MW scenarios vary due to the differing layouts of the two turbine sizes.

Table 1-1 Summary of the soft start and ramp up procedure assumed for the modelling.

| 3 MW turbine | | 7 MW turbine | |
|---|---|---|---|
| Energy (kJ) | Time (minutes) | Energy (kJ) | Time (minutes) |
| 250 (soft start) | 20 | 350 (soft start) | 20 |
| 400 | 20 | 500 | 30 |
| 600 | 20 | 750 | 30 |
| 800 | 20 | 1000 | 30 |
| 1000 | 20 | 1250 | 30 |
| 1200 | 20 | 1500 | 40 |
| | | 1800 | 60 |

Table 1-2 Co-ordinates of the four modelling locations (UTM (north)-WGS84, Zone 32).

| | T53 (3 MW) | T20 (7 MW) | T31 (3 MW) | T10 (7 MW) |
|---|---|---|---|---|
| Easting | 624.970 | 622.275 | 625.576 | 626.004 |
| Northing | 6.165.109 | 6.163.694 | 6.156.158 | 6.155.807 |

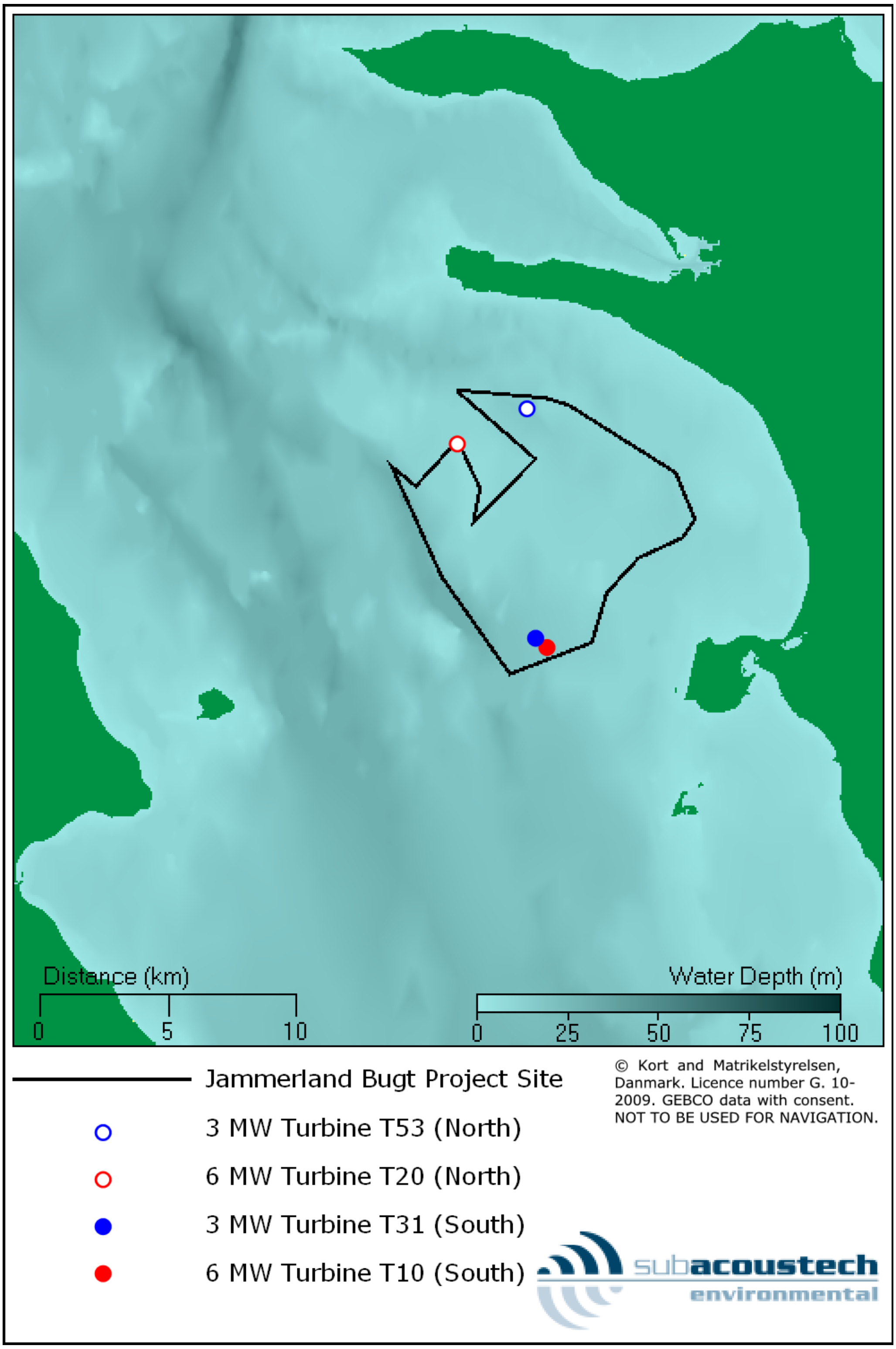


Figure 1-1 Map showing the boundary of the Jammerland Bugt site along with the four

# 2 ASSESSMENT METRICS AND CRITERIA

## 2.1 Lethal and physical injury

Two criteria have been identified to assess lethal effect and physical injury, unrelated to hearing, to all receptors using unweighted peak sound pressure levels (SPLs) (Parvin *et al*, 2007). These are:

- 240 dB re 1 µPa single strike unweighted peak SPL for lethal effect; and
- 220 dB re 1 µPa single strike unweighted peak SPL for physical traumatic injury, in excess of hearing damage.

## 2.2 Modelling of PTS in marine mammals

Two criteria for assessing permanent threshold shift (PTS) in marine mammals have been used. The two criteria are:

- 186 dB re 1 µPa$^2$s ($M_{pw}$) cumulative M-Weighted SEL for PTS in pinnipeds (Southall *et al,* 2007); and
- 180 dB re 1 µPa$^2$s cumulative unweighted SEL for PTS in harbour porpoise (Lucke *et al*, 2009).

