UNDERWATER NOISE IN GDYNIA HARBOUR DURING PILING

ZYGMUNT KLUSEK[1], PIOTR KUKLIŃSKI[1], DARIA MRÓZ[2,]
BARTOSZ WITALIS[3]

[1]Institute of Oceanology PAS,
Powstańców Warszawy Str. 55, 81-712 Sopot, Poland
[2]Gdynia Port Authority, Poland
[3] National Marine Fisheries Research Institute
Kołłątaja 1,81-332, Gdynia
klusek @iopan.gda.pl

A short review of the results of noise investigation in Gdynia Harbour during pile driving at Hel Quay is presented. The spatial pattern of noise distribution and the recorded noise levels are compared with data regarding the potential impacts of noise on marine animals.

INTRODUCTION

Understanding the influence of sounds on marine animals nowadays is within the interests of marine biologists and environmentalists [1]. A set of the distinctive elements of sound field properties were regarded as significant, concerning their influence on the wellness of marine organisms, i.e. the structure of the acoustic spectrum (frequency distribution of acoustic energy), broadband sound level (sound intensity), duration of sounds (acoustic energy) and peak-to-peak sound pressure level [2,3,4,5 as examples].

However, it is not an easy task to discover which parameters of sounds have a relevant effect on different animal species. In addition, the insight into high intensity sound stressogenic consequences has only recently been studied. [3]

Pile driving at sea associated with extremely high sound levels is one of the most worrying sound generation processes. According to the data from various field observations, the peak acoustic pressures are of an order of ~10^3 Pa measured [6] at a range of 3000m, and ~10^4 Pa at a range of 60m [7].

Due to the consequences of high level of acoustic pulses accompanying pile driving on marine animals, the procedure is highly controlled and monitored. To diminish the undesirable effects of high-energy impulsive sounds, a variety of sound mitigation measures are initiated, such as driving animals away, lowering source levels, or raising gas bubble curtains.

However, it is impossible to try to accomplish each particular combination of acoustic characteristics that could upset or injure marine animals. Thus far, only the most important characteristics of these acoustic disturbances have been estimated and quantitatively analyzed in areas of intense technical activity, such as in harbours, and around wind farm construction, etc.

Another source of annoyance for marine life is the continuous or semi-continuous noise from the technical activities of ship traffic near the shore.

According to the recent Decisions of the European Commission [8] two indicators of Descriptor 11 “Introduction of energy, including underwater noise, is at levels that do not adversely affect the marine environment”, were established for intermittent and continuous noise in the sea.

Indicator 11.1 is related to sporadic events and states the number of days during a calendar year in which sound levels (from 10 Hz to 10 kHz) are high enough to produce an environmental impact. This obliges EU member states to register human activities in an area.

The second - Indicator 11.2 - assigns trends with a continuous low frequency sound in two selected third octave bands, with a central frequency of 63 and 125 Hz, expressed as a level in decibels, in units of dB re 1 μPa. The European Commission provides the normative form of this indicator. The levels in these third-octave bands can be of interest for measuring noise produced mainly by ships.

Under a Gdynia Port Authorities contract measurements and analysis of underwater noise generated during piling at Hel Quay in Gdynia Harbour were conducted.

The main goal of the investigation was the estimation of the most important parameters of underwater noise and vibration during piling operations at Gdynia Harbour during the period of the new quay wall construction at Gdynia Harbour, and to build-up a basis for the further monitoring and prediction of noise due to an increment in ship traffic in the future.

At the next stage of the operation, the determination of the range of the impact zone of piling work and ship traffic noise on the health or the behaviour of different animals, such as the harbour porpoise, seals and fish, was scheduled.

2. MATERIALS AND METHOD

2.1. Study area and conditions

During the construction of the Hel Quay in Gdynia Harbour, a set of four pile-driving type of was situated in the land just to the western edge of the Hel Quay. Different type diesel pile hammers were used during the action (diesel pile hammers DELMAG and Junnttan HHK) and the Junttan PM 25H with an optional vibrator hammer.

