Investigations into the effects of pile driving at the offshore wind farm Horns Rev II and the FINO III research plattform

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Content

1. Summary

During summer 2008, 92 monopile foundations of 3.9 m diameter were rammed into the seabed of the Danish North Sea west of Esbjerg to construct the offshore wind farm Horns Rev II. Effects of pile driving on harbour porpoise behaviour were studied by Brandt *et al.* (2009a) and a strong effect with reduced porpoise recordings that lasted up to 23 hours in the vicinity was found. The length of this effect rapidly decreased with distance. At more than 10 km distance it only lasted about 1-2 hours and was thus more or less limited to the time that pile driving took place.

In this study, we tested the effects of the construction of the research platform FINO III in the German North Sea and the wind farm Horns Rev II in the Danish North Sea on harbour porpoises on a large scale by passive acoustic monitoring. As the previous study at Horns Rev II only covered a maximum distance of about 20 km, the aim of this study was to investigate potentially further reaching effects of pile driving. For this purpose five C-PODs were deployed along a 50 km transect reaching from the Horns Rev II construction site southwest to the research platform FINO III.

Unlike during the previous study the parameter *PP10M/day* and *PPM/H* did not show a clear effect of pile driving on harbour porpoises at any location. However, the duration of *waiting time* indicated an effect which was statistically detectable at close distance (7 km) to the construction site. There may be some methodological reasons, why an effect was detectable by analysing *waitingtimes* but not the other parameters, which are discussed..
Compared to random waiting times first waiting times after pile driving increased 4.5fold by 7.6 hours (from 2.2 hours to 9.8 hours) at a distance of 7 km. A somewhat weaker effect was found at greater distances (15 - 37 km) where the increase of first waiting times was between 1.3 and 3.6 hours compared to random waiting times. However, here the difference was not statistically significant. A significant effect at 46 km was likely to have been an artefact.

The results are discussed in relation to expected noise levels at large distances and possibly diverging responses of harbour porpoises in habitats of differing function or quality.

From available data it cannot be finally concluded until what range piling noise from Horns Rev 2 was audible to harbour porpoises, but they are likely to be masked by background noise at 50 km. It is concluded, that harbour porpoise responses at distances beyond 15 km, if at all present, are certainly weak and of short duration.

2. Introduction

In 2008, DONG Energy, constructed the offshore wind farm Horns Rev II in the Danish North Sea west of Esbjerg. Pile driving activities were carried out from May to October. The wind farm consists of 92 turbines and a transformer platform based on mono-pile foundations. Pile driving activities to construct offshore wind farms cause high underwater noise emissions, which may adversely affect marine mammals such as harbour porpoises (Madsen *et al.* 2005). The Horns Rev site has been identified as an area with high porpoise numbers (Tougaard *et al.* 2006a, Skov & Thomsen 2006) and the wind farm was constructed in relatively shallow waters within this area at a time when porpoise numbers are observed to be high. Therefore an investigation into the effects of pile driving on harbour porpoises at Horns Rev II using T-PODs was conducted by BioConsult SH on behalf of DONG Energy (Brandt *et al.* 2009a). This study found a clear effect on porpoise echolocation activity. Analysing the parameter *porpoise positive minutes per hour (PPM/H)*, this negative effect was clearly detectable and statistically significant up to a distance of about 18 km and lasted between 22-70 hours in the vicinity (Brandt *et al.*, in prep.). At the greatest distance (at 22 km) no negative effect on PPM/H could be detected, instead PPM/H temporarily increased.

At the 31st of July 2008 the research platform FINO III was constructed in the German North Sea about 50 km south of Horns Rev. A study by BioConsult SH funded by the Federal German Ministry for Environment found porpoise density recorded via aerial surveys in a 1700 km² area around the construction site to be reduced by 78 % as compared to the day before. Acoustic monitoring revealed that the near vicinity at 1 km distance) from the construction site was avoided by harbour porpoises for 18 to 45 hours in total (depending on POD-position) and for 5 to 11 hours after pile driving (Brandt *et al.* 2009b).

A previous study found a shorter but further (over 20 km) reaching effect during construction of the Offshore windfarm Horns Rev I (Tougaard *et al.* 2009).

To study possible large-range effects of both pile driving activities in 2008, the Danish Environmental Group financed an additional investigation in the framework of the continued environmental monitoring programmes of Horns Rev and Nysted offshore wind farms to study the responses of harbour porpoises to pile driving during construction of Horns Rev II and FINO III. For this purpose five C-PODs were deployed along a transect extending south from Horns Rev II to the research platform FINO III. This report shows the results of this study.

2.1. Design of this study

Identifying the temporal and spatial scale of pile driving effects on harbour porpoises is crucial for deciding whether or not an effect is acceptable. Therefore, we decided to use a technique that enables the determination of both the temporal and spatial scale at which an effect is detectable. We applied passive acoustic monitoring using C-PODs. C-PODs are a new version of the widely used T-PODs and differ from these in that they record at a broader frequency spectrum and save a number of additional click characteristica. C-PODs save the wave characteristics for each click in a digital form. For each sound event the duration, main frequency, intensity and bandwidth are saved. Those characteristics are then compared by the accompanying algorithm to differentiate between true porpoise clicks and background noise.

In order to study spatial and temporal changes in harbour porpoise presence during and after pile driving we deployed one C-POD each at five different positions along a 45 km transect line running from 2 km south of Horn Rev II southwest to 7 km northwest of FINO III. Distances between PODs were between 7 and 13 km. The study period lasted from 10.07.08 to 02.11.08.
This investigation differs from the other two referred to above in that it covers a much larger distance from the construction site to detect potentially far reaching effects which would not be covered by the other two studies.

3. Methods

3.1. Study area

The offshore wind farm Horns Rev II (consisting of 92 2.3 MW wind turbines) was erected northwest of the reef Horns Rev, which extends from the westernmost point of the Danish west coast at Blavands Huk approximately 40 km to the west. Details on the study area and the construction procedure are described in the main report (Brandt *et al.* 2009a). The research platform FINO III was erected about 80 km west of Sylt (Fig. 1).

3.2. Principle of operation and characteristics of C-PODs

Harbour porpoise responses to wind farm construction were monitored by continuous registration of echo-location clicks using Porpoise Detectors (C-PODs; www.chelonia.demon.co.uk). C-PODs consist of a 80 cm long plastic pipe with a hydrophone at one end below which an electronic filter and an amplifier are positioned. The hydrophone omnidirectionally records sound within the frequency range 20 – 150 kHz. For each sound main frequency, duration, intensity, bandwidth and envelope of the frequency spectrum are logged. The devices are calibrated for main sensitivity in the frequency of harbour porpoise clicks (130 kHz) and with the same threshold (± 2 dB) by the supplier. With an algorithm included in the software CPOD.exe (Chelonia Ltd., UK), sound originating from porpoises, dolphins and boat sonar, can be extracted.

3.3. C-POD deployment

Five C-PODs were deployed at five positions along a transect line reaching from inside the area where Horns Rev II was built (DK5) south to the FINO III construction site (DK1) (Fig. 1).

PODs were placed in the water column approximately one meter above the sea bottom. Inflatable yellow buoys indicated the POD-position, and an official yellow warning buoy was deployed at a distance of 100 to 150m. C-PODs were changed approximately every four weeks, data were extracted and C-PODs changed between positions when redeployed.

During the period 10.07.2008-02.01.2008, a total of 399 POD-days (no of PODs deployed x days of deployment) were achieved. No POD was deployed at position DK5 after the 8th of Sept because the warning boy was lost at that position.

Some further data gaps occurred due to equipment loss or malfunctioning (Fig. 2).

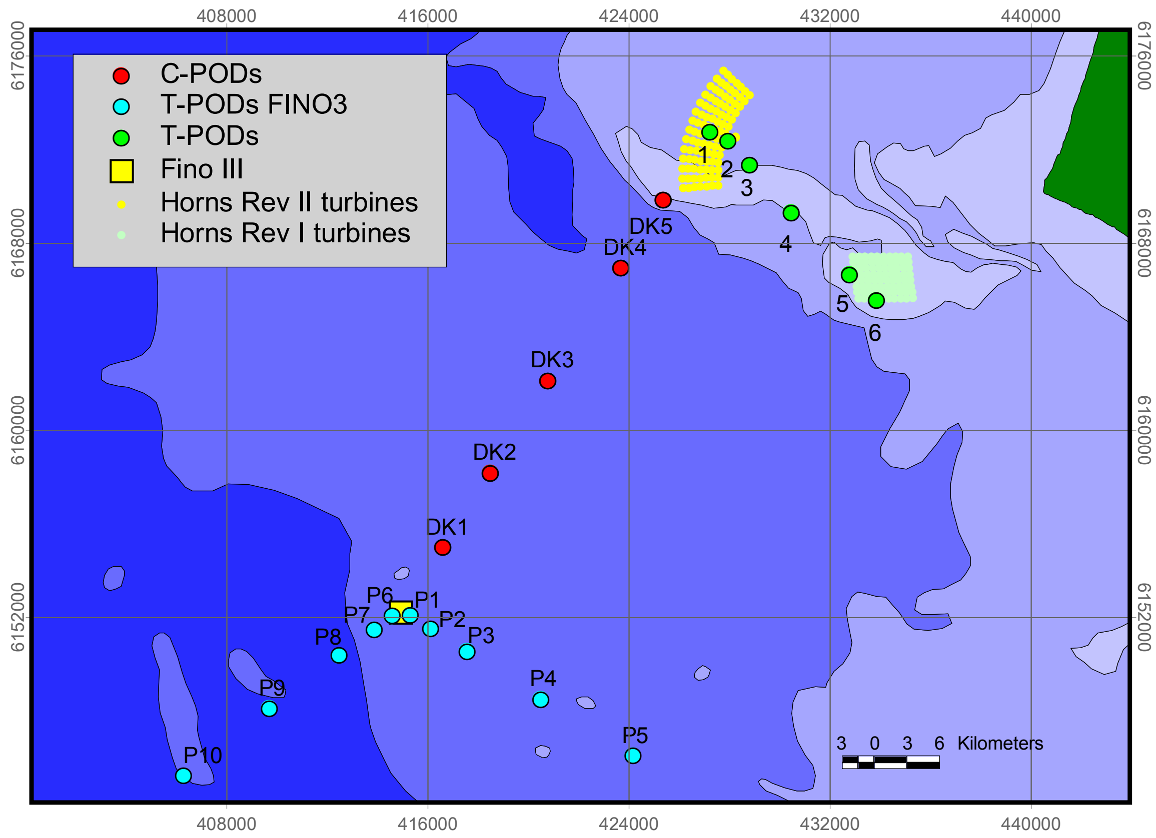


Fig. 1: Study area, position of wind farms, FINO III and POD-positions. Red points show C-PODs deployed during this study, green points mark the positions of T-PODs used during the main Horns Rev II study and blue points show the C-PODs deployed during the FINO III study.