Both of these criteria take into account the cumulative received Sound Exposure Level (SEL) for a marine mammal over the entire piling operation. For this modelling it is assumed that the receptor is fleeing from the noise at a rate of 1.5 m/s (Otani *et al*, 2000).

The noise propagation model handles fleeing animals and cumulative noise impacts over time by calculating “starting range” for receptor. The contour output defines the noise exposure an animal would receive if it was at that point when the piling began and swam radially away. Thus, if an animal was inside the contour at the start of piling, it would receive a cumulative exposure in excess of the respective criterion. The noise model assumes that if the fleeing animal meets the coast it will stop in the shallow water for the remainder of the piling.

## 2.3 Modelling of TTS in marine mammals

Two criteria for assessing temporary threshold shift (TTS) in marine mammals have been used. These criteria are as follows:

- 171 dB re 1 µPa$^2$s ($M_{pw}$) single strike M-Weighted SEL for TTS in pinnipeds (Southall *et al,* 2007); and
- 165 dB re 1 µPa$^2$s single strike unweighted SEL for TTS in harbour porpoise (Lucke *et al*, 2009).

## 2.4 Modelling of injury in fish

Three criteria for assessing injury in fish have been identified (FHWG, 2008). These criteria are:

- 206 dB re 1 µPa single strike unweighted SPL (peak) for injury in all sizes of fish;
- 187 dB re 1 µPa$^2$s cumulative unweighted SEL for injury in all sizes of fish; and
- 183 dB re 1 µPa$^2$s cumulative unweighted SEL for injury for fish under 2 g in mass.
-

The second and third of these criteria take into account the cumulative received SEL for a receptor over the entire piling operation. For this modelling it is assumed that the receptor is stationary, not fleeing, throughout the piling operation.
A recent publication by Popper et al (2014) has identified a noise level of 207 dB $SPL_{peak}$ and 203 dB re 1 µPa$^2$s cumulative unweighted SEL, which could potentially lead to an injury in fish. These are both greater than the levels identified above, and with respect to the cumulative level, substantially greater. The criteria bulleted above will continue to be used as conservative values.

## 2.5 Modelling of behavioural effect in marine mammals using unweighted SELs

Two criteria have been identified for assessing the behavioural effect in marine mammals, both using the level from a single strike in terms of unweighted SEL. The two criteria are:

- 150 dB re 1 µPa$^2$s single strike unweighted SEL for behavioural effect in harbour porpoise and pinnipeds (Brandt *et al*, 2009); and
- 145 dB re 1 µPa$^2$s single strike unweighted SEL for minor behavioural effect in harbour porpoise and pinnipeds (Lucke *et al*, 2009).

## 2.6 Modelling of behavioural effect using the $dB_{ht}$(*Species*)

The $dB_{ht}$(*Species*) value represents the number of decibels above the hearing threshold of a species, so in effect a perceived noise level by that species. 0 $dB_{ht}$(*Species*) is therefore, in effect, the minimum perceptible noise level by that species, based on its audiogram where available. A criterion of 90 $dB_{ht}$ with reference to a species' audiogram is a noise level perceived as sufficiently loud that the majority of individuals will try to avoid a region insonified to that extent (Nedwell *et al*, 2007).

## 2.7 Summary of criteria

Table 2-1 collates all the criteria used in this assessment from the previous sections.

Table 2-1 Summary of noise criteria used for the assessment of potential impact on marine mammals and fish.

| Effect | Criteria | Weighting | Species covered |
|---|---|---|---|
| Lethal | 240 dB re 1 µPa | Unweighted $SPL_{peak}$ | All |
| Physical injury | 220 dB re 1 µPa | Unweighted $SPL_{peak}$ | All |
| PTS | 186 dB re 1 $µPa^2s(M_{pw})$ | Cumulative M-Weighted SEL (pinnipeds in water) | Pinniped (seal) |
| PTS | 180 dB re 1 $µPa^2s$ | Cumulative unweighted SEL | Harbour porpoise |
| TTS | 171 dB re 1 $µPa^2s(M_{pw})$ | Single strike M-Weighted SEL (pinnipeds in water) | Pinniped (seal) |
| TTS | 165 dB re 1 $µPa^2s$ | Single strike unweighted SEL | Harbour porpoise |
| Injury | 206 dB re 1 µPa | Unweighted $SPL_{peak}$ | All fish |
| Injury | 187 dB re 1 $µPa^2s$ | Cumulative unweighted SEL | All fish |
| Injury | 183 dB re 1 $µPa^2s$ | Cumulative unweighted SEL | Fish with mass < 2 g |
| Behavioural effect | 150 dB re 1 $µPa^2s$ | Single strike unweighted SEL | Harbour porpoise and pinniped (seal) |
| Behavioural effect | 90 $dB_{ht}$(*Species*) | $dB_{ht}$(*Species*) | Various (species specific) |
| Minor behavioural effect | 145 dB re 1 $µPa^2s$ | Single strike unweighted SEL | Harbour porpoise and pinniped (seal) |

# 3 MODELLING RESULTS

## 3.1 Source levels

In order to establish likely levels of noise arising from impact piling operations, source levels of the piling activities at Jammerland Bugt have been modelling using the INSPIRE model, based on measurements undertaken by Subacoustech Environmental. The estimated source levels, in terms of unweighted peak SPLs and unweighted, single strike, SELs are summarised in Table 3-1 below.

