The effects of pile driving on marine mammals and fish in Belgian waters

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Pile driving generates very high levels of low frequency impulsive underwater noise, with possible consequences for marine mammals and fish. To describe the effects of pile driving on harbour porpoises we developed a model based on the results of aerial surveys, which clearly pointed at disturbance effects. Especially fish with a swim bladder can be affected by piling operations, but the investigation of sub-lethal effects and the sensitivity of different fish species and life stages is complex. A multidisciplinary study is proposed to investigate these effects in the field and under controlled laboratory conditions.

INTRODUCTION

The installation of numerous offshore wind farms across the North Sea has triggered a range of questions regarding its impact on the marine ecosystem. In most cases, wind turbine foundations are hammered into the seafloor. This activity is known to produce low frequency impulsive underwater noise (see chapter 6; ICES, 2010). Underwater sound travels at a speed of 1500 m/s, and can travel up to considerable distances. For pile driving, sound pressure levels (peak to peak, SPL_{p-p}) of up to 200 dB re 1 µPa at a distance of 750 m from the noise source have been measured or estimated (Madsen et al., 2006; Norro et al., 2010; 2012). Such noise levels can have consequences on living organisms ranging from masking, behavioural disturbance, physiological stress, hearing loss (temporary or permanent), and even to injury or death (Popper et al., 2004; Hastings and Popper, 2005; Wahlberg and Westerberg, 2005). Given such consequences, noise is increasingly considered as an important form of pollution. One

of the aims of the European Marine Strategy Framework Directive (MSFD; 2008/56/EC) is to establish a framework for community action in the field of marine environmental policy, with anthropogenic underwater noise at levels that do not adversely affect the marine environment. To implement the MSFD, Belgium adopted an interim criterion of a maximum zero to peak noise level (L_{z-p}) of less than 185 dB re 1 µPa at 750 m from the source for anthropogenic impulsive sounds (Anonymous, 2012a).

The impact of noise is of particular concern for marine mammals and fish, which utilise sound in their everyday lives. To assess the effects of pile driving on marine mammals, the research has focused on the harbour porpoise *Phocoena phocoena*, as this is by far the most common cetacean in European, including Belgian, waters (Haelters et al., 2011). Harbour porpoises use sound production and reception for foraging, spatial orientation and social interactions. Sound has essentially

taken over many of the roles normally requiring vision. Therefore, this species may be heavily impacted by excessive underwater noise, an impact not yet fully understood. Around a pile driving site, areas can be defined where exposure to the noise can lead to injury, permanent and temporal hearing threshold shifts (PTS; TTS), masking of the animal's sonar system, behavioural reactions (possibly leading to stress) and audibility of the noise to the harbour porpoise (Lucke et al., 2009).

At the very start of bio-acoustic research, marine mammals were the main target group. Later, researchers took an interest in fish, as sound enables them to communicate, forage, find a mate, orientate, avoid predators, defend their territory and express aggression (Hastings and Popper, 2005; Kikuchi et al., 2010).

Underwater sound consists of two components: particle motion, indicating the movement of the molecules in the

medium due to the sound waves, and sound pressure. Particle motion moves through a fish's body and is detected by the inner ear, which acts as a biological accelerometer and enables fish to hear (Popper and Fay, 1999; Wysocki et al., 2009). Fish rely especially on particle motion in their response to sounds from different directions. In contrast to fish without swim bladders, those with gas-filled swim bladders will respond to sound pressure waves because of the higher compressibility of gas compared to seawater (Thomsen et al., 2006). These compressions may be transmitted to the inner ear whereby sound pressure is transformed into particle motion and will give them an auditory advantage, with information on sound characteristics such as distance and location.

Only for a limited number of fish species the hearing range is known, and although it varies greatly between species, frequencies from below 50 Hz up to 500-1500 Hz are detectable by the majority of them (Thomsen et al., 2006; Popper and Hastings, 2009; Andersson, 2011). A few species, including the Atlantic herring *Clupea harengus*, can perceive sound above 1500 Hz (Wysocki et al., 2009). The hearing range of the harbour porpoise stretches from 250 Hz to 160 kHz, while it is most sensitive between 100 and 140 kHz (Kastelein et al., 2002).