Piling activities in Gdynia Harbour lasted over 4 months.

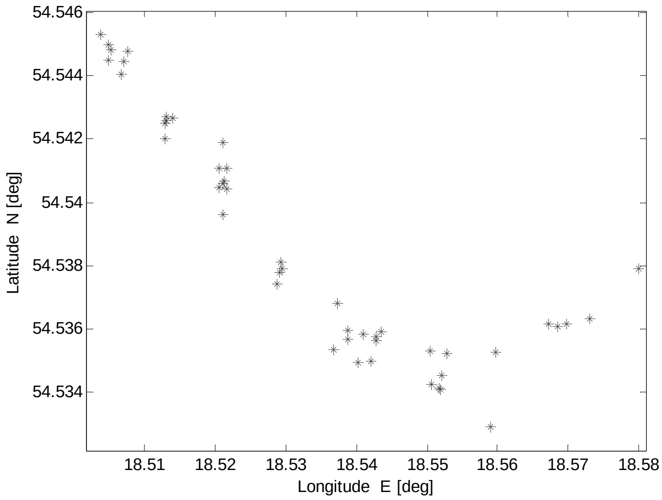

Fig. 1. Locations of the noise measurements within Gdynia Harbour basins.

A single pile driver consisted of a diesel hammer that fell by gravity, detonating a fuel–air mixture to drive down the hammer. According to different sources, blow heights and detonation explosions depend on substrate hardness or other geo-mechanical features (such as layering). It is typical that the strike rates of single pile drivers varied between 1 and 3 strikes/s. The maximum observed strike number from all pile hammers surpassed 120 strikes/minute.

The noise measurements were conducted over five days, on 25-28 February and 3 March 2014.

Each day, measurements were repeated many times on the pathway extended out from the Hel Quay at a distance approximately 50 m from the area of the pile drivers, through each of the harbour basins and outside the harbour sea wall, heading north towards the PLH 220032 Natura 2000 area (Fig.1).

A small, 6-meter long small boat “CETEEMKA” was used to record noise, both stationary and drifting. The boat was equipped with a GPS positioning system.

The noise from the waves crashing on the boat hull was diminished choosing optimal weather conditions, and all measurements outside the port were performed during a sea state below 3 Bf, at some distance (up to 30m) from the boat.

Small cylindrical rubber buoys attached to the hydrophone cables decoupled the hydrophones from wave and the boat motion. One of the hydrophones was deployed in close proximity to the boat, with another drifting freely. The hydrophones were at distances of up to 30m from each other. The hydrophones were deployed in all measurements, at depths of 4.5 m, approximately in the middle of the water column.

During the recording, all the boat’s equipment was switched off, except the GPS system. The only sources of energy for the recording equipment were batteries.

2.2. Noise sampling and data processing procedures

The recording setup consisted of two calibrated hydrophones – the Bruel & Kjaer 8104/8105 and a Г-005 Soviet manufacturing high-sensitivity low frequency hydrophone, with a removed factory preamplifier. The signals were digitized by a multichannel analogue-to-digital converter, National Instrument 6251, and saved in a laptop computer. The signals from the hydrophones were amplified with the RESON VC-1000 signal amplifier in a frequency band of 10 Hz – 10 kHz, or with the Bruel & Kjaer conditioning amplifier 2635 in the second channel. The Г-005 hydrophone was inter-calibrated with the Bruel & Kjaer hydrophones through simultaneous recording. The high-pass filters at the input of the preamplifier unit prevented saturation from the changing hydrodynamic pressure from the surface waves.

The main recording parameters were a sampling rate of 20 kS/sec (only occasionally 30kS/sec), with a record length of 20 - 30s. A total number of over 350 time series were collected during the operation.

The piling records were obtained randomly during a working day. The first records were examined for possible clipping or too small signals and then properly amplified. The NI reading scale was tuned to make sure that the full dynamic range of noises was received.