Table 3-1 Summary of the modelled source levels for the two piling scenarios.

| | Unweighted $SPL_{peak}$ | Unweighted SEL |
|---|---|---|
| **3 MW turbine**<br>(3 m diameter pile, 1200 kJ maximum blow energy) | 240.4 dB re 1 µPa @ 1 m | 214.8 dB re 1 µPa$^2$s @ 1 m |
| **7 MW turbine**<br>(6 m diameter pile, 1800 kJ maximum blow energy) | 243.1 dB re 1 µPa @ 1 m | 219.1 dB re 1 µPa$^2$s @ 1 m |

It is important to note that source noise levels are estimated from apparent levels back-calculated from the far-field, and actual levels at 1 m from the pile will be variable within the water column.

## 3.2 Level with range

For each modelling scenario the transect with minimum attenuation (i.e. the longest predicted range) has been selected and an appropriate fit to the data has been made using an equation in the form $L_r = SL - N\log_{10} r - \alpha_r$, where $L_r$ is the level at any range, *r*. At all locations, the transects with minimum attenuation were those extending to the south between 170° and 180°. This has been carried out for both unweighted peak SPLs and unweighted, single strike, SELs. Also included are the predicted noise levels at 750 m from the piling.

### 3.2.1 Unweighted peak SPL

- For the 3 MW turbine modelling at the north location (turbine ref. T53), the predicted unweighted peak SPLs along the 178° transect can be approximated as $L_r = 240.4 - 16\log_{10} r - 0.00096r$. At 750 m the unweighted peak SPL is predicted to be 193.3 dB re 1 µPa.
- For the 7 MW turbine modelling at the north location (turbine ref. T20), the predicted unweighted peak SPLs along the 170° transect can be approximated as $L_r = 243.1 - 17.3\log_{10} r - 0.00085r$. At 750 m the unweighted peak SPL is predicted to be 192.6 dB re 1 µPa. This is lower than the 3 MW model, despite the higher source level above, because of the shallower water in the most northerly 7 MW location.

- For the 3 MW turbine modelling at the south location (turbine ref. T31), the predicted unweighted peak SPLs along the 178° transect can be approximated as $L_r = 240.4 - 16\log_{10} r - 0.00085r$. At 750 m the unweighted peak SPL is predicted to be 193.3 dB re 1 µPa.
- For the 7 MW turbine modelling at the south location (turbine ref. T10), the predicted unweighted peak SPLs along the 180° transect can be approximated as $L_r = 243.1 - 16.1\log_{10} r - 0.00087r$. At 750 m the unweighted peak SPL is predicted to be 195.9 dB re 1 µPa.

These fits are provided as level versus range plots in Figure 3-1 to Figure 3-4, below.

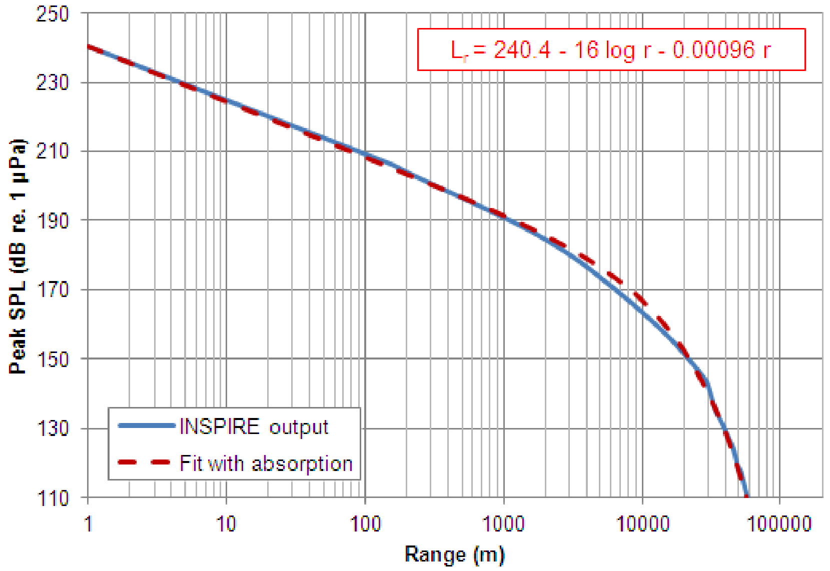


Figure 3-1 Level versus range plot showing the predicted unweighted peak SPL values along the 178° transect from the north location for the 3 MW turbine (T53), and the attenuation approximated as an N log R curve.

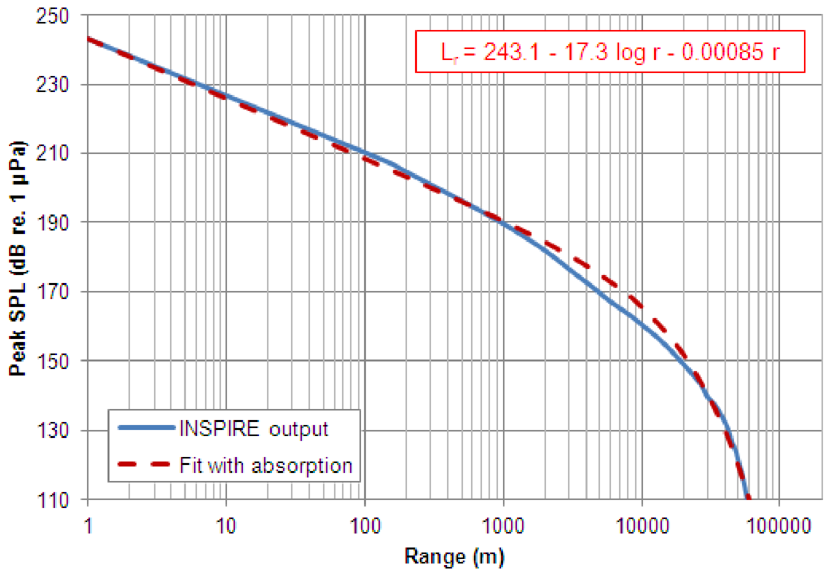


Figure 3-2 Level versus range plot showing the predicted unweighted peak SPL values along the 170° transect from the north location for the 7 MW turbine (T20), and the attenuation approximated as an N log R curve.

