Evaluation of the Effect of Noise from Offshore Pile-Driving on Marine Fish

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Abstract

The purpose of this memo is to evaluate the possible effects of noise from offshore pile-driving activity on fish.

As part of a plan to establish offshore wind turbines in Denmark, the Ministry of the Environment and Energy introduced a government order asking the electricity companies to set up five large-scale offshore wind farms with a total output of 750 MW. Rødsand in the Femer Belt was selected as the location for one demonstration project with an output of 150 MW.

The project was approved on the condition that an EIA (Environmental Impact Assessment) study was conducted in accordance with the guidelines of the Ministry of the Environment and Energy (May 1999). Permission was also given to carry out the necessary preliminary studies.

The construction of an offshore wind farm at Rødsand may potentially affect the fish population in the area during construction and operation.

Technical background reports are prepared to form the basis for the actual EIA study.

As part of this work, a report on underwater and above-water noise measurements and analysis during offshore pile-driving at a wind-turbine park under construction in Sweden was conducted (Ødegaard & Danneskoild-Samsøe, 2000).

This paper attempts to estimate the effect that noise from the offshore pile-driving will have on the behaviour and physiology of the fish present in the area of the proposed wind farm. According to information given by SEAS, the piledriving of one monopile at Rødsand will last four hours. There will most probably be 72 mills in the demonstration project at Rødsand.

The hearing ability and avoidance of sound by fish species present in the area of the proposed wind farm (Bio/consult, 2000a, b) is taken into consideration.

Different species of fish have different hearing abilities and the reason for this is mainly differences in the physiology. Thus, in order to make a meaningful evaluation of the possible effects of noise on fish, it is essential to have an understanding of the hearing capability of fish, the physiology behind it, and how it influences the behaviour of the fish.

A short description of the hearing abilities of fish is given. This includes a description of audible thresholds and the differences between different fish species. On the basis of the scientific knowledge gathered, the possible hearing ability of the fish found at Rødsand is described and the possible impact that noise will have upon the fish is evaluated.

Even though the noise from pile-driving might seem tremendous to the human ear, this is not the case for all species of fish.

Bottom living fish in which the swimbladder has degenerated and hearing is not specialised generally have high auditory threshold levels and will probably hardly hear the noise frequencies above 250 Hz. At frequencies below 250 Hz the lowest auditory thresholds is app. 90-110 dB. This group of fish includes flounder, plaice, dab, turbot, sea scorpions, eelpout, sandeels and gobies that are all present in the proposed construction area at Rødsand.

Cod, whiting and silver eel, that are also present in the proposed construction area at Rødsand has a swimbladder and can probably hear frequencies up to 300-500 Hz. At frequencies below 300-500 Hz. the lowest auditory thresholds is app. 75-100 dB.

Although the reported avoidance reaction of fish at low frequencies is not completely clear it is possible, that low sound frequencies from pile-driving could elicit some avoidance from species without specialised hearing, especially those with a swimbladder (cod, whiting and silver eel). Avoidance reactions would be most plausible at short distances (less than 30 meter) from the sound source.

It is not likely, that the hearing of flounder, plaice, dab, turbot, sea scorpions, eelpout, sandeels and gobies, cod, whiting and silver eel will be harmed by the noise. Some degree of habituation of the same fish species to the noise from pile-driving is also plausible.

Herring and sprat (brisling), that are also found at Rødsand has a specialised hearing with low auditory threshold levels and a broad hearing bandwidth (50-75 dB at 200-3000Hz), which is probably reflected in the avoidance threshold.

Some damage to the sensory cells of the ear has been reported from clupeid fish (like herring and sprat) to occur at sound pressures of 153-170 dB. These noise levels occur at frequencies from 100 Hz to 2500 Hz at the four distances investigated from the pile-driving (Ødegaard & Danneskiold-Samsøe, 2000). Therefore herring and sprat will probably show escape response as a result of pile-driving. The noise from pile-driving could harm the hearing ability of these two fish species. Some studies have provided evidence, that hearing ability can be regenerated after damage.

It is not likely, that the noise from pile-driving will produce any other physical injuries to any of the fish species.

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1 Introduction

The purpose of this memo is to evaluate the possible effects of noise from offshore pile-driving activity on fish.

As part of a plan to establish offshore wind turbines in Denmark, the Ministry of the Environment and Energy introduced a government order asking the electricity companies to set up five large-scale offshore wind farms with a total output of 750 MW. Rødsand in the Femer Belt was selected as the location for one demonstration project with an output of 150 MW. Dredging and drilling for the foundations and burying of the sea cables are planned to take place in the period 1 April 2003 to 1 October 2003 where the trial run of the whole wind farm is scheduled.

The project was approved on the condition that an EIA (Environmental Impact Assessment) study was conducted in accordance with the guidelines of the Ministry of the Environment and Energy (May 1999). Permission was also given to carry out the necessary preliminary studies.

The construction of an offshore wind farm at Rødsand may potentially affect the fish population in the area during construction and operation.

Technical background reports are prepared to form the basis for the actual EIA study.

As part of this work, a report on underwater and above-water noise measurements and analysis during offshore pile-driving was conducted (Ødegaard & Danneskoild-Samsøe, 2000).

This paper attempts to estimate the effect that noise from the offshore pile-driving will have on the behaviour and physiology of the fish present in the area of the proposed wind farm.

The hearing ability and avoidance of sound by fish species present in the area of the proposed wind farm (Bio/consult, 2000a, b) is taken into consideration.

Different species of fish have different hearing abilities and the reason for this is mainly differences in the physiology. Thus, in order to make a meaningful evaluation of the possible effects of noise on fish, it is essential to have an understanding of the hearing capability of fish, the physiology behind it, and how it influences the behaviour of the fish.