Raw voltage was converted to sound amplitudes by using sensor calibration data and amplifier gain by standard formulae.

3. MAIN SOUND PARAMETERS

While there is general agreement on the devastating effect of high intensity underwater noise, at the present time it is not fully clear which characteristics (metrics) or magnitude are the most unsafe or perilous to various groups of marine animals. What is more, some ambiguity arises with the precise depiction of such a key acoustic descriptor as source level or the proper modelling of sound sources, or transmission loss [9].

However, it is commonly accepted that considering the potential impacts of noise on marine animals we should include the calculations of the instantaneous and integral properties of the noise from narrow band frequencies with the whole frequency range. Two related sound impulse metrics commonly used to describe features of impulse sound are believed to present risk of injury to fauna. These are sound pressure level, L_{eq}, and sound exposure level, SEL. Both of these metrics are dimensionless units expressed in decibels.

3.1. Sound pressure level, SPL

The basic quantity of the sound field in an environment is the sound pressure level, or rms time-averaged sound level defined as

$$SPL = 10\log_{10}\left(\frac{1}{T}\int_0^T \frac{p^2(t)}{p_{ref}^2}dt\right) \tag{1}$$

where - p(t) is the measured sound pressure, p_{ref} the reference pressure, and as a rule 1 μPa and T the average time (measurement period).

In the case of non-stationary, intermittent signals, like the sounds of pile driving strikes, less sensitive to transmission loss fluctuations and pulse duration measure of the influence of sound intensity on animals, was proposed the sound exposure level of single strike (SEL_S)

$$SPL = 10\log_{10}\left(\frac{1}{T_{ref}}\int_{T_1}^{T_2} \frac{p^2(t)}{p_{ref}^2}dt\right) \tag{2}$$

where $|T_1-T_2|$ represents thump duration (averaging time) and are chosen as the start and end of the sound event, and T_{ref} is 1 second.

As the stop-time T_2, necessary for estimation of the pulse duration, the time contained 90% of the total energy in the signal was proposed [10] (t_{90} in s). However, in our opinion a more appropriate stop-time of 95% should be applied.

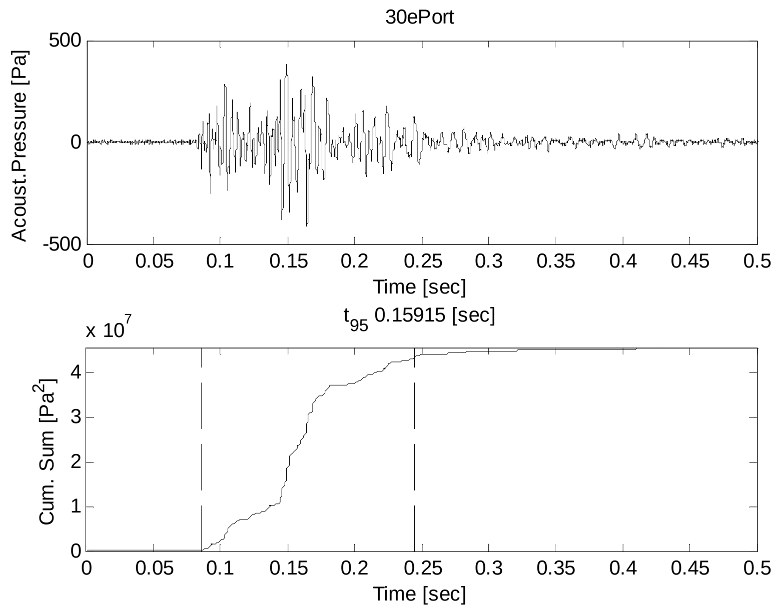

Fig. 2. The waveform of the one strike acoustic pressure and cumulative sum of the signal. Vertical dashed lines represent start of the strike and the moment where 95% of the entire signal energy was approached.

3.2. Sound exposure level, SEL

The SEL is a measure of the energy in the acoustic pulse obtained by integrating the square of the acoustic pressure (the units are μPa^2 s).