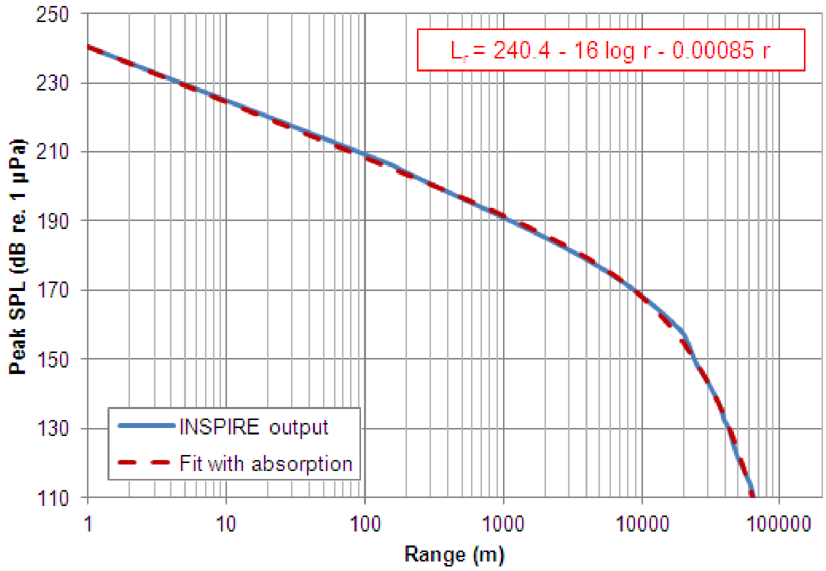


Figure 3-3 Level versus range plot showing the predicted unweighted peak SPL values along the 178° transect from the south location for the 3 MW turbine (T31), and the attenuation approximated as an N log R curve.

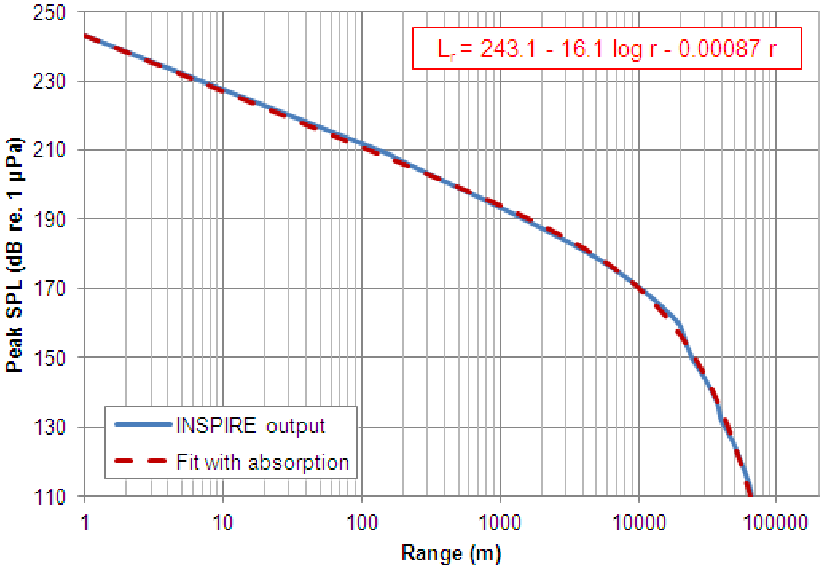


Figure 3-4 Level versus range plot showing the predicted unweighted peak SPL values along the 180° transect from the south location for the 7 MW turbine (T10), and the attenuation approximated as an N log R curve.

### 3.2.2 Unweighted single strike SEL

- For the 3 MW turbine modelling at the north location (T53), the predicted unweighted single strike SELs along the 176° transect can be approximated as $L_r = 214.8 - 14\log_{10} \mathrm{r} - 0.0007\mathrm{r}$. At 750 m the unweighted, single strike, SEL is predicted to be 174.1 dB re 1 µPa²s.
- For the 7 MW turbine modelling at the north location (T20), the predicted unweighted single strike SELs along the 170° transect can be approximated as $L_r = 219.1 - 14.7\log_{10} r - 0.00068r$. At 750 m the unweighted, single strike, SEL is predicted to be 176.1 dB re 1 µPa²s.
- For the 3 MW turbine modelling at the south location (T31), the predicted unweighted single strike SELs along the 178° transect can be approximated as $L_r = 214.8 - 13.8\log_{10} r - 0.0007r$. At 750 m the unweighted, single strike, SEL is predicted to be 174.2 dB re 1 µPa²s.
- For the 7 MW turbine modelling at the south location (T10), the predicted unweighted single strike SELs along the 180° transect can be approximated as $L_r = 219.1 - 13.8\log_{10} r - 0.0007r$. At 750 m the unweighted, single strike, SEL is predicted to be 178.3 dB re 1 µPa²s.

These fits are provided as level versus range plots in Figure 3-5 to Figure 3-8 below.