RESEARCH STRATEGY

One of the aims of the Belgian wind farm monitoring programme is to investigate the ecological impact of noise on marine mammals and fish. While the research on marine mammals already made some major achievements, the investigation of the effect of underwater noise on fish only recently started and its description here is limited to a scientific justification of what is and will be done.

Harbour porpoise *Phocoena phocoena*

Harbour porpoises are notoriously difficult to study in the wild because of their elusive nature and the technical difficulties related to the environment they live in. Our knowledge of the impact of piling on harbour porpoises is limited to exposure studies of individual animals in captivity with extrapolations to the marine environment, simple predictions of disturbance

distance such as made in environmental impact assessments and a few studies at construction sites (ICES, 2010; Murphy et al., 2012). To describe and predict the impact of pile driving, we developed a model based on anticipated harbour porpoise behaviour. We compared the model results with changes in the in situ distribution patterns of harbour porpoises due to pile driving.

Before and during the piling of jacket foundations at the Thorntonbank in 2011, we performed a number of standardised aerial line transect surveys (Buckland et al, 2001), making observations in a predefined pattern consisting of parallel tracks 5 km apart and approximately covering the Belgian marine waters (Haelters, 2009). To assess possible effects of piling on the distribution and abundance of harbour porpoises, observations were transferred to a fine-scale density map, in which the density in unvisited areas was extrapolated from observations using inverse distance weighting.

As it is difficult to objectively qualify and quantify the impact of piling based on maps from aerial surveillance data, a model was developed describing the fundamental phenomena at the basis of the harbour porpoises' redistribution. We presumed that the speed of a harbour porpoise may be described as a combination of a directional movement and random dispersal. Close to the impact area and during piling, we presumed that a porpoise would exclusively head away from the piling location at a speed which would decrease as a function of disturbance, i.e. the noise level the animal is exposed to. In the absence of piling or at a distance where the piling noise is tolerated, harbour porpoises would – at least over the short time frame as applicable in this study – move more slowly and in random directions (i.e. random dispersal).

The model was first applied to hypothetical data, described by an even distribution of harbour porpoises throughout the area (1 animal/km²). The resulting density pattern after a first period of disturbance (piling), without taking account of random motion, can be described as an area near the impact location where the density is lower than average (due to animals moving away), surrounded by an area with a higher density (due to movement of individuals away from the piling zone), and an area with no change in density (i.e. the area beyond the influence of the pile driving activity). In the case of short, consecutive pile driving periods, the areas described above would systematically shift further away from the impact location (Figure 1).
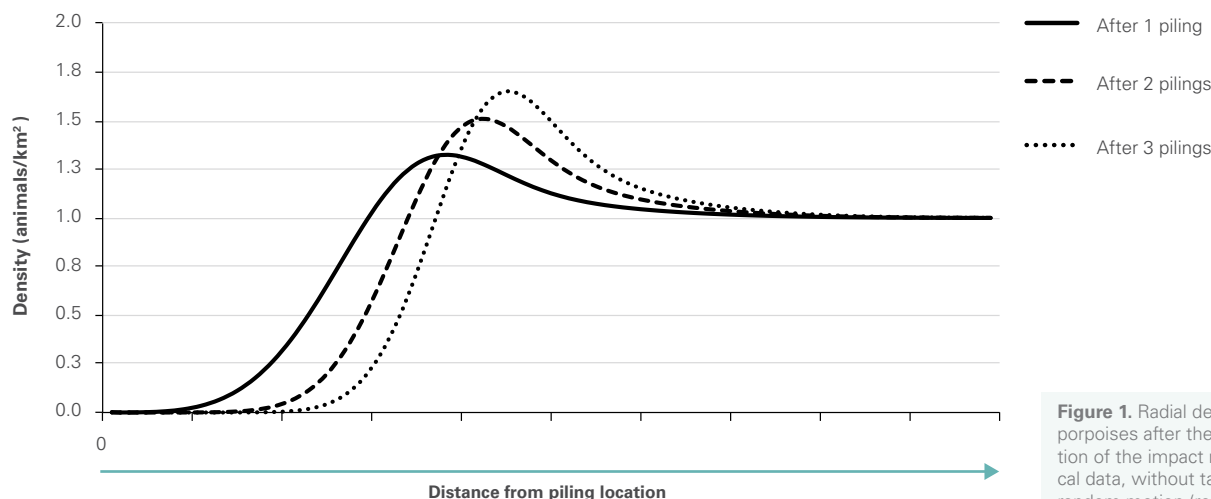
Figure 1. Radial density of harbour porpoises after the repeated application of the impact model to hypothetical data, without taking account of random motion (reference density = 1 animal/km²).