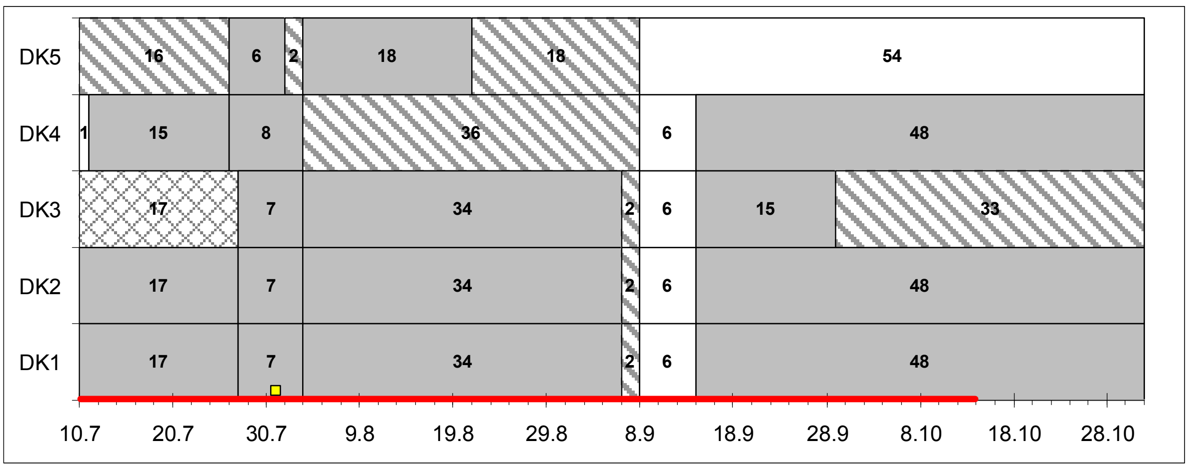


Fig. 2: Deployment of C-PODs at the different positions. Vertical black lines show changes of PODs. Grey bars: POD recorded data; checked bars: POD deployed but lost; hatched bars: POD deployed but did not record data; white bars: no POD deployed. The red horizontal line marks the pile driving period at Horns Rev II and the yellow square the day of pile driving at FINO III.

Tab. 1: Average, minimum and maximum distance of the five POD-positions to rammed monopiles and sample size of pile driving events that could be recorded at each POD-position.

POD-Position	N	Average distance to pile in m	Min. distance to pile in m	Max. distance to pile in m
DK1	49	45.6	40.1	50.0
DK2	48	37.4	32.0	41.9
DK3	37	28.1	21.7	31.6
DK4	30	14.7	10.0	19.6
DK5	15	6.7	2.1	9.1

Pile driving activities at Horns Rev II started on the 19.05.2008 and continued until 14.10.2008. A piling event lasted on average 46 ± 14 min. Mean time between piling events (measured from the end of a piling event to the start of the next piling event) was 38 ± 45 hours.

FINO III was rammed into the sea floor on the 31.07.08. Piling activities consisted of four bouts spread over a total period of 13 hours (Tab. 2) The third of these four bouts consisted of only a few “test blows” over a period of two minutes while the others contuniued over a longer period. A pile driving bout is defined as the period of time during which pile driving occurred with single blows separated by less than 30 min. During the same day two monopiles were driven into the sea bed at Horns Rev II between 0:02-0:44 and 13:28-14:12 (UTC).

In order to minimise the risk of physical damage to harbour porpoises and seals, mitigation procedures were applied at both sites. These consisted of the deployment of a seal scarer (Lofitech) and one (Horns Rev) or two (FINO III) pingers (Aquamark 100) 2-3 hours before pile driving started. Both devices produce sound that was shown to deter harbour porpoises (seal scarer: Johnston 2002, Olesiuk et al. 2002; pinger: Koschinski and Culik 1997, Culik et al. 2001, Kastelein 2001).

Tab. 2: Date and time of pile driving, seal scarer and pinger activity during construction of the research platform FINO III.

Activity	Date and starttime (UTC)	Date an endtime (UTC)
Pinger	30.07.2008 17:00	30.07.2008 19:50
Seal-scarer	30.07.2008 18:00	30.07.2008 19:50
Pinger	30.07.2008 23:30	31.07.2008 13:45
Seal-scarer	31.07.2008 00:30	31.07.2008 13:45
Pile driving	31.07.2008 00:10	31.07.2008 02:44
Pile driving	31.07.2008 05:10	31.07.2008 07:47
Pile driving	31.07.2008 09:10	31.07.2008 09:12
Pile driving	31.07.2008 10:03	31.07.2008 13:23

3.4. Parameters of POD recordings

Following the method used in the main report three parameters were derived from C-POD data to describe porpoise activity: For a general description of porpoise presence at the different POD-positions the parameter "porpoise positive 10 minutes per day" (PP10M/day) was analysed. The parameter "porpoise positive minutes per hour" (PPM/H) expresses the utilisation of a specific area with increasing precision.
In addition the parameter "waiting time" (time between two consecutive porpoise encounters) was analysed. An encounter is defined as a period with click activity separated by a silent period of at least ten minutes without any click activity. This parameter was used to describe how long the area near the construction site was completely avoided by porpoises. It is better to use "waiting time" to describe effects of pile driving when sample size is low (such as during construction of FINO III) or porpoise density is low resulting in small values for PPM/H.

3.5. Statistical analyses

Statistical analyses was performed using the software "SPSS13" and "R", version 2.8.0 (http://www.r-project.org/).

3.5.1. Porpoise positive ten minutes per day (PP10M/day)

For the parameter *PP10M/day* we calculated the percentage of *PP10M/day* relative to the amount of hours covered during that day. This was 24 hours in most cases, only when PODs were deployed, recovered or changed, there were a few hours missing during that day.

To test for seasonal differences and for differences between POD-positions we calculated a "general linear mixed model" (GLMM) fitted to a Poisson distribution, where *PP10M/day* was the dependent variable, *POD-position*, *month* and *piling* (0= no piling during this day, 1= piling during that day) were entered as fixed factors, and the interaction term *POD-position* with *piling* was included. Only months with at least 5 days of data recording were included in the analyses.

At each POD-position we used a non-parametric Mann-Whitney-U-test to test for differences between days with and days without piling.

3.5.2. Porpoise positive minutes per hour (PPM/hour)

To analyse the impact of pile driving on porpoise acoustic activity we further analysed the parameter *porpoise positive minutes per hour (PPM/H)*, which can directly be linked to pile driving events. Hours after pile driving were numbered consecutively after pile driving, and for analysis we included only the first 50 hours after pile driving.
Data were analysed using a "general additive model" (GAM) fitted to a Poisson distribution, where *PPM/H* was the dependent variable, *POD-position* was entered as a fixed factor and *time of day* and *hour after pile driving* were entered as nonlinear continuous variables. Gam

analysis allow to test for the significance of non linear correlations between parameters. A plot with the best fittet curve then shows where the response variable significantly differs from the overall mean.

In a second step we spilt the analysis by position and investigated the effects of *time of day* and *hour after pile driving* on *PPPM/H* separately for each *POD-position*. Here *time of day* and *hour after pile driving* were also included as non-linear continuous variables.

Effects were then visualised by plotting the deviation from the overall mean of *PPM/H* against *time of day* and *hour after pile driving*.

3.5.3. Waiting times

Waiting times were assigned to each piling event by sorting them according to their order of occurrence after the piling event. The first waiting time after piling was defined as the first waiting time, which ended after the piling event was finished. The first waiting time after piling might therefore cover the whole time a piling event lasted and in some cases also some time before piling started. As waiting time data were not normally distributed (but near Poisson distributed) we calculated statistics using median waiting times.

Waiting times were then numbered according to their occurance after the pile driving event. We then calculated a GAM as described above for PPM/H with *waiting time* as the response variable and *order after piling* and *distance* as the predictor variables.

To avoid statistical problems caused by the "bus paradox" (Ito *et al.* 2003) when comparing first waiting times with all other waiting times, we compared first waiting times to 15 randomly assigned ones. This was done by randomly choosing 15 timepoints for the timeperiod that PODs were deployed at each position and then identifying the waiting times corresponding to this timepoint. We randomly assigned waiting times during the time period after pile driving was finished where this was possible. Because no such data existed for DK3 and DK5, here we randomly assigned waiting times to the whole study period excluding first waiting times after pile driving (Tab. 7). These *random waiting times* were then compared to *first waiting times* using non-parametric Mann-Whitney-U-test. Fifeteen random waiting times were choosen as a compromise of obtaining enough statistical power to apply a meaningful test (for which a sample size of 6 is usually considered the absolute minuímum) and the limitation given by the short time period for baseline data.

4. Results

4.1. Effects of pile driving at Horns Rev II

4.1.1. Porpoise positive ten minutes per day (PP10M/day)

Porpoise activity varied somewhat seasonally between July and October, with slight differences between the five locations where PODs were deployed. When calculating a GLM, *position* ($Chi^2=43.6$, df=4, $p<0.001$), *month* ($Chi^2=20.0$, df=3, $p<0.001$) and *piling* ($Chi^2=7.4$, df=1, $p<0.01$) all had a significant influence on *PP10M/day*. The interaction between *piling* and *position* was not significant ($Chi^2=5.2$, df=4, $p=0.27$, controlling for month). Thus, while *piling* significantly affected *PP10M/day*, there was no difference in this effect between *POD-positions*. Due to uneven sample sizes at the different positions we could not statistically test for a significant interaction between *month* and *position*. However, as can be seen in Fig. 3 and Fig. 4, there seemed to be differences in the seasonal pattern of *PPP10M/day* between the different *POD-positions*: Porpoise activity was quite similar at positions DK1 and DK2, decreasing from July to September and again increasing in October. At DK3 data were only available for August and September, and contrary to the pattern at the other positions, activity was considerably higher in September. At DK4 activity was highest in July and decreased in September and October and at DK5 data only existed for July and August, with activity being slightly higher in July (Fig. 3, Fig. 4, Tab. 3).
Most recordings were made at positions DK1 and DK2, while relatively few recordings were made at DK4 and DK5 (Fig. 4, Tab. 3).