In the following a short description of the hearing abilities of fish will be given. This includes a description of audible thresholds and the differences between hearing-”specialists” and hearing-”generalists”. On the basis of the scientific knowledge gathered, the possible hearing ability of the fish found at Rødsand is described and the possible impact that noise will have upon the fish is evaluated.

2 The hearing abilities of fish

2.1 Introduction to hearing abilities

For auditory sensing fish use the lateral line, the ear and the swimbladder. However, not all fish have a swimbladder. Both the lateral line and the ear detect water motions; the lateral line is responsive to relative movements between the animal and surrounding water; the ear is responsive to the relative motion between the otolith and the fish's body, and to sound pressure (Popper & Fay, 1993).

The hearing ability enables the fish to avoid predator attack to some extent and thus constitutes an obvious survival value.

The lateral line and the ear overlap in frequency range, with the lateral line responding over a frequency range of several Hz to about 200 Hz, and the ear from several Hz to several thousand Hz in some species. The source distance over which the two systems respond differs, from a body length or two for the lateral line, to considerably greater distances for the ears (Popper & Fay, 1993).

The lateral line

The lateral line detects particle motions outside the body of the fish, and is probably mainly used to detect nearby prey or predators. The lateral line itself detects movements in the surrounding water and is responding over a frequency range of a few Hz to 200 Hz.

When the lateral line is connected to the swimbladder, the lateral line may have pressure-detecting abilities as well.

The ear

The otolithic organs (the saccule, lagena, and utricle) of the fish ear are considered to be responsible for hearing.

The ear is responsive to the relative motion between the otolith and the fish body and to sound pressure and is responding over a frequency range of several Hz to several thousand Hz.

If the head of the fish vibrates in a sound field, the calcareous otoliths make smaller movements than the surrounding tissues, since their density is higher. This causes a reaction from the hair cells.

The otolith organs of fish are capable of detecting particle motion 'directly' via the inertial response of the otoliths to motion, and 'indirectly' via the swimbladdersfluctuating volume in a pressure field.

2.2 Hearing "generalists" and hearing ""specialists""

Fish having specialisation's that enhance hearing have been referred to as hearing "specialists", whereas fish that do not have such specialisation's (e.g. Weberian ossicles, swimbladder diverticulae and gas filled bullae) are referred to as hearing "generalists". Hearing "specialists" tend to detect sound pressure with greater sensitivity and in a wider bandwidth than "generalists".

2.3 Sound frequency and intensity

A propagating sound wave consists of alternating compressions that are detected by a receiver as changes in pressure. Structures in the fish ear are sensitive to these changes in sound pressure.

The basic components of a sound wave are amplitude, wavelength, and frequency. The amplitude of a sound wave is proportional to the maximum distance a vibrating particle is displaced from rest. The wavelength is the distance a wave travels in one cycle of vibration. The frequency of a sound wave is the rate of oscillation or vibration of the wave particles. Frequency is measured in cycles/sec or Hertz (Hz).

Humans generally hear sound waves of frequencies between 20 and 20.000 Hz. Below 20 Hz, sounds are referred to as infrasonic, and above 20.000 Hz as ultrasonic.

If the amplitude of a sound is increased in a series of equal steps, the loudness of the sound will increase in steps that are perceived as successively smaller. Therefore, sound intensity is generally described using logarithmic units called decibels (dB).

Water is a good conductor of sound, considerably better than air. The speed of sound in water is approximately 1500 m/s while the speed of sound in air is approximately 340 m/s. Therefore, a 20 Hz sound in water is 75m long whereas a 20 Hz sound in air is 17m

long.

2.4 Auditory filters

Sound sources can often be identified on the basis of the frequency components present.

Fish have the ability to determine these components and/or discriminate between sounds on the basis of frequency. Fish typically respond strongly to low-frequency hydrodynamic or acoustic fields.

Low-frequency flow fields are thought to be of crucial importance for fish, since the awareness and correct interpretation of them is important for survival. This applies to both the search for moving prey and location of moving predators. This is probably the reason why low-frequency disturbances produce such consistent behavioural responses in fish (Knudsen et al., 1992, 1994).

Behavioural studies have shown that, whereas most fish species can only detect sound up to 1 to 3 kHz, several species of the clupeids (e.g. herring-like fish) can detect sounds up to 180kHz (or even higher) (Popper, 2000b).

It has been suggested that this capability evolved so that these fish can detect one of their major predators, echolocating dolphins and whales.

2.5 Auditory threshold

The auditory threshold is defined as the minimal level of sound that a fish can detect at a particular frequency 50% of the time. Different fish species have different auditory thresholds.

An audiogram is a presentation of the threshold for each frequency, for a certain fish species.

Figure 1 and 2 shows a variation of audiograms determined in two studies.