To apply the model to real data, we made several assumptions. The density distribution on 29 March 2011 was used as a reference situation. We used a particle tracking approach to simulate the displacement of harbour porpoises. As an average and maximum swimming speed we used respectively 0.9 and 4.3 m/s (after Otani et al., 2001). For the random dispersal during periods or in areas without disturbance, we ignored water currents. We modelled one impact phase that lasted for two hours and was followed by a quiet period of two hours. In the model, we used 19 km as the distance from the noise source where a noise level (L_{p-p}) of 140 dB re 1µPa is reached (Norro et al., 2013). Tougaard et al. (2011) consider 140 dB re 1µPa as the discomfort noise level for harbour porpoises. We did not take account of a different reaction of individual harbour porpoises to noise: e.g. some animals may be tolerant to higher noise levels than others and some may remain in a noisy area because of good feeding opportunities, less competition with other porpoises or fewer predators.

Fish

Most of the energy emitted by the construction and operational noise of offshore wind farms is at frequencies below 1 kHz, which is well within the hearing range of fish (Figure 2). The actual effects of noise depend on the physical characteristics of the sound and the environment, and on the characteristics of the fish itself, such as size, life stage and species-specific hearing capabilities. All these factors make bio-acoustic research a complex matter.

The variables used to describe impulsive sounds generated through piling are the sound exposure level to a single strike (SEL_{ss}), the cumulative sound exposure level (SEL_{cum}) and the number of strikes (Slabbekoorn et al., 2010). The first results on the effects of low and mid frequency impulsive noise

on fish showed that SEL_{ss} >176 dB re 1 µPa²s and SEL_{cum} >207 dB re 1µPa²s are needed to induce significant tissue damage in juvenile and adult roundfish (Halvorsen et al., 2012; Casper et al., 2012). Something more difficult to assess is the disturbance of the natural behaviour of fish or the masking of the communication and orientation signals due to exposure to lower noise levels (Hastings and Popper, 2005; Thomsen et al., 2006; Walhberg and Westerberg, 2005; Mueller-Blenkle et al., 2010). On average, SEL_{ss} of 163 dB re 1 µPa²s at 750m and SEL_{cum} of 196 dB re 1µPa²s at 750m were measured at the Bligh Bank during monopile-driving (Norro et al., 2013).

In a controlled environment, Bolle et al. (2012) exposed newly hatched sole *Solea solea* larvae to noise resembling piling noise at 100 m. No difference in immediate mortality or mortality up to 7 days after exposure was observed between the control and exposed groups. However, the few studies concerning fish larvae leave many questions unanswered (Booman et al., 1996; Govoni et al., 2006; Bolle et al., 2012). Defining the sound level thresholds causing mortality, injury, hatching failure, and delayed or abnormal development should have priority. Particular developmental stages which are more vulnerable than others should be identified. Overall, the ecological impact of these effects should be assessed and, if significant, taken into account by policy makers.