In the case of highly non-stationary, intermittent signals, like the sounds of pile driving strikes, less sensitive to the transmission loss fluctuations and pulse duration the measure of the influence of sound intensity on animals, the sound exposure level of single strike (SEL) was proposed.

$$SEL = 10\log_{10}\left(\int_0^T \frac{p^2(t)}{p_{ref}^2}dt\right) \quad (3)$$

When the effects of sound on various species are appraised, it is valuable to compute the sound exposure level in third-octave bands.

3.3. Cumulative SEL

For evaluating the biological impact of continual pile driving in terms of a noise dose, the whole pile driving process should be taken into account. This value is referred to as "cumulative SEL".

3.4. Peak-to-peak level, L_{P-P}

Impulsive sounds can have modest SPL or SEL values, but very high instantaneous pressure peaks. The absolute peak pressure (or more precisely peak-to-peak) in a sound impulse is assumed to present a risk of physical damage to body tissues surrounding the gas bladder, caused by a difference in pressure between the inside of the gas bladder to a fish body.

A measure for these peaks is the peak-to-peak level -

$$L_{P-P} = 20\log_{10}\frac{\max(p(t)) + \min(p(t))}{p_0} \quad (4)$$

Sometimes, in a similar way, the zero-to-peak" $L_{(0-p)}$, level is presented, which is the highest absolute observed sound pressure (which may be the most negative value too). The positive pressure peak of a wave is approximately equal to half of the "peak-to-peak" pressure.

3.5. Weighted characteristics

It is unquestionable that sound affects different species in several different ways. Therefore, like in the field of physiology of human hearing, frequency weighted sound levels reflecting the sensitivity of different animal species' hearing had been introduced. Among them are weighted peak sound pressure levels (dB_{ht} (*for a given species*)) observed during single piling pulses (or the "sensation level") and weighted sound exposure levels (SELs) dB_{ht} (for a given species) over a single pulse.

This approach uses information on each species' hearing ability to provide species-specific frequency weightings. This allows an assessment of the "perceived loudness" of the sound to the animal. Among Baltic mammals, the harbour porpoise is the most sensitive to a wide range of man-made sounds and reacts to very low exposure levels (90 to 120 dB re 1μPa), at least at the beginning of sound exposure.

It was reported that offshore pile driving sounds reduced detected harbour porpoise acoustic signals at distances of up to 20km from the sound source [11, 12, 13]. In addition, strong avoidance of the noisy area at distances of tens of kilometres from the pile-driving source was observed.

The occurrence of the harbour porpoise (*Phocoena phocoena*) in the Bay of Gdansk has been persistently documented, so the troubling impact of the sound on the behaviour of harbour porpoises was expected at the start of investigations.

Extremely popular in the Baltic Sea, clupeiform fish, e.g. herring (*Clupea harengus*) and sprat (*Sprattus sprattus*) are the most sensitive to sound, with their hearing abilities in a frequency range from tens of Hz up to 3-4 kHz. The herring sound pressure threshold is more or less flatly in a broad frequency range from 30 Hz to 1 kHz and equal approximately to 75 dB re 1 μPa. Other Baltic fish are known or expected to be less sensitive to acoustic stimuli [14].

4. RESULTS

4.1. Pile-driving noise

As assumed at the start, the highest level of sound in the harbour was registered in the zone of the pile-driving operations. The sound level and other characteristics of the emitted sound were fairly variable during the driving of a single pile and between any one of them.

In the majority of cases in this basin, the observed maximum negative pressure value was higher than the positive maximum pressure.