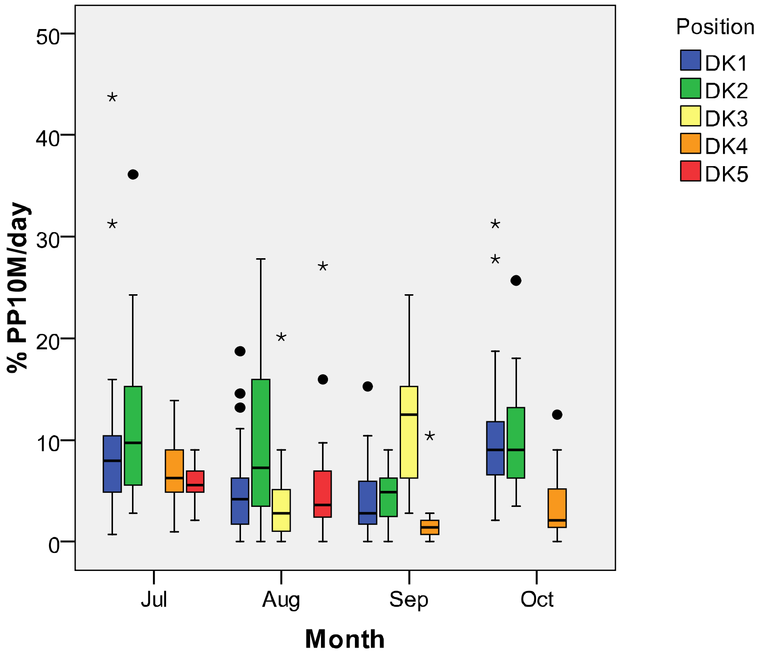


Fig. 3: Seasonal changes in *PP10M/day* at the different *POD-positions*. Only months with a minimum of five days of data were considered.

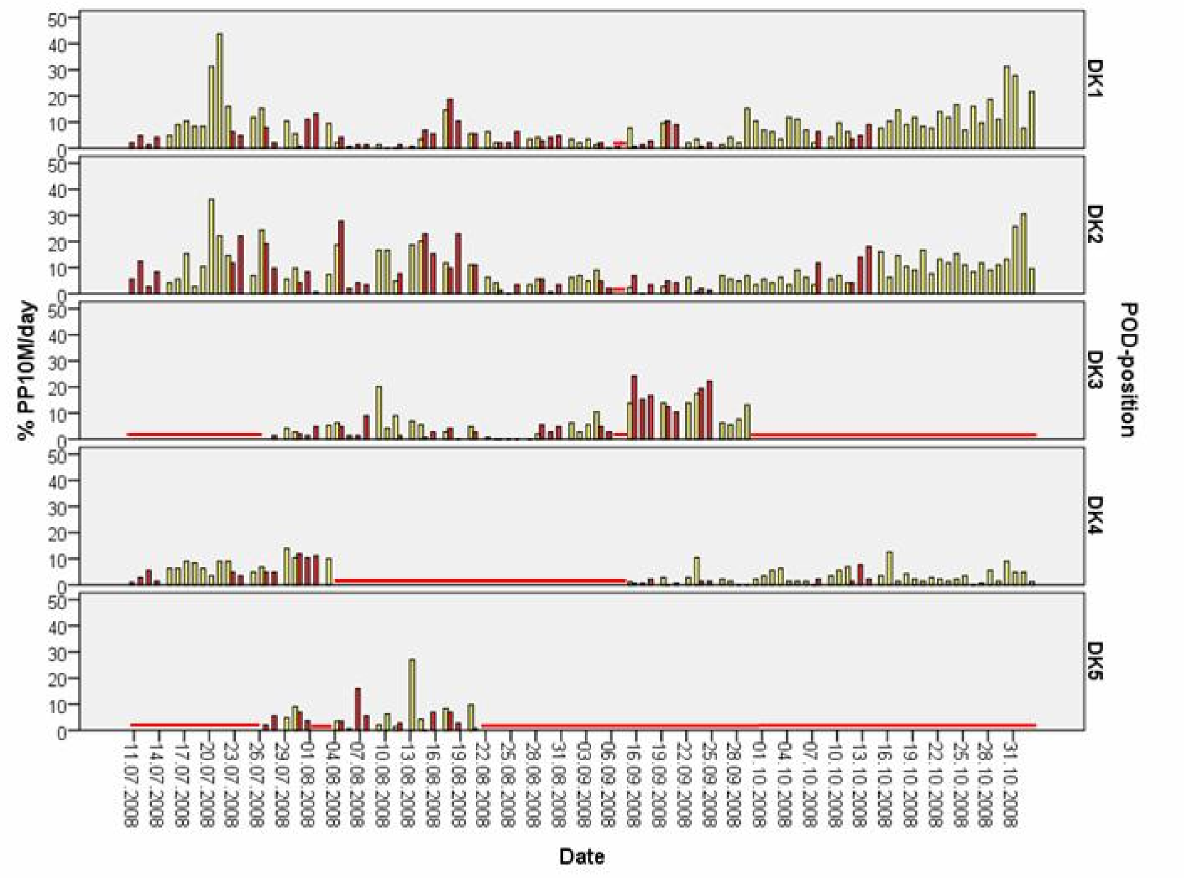


Fig. 4: Detailed phenology of *PP10M/day* at the different *POD-positions*. PP10M at days during which pile driving took place are shown as red bars, those at days without pile driving as yellow bars. Periods with data gaps are indicated by red horizontal lines.

There was no significant interaction between *piling* and *POD-position* meaning that it could not statistically be proven that piling affected PP10M/day differently at the different POD-positions. Rather there was a general negative effect on *PP10M/day regardless of POD-position. However*, because sample sizes was very different at the different POD-positions, we still tested for significant effects of pile driving at each position separately. This was done to see at which positions the differences between piling days and non-piling days could statistically be proven and where this might not be the case. During previous analyses of T-POD data it was found that the strength of the effect decreased with distance from the noise source (Brandt *et al.* 2009a). Thus, this effect would also be expected during this study and we wanted to look at it in more detail. It turned out that the decrease in *PP10M/day* was significant at DK1 ($Z_{41,67}$=-3.7, p<0.001) and DK2 ($Z_{40,67}$=-2.1, p<0.05), the positions with the greatest distance to the pile driving site while no significant effect could be found at DK3 ($Z_{27,29}$=-1.6 p=0.12), DK4 ($Z_{22,51=}$-1.0, p=0.31) or at DK5 ($Z_{14,10}$=-1.3, p=0.21), the positions closest to the construction site. However, as can be seen in Fig. 4, the high values for % PP10M/day during days without piling at DK1 and DK2 are largely due to two periods with unusually high % PP10M/day between the 20.7.-23.07.08 and from the 15.10.-1.11.08. When excluding these periods from the analysis, differences were no longer significant at either DK1 ($Z_{40,45}$=-1.8, p=0.07) or DK2 ($Z_{40,45}$=-0.7, p=0.46). Thus, it is possible that seemingly significant effects between days with and without piling are simply due to some random effect. This is because of some days with many porpoise recordings (possibly by chance) happen to be without pile driving events. It further has to be noted that sample size at DK3, DK4 and especially DK5 was small compared to those at DK1 and DK2. As the strongest effects appear to be present at the positions with the largest sample sizes, this further seems to be a result related to sample size rather than having a biological meaning. Nevertheless as can be seen in Tab. 3 and Fig. 5, *PP10M/day* tended to be lower during days with pile driving events at all positions. However, the difference was only slight and even at days, during which pile driving took place, porpoise activity was highly variable (Fig. 4) at all positions. At present it is thus unclear how much of this difference is really caused by pile driving.

Tab. 3: PP10M/day at the different POD-positions between July and October 2009.

POD-position	Month	Median	Min	Max	N
DK1	Jul	7.9	0.7	43.8	21
	Aug	4.2	0.0	18.8	31
	Sep	2.8	0.0	15.3	23
	Oct	9.0	2.1	31.3	31
	all	***6.3***	***0***	***43.8***	***108***
DK2	Jul	9.7	2.8	36.1	21
	Aug	7.3	0.0	27.8	31
	Sep	4.9	0.0	9.0	22
	Oct	9.0	3.5	25.7	31
	all	***6.9***	***0***	***36.1***	***107***
DK3	Aug	2.8	0.0	20.1	31
	Sep	12.5	2.8	24.3	21
	all	***4.9***	***0***	***24.3***	***56***
DK4	Jul	6.3	1.0	13.9	21
	Sep	1.4	0.0	10.4	16
	Oct	2.1	0.0	12.5	31
	all	***3.5***	***0***	***13.9***	***73***
DK5	Jul	5.6	2.1	9.0	5
	Aug	3.6	0.0	27.1	19
	all	***4.5***	***0***	***27.1***	***24***

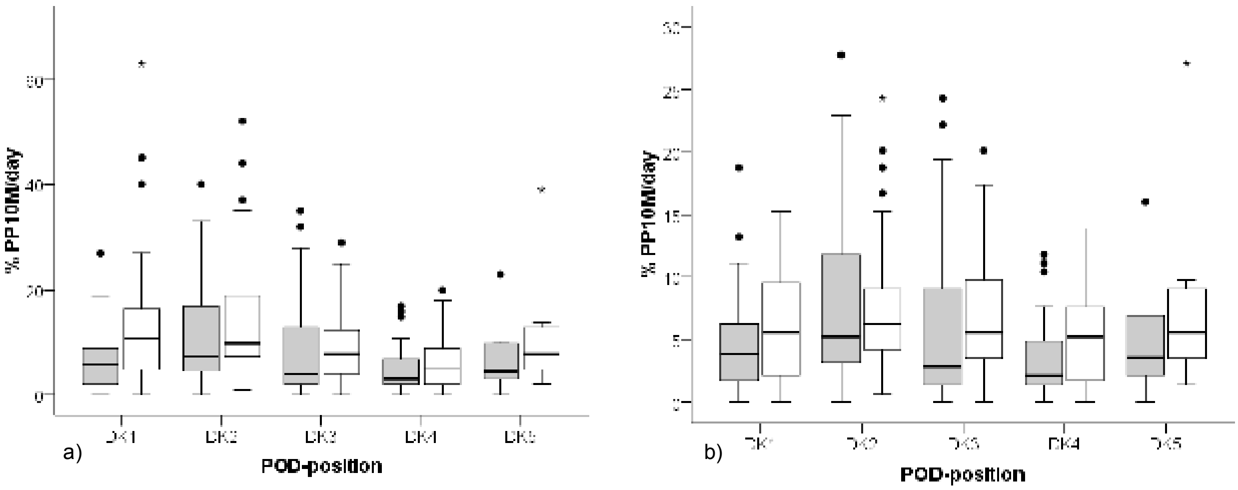


Fig. 5: Boxplots showing PP10M/day at the different POD-positions for days with (grey bars) and days without (white bars) pile driving activity. In a) all data were included, in b) we excluded data with unusually high PP10M between 11.7.-23.7.08 for DK1 and DK2 and from the period after piling between 15.7.-2.11.08 for all positions. In a) only differences at DK1 and DK2 were statistically significant, in b) no differences were significant.