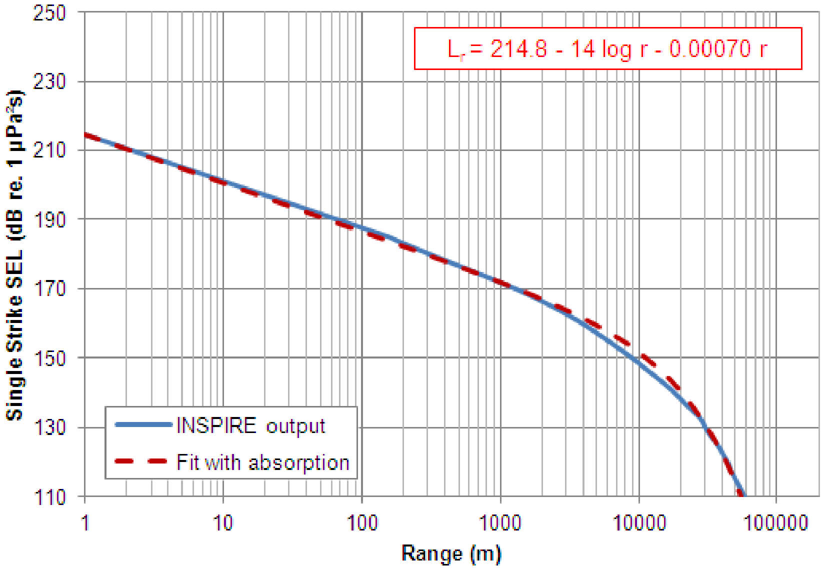


Figure 3-5 Level versus range plot showing the predicted unweighted single strike SEL values along the 176° transect from the north location for the 3 MW turbine (T53), and the attenuation approximated as an N log R curve.

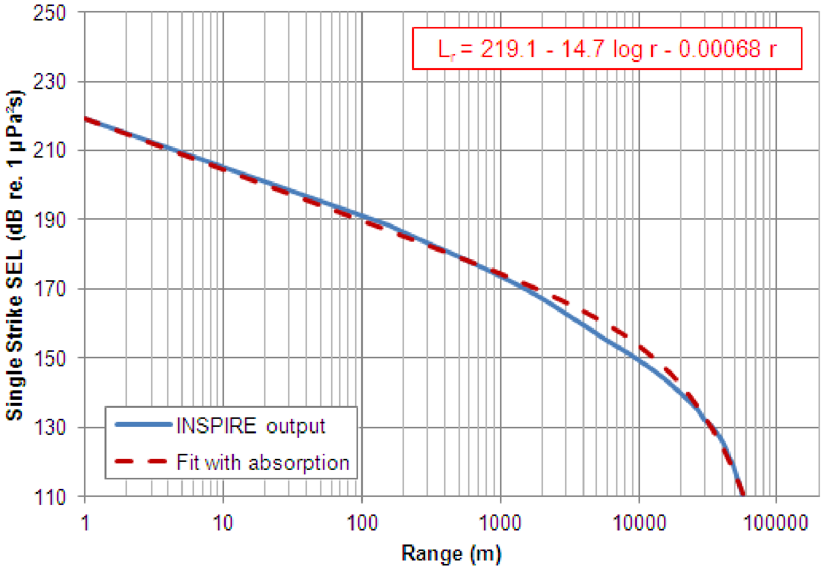


Figure 3-6 Level versus range plot showing the predicted unweighted single strike SEL values along the 170° transect from the north location for the 7 MW turbine (T20), and the attenuation approximated as an N log R curve.

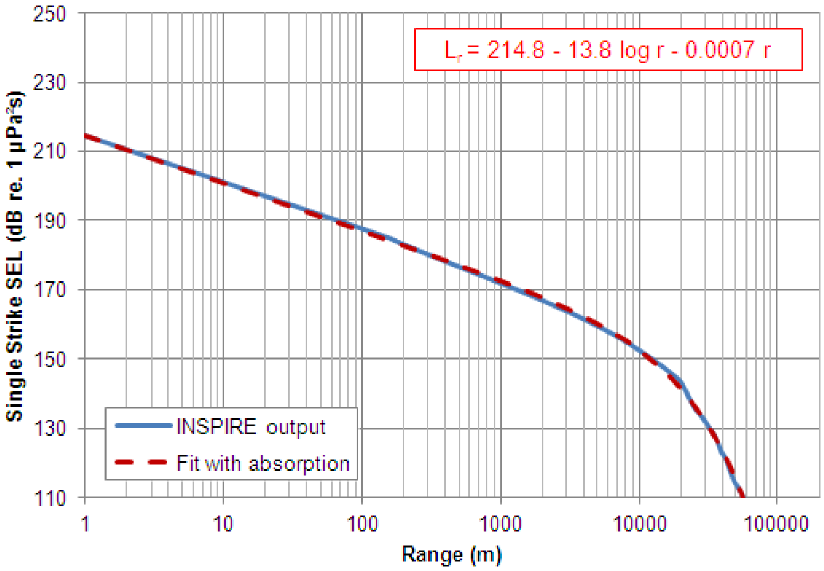


Figure 3-7 Level versus range plot showing the predicted unweighted single strike SEL values along the 178° transect from the south location for the 3 MW turbine (T31), and the attenuation approximated as an N log R curve.

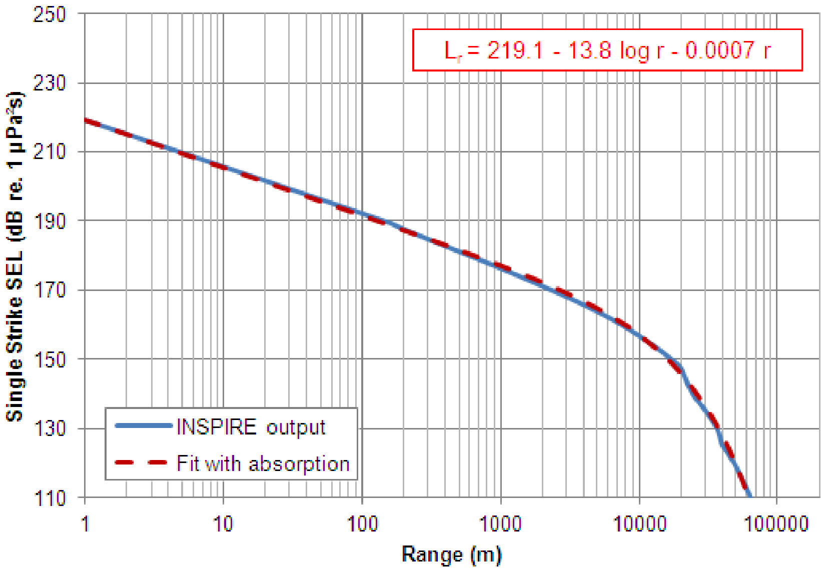


*Figure 3-8 Level versus range plot showing the predicted unweighted single strike SEL values along the 180° transect from the south location for the 7 MW turbine (T10), and the attenuation approximated as an N log R curve.*

## 3.3 Lethal and physical injury

The results of modelling the 3 MW and 7 MW turbine foundation piles being installed at the maximum blow energy are summarised in Table 3-2 below.