The observed extreme peak pressures of an impulse were regularly below 1 000 Pa, although in some series of impulses, values reached roughly 3 000 Pa, and a peak-to-peak level of 197 dB re 1 μPa was observed. The rms single pulse pressure level, over the period that contained 95% of the sound energy (rms impulse) was equal to 168 dB re 1 μPa, and the sound-exposure level (SEL) 172 dB re 1 μPa^2 s. Computed for the duration of a recording lasting 30s, other sound parameters were - SPL 167 dB re 1 μPa and SEL 179 dB re 1 $\mu Pa^2 \cdot s$. The impulses comprised of the most significant sound pulse, followed by a slightly higher frequency after-pulse with lower amplitude. The impulse durations (95%) of these most extreme strikes lasted only about 0.06sec.

The waveform of the recorded impulses and their spectrogram in the Hel Basin in the case of two simultaneously working pile-driving machines is shown in Figs. 2a and 2b. Instantaneous noise spectrum levels are presented in third-octave bands. In the given example, in a spectrum level averaged over 30 sec, a broad maximum of around 150 Hz was observed, with most of the energy in the frequency range 100-500 Hz. However, in some strikes a maximum in the spectrum was detected at 80 Hz.

Due to the fact that the piling was performed on the shore with unknown sound attenuation in the ground, the computed in-water sound levels were not converted to source levels (SL), i.e., normalized to an equivalent noise level at a distance of 1m.

Due to the rather intricate geometry of the harbour basins and the ground's mechanical properties, all the parameters of the sound pulses quickly decreased, and at distances of 1000m, impulse noise spectra levels were close to those typical for ambient noise spectra levels in the Bay of Gdansk at sea state 2 B.

At a 1500m distance, the received levels of piling activities due to the substantial input of a noise from other sources were too low to be satisfactorily documented.

The dependence of key parameters both of a single strike (most energetic) and 20sec length recordings, at different distances from the piling area, are demonstrated in Table.1.

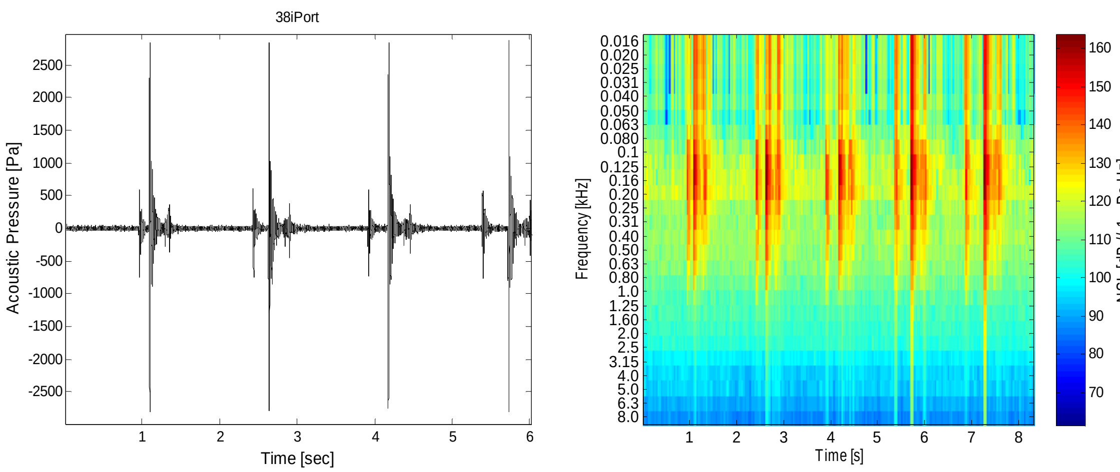

Fig. 3. Waveform of the recorded impulse sounds and their 1/3-octave band spectrogram registered in the Hel Basin at the distance about 50 m from the shoreline where two types of pile driving machines operated.

Tab. 1. Key parameters of a single strike (most energetic) and for 20sec recordings at different distances from the piling area.