Tab. 4: Median, minimum and maximum PP10M/day at the different POD-positions during days with and without piling events.

POD-position	Period	Median	Min	Max	N
DK1	piling	4.2	0	18.7	41
	no piling	7.7	0	43.8	67
DK2	piling	5.2	0	27.8	40
	no piling	7.6	1	36.1	67
DK3	piling	2.8	0	24.3	29
	no piling	5.6	0	20.1	27
DK4	piling	2.1	0	11.8	22
	no piling	3.5	0	13.9	51
DK5	piling	3.5	0	16.0	14
	no piling	5.6	1	27.1	10

4.1.2. Porpoise positive minutes per hour (PPM/H)

Results from a General additive model (GAM) that allows to test for also non-linear effects, reveal that *POD-position* (F=23.0, edf=3.0, p<0.001), *time of day* (F=12.3, df=8.1, p<0.001) and *hour after piling* (F=2.9, df=2.9, p<0.05) all significantly influenced *PPM/H*. However, while the effects of *time of day* and *POD-position* were clear, *hour after piling* only explained little variance. Differences between POD-positions were such that porpoise activity was highest at DK2 and lowest at DK1 and DK4 (Fig. 7). Activity slightly increased after pile driving but decreased again later (Fig. 7). The daily porpoise activity rhythm was clearly characterised by more activity from early morning to early afternoon (5:00 to 15:00) than during late afternoon and night (Fig. 7).

Tab. 5: Mean, min. and max. PPM/H recorded at each POD-posiition.

POD-position	Mean PPM/H	Min PPM/H	Max PPM/H
DK1	0.7	0	25
DK2	1.0	0	24
DK3	0.7	0	17
DK4	0.4	0	21
DK5	0.5	0	21

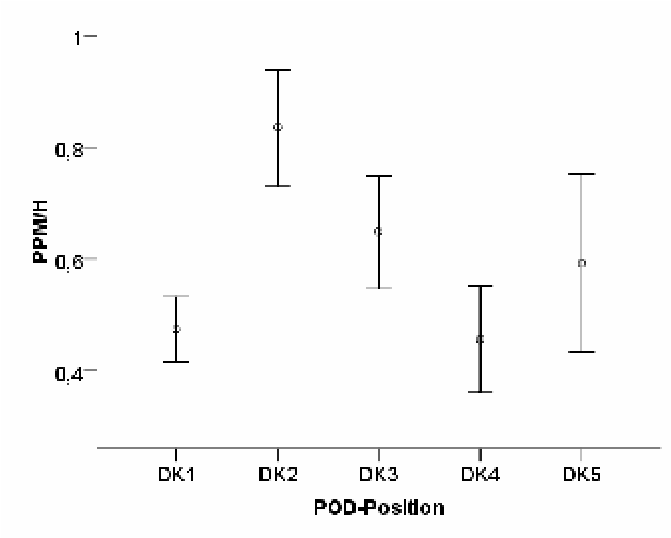


Fig. 6: Mean and 95 % confidence interval of *PPM/H* at the different POD-positions.

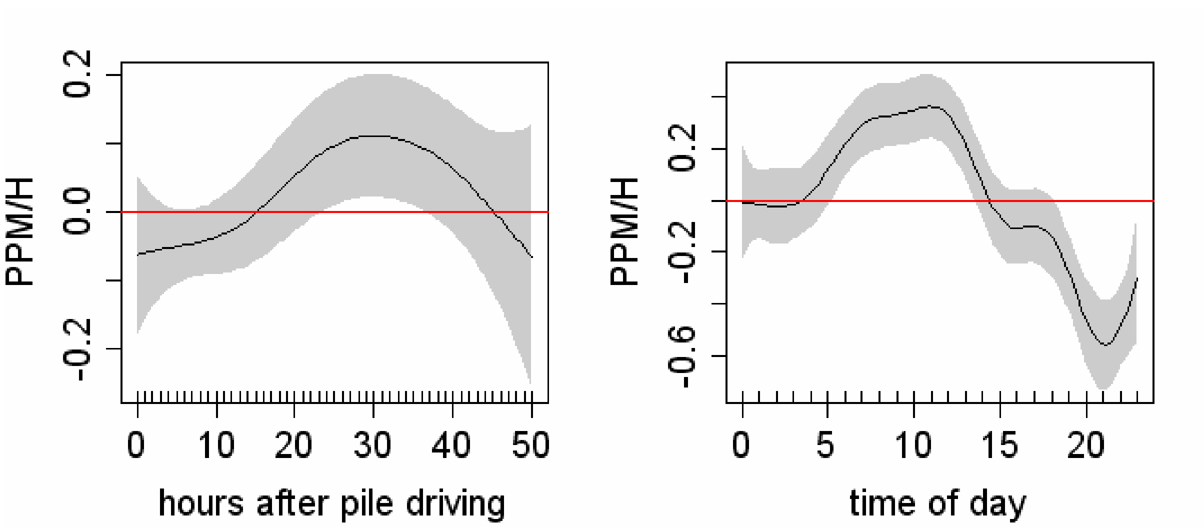


Fig. 7: The effects of hours after pile driving and time of day on PPM/H. Shown is the deviation from the overall mean as calculated by the GAM. Shaded areas indicate 95 % confidence intervals.

When the analysis was split by position, *time of day* significantly affected *PPM/H* at every position, while *hour after piling* only had a significant effect at DK2 and DK4. However, explanatory power of the models was low with only 1-11 % of the variance explained (Tab. 6). The daily activity pattern was similar at all positions with more activity during the early day than during afternoon and night. When looking at the effect of *hour after piling* on *PPM/H* at those positions where the influence was significant *PPM/H* did not significantly differ from the mean directly after pile driving at any position (Fig. 8). At DK2 there was only slightly higher activity than usual more than 30 hours after pile driving, which is unlikely to be linked to pile driving and can be neglected (Fig. 8). At DK4 *PPM/H* was slightly lower than the overall mean 11-16 hours after pile driving and higher than the mean 20-30 hours after pile driving (Fig. 8). There was thus no straightforward effect of pile driving on *PPM/H* detectable at any POD-position, in that *PPM/H* either decreased or increased directly after pile driving. The effect, if it was present at all, appears to be more complicated.

Tab. 6: Results from the GAM on the effects of hour after piling and hour of day on PPM/hour at the different POD-positions.

POD-position	variance explained by model	Dependent variable	F	error df	p
DK1	5.1 %	hour after piling	0.93	1.7	0.38
		time of day	11.71	4.8	<0.001
DK2	2.7 %	hour after piling	4.7	2.7	<0.05
		time of day	2.5	7.5	<0.001
DK3	0.9 %	hour after piling	0.3	1.0	0.57
		time of day	8.8	1.0	<0.01
DK4	11.2 %	hour after piling	7.2	7.4	<0.001
		time of day	10.5	3.7	<0.001
DK5	11.2 %	hour after piling	1.0	1.2	0.28
		time of day	5.9	7.6	<0.001

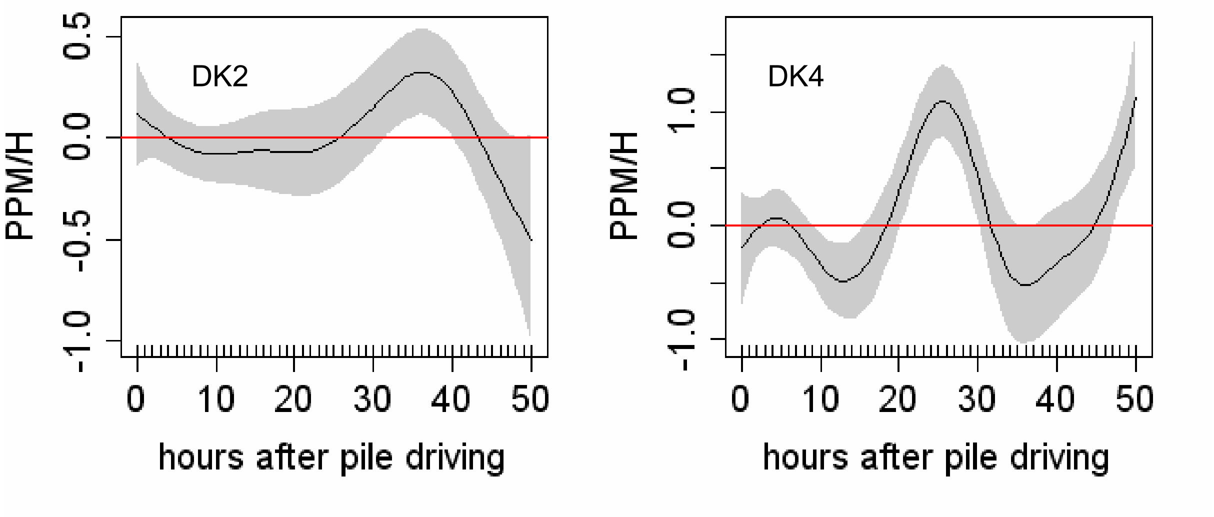


Fig. 8: The effect of hour after piling on PPM/H at POD-position DK2 and DK4. Shown is the deviation from the overall mean and the confidence intervals. If the confidence intervals are above or below the overall mean (depicted as red line) the deviation is statistically significant. Here the effects did not seem to be linked to an effect of pile driving.

4.1.3. Waiting times

At DK3 there was a period over five continuous days (22.08.-27.08.08) when there was no porpoise recording. We excluded this period from waiting times analyses as this long waiting time was unrelated to pile driving, as it happened in the middle of this period. Including this unusually long waiting time, which was probably caused by some other natural or anthropogenic unknown factor, would have incorrectly produced a very long waiting time after pile driving.