Table 3-2 Maximum predicted impact ranges for lethal effect and physical traumatic injury.

| | **Lethal effect** 240 dB re 1 µPa ($SPL_{peak}$) | | **Physical traumatic injury** 220 dB re 1 µPa ($SPL_{peak}$) | |
|---|---|---|---|---|
| | **3 MW turbine** | **7 MW turbine** | **3 MW turbine** | **8 MW turbine** |
| **North** | 2 m | 2 m | 18 m | 23 m |
| **South** | 2 m | 2 m | 18 m | 27 m |

## 3.4 Modelling of PTS in marine mammals

It is assumed that at the start of piling, the noise level will be such that an animal will flee from the source. The ranges in Table 3-3 and
Table 3-4 below define the modelled distance from the pile at which an animal would just receive the criterion dose for PTS if it was at that distance at the start of piling and fled. If an animal was closer than this distance to the pile at the start of piling and fled, it would receive a noise exposure greater than the criterion. If it was further from the pile, then it would receive a dose lower than the criterion.

For this modelling it is assumed that the receptor is fleeing from the noise at a rate of 1.5 m/s (Otani *et al*, 2000). As a comparison, modelling assuming a stationary animal has also been undertaken. The ranges below show the ranges where a receptor would need to be for the entire piling duration to receive a noise exposure greater than the criterion. This approach is briefly discussed in section 2.2.

Table 3-3 Predicted impact ranges using the PTS criteria for pinnipeds, an animal closer than this distance at the start of piling will receive an exposure in excess of the criterion.

| **PTS (Pinniped/Seal)** 186 dB SEL re 1 µPa$^2$s ($M_{pw}$) (cumulative SEL) | | **3 MW turbine** (fleeing 1.5 ms$^{-1}$) | **7 MW turbine** (fleeing 1.5 ms$^{-1}$) | **3 MW turbine** (stationary) | **7 MW turbine** (stationary) |
|---|---|---|---|---|---|
| **North** | Maximum | 0.3 km | 0.3 km | 3.5 km | 4.6 km |
| | Minimum | 0.2 km | 0.2 km | 2.9 km | 3.0 km |
| | Mean | 0.3 km | 0.2 km | 3.2 km | 4.0 km |
| **South** | Maximum | 0.4 km | 1.0 km | 4.1 km | 8.2 km |
| | Minimum | 0.3 km | 0.6 km | 3.1 km | 5.2 km |
| | Mean | 0.3 km | 0.8 km | 3.5 km | 6.5 km |

Table 3-4 Predicted impact ranges using the PTS criteria for harbour porpoises, an animal closer than this distance at the start of piling will receive an exposure in excess of the criterion.

| **PTS (Harbour Porpoise)** 180 dB SEL re 1 µPa$^2$s (cumulative SEL) | | **3 MW turbine** (fleeing 1.5 ms$^{-1}$) | **7 MW turbine** (fleeing 1.5 ms$^{-1}$) | **3 MW turbine** (stationary) | **7 MW turbine** (stationary) |
|---|---|---|---|---|---|
| **North** | Maximum | 3.9 km | 5.0 km | 9.1 km | 15.7 km |
| | Minimum | 1.9 km | 2.4 km | 4.5 km | 6.1 km |
| | Mean | 2.5 km | 3.5 km | 6.6 km | 10.7 km |
| **South** | Maximum | 4.7 km | 8.1 km | 4.1 km | 18.4 km |
| | Minimum | 2.1 km | 3.0 km | 3.1 km | 5.2 km |
| | Mean | 3.3 km | 5.2 km | 3.5 km | 12.8 km |

Thus, an animal inside the ranges above at the start of piling is at risk of PTS according to the defined criterion.

## 3.5 Modelling of TTS in marine mammals

The range within which a marine mammal must be at the start of piling to elicit TTS to the criteria discussed in Section 2.3 is summarised in Table 3-5 and

Table 3-6.

Table 3-5 Predicted impact ranges using the TTS criteria for pinnipeds using single strike M-Weighted SELs.

| **TTS (Pinniped/Seal)** 171 dB re 1 µPa$^2$s ($M_{pw}$) (single strike SEL) | | **3 MW turbine** | **7 MW turbine** |
|---|---|---|---|
| **North** | Maximum | 730 m | 660 m |
| | Minimum | 670 m | 600 m |
| | Mean | 710 m | 640 m |
| **South** | Maximum | 730 m | 1160 m |
| | Minimum | 710 m | 1080 m |
| | Mean | 720 m | 1120 m |

Table 3-6 Predicted impact ranges using the TTS criteria for harbour porpoise using unweighted single strike SELs.

| **TTS (Harbour Porpoise)** 165 dB re 1 µPa$^2$s (single strike SEL) | | **3 MW turbine** | **7 MW turbine** |
|---|---|---|---|
| **North** | Maximum | 2.6 km | 3.3 km |
| | Minimum | 2.3 km | 2.5 km |
| | Mean | 2.4 km | 3.1 km |
| **South** | Maximum | 2.8 km | 4.7 km |
| | Minimum | 2.5 km | 3.6 km |
| | Mean | 2.6 km | 4.1 km |

## 3.6 Modelling of injury in fish

The range within which a fish must be at the start of piling to elicit TTS are summarised in Table 3-7 and
Table 3-8. As stated in section 2.4, it is assumed for this modelling that the receptor is stationary throughout the piling operation.