Position of the record	SEL (one strike) dB re 1 µPa^2 s	SPL (one strike) dB re 1 µPa^2	SEL (30 s) dB re 1 µPa^2 s	L_{p-p} dB re 1 µPa	SPL (30s) dB re 1 µPa^2
λ=54^{O}32.669’ ϕ=18^{O}30.298’	129.6	133.6	153	180	166
λ=54^{O}32.551’ ϕ=18^{O}30.781’	121.8	124.1	151	175	159
λ=54^{O}32.435’ ϕ=18^{O}31.273’	118.8	119.5	139	164	152
λ=54^{O}32.275 ϕ=18^{O}31.765	118.0	119.3	130	153	143

An example of the time series of acoustic pressure and averaged over a 10s sound spectrum level of underwater noise registered at a distance of around 250m from the piling area, is depicted in Fig. 4 (within the vicinity of the shipyard dry dock). Multiple local maxima reflect the pseudoharmonic components of signals from shipyard machinery.

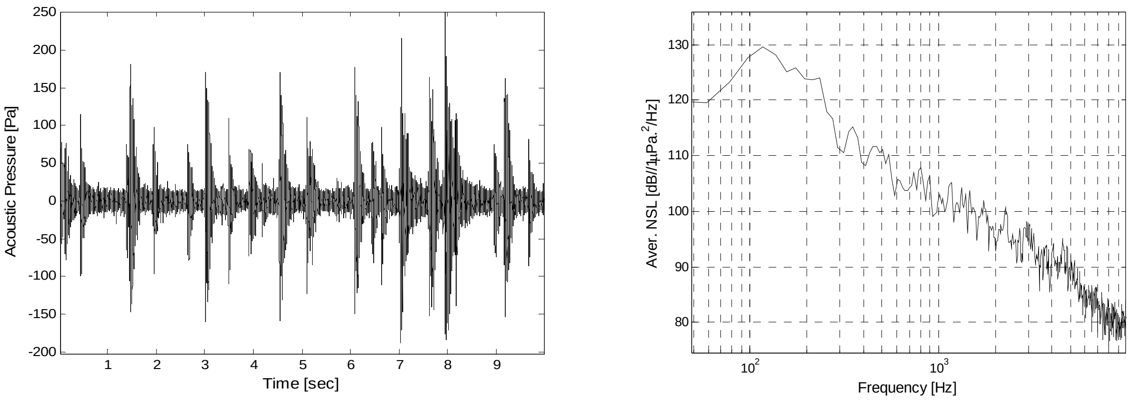

Fig. 4. Time series of acoustic pressure of four working pile drivers and averaged over 10 s of hammering the sound spectrum level.

4.2. Others sources

Ambient noise in different harbour basins is highly diverse in terms of noise levels as well as the energy distribution in the frequency domain. Observed background-noise levels within the harbour were relatively high at frequencies of some kilohertz. As a source of the noise, various mechanisms working on the land in the nearby shipyard were recognised. As an example, a vibro-hammer at the French pier was observed, with L_{p-p} ~160 dB re 1µPa.

A large amount of the observed noise was derived from sea- and harbour-going, manoeuvring and stationary ships. Most of the acoustic energy radiated from commercial vessels is below 1 kHz, with many characteristic peaks visible in high-resolution spectra.

What was interesting that during the time of observations, the signals emitted from a broadband chirp sonar from a navy vessel, were registered in every harbour basin.

5. SUMMARY

Results of measurement, have stated that levels of strong avoidance reactions due to underwater noise on marine species above 90 dBht(*herring*) – for the most sensitive fishes was not exceeded, with the exception of the Hel Basin and the EWOS shipyard. A low disturbance level of 50 dBht(*herring*) was frequently observed, but mostly due to the ship traffic.

The amount of produced sound during the piling activity and its key characteristics both for instantaneous or integral metric levels for all kind of animals had not reached the level harmful to animals, except at relatively small distances from pile-driving.

Evidently, none of the injury criteria for fish exposed to the impact piling noise was surpassed in harbour basins, except of the Hel Basin. Even for the most sensitive animals, such as the smallest fishes, with a mass of 0.01 g, for which a 214 dB re 1 μPa peak-to-peak level or an SEL of 187 dB re 1 $\mu Pa^2 s$ could be dangerous the noise have not reach a hazardous level [1].