The duration of normal waiting times ranged between 0.8-1.6 hours at the different POD-positions. Waiting times were longest at DK4 and shortest at DK5 (Tab. 7). Fifteen randomly choosen waiting times ranged between 2.2-6.3 hours and again they were shortest at DK5 and longest at DK4 (Tab. 7). First waiting times after pile driving were between 4.7-10.5 hours long and thus considerably longer than all others and the randomly chosen ones (Tab. 7).

Tab. 7: Durations of a) the first waiting times in min directly after a piling event, of b) 15 randomly assigned waiting times and of c) all waiting times recorded (with the first after piling excluded) at the different POD-positions. Note that random waiting times were chosen from the period when pile driving was finished where this was possible. Because at DK3 and DK5 no such data existed, here we chose them from the whole study period excluding first waiting times after pile driving (see methods for details).

POD-position	Dependent variable	Median waitingtime in min [h]	Min. waitingtime in min	Max. waitingtime in min [h]	N	Random sample	Increase first to random waiting time [h]
DK1	after piling	378 (6.3 h)	21	4405 (73.4)	49		3.6 h
	random	163 (2.7 h)	34	951 (15.9 h)	15	basis	
	all without first after piling	68 (1.1 h)	10	1268 (21.1 h)	818		
DK2	after piling	284 (4.7 h)	12	2107 (35.1 h)	48		1.3 h
	random	204 (3.4 h)	29	491 (8.2 h)	15	basis	
	all without first after piling	75 (1.3 h)	10	1471 (24.5 h)	920		
DK3	after piling	393 (6.6 h)	29	2185 (36.4 h)	36		2.8 h
	random	230 (3.8 h)	213	827 (13.8 h)	15	all	
	all without first after piling	82 (1.4 h)	10	837(14.0 h)	334		
DK4	after piling	631 (10.5 h)	48	2362 (39.4 h)	30		3.8 h
	random	379 (6.3 h)	52	1813 (30.2 h)	15	basis	
	all without first after piling	98 (1.6 h)	10	4387 (73.1 h)	327		
DK5	after piling	589 (9.8 h)	161	2838 (47.3 h)	15		7.6 h
	random	131 (2.2 h)	29	999 (16.7 h)	15	all	
	all without first after piling	45 (0.8 h)	10	999 (16.7 h)	130		

When comparing the first waiting times after pile driving to 15 randomly assigned waiting times, the first waiting times were significantly longer than the 15 random ones at DK1 ($Z_{49,15}$= -2.78, p<0.01) and DK5 ($Z_{15,15}$= -3.51, p<0.001) but not at DK2 ($Z_{48,15}$= -1.56, p=0.12), DK3 ($Z_{36,15}$= -1.41, p=0.16) and DK4 ($Z_{30,15}$= -0.60, p=0.55) (Fig. 9). At all positions but at DK4 the longest waitingtimes were recorded after pile driving (Fig. 9, Tab. 7). At DK 5, the position nearest to the construction site (2-9 km), median waiting times after pile driving increased 4.5 fold by 7.6 h as compared to random waiting times. At DK4, DK3 and DK2 at distances between 10-40 km this increase was about 2 fold, and first waiting times were between 1.3 and 3.8 hours longer than random waiting times. However, differences were not statistically significant. At DK1 there was a statistically significant 2.3 fold increase of 3.6 hours (Tab. 7).

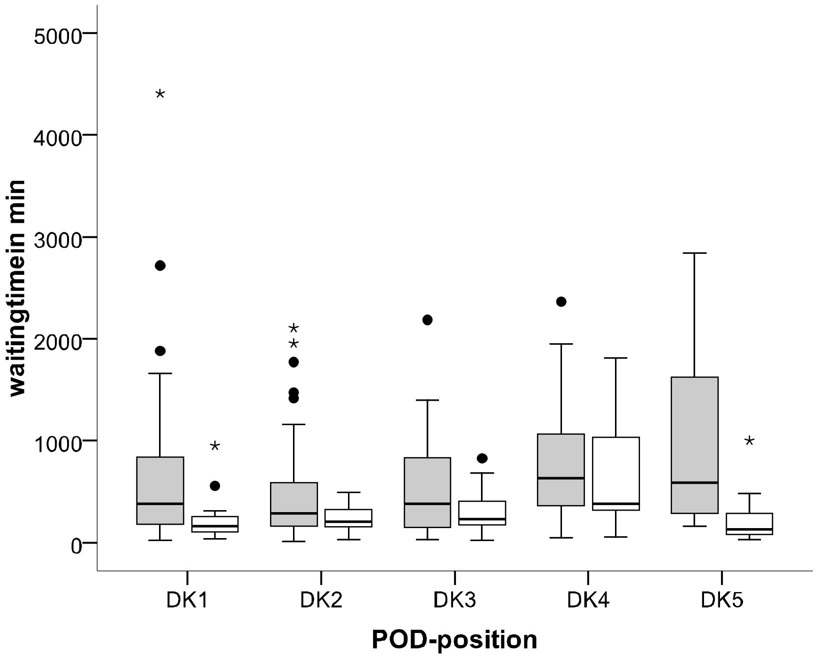
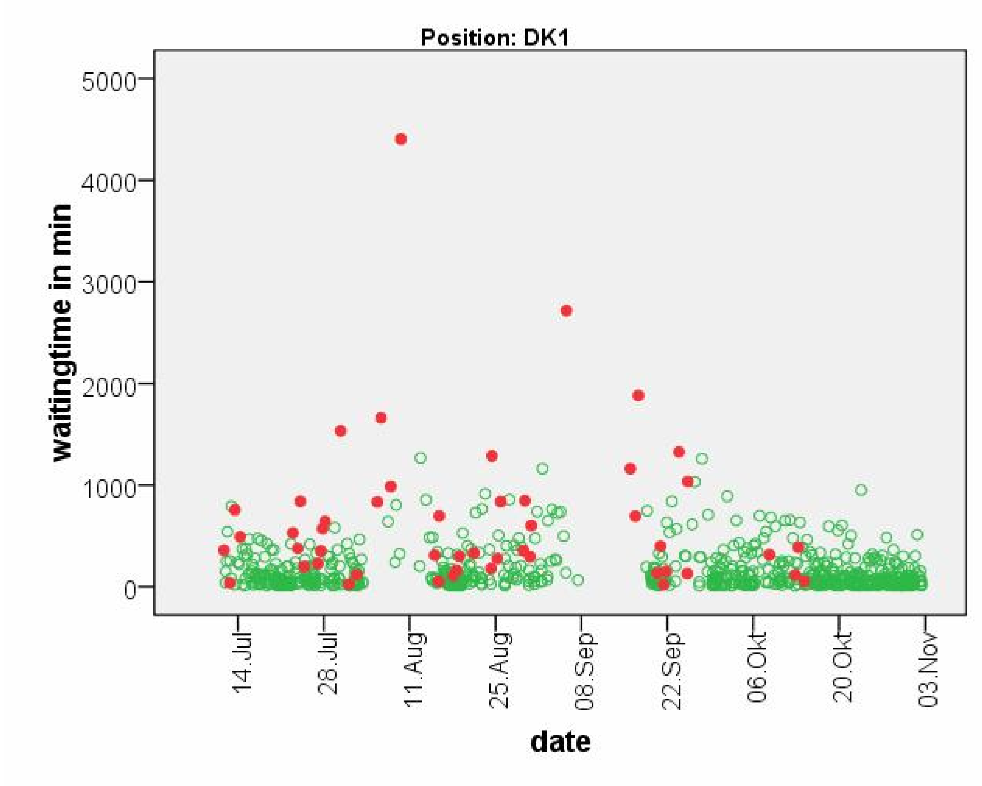


Fig. 9: Boxplots showing the duration of waiting times in min at the different POD-positions for those directly after piling (grey bars) and 15 randomly assigned ones (white bars). Only the differences at DK1 and DK5 are statistically significant.



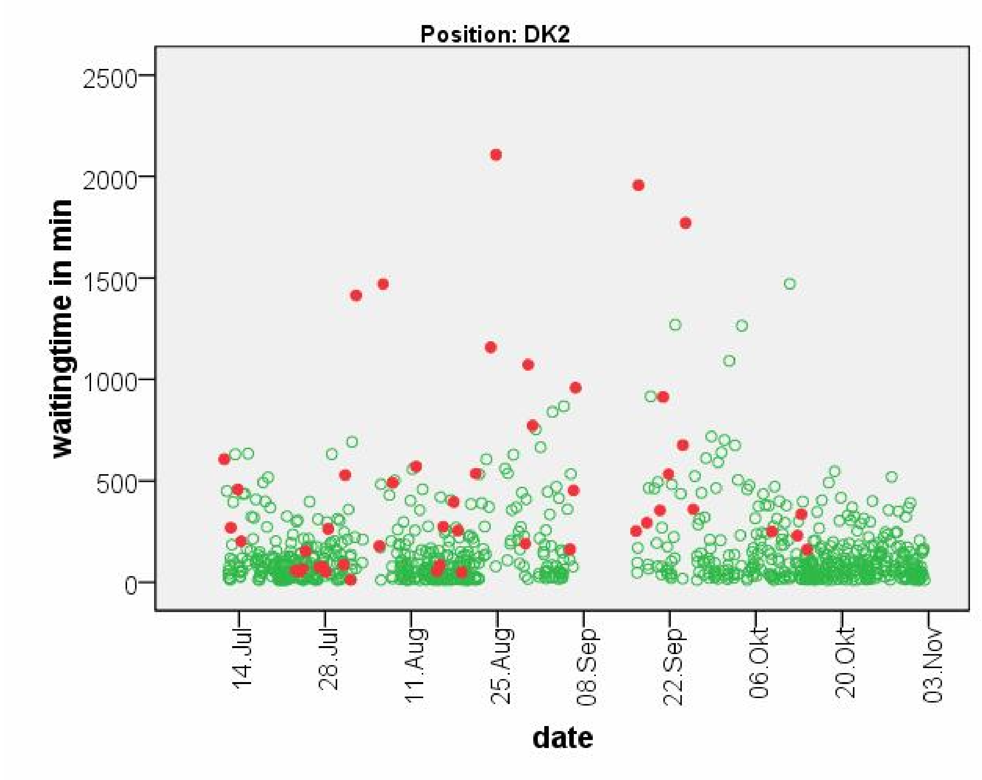
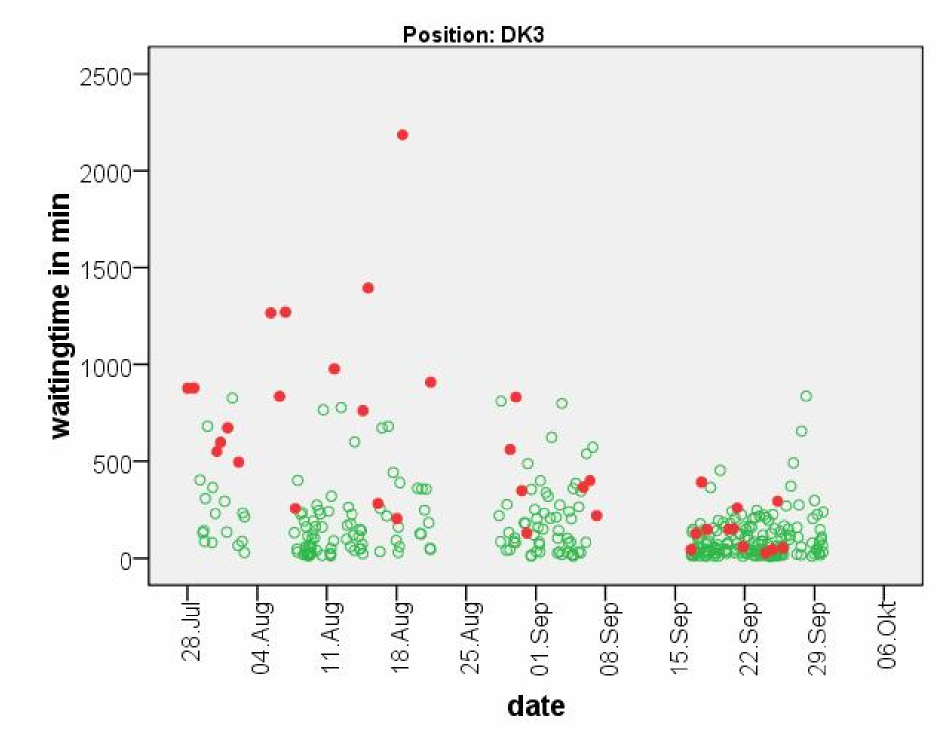