Given the scarcity of data on the impact of noise on fish and fish larvae, criteria for underwater noise or accompanying legislation in relation to fish are rare. The US Fisheries Hydroacoustic Working Group formulated interim criteria for the maximum noise levels that fish could be exposed to without causing non-auditory tissue damage. The interim criterion for maximum SEL_{cum} for fish of 2 grams or more is set at 187 dB re 1µPa²s, and for fish less than 2 grams at 183 dB re 1µPa²s (Oestman et al., 2011).
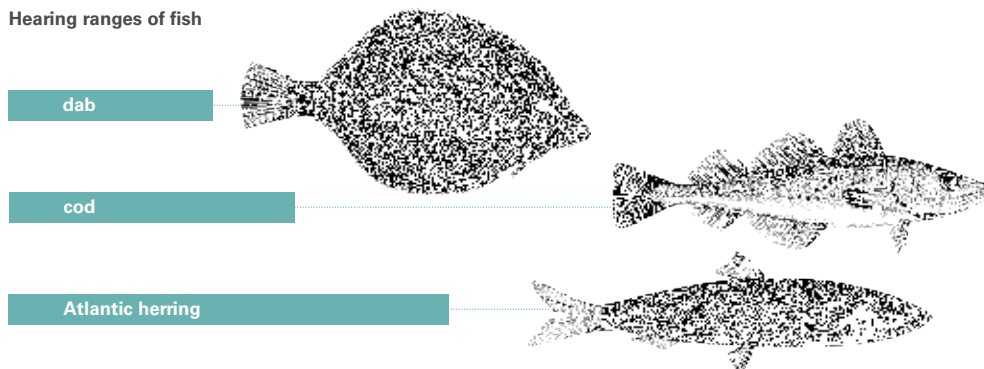
Figure 2. Hearing ranges of dab *Limanda limanda*, cod *Gadus morhua* and Atlantic herring *Clupea harengus*. Dab has no swim bladder and therefore has a narrow hearing range. The hearing range of cod is slightly wider as it has a swim bladder, and Atlantic herring has a wide hearing range due to a pair of elongated gas ducts extending from the swim bladder to the inner ear (based on Slabbekoorn et al., 2010). The grey scale represents the energy intensity level in the frequency range of the piling noise.
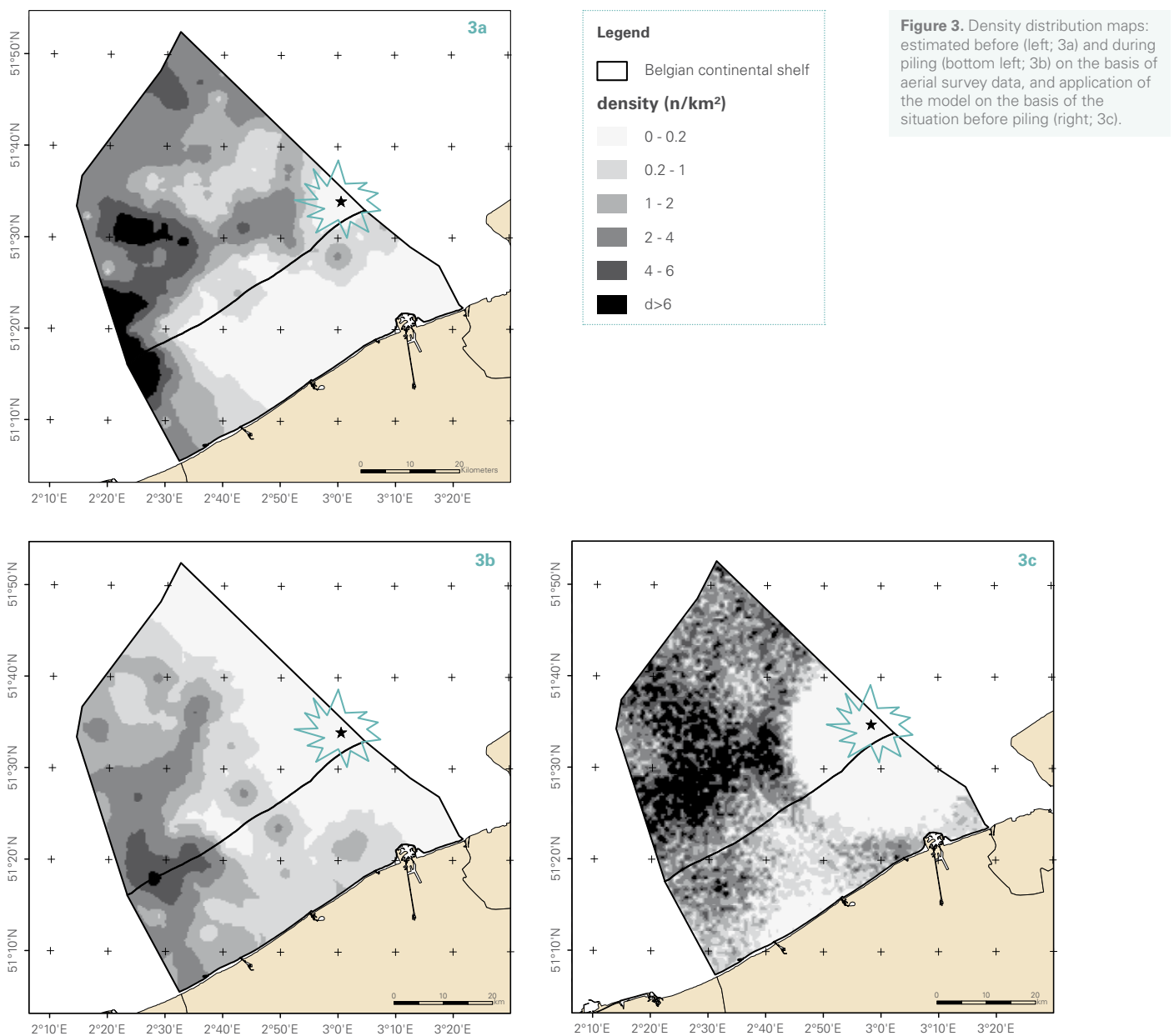
Hearing ranges of fish