Moreover, the piling noise did not propagate to outside of the harbour seawall and the noise from the pile activity was frequently below the local ambient sea noise in the Gulf of Gdansk in the harbour vicinity.

ACKNOWLEDGEMENTS

The study was performed under contract and funded by Gdynia Port Authorities, and permitted to publish with their permission. We also thank J. Wejer, Ł. Hoppe and “CETEEMKA” boat crew for their assistance during fieldwork.

REFERENCES

[1] A., Popper, M., Hastings, 2009, The effects of anthropogenic sources of sound on fishes, J. Fish Biol., 75, 455–489.

[2] J. R, Nedwell, A.W.H., Turnpenny, J., Lovell, S.J, Parvin, R, Workman, J. A. L., Spinks, D., Howell, 2007, A validation of the dBht as a measure of the behavioural and auditory effects of underwater noise. Subacoustech Report Reference: 534R1231, Published by Department for Business, Enterprise and Regulatory Reform

[3] R., McCauley, Fewtrell, J., Popper, A., 2003. High intensity anthropogenic sound damages fish ears. J. Acoust. Soc. Am., 113, 638–642.

[4] L.E., Wysocki, J.P., Dittami, F., Ladich, 2006, Ship noise and cortisol secretion in European freshwater fishes, Biol. Conserv., 128, 4, 501-508.

[5] M., McDonald, J., Hildebrand, S., Wiggins, 2006, Temporary threshold shifts and recovery in a harbor porpoise (Phocoena phocoena) after octave-band noise at 4 kHz, J. Acoust. Soc. Am. 120, 711–718.

[6] C., de Jong, M., Ainslie, 2008, Underwater Radiated Noise Due to the Piling for the Q7 Off-shore Wind Park. In: Zakharia, M. (Ed.), Proceedings of the European conference on Underwater Acoustics 2008, pp. 118–122.

[7] S.P., Robinson, P.A., Lepper, J., Ablitt, “The measurement of the underwater radiated noise from marine piling including characterisation of a “soft start” period”. Proceedings of IEEE Oceans 2007, IEEE cat. 07EX1527C, ISBN: 1-4244-0635-8, 061215-074, Aberdeen, June 2007.

[8] European Commission, 2010. Commission Decision of 1 September 2010 on Criteria and Methodological Standards on Good Environmental Status of Marine Waters.

(2010/477/eu). Available from: http://eurlex.europa.eu/LexUriServ/LexUriServ.do?uri= OJ:L:2010: 232: 0014: 0024 :EN:PDF.

[9] M.A., Ainslie., Ch.A.F., de Jong, S.P., Robinson, P.A., Lepper, What is the Source Level of Pile Driving Noise in Water? Loughborough's Institutional Repository (https://dspace.lboro.ac.uk/)

[10] Madsen, P.T., 2005. Marine mammals and noise: problems with root mean square sound pressure levels for transients. J. Acoust. Soc. Am., 117, 3952-3957.

[11] M.J., Brandt, A., Diederichs, K., Betke, G., Nehls, 2011. Responses of harbour porpoises to pile driving at the Horns Rev II offshore wind farm in the Danish North Sea. Mar. Ecol. Prog. Ser., 421, 205-216.

[12] J., Tougaard, J., Carstensen, J., Teilmann, H., Skov, P., Rasmussen, 2009, Pile driving zone of responsiveness extends beyond 20 km for harbor porpoises (Phocoena phocoena (L.)), J Acoust Soc Am., 126, 8, 11-14

[13] R.A., Kastelein, P., Bunskoek , M., Hagedoorn, W.W., Au ,D., de Haan, 2002, Audiogram of a harbor porpoise (Phocoena phocoena) measured with narrow-band frequency-modulated signals. J Acoust Soc Am., 112, 1, 334-344.

[14] M. H., Andersson, 2011, Offshore wind farms – ecological effects of noise and habitat alteration on fish, Department of Zoology Stockholm University, pp. 48.