Fig. 10 to be continued.



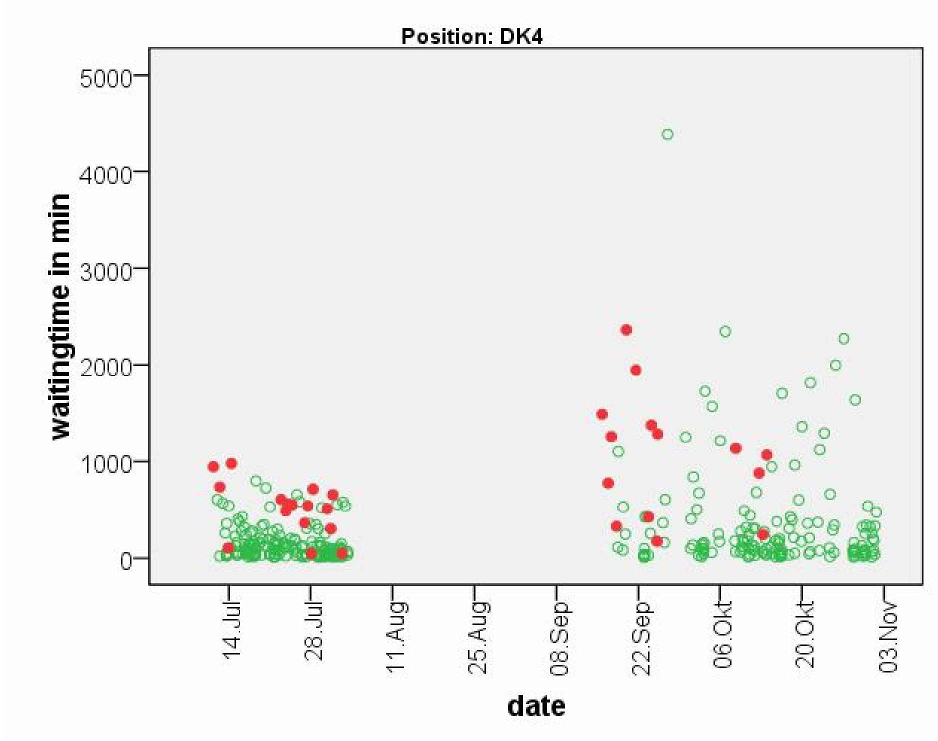


Fig. 10 to be continued.

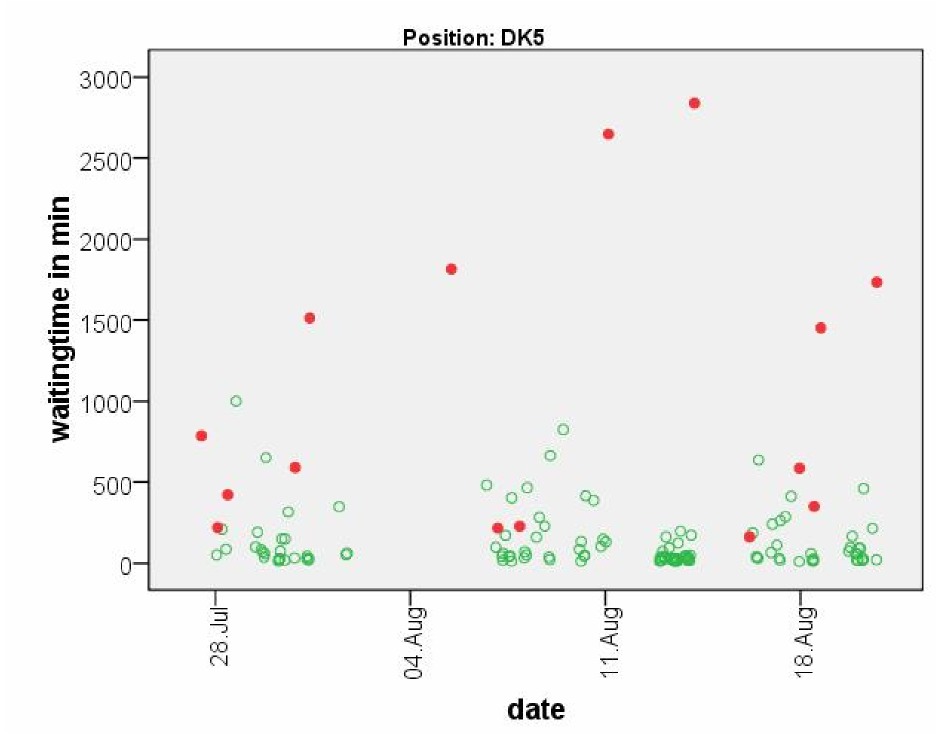


Fig. 10: Duration of all waitingtimes in min plotted by their start date/time for the different POD-positions DK1-DK5. Waitingtimes that occurred directly after pile driving are depicted as red filled circles, all other waiting times are depicted as open green circles.

4.1.4. Summary of main results

Analysis of PP10M/day revealed a negative impact of pile driving on porpoise activity, as values were lower during days when piling took place than during days without piling at all POD-positions. However, these differences were small and only statistically significant at positions DK1 and DK2, the ones furthest from the construction site (30-50 km distance). This may be related to larger sample sizes at these positions. Further the significant differences at these positions were mainly due to a few days with high porpoise activity after the construction phase and during two days at the beginning of the study period. When these days were excluded from analysis, differences between piling days and non-piling days were no longer significant. The effects might therefore simply be caused by a random effect and not be related to pile driving itself.

When analysing PPM/H, there was a significant effect of piling on this parameter at DK2 and DK4. However, when looking at the effect more closely, this did not seem to be linked to pile driving as there was no clear decrease or increase directly after the pile driving event. They were probably caused by natural stochasticity.

When comparing first waiting times to random waiting times using non-parametric tests, there there was a strong negative effect of pile driving at the POD-position closest to the construction site (DK5, 2-9 km distance), where waiting times increased by 7.6 hours from 2.2 to 9.8 hours. A slight but significant effect was also found at the POD-position furthest from the construction site (DK1 at 50 km distance), where waiting times increased by 3.6 hours from 2.7 to 6.3 hours. At the other positions the effect was not statistically significant.

4.2. Summary of the effects of pile driving at FINO III

4.2.1. PP10M/day

When looking at the effects of piling during construction of FINO III, there was a 95-100% reduction in PP10M/day at the closest two POD-positions (P1 and P6). At 3 km distance there was a 94% reduction at one position (P2) but an increase at the other (P7). PP10M/day decreased during piling about 89 % at DK1 at 7 km distance. At the positions at 15-25 km distance there was a decrease up to 64 % at some positions but an increase at others. At the maximum distances of 35 and 45 km at DK4 and DK5 PP10M/day increased during the pile driving day by 237 % and 54 % respectively. Thus there appears to be a negative effect of pile driving on PP10M/day up to a minimum distance of 7 km from the construction site (Tab. 8). At greater distances the effect is less clear and at 30-45 km distance there appears to be an increase in PP10M/day during the day of pile driving.

Tab. 8: Median, minimum and maximum of PP10M/day at the different POD-positions

POD-position	Distance To pile driving in km	Median PP10M/ day	Min. and Max. PP10M/ day	N days	PP10M/ Day during piling day	Change relative to other days
P1	1	37,9	0-65,3	52	2,1	- 95,2 %
P2	3	22,3	0-49,3	52	1,4	- 93,5 %
P3	7	6,8	0-27,8	47		
P4	15	8,7	0-22,9	23	2,8	- 55,6 %
P5	25	14,2	0-49,3	60	4,2	- 64,4 %
P6	1	16,1	0-54,9	54	0,0	- 100 %
P7	3	7,7	0-20,8	54	6,9	+ 35,5 %
P8	7	5,8	0-15,3	55		
P9	15	9,0	0-40,3	24	4,9	- 12,5 %
P10	25	4,1	0-28,5	60	6,3	+ 125,0 %
DK1	7	7,6	0-43,8	108	0,7	- 88,9 %
DK2	15	9,4	0-36,1	107	4,2	- 39,1 %
DK3	25	6,6	0-24,3	56	2,1	- 57,1 %
DK4	35	4,2	0-13,9	73	11,8	+ 237,1 %
DK5	45	5,9	0-27,1	24	6,9	+ 53,3 %

4.2.2. PPM/H

Mean PPM/H varied between 0.4 and 6.7 at the different POD-positions. High values were found at P1 and P2, while at the other POD-positions PPM/H was considerably lower (Tab. 9). This was independent of POD-ID. Thus, there seem to be great local differences in harbour porpoise activity as measured by PPM/H.
We did not test the effect of pile driving on this parameter as a sample size of only one pile driving event does not allow for any meaningful analysis on the basis of PPM/H.