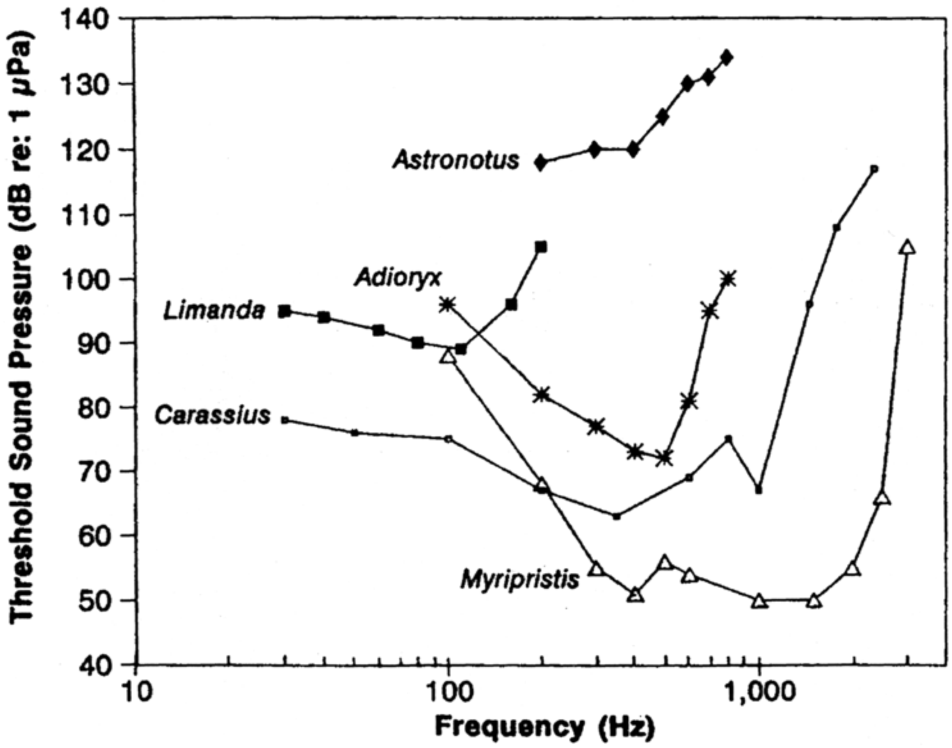

Figure 1. Behavioural audiogram for two hearing “specialists”: goldfish – *Carassius auratus* and *Myripristis kuntee* – a squirrelfish, for two hearing “generalists” having a swimbladder: *Adioryx xantherythrus* (another squirrelfish) and oscar (*Astronotus ocellatus*) and for a generalist without a swimbladder –dab (*Limanda limanda*). Source: Popper & Fay, 1993.

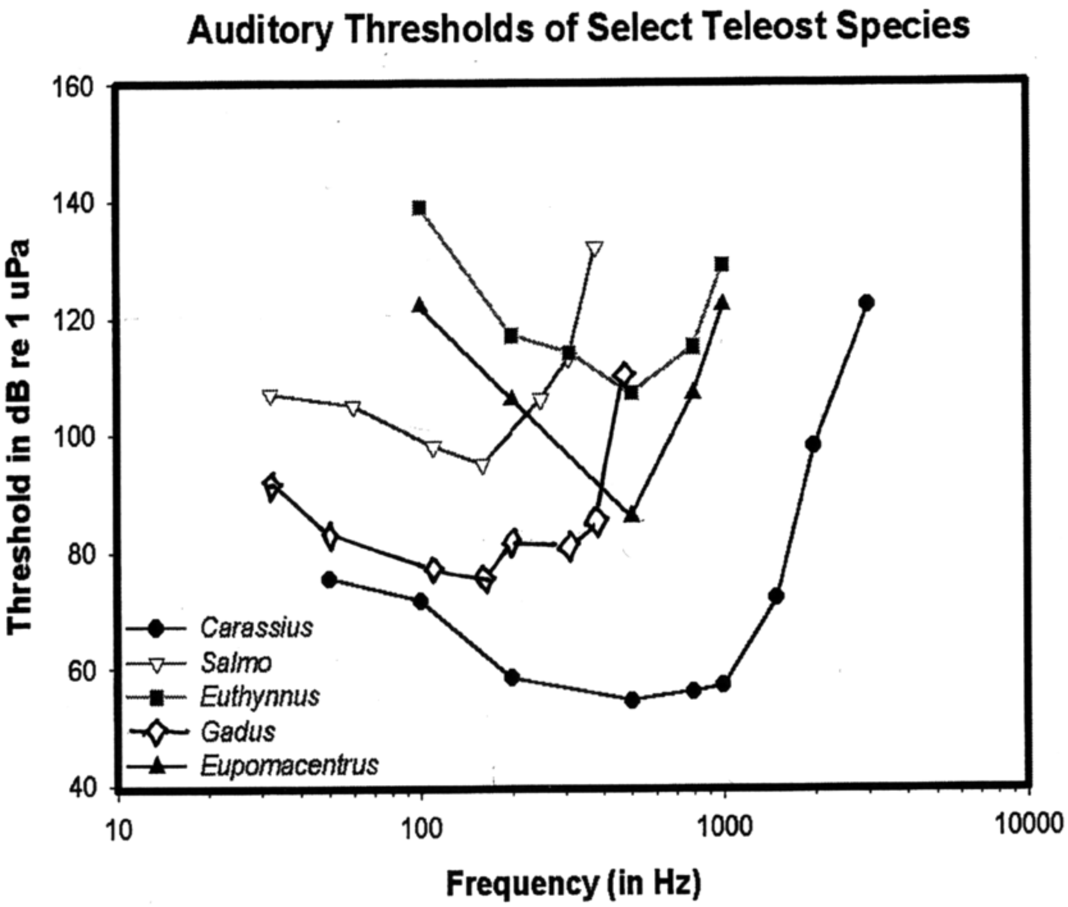

Figure 2. Behavioural audiogram for A) A hearing “specialists”: goldfish – *Carassius auratus*, B) Two hearing “generalists” having a swimbladder: Atlantic salmon (*Salmo salar*) and cod (*Gadus morhua*) and for C) Two generalist without a swimbladder – tuna (*Euthynnus*) and *Eupomacentrus* (a damselfish). Source: Popper & Lu, 2000.

3 Hearing “generalists”

The hearing “generalists” are quite insensitive to sound frequencies above 1000 Hz, but sensitive to low frequencies.

Some hearing “generalists” have a swimbladder and some do not. It is generally assumed that presence of a swimbladder will enhance the hearing capability, since the swimbladder enhance the particle displacement aspect of the sound stimulus by transducing the sound pressure to particle displacement (Bone et al., 1995).