Table 3-7 Predicted impact ranges using the $SPL_{peak}$ injury criteria for fish.

| **All fish** 206 dB re 1 µPa ($SPL_{peak}$) | | **3 MW turbine** | **7 MW turbine** |
|---|---|---|---|
| **North** | Maximum | 131 m | 146 m |
| | Minimum | 129 m | 145 m |
| | Mean | 130 m | 146 m |
| **South** | Maximum | 130 m | 187 m |
| | Minimum | 129 m | 185 m |
| | Mean | 130 m | 186 m |

Table 3-8 Predicted impact ranges using the SEL injury criteria for all sizes of fish (assuming stationary animal).

| **All fish** 187 dB re 1 µPa$^2$s (cumulative SEL) | | **3 MW turbine** | **7 MW turbine** |
|---|---|---|---|
| **North** | Maximum | 4.6 km | 8.3 km |
| | Minimum | 3.6 km | 5.1 km |
| | Mean | 4.1 km | 6.8 km |
| **South** | Maximum | 5.1 km | 10.5 km |
| | Minimum | 3.8 km | 5.2 km |
| | Mean | 4.4 km | 8.4 km |

Where the fish are less than 2 grams in mass, the stricter criterion of 183 dB re 1 µPa$^2$s is relevant and shown in Table 3-9.

Table 3-9 Predicted impact ranges using the SEL injury criteria for fish with mass less than 2 grams in weight (assuming stationary animal).

| **Fish with mass < 2 g** 183 dB re 1 µPa$^2$s (cumulative SEL) | | **3 MW turbine** | **7 MW turbine** |
|---|---|---|---|
| **North** | Maximum | 6.9 km | 11.9 km |
| | Minimum | 4.5 km | 6.1 km |
| | Mean | 5.5 km | 8.9 km |
| **South** | Maximum | 7.6 km | 14.8 km |
| | Minimum | 5.3 km | 5.2 km |
| | Mean | 6.3 km | 10.9 km |

## 3.7 Modelling of behavioural effect in marine mammals using unweighted SELs

Table 3-10 summarises the levels at which a behavioural effect and a minor behavioural effect may be experienced by harbour porpoise and pinnipeds using the unweighted SEL criteria discussed in Section 2.5.

Table 3-10 Predicted impact ranges for behavioural effect using unweighted SEL criteria for marine mammals.

| Harbour porpoise and pinniped (seal) | | **Behavioural effect** 150 dB re 1 µPa$^2$s (single strike SEL) | | **Minor behavioural effect** 145 dB re 1 µPa$^2$s (single strike SEL) | |
|---|---|---|---|---|---|
| | | **3 MW** | **7 MW** | **3 MW** | **7 MW** |
| **North** | Maximum | 12.0 km | 14.5 km | 17.7 km | 19.6 km |
| | Minimum | 4.4 km | 6.1 km | 4.4 km | 6.1 km |
| | Mean | 7.9 km | 10.6 km | 10.4 km | 13.4 km |
| **South** | Maximum | 8.5 km | 18.1 km | 13.4 km | 24.6 km |
| | Minimum | 5.6 km | 5.2 km | 5.6 km | 5.2 km |
| | Mean | 7.0 km | 12.7 km | 10.2 km | 15.6 km |

It can be commented that the minimum ranges in Table 3-10 are limited by the nearest landfall to the piling event.

## 3.8 Modelling of behavioural effect using the $dB_{ht}$(*Species*) metric

Table 3-11, below, summarises the 90 $dB_{ht}$(*Species*) impact ranges for various species of fish and marine mammal. As discussed in Section 2.6, the $dB_{ht}$(*Species*) metric is a species specific metric based on a receptors audiogram. A criterion of 90 $dB_{ht}$(*Species*) is a noise level where a strong avoidance reaction is likely to occur in virtually all individuals.

Table 3-11 Summary of the modelled ranges out to 90 $dB_{ht}$(Species).

| 90 $dB_{ht}$(*Species*) | | North | | South | |
|---|---|---|---|---|---|
| | | **3 MW** | **7 MW** | **3 MW** | **7 MW** |
| **Cod** | Maximum | 10.5 km | 11.3 km | 12.2 km | 17.7 km |
| | Minimum | 4.4 km | 5.9 km | 5.6 km | 5.2 km |
| | Mean | 6.9 km | 8.2 km | 9.0 km | 12.0 km |
| **Dab** | Maximum | 2.6 km | 3.2 km | 2.9 km | 5.3 km |
| | Minimum | 2.3 km | 2.5 km | 2.5 km | 3.8 km |
| | Mean | 2.5 km | 3.0 km | 2.7 km | 4.5 km |
| **Herring** | Maximum | 13.4 km | 14.3 km | 15.2 km | 19.4 km |
| | Minimum | 4.4 km | 6.1 km | 5.6 km | 5.2 km |
| | Mean | 8.4 km | 10.2 km | 11.1 km | 13.1 km |
| **Sand lance** | Maximum | 0.1 km | 0.2 km | 0.1 km | 0.2 km |
| | Minimum | 0.1 km | 0.1 km | 0.1 km | 0.2 km |
| | Mean | 0.1 km | 0.2 km | 0.1 km | 0.2 km |
| **Harbour porpoise** | Maximum | 12.5 km | 11.5 km | 14.0 km | 14.2 km |
| | Minimum | 4.4 km | 6.1 km | 5.6 km | 5.2 km |
| | Mean | 8.6 km | 9.2 km | 10.8 km | 11.1 km |
| **Harbour seal** | Maximum | 8.9 km | 7.8 km | 9.7 km | 9.8 km |
| | Minimum | 4.4 km | 5.0 km | 5.6 km | 5.2 km |
| | Mean | 6.5 km | 6.5 km | 7.9 km | 7.9 km |

# 4 SUMMARY AND CONCLUSIONS

Subacoustech Environmental has undertaken a study of the impact of underwater piling in the Great Belt in relation to the proposed construction of offshore wind turbine foundations as part of the Jammerland Bugt project.
Modelling of underwater noise produced by the installation of foundations for 3 MW turbines and 7 MW turbines has been undertaken, using proposed parameters for the foundation piles. No direct noise control mitigation has been applied to the modelled noise levels.