dab

cod

Atlantic herring

Pile-diving noise

0.01   0.1   1   10   100   200

Frequency in kHz
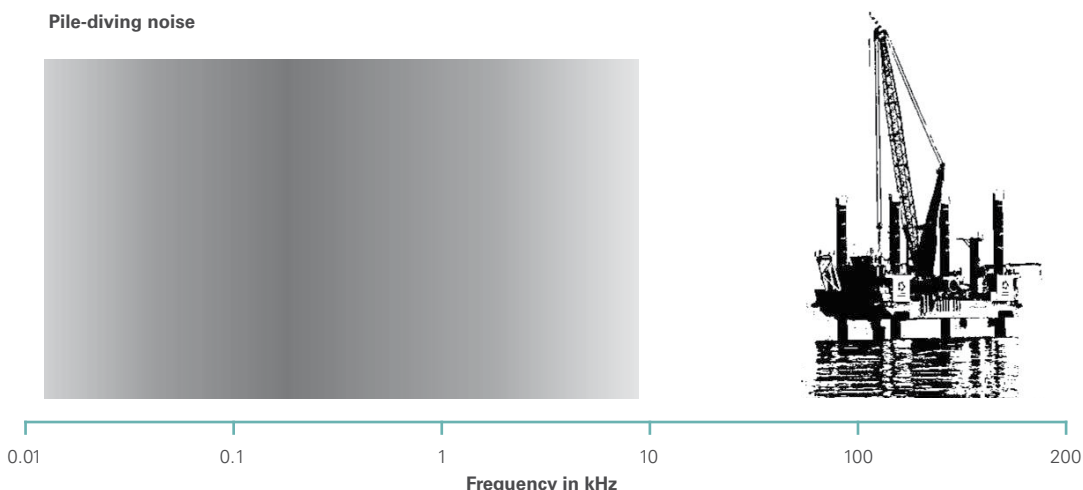
HARBOUR PORPOISES: SENSITIVE TO PILE DRIVING?

The estimated average densities of harbour porpoises over the surveyed area on 29 March (pre-piling phase) and 16 April (piling phase) were respectively 2.7 and 1.3 animals/km² (Haelters et al., 2012a). Before piling, harbour porpoises were unevenly distributed throughout Belgian waters, with the highest densities in the western and northern part (Figure 3a). During the piling event, no harbour porpoises were observed in a zone around and north of the piling location (Figure 3b). The results of the application of the model to the reference situation indicate a similar zone void of harbour porpoises (Figure 3c). While the model is able to reproduce the porpoise displacement in a wide area around the piling zone, outside of this area there are larger differences between the situation observed and the one modelled.

Both the results of the aerial surveys and the application of the model to a reference situation during pile driving indicated an apparent distance of disturbance of harbour porpoises of around 20 km in Belgian waters. This is consistent with the results of similar research (Brandt et al., 2011; 2012; Tougaard et al., 2009; 2011), and it is likely that a similar disturbance occurred in the adjacent Dutch waters. The observed disturbance distance could be the consequence of repeated piling events: as observed by Thompson et al. (2010), the distance over which harbour porpoises are disturbed becomes larger with each piling event.