The hearing capability of “generalists” without a swimbladder will decrease quickly above 100 Hz. This is due to the fact that frequencies above 100 Hz barely can affect the otolith and make it oscillate. Fish without a swimbladder are therefore virtually deaf at frequencies above 250 Hz (Westerberg, 1993).

If the fish has a swimbladder, the sound pressure will affect the volume of the swimbladder. This will affect the otolith, and therefore fish with a swimbladder and no other specialisation's will be sensitive to frequencies below app. 500 Hz (Westerberg, 1993).

It has recently been doubted that the swimbladder serves as an auditory enhancement function in bony fish that lack a mechanical coupling between the swimbladder and the inner ear (Yan et al., 2000).

Species that do not have a swimbladder generally includes sharks, skates and bony fish that are related to the bottom.

3.1 Species that have been scientifically investigated

Hearing "generalists" that have been thoroughly investigated are the blue gourami (*Trichogaster trichopterus*), oyster toadfish (*Opsanus tau*), salmon (*Salmo salar*) and the oscar (*Astronotus ocellatus*). They all have swimbladder. Some investigations were also done on dab (*Limanda limanda*), in which the swimbladder is absent.

As the audiograms shown in Figure 1 and 2 suggest hearing "generalists" have a narrower hearing bandwidth and lesser sensitivity than hearing "specialists". The hearing "generalists" are insensitive to ultrasound frequencies above 1000 Hz, but are sensitive to low frequencies. For most "generalists" the lowest overall threshold sound pressure (70-100 dB re. 1 μPa) is situated below 100 to 500 Hz. (Figure 1 and Figure 2).

Cod, *Gadus morhua*, is a hearing "generalist" but is known to detect sounds of at least 38 kHz, meaning it has ultrasonic hearing ability (Astrup & Møhl, 1993). If the cod are to detect the ultrasound, the sound pressure has to be very high (app. 200 dB). The cod has two short, air filled tubes as an extension of the swimbladder. The tubes are directed towards the inner ear but do not reach it. The short tubes are probably the reason why cod hear slightly better than other fish with a swimbladder and no specialities (Jan Christian Jensen, pers. comm.).

Jerkø et al. (1989) found that European eel *(Anguilla anguilla*) has an upper audible frequency limit of app. 300 Hz. The swimbladder is responsible for a conversion of pressure motion to particle motion at higher frequencies. The lowest threshold (95dB re 1 μPa) was measured at 80 Hz. This in consistent with results by Hawkins & Johnstone (1978), who found, that the upper audible frequency limit in eel was 380 Hz. The lowest sound pressure threshold (95 dB re. 1 μPa) was measured at 180 Hz.

3.2 Species found at Rødsand

The species of hearing "generalists" that were found at Rødsand were flounder, plaice, dab, turbot, cod, whiting, silver eel, eelpout, two-spotted goby and sand goby, small and great sandeel, short-spined sea scorpion and lumpsucker (Bio/consult, 2000a, 2000b).

Of these species cod, turbot and silver eel were reported to have large economical importance to local fishermen.

3.3 Comparison between scientifically investigated fish species and species found at Rødsand

The hearing capability of a hearing generalist is dependent on whether the fish has a swimbladder or not.

In flatfish (flounder, plaice, dab and turbot), sea scorpions, eelpout, sandeels and gobies, the swimbladder degenerates after the larval phase. Therefore these fish have poor hearing capabilities, and can probably not hear at frequencies above 250 Hz (Figure 2).

Cod and probably also whiting, that is closely related to cod, has a swimbladder and can probably hear at frequencies up to 500 Hz (Popper, 2000b).

Silver eel has a swimbladder and can probably hear frequencies up to 300 Hz (Jerkø et al., 1989).

Cod probably has the best hearing capability of the species mentioned above, and has auditory thresholds at about 80 dB from 50 to 400 Hz (Figure 1). Moreover, cod is able to hear high frequencies at very high sound pressure.

4 Hearing “specialists”

Behavioural studies have shown that, whereas hearing “generalists” can only detect sound frequencies below 1-3 kHz, several species of hearing “specialists” can detect sounds up to 180 kHz (or even higher).

As earlier mentioned fish hearing “specialists” have evolved specialised structures (e.g. Weberian ossicles, swimbladder diverticulae, gas-filled bullae) to enhance their auditory frequency and threshold sensitivity[1].

Hearing-”specialists” are primarily pressure-sensitive. The response to sound pressure is thought to be mediated by a coupling between the swimbladder or gas-filled bullae in the head of the fish and the inner ear. Due to this coupling, the motion of the swimbladder or bullae, as it expands and contracts in a pressure field is transported to ear by particle motion.

Specialisations of hair cell orientation patterns also appear to be closely associated with enhanced hearing, regardless of which end organ is involved (Popper & Fay, 1993).

[1] The hearing “specialists” include three forms (Yan, 1998):

1. Fish in which the first three vertebrae of the vertebral column have been modified as the Weberian ossicles. These ossicles physically connect the rostral end of the swimbladder to the fluid system of the inner ear at the midline between the two saccules. Includes catfish and carps.
2. Fish with rostral projections of the swimbladder directly to the ear. Includes squirrelfish.
3. The presence of separate gas-containing bullae in the head close to the inner ear. Includes mormyrids and clupeoides.

4.1 Species that have been scientifically investigated

The Goldfish (*Carassiu auratus*) has a very specialised hearing organ sensitive to frequencies in the kHz region. *Carassius* represents the otophysan fish, all of which have Weberian ossicles connecting the swimbladder to the inner ear. In goldfish the auditory threshold increased by 33-55 dB (frequency dependent) after deflation of the swimbladder, strongly suggesting that the swimbladder serves as an auditory enhancement function in teleost fish that have a mechanical coupling between the swimbladder and the inner ear (Yan et al., 2000).