Tab. 9: Mean, minimum and maximum PPM/H recorded at the different POD-positions

POD-position	Mean PPM/H	Min PPM/H	Max PPM/H
P1	6.7	0	56
P2	3.0	0	43
P3	0.6	0	16
P4	0.8	0	16
P5	1.6	0	46
P6	1.5	0	39
P7	0.7	0	13
P8	0.6	0	23
P9	1.0	0	14
P10	0.4	0	14

4.2.3. Waiting times

Based on analysis of waiting times (the most meaningful parameter to analyse when there is only one pile driving event) we found a clear effect of pile driving during construction of FINO III up to a distance of 7 km, while at a distance of 15 km this was no longer detectable.

With a total of 17.8 (at P1) and 44.6 (at P6) hours the first waiting times after pile driving at the nearest positions (1 km distance to the construction site) were 30 times and 74 times longer than the median of 15 randomly assigned ones and lasted 4.8 and 11.4 hours after pile driving was finished (Tab. 10). The waiting times after the end of pile driving were the longest ones recorded at those positions (Fig. 13). At 3 km distance first waiting times lasted a total of 17.6 (P2) and 8.8 hours (P7), were 20 times and 4 times longer than random ones, and at least at P2 it was also the longest one recorded at that position (Tab. 10, Fig. 13). At 7 km distance the first waiting time lasted 25.6 hours (DK1) and was 12 times longer than random ones. Here it was also the longest one recorded (Fig. 13). At the positions 15-25 km from the construction site there was only a marginal effect and first waiting times lasted between 5.6 and 13.8 hours and were between 1-7 times longer than random ones (Tab.

10). However, they fell into the range of waiting times that were recorded outside the pile driving times (Fig. 13).

When comparing the duration of that part of the first waiting times that continued after pile driving had finnished to the median of 15 randomly assigned ones, there also appears a clear difference at the positions between 1 to 7 km from the construction site, while at distances of 15-25 km this difference is less clear (Fig. 12). Due to a sample size of only one no meaningful statistical test could be conducted to test for significant effects in these differences.

Tab. 10: Median, maximum and minimum of 15 random waiting times and their duration after a random point in time, as well as total duration of the first waiting times after pile driving and their duration after the pile driving event was finished. Given is also how much longer first waiting times were enlarged as compared to random waiting times.

		Random waiting times (n=15)			**First waiting time after piling (n=1)**		**Effect**	
POD-Posi-tion	**Distance to FINO III [km]**	**Median [h]**	**Min. - Max. [h]**	**Medians of time after a random timepoint [h]**	**Waiting time [h]**	**Duration of waiting time after piling [h]**	**Prolonga-tion of waiting time**	**Prolonga-tion of waiting time duration after pile driving**
P1	1	0,6	0,2 – 11,1	0,2	17,8	4,8	30x	24x
P2	3	0,9	0,4 – 7,3	0,3	17,6	2,5	20x	8x
P3	7	2,7	0,4 – 8,2	0,5				
P4	15	3,0	0,8 – 33,6	1,4	13,8	8,1	5x	6x
P5	25	1,6	0,6 – 5,7	0,7	10,4	5,4	7x	8x
P6	1	0,6	0,2 – 34,0	0,1	44,6	11,4	74x	114x
P7	3	2,5	0,2 – 14,6	0,9	8,8	8,0	4x	9x
P8	7	10,5	0,7 – 27,9	1,8				
P9	15	4,2	0,3 – 22,2	2,1	5,6	3,8	1x	2x
P10	25	13,0	0,3 – 49,5	5,4	9,5	9,5	1x	2x
DK1	7	2,1	0,5 – 12,6	1,4	25,6	6,4	12x	5x
DK2	15	2,8	0,5 – 10,6	0,8	8,8	1,8	3x	2x
DK3	25	9,4	0,7 – 36,4	4,0	10,0	4,7	1x	1x
	Mean	*1,2*						

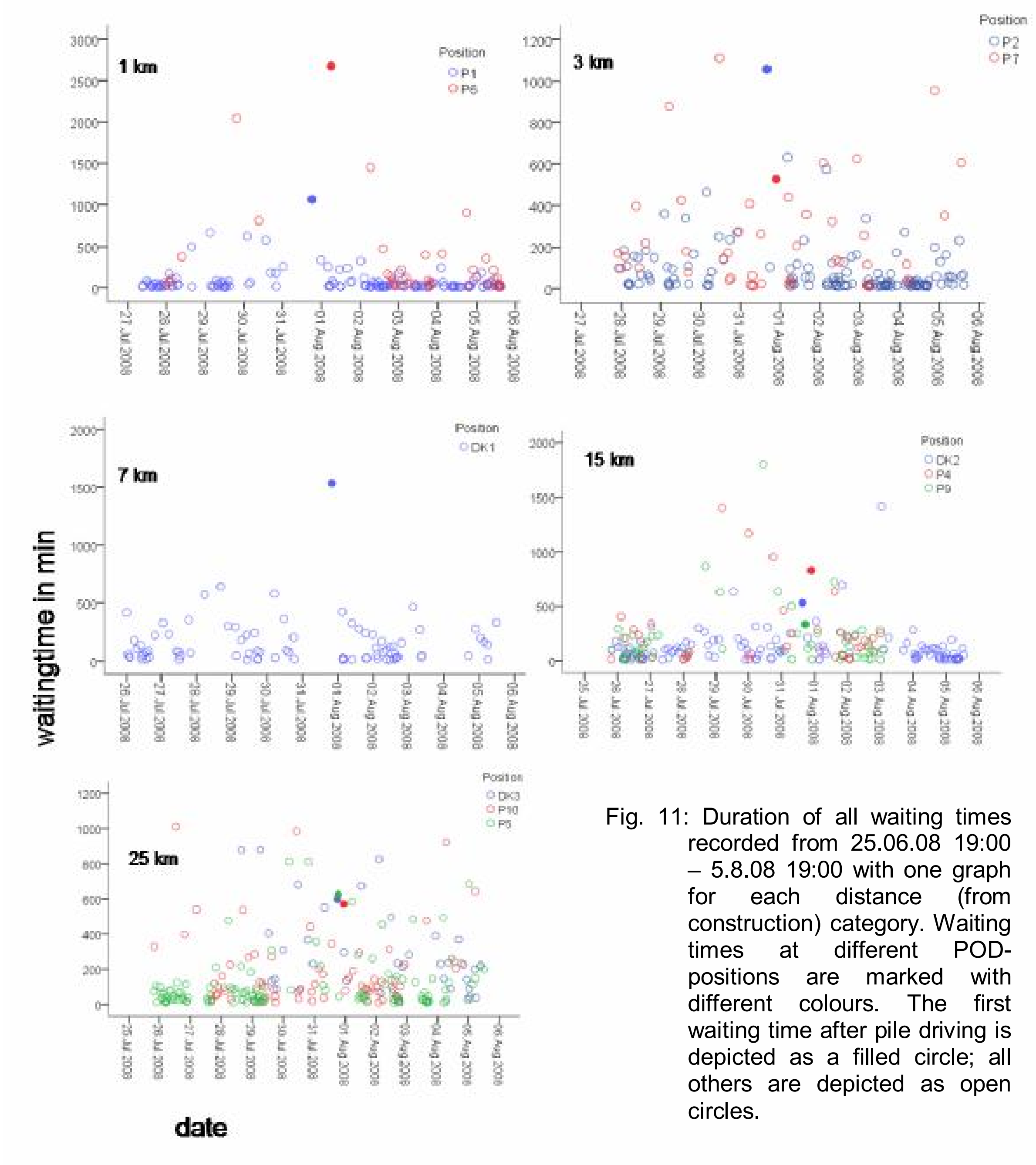


Fig. 11: Duration of all waiting times recorded from 25.06.08 19:00 – 5.8.08 19:00 with one graph for each distance (from construction) category. Waiting times at different POD-positions are marked with different colours. The first waiting time after pile driving is depicted as a filled circle; all others are depicted as open circles.

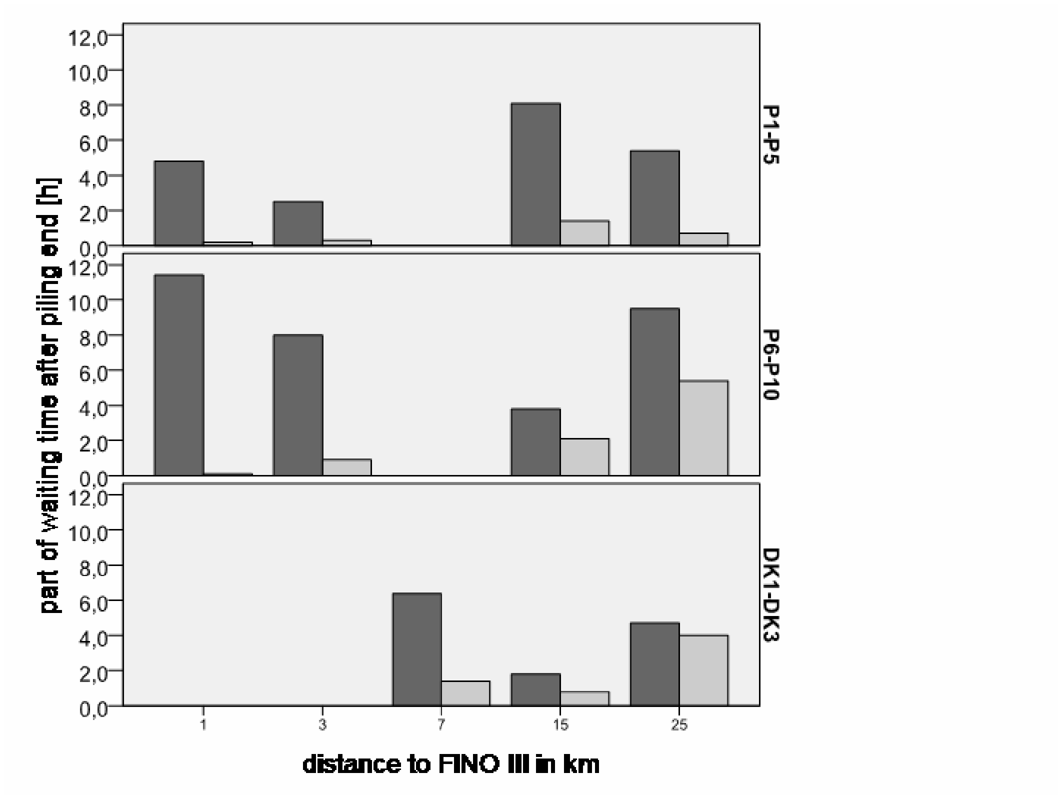


Fig. 12: Duration of waiting times **after** pile driving was finished at the separate POD-positions with their distances to the FINO III - construction site at the x-axis. Duration of the first waiting time after pile driving is shown as a dark grey bar and the median of 15 randomly assigned waiting times is shown as a light grey bar.