Unweighted peak source levels of noise during installation are expected to be 240.4 dB re 1 µPa @ 1 m for the 3 MW turbine, and 243.1 dB re 1 µPa @ 1 m for the 7 MW turbine. Approximate N log R fits to the predicted noise attenuation have also been made.

Modelling shows that lethality and physical injury, using the Parvin *et al* (2007) criteria, may occur out to a maximum of 2 m and 27 m respectively for the installation of the larger 7 MW turbine.

The criteria for assessing PTS (permanent threshold shift) in marine mammals show that species of pinniped (Southall *et al*, 2007) are likely to experience PTS at a maximum range of 8.2 km and harbour porpoise (Lucke *et al*, 2009) are likely to experience PTS at a maximum range of 18.4 km, assuming the worst case ‘stationary animal’ model during installation of an 7 MW turbine. Using the single strike criteria, pinnipeds (Southall *et al*, 2007) are likely to experience TTS at a maximum range of 1.2 km and harbour porpoise (Lucke *et al*, 2009) would experience TTS at 4.7 km, for the 7 MW turbine.

Injury in species of fish has been assessed using the FHWG (2008) criteria. Predicted maximum impact ranges for all fish assuming a stationary animal model is 10.5 km, or, using the stricter criteria for fish of < 2 g mass, up to 14.8 km.

Criteria for assessing behavioural effect for harbour porpoises and pinnipeds using unweighted, single strike, SELs (Brandt *et al*, 2009 and Lucke *et al*, 2009) show that maximum ranges are predicted out to 18.1 km for a behavioural effect and 24.6 km for a minor behavioural effect when installing the foundations for the larger 7 MW turbine. Behavioural effect was also assessed using the $dB_{ht}$(*Species*) metric (Nedwell *et al*, 2007), using the 90 $dB_{ht}$ criteria for strong avoidance behaviour. Maximum ranges were predicted out to 19.4 km for herring and 14.2 km for harbour porpoise during installation of the 7 MW turbine foundations.

It is also worth noting that these ranges are the greatest expected during piling and are only expected when the piling is undertaken at the maximum blow energy. This is not generally a common occurrence, with a pile typically being driven at much lower blow energies for the majority of time.

## 5 REFERENCES

Brandt M J, Diederichs A, and Nehls G. (2009). Harbour porpoise responses to pile driving at the Horns Rev II offshore wind farm in the Danish North Sea. BioConsult SH, Husum, Germany. Report to DONG Energy.

Brandt M J, Diederichs A, Betke K, and Nehls G. (2011). *Responses of harbour porpoises to pile driving at the Horns Rev II offshore wind farm in the Danish North Sea*. Mar Ecol Prog Ser 421:205–216.

Fisheries Hydroacoustic Working Group (FHWG) (2008). *Agreement in Principle for Interim Criteria for Injury to Fish from Pile Driving Activities.* Memorandum following a meeting of the United States Federal Highway Administration, NOAA Fisheries, U.S. Fish and Wildlife Service, the Departments of Transportation from California, Oregon and Washington and others. June 12, 2008.

Lucke K, Lepper P A, and Blanchet M. (2009). *Temporary shift in masked hearing thresholds in a harbour porpoise (Phocoena phocoena) after exposure to seismic airgun stimuli*. J. Acoust. Soc. Am. 125(6) 4060-4070.

Nedwell J R, Turnpenny A W H, Lovell J, Parvin S J, Workman R, Spinks J A L, Howell D (2007). *A validation of the* $dB_{ht}$ *as a measure of the behavioural and auditory effects of underwater noise.* Subacoustech Report Reference: 534R1231, Published by Department for Business, Enterprise and Regulatory Reform.

Otani S, Naito T, Kato A, and Kawamura A, (2000). *Diving behaviour and swimming speed of a free-ranging harbour porpoise (Phocoena phocoena).* Marine Mammal Science, Volume 16, Issue 4, pp 811-814, October 2000.

Parvin S J, Nedwell J R and Harland E (2007). *Lethal and physical injury of marine mammals, and requirements for Passive Acoustic Monitoring.* Subacoustech Report 565R0212, report prepared for the UK Government Department for Business, Enterprise and Regulatory Reform.

Popper A N, Carlson T J, Hawkins A D, Southall B L and Gentry R L. (2006*) Interim Criteria for injury of fish exposed to pile driving operations*: A white paper.

Popper A N, Hawkins A D, Fay R R. (2014). *Sound Exposure Guidelines for Fishes and Sea Turtles*: A Technical Report prepared by ANSI-Accredited Standards Committee S3/SC1 and registered with ANSI. Published by Springer Briefs in Oceanography 2014. ASA S3/SC1.4 TR-2014.

Southall B L, Bowles A E, Ellison W T, Finneran J J, Gentry R L, Greene C R, Kastak D, Ketten D R, Miller J H, Nachtigall P E, Richardson W J, Thomas J A, Tyack P L.

(2007). *Marine Mammal Noise Exposure Criteria: Initial Scientific Recommendations*. Aquatic Mammals. Vol. 33, No. 4, 411-521