All clupeids (herring-fish) investigated so far have a unique ear structure in which a pair of thin air-filled tubes project from the swimbladder and terminate in air chambers that are connected with the utricles of the inner ear. Studies have demonstrated that at least one clupeid, the American shad (*Alosa sapidissima*) can detect ultrasonic sounds from 100 Hz to over 180 kHz, with two regions of best sensitivity, one from 200 to 800 Hz and the other from 25 to 150 kHz (Mann et al., 1997). The study shows that there are two regions of sensitivity for the American shad, one at low frequencies, as is commonly found among fish, and one at high frequencies, at which only very few fish species have been tested so far.

Mann et al. (1998) reported that shad was able to detect echolocation clicks with a threshold of 171 dB (re: 1 μPa). If spherical spreading and an absorption coefficient of 0.02 dB/m of dolphin echolocation clicks was assumed, shad should be able to detect echolocating dolphins at ranges up to 187m. The authors suggested that ultrasonic hearing evolved in shad in response to selection pressures from echolocating dolphins.

4.2 Comparison between scientifically investigated fish species and species found at Rødsand

The hearing “specialists” found at Rødsand were two clupeid fish namely herring (*Clupea harengus*) and sprat (*Sprattus sprattus*) (also called brisling). Both herring and sprat are pelagic and form shoals.

As the audiograms suggest (Figure 1 and Figure 2) hearing “specialists” have a broader hearing bandwidth and greater sensitivity than hearing “specialists”. The hearing “specialists” are both sensitive to infrasound and ultrasound. For most “specialists” the lowest overall threshold sound pressure (50-60 dB re. 1 μPa) was situated below 500 to 1000 Hz (Figure 1 to Figure 2).

5 Physiological responses to noise

5.1 Effects of intense sounds on the sensory hair in the ear of fish

Some studies suggest, that intense sound impact result in damage of the sensory-hair-cells in the fish ears.

Enger (1981) (as cited in Hastings et al., 1996) exposed cod (*Gadus morhua*) to frequencies between 50 and 400 Hz at 180 dB (*re*: 1μPa), which is about 100-110 dB above the hearing threshold for cod. It was found that in the 150 to 250 Hz area, which is the most sensitive to cod, such sound signals would cause repeatable damage (loss of ciliary bundles) in animals that were exposed to sounds 1-5 hours.

Denton and Gray (1993) demonstrated that sound frequencies of 1Hz to 200 Hz with a pressure of 153 dB to 170 dB resulted in damage to the hair cells of the lateral line of clupeid fish (herring and relatives).

Hastings et al. (1996) investigated the effect of high intensity sound on the ears of the oscar, *Astronotus oscellatus*. They found that sounds that were lower than 180 dB (re: 1 μPa) and sounds that were not on continuously had no apparent impact on the sensory cells of the ear. However, when they subjected the fish to 180 dB signals 300 Hz pure tones for four continuous hours, and examined the ears after four days, there was some damage to the sensory cells of the lagena.

Hastings et al. (1996) suggest the hearing-"generalists" must be exposed to a much higher sound intensity (dB) to get their sensory-hair-cells destroyed, compared to hearing-"specialists".

Some studies have provided evidence that hair cells can be regenerated after damage (Lombarte et al., 1993).

5.2 Other physical damages

Sound pressures have to be higher than 240 dB or explosion-like to result in severe damages to the tissue of the fish (Bertel Møhl, pers. comm.). These noise levels are equal to the noise levels created by whales and dolphins during hunt (Astrup & Møhl, 1993).

6 Behavioural response to noise

6.1 Escape responses of fish affected by noise

Avoidance by salmon – a hearing "generalist":
Knudsen et al. (1994) studied avoidance response by using intense sound as an acoustic barrier for downstream migrating smolt of Atlantic salmon (*Salmo salar*). They found that sound with a frequency of 5 to 150 Hz had an effect on juvenile salmon.

The awareness reactions were strongest at lowest frequencies. The avoidance responses of free swimming fish to frequencies of 10 Hz and 150 Hz were stimulated at intensities 10-15 dB above threshold for spontaneous awareness reaction (Knudsen et al., 1994). This means, that avoidance reaction requires a higher sound pressure than awareness reaction – which is at least 100-110 dB (Popper, 2000b).

A frequency of 150 Hz failed to evoke avoidance responses, even at 120 dB (Knudsen et al., 1994). At 10 Hz, salmon showed avoidance reaction above approximately 70 dB. The heartbeat of salmon was 200-300% of normal heartbeat, when salmon were exposed to 10 Hz sound. When exposed to 150 Hz sound, the heartbeat was only slightly elevated.

Ploskey & Johnson (1999) examined the effectiveness of sound for eliciting avoidance reaction by juvenile salmon. They found, that 10-35 Hz infrasound did not elicit avoidance from two salmon juveniles, neither did a mixture of 300-400 Hz sounds. However, they did observe non-directional startle responses from juvenile chinook salmon exposed to 150 Hz and 180 Hz waves transmitted at 160 dB.

Avoidance by eel – a hearing "generalist"
Sand et al. (1999) found that migrating silver eels (*Anguilla anguilla*) did display startle behaviour and prolonged stress reactions (monitored as heart rate) as a response to intense infrasound at 11,8 Hz, corresponding to the threshold intensity for deterring effects on salmon smolts.

Avoidance by herring – a hearing "specialist"
Dunning et al. (1992) (As referred in Popper & Lu, 2000) did report successful use of ultrasounds (126 kHz) to keep clupeids from entering areas of danger.

Herring shoals response faster to sound stimulus than solitary herring. This is probably caused by stimulation of the lateral line of the herring from nearby fish (Domenici & Batty, 1997).