5. Discussion

The aim of this study was to investigate potentially far reaching effects of offshore pile driving on harbour porpoises (*Phocoena phocoena*). The present study accompanied two other studies that investigated pile driving effects only up to a distance of about 20 km. As Tougaard *et al.* (2009) found that effects potentially reach beyond this distance, it seemed plausible to also investigate distances beyond this.

The present study on the effects of pile driving on harbour porpoise activity yielded ambiguous results: There was a slight effect of piling on PP10M/H but only at the greatest distances, which disappeared when days with unusually high porpoise activity were excluded. There was no effect on PPM/H at any POD-position, while there was an effect of pile driving on the duration of waiting time at the closest and furthest distance.
Thus the results of this study, which is the first attempt to detect responses of porpoises to pile driving over large distances, are not clearcut and differ from previous studies. When interpreting these results it is important to consider some methodological aspects.

The temporal resolution of the parameter *PPM/H* seems to be too high to be a reasonable response variable to study the effects of pile driving during the present study. PPM/H was already low before pile driving and this might explain why no pile driving effect could be found based on this parameter. If *PPM/H* values are too low this leads to a high number of 0-values, which yields a data set where it becomes statistically difficult to detect a decreasing effect.
Lower values might be due to generally low porpoise activity at these positions or could in part be due to the only recently developed C-PODs. As T-PODs are no longer manufactured we had to use the successor device, which is the C-POD. Recent analyses by BioConsult SH revealed that the algorithm that accompanies the C-POD is considerably less effective in recognising porpoise clicks in a noisy background than the algorithm accompanying the T-POD (Höschle et al. pers. comm.). The area around FINO III seems to be a rather noisy environment and at several positions the Scan limit of the C-PODs was reached during the FINO III study (Brandt et al. 2009b), possibly making investigations with the current C-POD version difficult. Especially at a low temporal resolution T-POD and C-POD data are thus comparable only to a limited extent. This might also partly explain why clear pile driving effects were found analysing T-POD data but not when analysing C-POD data. The C-POD is consistently being developed further and will hopefully be as reliable as the T-POD in the near future.

When analysing *PP10M/day* results were unclear. There was a significant effect of pile driving on *PP10M/day* at the furthest POD-positions DK1 (46 km distance) and DK2 (37 km diastance). Here *PP10M/day* was lower during days of pile driving than during days without pile driving. However, these differences were largely due to a few days with exceptionally high values for *PP10M/day*, when there happened to be no pile driving activity. If these few days were excluded from analysis there was no longer a significant effect at any POD-position. Especially since we did not find an effect of pile driving on *PP10M/day* at the closer POD-positions, where a stronger effect would be expected, this initially significant difference was probably caused by random variation rather than by pile driving.

However, when analysing *waiting times*, which might be considered as the most conservative approach for analysing influences of pile driving on POD-data, we found an effect at the closest and furthest POD-position: The first *waiting times* after pile driving were significantly longer than randomly assigned ones at the closest and furthest POD-position to Horns Rev (DK5 and DK1), while no significant effect could be found at intermediate distances.
Given that we no longer detected a great increase in *waiting times* at 15 km distance during the previous study at Horns Rev II, and that we found no effect at intermediate distances during this study either, finding an effect of piling at 46 km distance during this study seems unrealistic. It is possible that transmission loss differed to the southwest of the reef (where C-PODs were located during this study) as compared to the southeast (where T-PODs were deployed during the first study). While water depth continued to be shallow along the T-POD-transect to the southeast (about 5-10 m water depth), it rapidly increased along the C-POD-transect to the southwest (where water depth was between 10-30 m). Nevertheless, a reef effect on sound transmission should also be present along the C-POD transect to the southwest. This is because most pile driving events happened north of the reef, so that sound had to travel across the reef to reach the C-POD-positions. However, as water depth to the southwest increases rapidly as compared to the southeast, the distance over which sound had to travel in shallow water was reduced. At present little is known about the differences in sound transmission in waters of different depths. It remains a possibility that transmission loss may have been less to the southwest due to deeper water, and therefore the effect on harbour porpoise behaviour may have reached further. However, as we found no clear effets at intermediate distances this seems unlikely. We conclude that most likely the effect at 46 km is an artefact. It also has to be kept in mind that it is difficult to compare T-POD and C-POD data without any intercalibration data yet existing. Therefore these comparisons have to be treated carefully.

In some aspects these results appear to be in contrast to what we found during the previous study at Horns Rev II where we deployed T-PODs in a transect line to the southeast. During the previous study all parameters (PP10M/day, PPM/H and waitingtime) were found to be negatively affected by pile driving (Brandt et al. 2009). Recent analyses show an effect on *PPM/H* up to a mean distance of about 18 km (Brandt et al. manuscript), In this study, only an effect on *waitingtime* could be proven byond reasonable doubt, reasons for which are discussed above. Waitingtime was significantly effected at the POD positions closest (7 km) and furthest (46 km) to pile driving, but the effect at 46 km we discussed as a possible artefact. No significant effect could be shown at intermediate distances between 15 and 37 km. Thus the effect during this study was not detectable at the same distance as during the previous investigation. The differing results might indicate that porpoise responses to underwater noise from pile driving may not be uniform and not always be easily detected. However, only two POD-positions were within the range where we found an effect during the previos study and at the closest position waitingtimes were affected. Thus results may not be so different afterall, and there might simply be no porpoise response at distances byond 15 km to the southwest of the construction site.

No noise measurements were undertaken at large distances to the construction site, thus noise levels received at a distance of 50 km are not known and it is not finally clear, whether they were audible for porpoises against background levels. Betke (pers. comm.) recently conducted noise measurements of pile driving of the NordEON transformer platform in the German North Sea with similar source levels compared to Horns Rev II at distances of up to 46 km. At a distance of 46 km, the main energy of underwater noise was around 100 to 300 Hz reaching 120 dB, which is below the hearing thresholds of harbour porpoises at these frequencies. At higher frequencies, noise levels were lower but above the hearing threshold of porpoises although some uncertainties remain. The different measurements of porpoise hearing abilities provide large variations of more than 40 dB and according to the highest measurements, pile driving at Horns Rev II would not be audible to porpoises at such a large distance. In addition, noise levels at frequencies above 300 Hz rapidly fell below 110 dB and at 4 kHz they were below 90 dB, which is in the range of ambient noise levels in the North Sea. Ambient noise levels in the North Sea vary around 80 to 100 dB at wide range of frequencies, mainly in relation to windspeed. At Horns Rev, ambient noise was above 100 dB even at high frequencies (Betke 2008), but at Horns Rev, comparatively shallow waters will cause stronger attenuation than in the open North Sea. According to these findings it is concluded, that noise levels from pile driving at a distance of 50 km to Horns Rev have been at the limit of porpoise hearing abilities and fell within the range of ambient noise. They might have been audible to porpoises only under some conditions of low windspeeds and low ambient noise and are thus unlikely to cause a marked response. However, at shorter distances of 20 km or 30 km higher noise levels are inferred, so that a response would have been more likely than at 50 km. This further supports the assumption that effects at the furthest distance at DK1 (46 km) was an artefact and no real effect of piledriving.

Skov and Thomsen (2008) found the near vicinity of the reef to be of high importance to harbour porpoises possibly as feeding grounds due to upwellings. Additionally Diederichs *et al.* (2008) found that the foundation of the Horns Rev I wind park might function as artificial reefs and be of some attraction to feeding porpoises due to elevated fish biomass. PODs during the first Horns Rev II study were all located in shallow waters of the reef and P5 and P6 were also positioned close to the Horns Rev I wind farm. On the contrary POD-positions during this study were located in deeper water and without artificial structures in the vicinity, representing a large scale uniform habitat. As feeding in porpoises is associated with changing swimming direction, and animals possibly stay at a feeding location for longer than when they only pass through an area, this may lead to higher PPM/H at feeding areas, even if density is not significantly higher. At present, the differing functions of areas for porpoises and the differing pile driving effects linked to these remain speculation and we urgently need to learn more about this. It would be possible to study POD-data more detailed by looking at feeding trains to shed light on this issue (Koschinski *et al.* 2008). If a pile driving event disrupts feeding behaviour an effect will show up in the parameter *PPM/H* more clearly at feeding areas than in areas where animals usually only pass by. Consequently *PPM/H* might only be a suitable parameter to study the effects of pile driving in areas where animals show a lot of feeding behaviour or at least where density is sufficiently high. As PPM/H was generally low during this study, the locations may not function as feeding habitat and therefore an effect might have been more difficult to detect.

It is interesting to note that during the day when pile driving happened at the FINO II research platform there was an increase in PP10M at DK5 which was at the greatest distance to FINO III. However, during the same day two monopiles were driven into the seabed at Horns Rev II, to which DK5 was the closest POD-position of the five. While at FINO III pile driving continued during the whole day, pile driving at Horns Rev II only lasted a total of 86 min from 0:02 to 0:44 and from 13:28 to 14:12. Thus while porpoises usually avoided the pile driving site at Horns Rev II, the effect of pile driving from FINO III might have been stronger due to its consideryby longer duration. Porpoises leaving the FINO III site might thus have entered the Horns Rev II site between pile driving events there. However, with only one such event this is difficult to test.

5.1. Conclusion

This is the first study aiming to detect responses of propoises to pile driving at large distances. Results indicate a response of harbour porpoises at a distance of 7 km to pile driving at Horns Rev II. A significant effect was also found at 46 km distance, however, this is contrasted by no significant results at 15 to 37 km. From available data it cannot finally be concluded until what range piling noise from Horns Rev 2 was audible to harbour porpoises and until where an avoidance reaction occurred. However, piling noise was likely to be masked by background noise at 50 km. The results thus indicate, that harbour porpoise responses at distances beyond 15 km if present at all are certainly weak and of short duration.

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