Legend

▢ Belgian continental shelf

density (n/km²)
- 0 - 0.2
- 0.2 - 1
- 1 - 2
- 2 - 4
- 4 - 6
- d>6

Figure 3. Density distribution maps: estimated before (left; 3a) and during piling (bottom left; 3b) on the basis of aerial survey data, and application of the model on the basis of the situation before piling (right; 3c).

The deviation between the model predictions and the density distribution estimates during piling outside the 20 km distance range indicate that there were likely other factors than piling that played a role in the spatial shifts of harbour porpoises between the reference survey and the survey performed during the piling. These could be food availability or seasonal movement. While harbour porpoises were very common in the survey area at the end of March 2011, their average density had halved by mid-April, probably due to a combination of disturbance by pile driving over a large part of this area and the onset of a general seasonal movement out of Belgian waters.

Harbour porpoises need to feed on a regular daily basis. Therefore prey availability is an important factor determining their distribution. Undoubtedly, pile driving disturbs harbour porpoises over a large area, with the population level consequences remaining unknown. Given the seasonally high densities of harbour porpoises in Belgian waters, thousands

of these protected animals could be affected. The sub-lethal effects on individual harbour porpoises, with possible consequences at the population level (through effects on breeding frequency and longevity), and the cumulative effects due to the construction at several sites in the Southern North Sea, remain poorly understood.

Independent of construction operations, harbour porpoises have shown important shifts in their overall distribution pattern within the North Sea during the last decades (Hammond et al., 2013). Next to the effects of construction operations, it is therefore necessary to have a good understanding of such natural background shifts. They need to be taken account of, as the current management measures include a temporal exclusion of piling activities based on seasonal harbour porpoise densities.

FUTURE MONITORING
Harbour porpoises

We presented a model to simulate the disturbance effects observed during pile driving in 2011. However, any extrapolation of the model should be treated with care. The piles driven in 2011 for example, were relatively small (jacket foundations) and it can be expected that the piling of larger piles (monopiles) leads to increased disturbance distances due to increased noise levels. It is therefore advisable to test the model during different piling conditions with different noise levels, but also with different recurrences in the disturbance events. A model extension should further aim at comprising the effects of noise mitigation techniques and the effects of simultaneous piling at several sites within e.g. the southern North Sea.

Next to data from aerial surveys, data collected using an array of passive acoustic monitoring devices, moored following the gradient of noise level, could help to better understand the disturbance effects. It is evident that the investigations of the impact of piling on harbour porpoise distribution and abundance need to be combined with acoustic measurements.

For piling operations at the different wind parks, amongst others the floating crane SVANEN was used.

Fish

A multidisciplinary study combining biology, acoustics, physiology and biochemistry has been designed to examine the impact of the construction and operational noise of offshore wind farms on fish in Belgian waters. The focus will be on the impact of impulsive noise on fish eggs and larvae, since these 'passive drifters' cannot actively escape the exposure. The European sea bass *Dicentrarchus labrax* (Figure 4) has been chosen as a model species for round fish, especially for the physoclist fish which are lacking a connection between their gut and swim bladder. Sea bass is a commercially important species in the Southern North Sea, and eggs, larvae and fry are year-round available from the Ecloserie Marine de Gravelines (France), which makes it an excellent model species.
The first part of the study deals with the impact of pile driving noise. The worst case scenario will be analysed on board of a piling platform (Figure 5), while the impact at 500 m will be examined from a rigid-hulled inflatable boat (RHIB). In parallel, noise exposure experiments will be carried out under controlled conditions in the laboratory. The embryonic and larval development of fish exposed to different noise levels will be monitored and compared with control groups through different replicates.

In the second part of the study, the impact of long-term exposure to operational noise will be studied under controlled conditions in the laboratory. During their embryonic and larval development, fish will be exposed to different operational noise recordings. Possible chronic effects of operational noise on growth, weight, physiological stress, morphology, survival, and behaviour will be examined.

Figure 4. European sea bass *Dicentrarchus labrax* juvenile.