Avoidance by goldfish – a hearing "specialist"
Popper & Clark (1976) demonstrated, that 4 hour exposures to 149 dB (re: 1 µPa) sounds at 300 Hz, 500 Hz, 800 Hz and 1000 Hz caused temporary threshold shifts lasting 2-4 hours. There was a complete recovery from this stimulation even after repeated exposure to the sound during daily experiments for several days or weeks.

6.2 General habituation

Habituation test of salmon showed that they were very fast habituated to 10 Hz sounds repeated every 35 seconds, but when intervals between sound stimuli were more than 10 minutes, habituation required several hours (Knudsen et al., 1994).

Westerberg (1994) made observations on the habituation of fish to low frequency noise from windmills. The investigation included recordings of silver eel caught by the fishermen, investigations using telemetrics to map the movements of silver eels and a survey of the fish fauna. When noise was measured, data showed that the wind mills produced noise in a broad frequency range (0 Hz to 1000 Hz, decreasing above 200 Hz). The general sound intensity of the mill running was less than 20 dB above background.

The catch data from the fishermen showed that eel catch by fishermen increased with increasing wind speed at three fishing grounds near the mills (Westerberg, 1994). The telemetrics data did not show any systematic change when the mills were on or off. The survey of the fish fauna showed that the fish were attracted to the area closer than 400 meter from the mills. This could be due to a reef effect of the windmill park. The attraction was strongest when the mills were off. Within 200 meters of the mills, catches of the most common species decreased when the mills were on.

7 Evaluation of possible effects of underwater noise from pile-driving at Rødsand

7.1 Sound Exposure Level

Ødegaard & Danneskiold-Samsøe (2000) made off-shore pile-driving underwater and above-water noise measurements and analysis at a wind-turbine park under construction in Sweden between the Swedish mainland and the island Öland. These measurements will be evaluated with respect to the possible effect on fish.

It is noted in the report that the underwater sound level can vary depending on the seabed conditions, the depth and the temperature.

In the frequency range from 1 Hz and 4 Hz, the average measured peak noise levels during the pile-driving impacts did not exceed the ambient (background) levels. For frequencies above 4 Hz the noise from the pile-driving impacts could clearly be seen (Ødegaard & Danneskiold-Samsøe, 2000).

In the frequency range from 4 Hz to 100 Hz the sound pressure generally was at a level from 120 dB to 150 dB depending on both the frequency and the distance from the sound source.

The sound pressure was greatest (140 dB to 180 dB – depending on frequency and distance from sound source) at frequencies from 100 Hz to 2000 Hz. Above a frequency of 2000 Hz the sound pressure decreased slowly.

The sound level was not considerably reduced at a distance of 760m from the pile-driving activity, compared to a distance of 30m, which is due to the fact that water is a good conductor of sound.

The sound pressure level time history plots show, that regardless of distance from sound source, the impact lasts for less than a second. The frequency of impacts varied from 2 impacts per minute to 30 impacts per minute (Ødegaard & Danneskiold-Samsøe, 2000).

7.2 Evaluation of the impact of sound exposure on the fish population at Rødsand

When evaluating impact of sound exposure on fish, different subjects have to be considered.

1. Are the fish able to detect the noise?

2. Will the noise affect the behaviour of the fish?

3. Will the noise harm the fish?

4. Will the fish habituate to the noise?

7.3 Can the fish hear the noise and will it affect their behaviour?

Hearing "generalists"
The flatfish (turbot, plaice, flounder and dab), sandeels, eelpout, gobies and sea scorpions are hearing "generalists" without a swimbladder and have poor hearing capabilities. These fish are not able to detect sound with a frequency above 250 Hz, but the hearing capability will decrease above 100 Hz. Lowest auditory thresholds for this group of fish is probably app. 90-110 dB at frequencies below 250 Hz (Figure 1 and Figure 2).

The underwater sound exposure levels from pile-driving hardly exceed the auditory thresholds for the group of hearing "generalists" without a swimbladder. This means that the flatfish (flounder, plaice, dab and turbot), small and great sandeel, eelpout, different species of goby and sea scorpions probably hardly hear the noise from the pile-driving, and it is therefore not likely, that these fish will be affected by the noise from the pile-driving at all.

The silver eel, cod and whiting are hearing "generalists" with a swimbladder, and hear slightly better than the hearing "generalists" lacking a swimbladder. This group of fish can probably hear sound frequencies up to 300-500 Hz and will have lowest auditory thresholds of app. 75-100 dB.

The fact, that this group of fish can hear the noise, is not enough to conclude that the noise will affect the fish. The avoidance reaction requires a higher sound pressure than the awareness reaction (Popper, 2000b).

All though the scientific data are limited, avoidance reactions from hearing “generalists” imply either frequencies lower than 300-500 Hz or sound pressures above 200 dB (section 5.1).

Sound pressures during pile-driving were lower than 200 dB at all frequencies and all distances recorded (Ødegaard & Danneskiold-Samsøe, 2000).
To provoke an avoidance reaction from hearing “generalists” at frequencies below 300-500 Hz, sound pressures have to be at least 70-160 dB (section 5.1). Knudsen et al. (1992) reported an avoidance reaction from juvenile salmon at 10 Hz and 70 dB, but Ploskey & Johnson (1999) found that sound at 10-35 Hz did not elicit avoidance from two juvenile salmon, even at 160 dB. European eel was reported to have its lowest auditory threshold at 80 Hz and 95 dB (Jerkø et al., 1989), and was recorded to have a similar avoidance response as salmon at 10 Hz (Sand et al., 1999).

In the frequency range 4-50 Hz sound pressure was 120-140 dB at distances 320-760 m from the sound source, and 135-160 dB 30 meter from the sound source (Ødegaard & Danneskiold-Samsøe, 2000).

Although the reported avoidance data for low frequencies are not clear, it is possible that low sound frequencies from pile-driving could elicit some avoidance response from hearing “generalists”, especially the hearing “generalists” with a swimbladder. Avoidance reactions are most likely to occur at short distances (less than 30 meter) from the sound source.

Hearing “specialist”
Hearing “specialists” have lower auditory threshold levels than hearing “generalists” (Figure 1 and Figure 2). The lowest auditory threshold is app. 50-75 dB at 200-3000 Hz. This might affect the avoidance threshold as results from goldfish suggest (Popper and Clark, 1976). Hearing “specialists” also have a broader range of hearing bandwidth than hearing “generalists”. Different authors have reported successful use of ultrasounds to keep clupeids from entering areas of danger.

The fact that clupeids are in shoals seems to make their avoidance reaction towards a sound source faster (Domenici & Batty, 1997).

7.4 Is the noise harmful?

To the question whether the noise will harm the hearing “generalists”, results from different authors (section 6.1.) suggest, that quiet high and continuously sound can result in damage of the hair cells of the fish ear.

Hastings et al. (1996) suggest the fish have to be exposed to sound pressures 90-140 dB above auditory threshold to get their sensory-hair-cells destroyed.
In the case of hearing “generalists”, this would require sound levels of app. 200 dB and continuous exposure through a longer period (some hours). Therefore, the noise from

pile-driving is not expected to harm the hearing "generalist", whether they have a swimbladder or not.

In the case of hearing "specialists" they have lower auditory threshold levels. The lowest auditory threshold is app. 50-75 dB at 200-3000 Hz, and it could be expected that damage to hearing could occur at lower sound pressures. Denton & Gray (1993) demonstrated that damage to the hair cells of the lateral line of clupeid fish could occur at sound pressure of 153-170 dB.

At Rødsand noise levels above 153-170 dB occur at frequencies from 100 Hz to 2500 Hz at the four distances from the pile-driving (Ødegaard & Danneskiold-Samsøe, 2000). Therefore, the clupeid fish (herring and sprat) will probably not only show escape responses as a result of pile-driving, but the noise will probably also be harmful to the herring and sprat if they have not escaped.

Herring and sprat were caught in the wind farm area in spring 1999 when preparing the technical background report concerning fish for the EIA study (Bio/consult, 2000a).

Herring and sprat were not reported to be caught by the local fishermen inside the windfarm area (Bio/consult, 2000b). Area 38G1 is a defined coastal area surrounding the wind farm (for definition see Bio/consult, 2000b). Data from 38G1 taken from the logbook records of the Directorate for Fishery from 1997 to 1999 show that herring and sprat were caught in two periods of the year, namely spring and autumn. When comparing the catch season with the proposed construction period, it is shown that during the construction period herring and sprat would probably be present in April, May, September and October. Almost no herring were caught in area 38G1 in June and July the 3 years.

7.5 Will the fish habituate to the noise?

Habituation test of salmon (a hearing "generalist") showed that they were very fast habituated to 10 Hz sounds repeated every 35 seconds (Knudsen et al., 1992). Regardless of distance from sound source, the impact from pile-driving lasts for less than a minute and the frequency of impacts varied from 2 impacts per minute to 30 impacts per minute (Ødegaard & Danneskiold-Samsøe, 2000). Therefore, it is very possible that fish showing escape responses at the beginning of the construction work will habituate to the noise and return to the construction area after some time, especially since the pile-driving will result in discontinuous noise with frequencies of impacts varying between 2 to 30 impacts per min., each impact lasting less than a second.

8 Conclusion

Even though the noise from pile-driving might seem tremendous to the human ear, this is not the case for all species of fish.

Bottom living fish in which the swimbladder has degenerated and hearing is not specialised generally have high auditory threshold levels and will probably not be able to hear the sound frequencies above 250 Hz. At frequencies below 250 Hz the lowest auditory thresholds are app. 90-110 dB. This group of fish includes flounder, plaice, dab, turbot, sea scorpions, eelpout, sandeels and gobies that are all present in the proposed construction area at Rødsand.

Cod, whiting and silver eel that are also present in the proposed construction area at Rødsand all have a swimbladder and can probably hear frequencies up to 300-500 Hz. At frequencies below 300-500 Hz. the lowest auditory thresholds are app. 75-100 dB.

Although the reported avoidance reactions of fish at low frequencies are not completely clear, it is possible that low sound frequencies from pile-driving could elicit some avoidance from species without specialised hearing, especially those with a swimbladder (cod, whiting and silver eel). Avoidance reactions would be most likely to occur at short distances (less than 30 meter) from the sound source.

It is unlikely that the hearing of flounder, plaice, dab, turbot, sea scorpions, eelpout, sandeels and gobies, cod, whiting and silver eel will be harmed by the noise. Some degree of habituation of the same fish species to the noise from pile-driving is possible.

Herring and sprat (brisling) that are also found at Rødsand, have a specialised hearing with low auditory threshold levels and a broad hearing bandwidth (50-75 dB at 200-3000 Hz), which is probably reflected in the avoidance threshold.

Some damage to the sensory cells of the ear has been reported from clupeid fish (like herring and sprat) to occur at sound densities of 153-170 dB. At Rødsand these noise levels occur at frequencies from 100 Hz to 2500 Hz at the four distances from the pile-driving (Ødegaard & Danneskiold-Samsøe, 2000). Therefore, herring and sprat will probably show escape response as a result of pile-driving. The noise from pile-driving could harm the hearing ability of these two fish species. However, some studies have provided evidence, that hearing ability can be regenerated after damage.