Figure 5. Experimental set-up on board of the piling platform. The vials containing larvae are all part of one replicate. Dividing the larvae over multiple vials decreases the risk of hypoxia. A comparable set-up will be used on board of the RHIB.
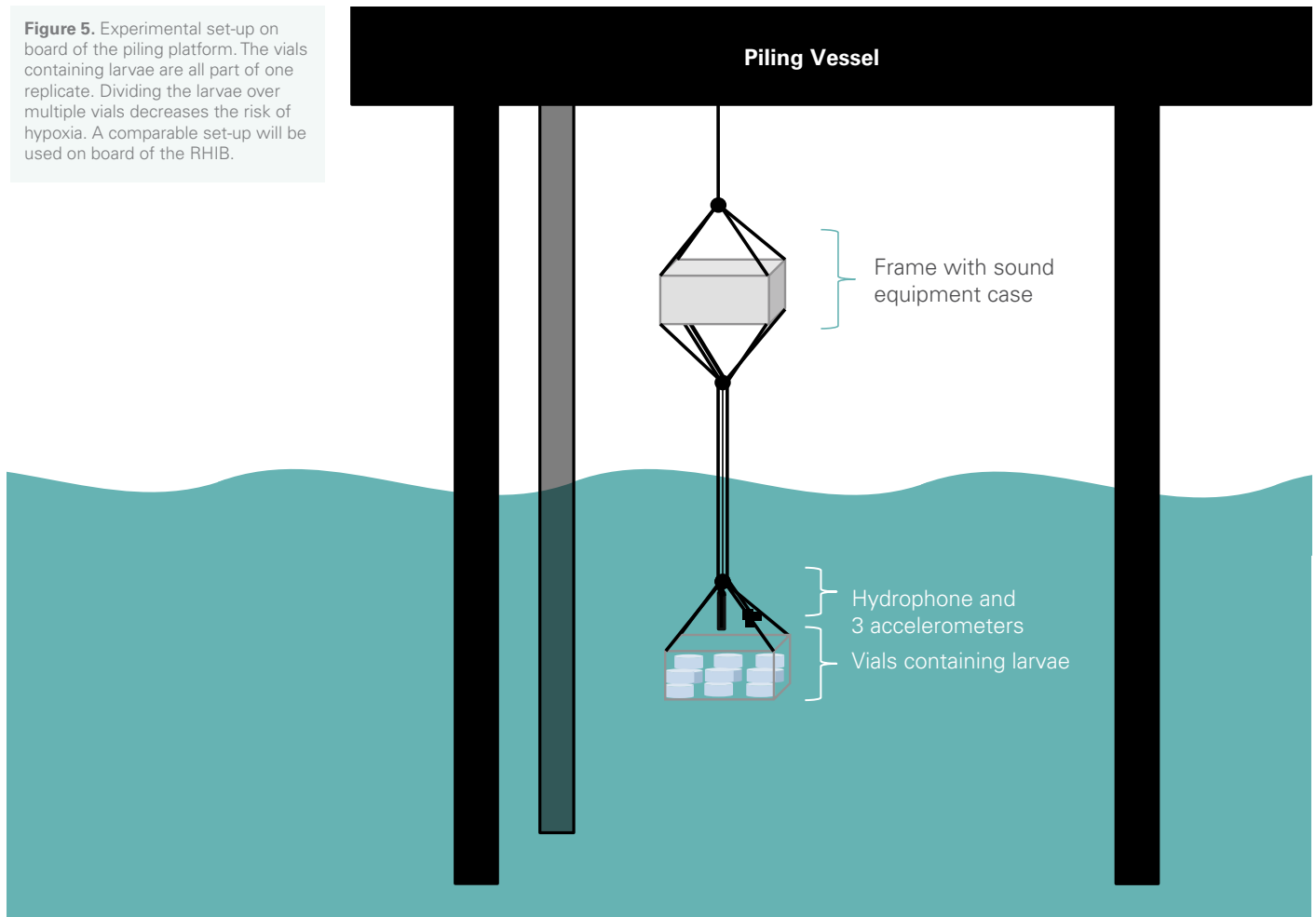
The harbour porpoise is the smallest and most common cetacean of the North Sea.