It is unlikely, that the noise from pile-driving will produce any other physical injuries to any of the fish species at Rødsand.

9 References

Astrup J & Møhl B (1993). Detection of intense ultrasound by the cod (*Gadus morhua*). Journal of experimental Biology, vol. 182, 71-80.

Bio/consult as (2000a). EIA study of the proposed offshore wind farm at Rødsand. Technical background report concerning fish.

Bio/consult as (2000b). EIA study of the proposed offshore wind farm at Rødsand. Technical background report concerning fishery.

Bone Q, Marshall NB & Blaxter JHS (1995). Biology of fish. Second edition. Blackie Academic & Professional.

Denton EJ & Gray JAB (1993). Stimulation of the acusto-lateralis system of clupeid fish by external sources and their own movement. Philosophical Transactions of the Royal Society of London B., vol. 341, 113-127.

Domenici P & Batty RS (1997). Escape Behaviour of solitary herring (*Clupea harengus*) and comparisons with schooling individuals. Marine Biology, vol. 128, 29-38.

Dunning DJ, Ross QE, Geoghegan P, Reichle J, Menezes JK, Watson JK (1992). Alewives avoid high-frequency sound. North American Journal of Fishery Management, vol. 12, 407-416.

Enger PS (1981). Frequency discrimination in teleosts – central or peripheral?. In: Hearing and Sound Communication in Fish, edited by W. N. Tavolga, A. N. Popper & R. R. Fay. Springer-Verlag, New York, p. 243-255.

Hastings MC, Popper AN, Finneran JJ & Lanford PJ (1996). Effects of low-frequency underwater sound on hair cells of the inner ear and lateral line of the teleost fish *Astronotus ocellatus*. Journal of the Acoustical Society of America, vol. 99 (3), 1759-1766.

Hawkins AD & Johnstone ADF (1978). The hearing of Atlantic Salmon, *Salmo salar*. Journal of Fish Biology, vol. 13, 655-673.

Jensen JC (pers. comm.). Department of zoophysiology, Biological Institute, Aarhus University, DK.

Jerkø H, Turunen I, Enger PS & Sand O (1989). Hearing in the eel (*Anguilla anguilla*). Journal of Comparative Physiology A, vol. 165, 455-459.

Knudsen FR, Enger PS & Sand O (1992). Awareness reactions and avoidance responses to sound in juvenile Atlantic salmon, *Salmo salar* L. Journal of Fish Biology, vol. 40, 523-534.

Knudsen FR, Enger P & Sand O (1994). Avoidance responses to low frequency sound in downstream migrating Atlantic salmon smolt, *Salmo salar*. Journal of Fish Biology, vol. 45, 227-233.

Lombarte A, Yan HY, Popper AN, Chang JS & Platt C (1993). Damage and regeneration of hair cell ciliary bundles in a fish ear following treatment with gentamicin. Hearing Research, vol. 64 (2), 166-174.

Mann DA, Lu Z & Popper AN (1997). A clupeid fish can detect ultrasound. Nature, vol. 389, 341.

Mann DA, Lu Z, Hastings MC & Popper AN (1998). Detection of ultrasonic tones and simulated dolphin echolocation clicks by a teleost fish, the American shad (*Alosa sapidissima*). Journal of the Acoustical Society of America, vol. 104 (1), 562-568.

Møhl B (pers. comm.). Department of zoophysiology, Biological Institute, Aarhus University, DK.

Ploskey GR & Johnson PNJ (1999). Effectiveness of strobe lights and two sound devices for eliciting avoidance by juvenile salmon. In: Proceedings from 1999 American Fisheries Society Annual Meeting. Integrating Fisheries Principles from Mountain to Marine Habitats. August 29 – September 2, 1999, Charlotte, North Carolina (abstract).

Popper AN & Clarke NL (1976). The auditory system of the goldfish (*Carassius auratus*): effects of intense acoustic stimulation. Comparative Biochemistry and Physiology, vol. 53, 11-18.

Popper AN & Fay RR (1993). Sound detection and processing by fish: Critical review and major research questions. Brain, behavior and evolution, vol. 41, 14-38.

Popper AN (2000b). www.life.umd.edu/biology/popperlab/hearingthresholds.htm

Popper AN & Lu Z (2000). Structure-function relationships in fish otolith organs. Fishery Research, vol. 46, 15-25.

Sand O, Enger PS, Karlsen HE & Knudsen F (1999). Deflection of migrating silver eels (*Anguilla anguilla*) by infrasound. In: Proceedings from 1999 American Fisheries Society Annual Meeting. Integrating Fisheries Principles from Mountain to Marine Habitats. August 29 – September 2, 1999, Charlotte, North Carolina (abstract).

Westerberg H (1993). Öresundskonsortiet, miljökonsekvensbeskrivning for Öresundsforbindelsen. Effekter på ljus och vibrationer på fiskvandringer i området kring Öresundsbron. Fiskeriverket, Utredningskontoret i Jönköbing.

Westerberg H (1994). Fiskeriundersökninger vid havbaseret vindkraftverk 1990-1993. Fiskeriverket. Rapport 5 – 1994. Göteborgsfilialen Utredningskontoret i Jönköbing.

Yan HY (1998). Auditory role of the suprabranchial chamber in gourami fish. Journal of Comparative Physiology, vol. 186, 435-445.

Yan HY, Fine ML, Horn NS, Colón WE (2000). Variability in the role of the gasbladder in fish audition. Journal of Comparative Physiology, vol. 186, 435-445.

Ødegaard & Danneskoild-Samsøe A/S (2000). Offshore Wind-Turbine Construction. Off-shore Pile-Driving Underwater and Above-Water Noise Measurements and Analysis. SEAS Distribution A.m.b.A. & Enron Wind GmbH. Report no. 00.877.