Hydro sound and soil vibration measurements during the installation of offshore foundations

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ABSTRACT
During the installation of pile foundations for the offshore wind farm Amrumbank West the new noise mitigation system of Hydro Sound Damper (HSD) was used besides the single and double big bubble curtain. To determine the wave propagation and the efficiency of the different noise mitigation methods the Institute for Soil Mechanics and Foundation Engineering of the Technische Universität Braunschweig (IGB-TUBS) carried out extensive measuring campaigns. During these campaigns a dense matrix of hydrophones in different water depths and also geophones on the sea bed in distances between 25 m and 1500 m from pile was installed to determine the effects of the different combinations of noise mitigation systems. Additionally the pile itself was instrumented with sensors. Based on these measurements the wave propagation in pile, water and soil is investigated and the efficiency of the noise mitigation measures in different distances to the pile and over the most important frequency range is determined.

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1. INTRODUCTION
Impact pile driving is the state of the art for installing monopile foundation of offshore wind farms (OWF). This piling method is proved and can be used in most soils in the North and Baltic Sea. The high impact energy causes hydro sound emissions in the seawater which can disturb, injure, or even kill marine animals (1).

In order to protect the natural habitat the German Umweltbundesamt (UBA) has published recommendation for limiting values for offshore piling noise. The limiting values for the sound exposure level, (SEL) is set to 160 dB re 1 μPa²s and the maximum sound peak level (Lpeak) is set to 190 dB re 1 μPa (2).

The Federal Maritime and Hydrographic Agency (BSH) is the responsible approving authority for offshore construction projects in the German exclusive economic zone and have incorporated the discussed limiting values into the approval procedures for new projects (3).

At present offshore projects the regulations for hydro sound can be satisfied by the use of underwater noise mitigation systems (NMS). Three systems are currently available. The big bubble curtain (BBC) is deployed in a radius of 80 m to 100 m around the installation vessel including the driven pile. The noise mitigation screen (IHC Merwede) and the Hydro Sound Damper (OffNoise-Solutions) are mounted directly at the monopile. The experience of finished projects has shown that each of the NMS was able to mitigate the sound emission up to 18 dB (SEL). Unfortunately the reliable efficacy does not reach these values.

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In current projects monopiles with a diameter of up to 7 m are used which require reliable noise mitigation levels of 20 dB (SEL) (4). This cannot be accomplished with a single system. Consequently the noise mitigation concept receives a higher relevance in the approval procedure of the designed OWF projects.

At the OWF Amrumbank West monopile with a diameter of 6 m where installed in and a combination of two NMS was used to reach the required noise mitigation. The HSD located at the pile (deployed by the main crane) and a double bubble curtain (DBBC), later only a single BBC, in a greater distance (deployed from a separate vessel).

Due to the fact that the combined use of a HSD and a BBC has not been tested before the Institute for Soil Mechanics and Foundation Engineering at the Technische Universität Braunschweig (IGB-TUBS) in cooperation with E.ON Kraftwerke GmbH conducted the research project called triad. Part of the project was three measuring campaigns to examine the wave propagation in the monopile, the hydro sound propagation in the water and the ground vibrations on the seabed.

2. OWF Amrumbank West

From 2014 to 2015 E.ON Kraftwerke GmbH was constructing the OWF Amrumbank West with 80 offshore wind turbines (OWT) with an overall performance of 288 MW. The OWF Amrumbank West is located north of Helgoland and western of the island Amrum. Monopile with a length of about 55 m and a diameter of 6 m were used as foundations in water depth between 19 m and 24 m (5). The installation of the monopile was accomplished in the beginning of 2015. The subsoil is homogenous and consists mostly of dense and very dense sands. The installation of the monopiles and the transition peace carried out from the jack up vessel MPI Discovery. The piling was performed with a Menck hydro hammer type MHU 1900S. To reduce the induced hydro sound in the water the HSD was installed around the pile directly from the installation vessel and a BBC was constructed around the vessel with a separate ship. For technical reasons it was necessary that the pile reached self-standing stability before the HSD system could be positioned. In terms of noise mitigation there were two phases of installation. In phase 1 the pile driving was performed with lower blow energy so the BBC was able the keep the limiting values of piling noise. Once the pile reached a depth of about 12 m the HSD was placed around the pile and phase 2 could be executed with a higher energy level. The deeper the pile gets driven into the subsoil the higher the energy needed to overcome the soil resistance to continue pile driving.

More information on the operation and effect of the HSD and BBC can be obtained from (6), (7) and (3).

3. Research project triad

3.1 Content and scope

Monopiles are open steel tubes which are driven into the subsoil. When the hammer hits the pile head a strain wave travels in axial direction towards the pile toe with a radial deformation caused by the transverse strain. Depending on the boundary condition at the pile toe, a compressive or tension wave gets reflected (8).

The dynamic radial deformation of the pile induces a compression wave in the surrounding sea water, which is propagated as hydro sound. Compression waves, shear waves and Scholte waves are emitted into the subsoil due to the deformation of the pile shaft and the impact at the pile toe. Compression and shear waves travel through spherical half space. The Scholte wave appears at interface between soil and water at the seabed. The seismic waves can provoke hydro sound pressure in the water. The different spreading paths in the combined system consisting of pile, water and soil are displayed in Figure 1.

As part of the research project triad the wave propagation in the system pile, water and soil during the installation of monopile foundations as well as the mitigating influences of HSD and BBC have been evaluated.

For this purpose, strain measurements and acceleration measurements at the pile, vibration measurements on the seabed and hydro sound measurements in the water column were carried out. This article focuses on the vibration and hydro sound measurements. Further information and published results on the strain and acceleration measurements on the monopiles can be found in (8) and (3).
3.2 Measuring concept

For investigation of the hydro sound emission and soil vibration strain- and acceleration measurements were taken out at three chosen monopile. Strain- and acceleration sensors were placed in different directions and in different sections of the pile.

The selected measurement location (ML) for investigating the hydro sound and soil vibration in the perimeter to be installed pile can logistical divided into near range and remote range. In near range triaxial geophone and hydrophone chains at five different ML were located on deck of the installation vessel. All near range ML were lowered inside the surrounding BBC. In the remote range outside the BBC three ML with distances from 150 m to 1500 m to the pile were set out. Each ML in the remote range is equipped with a geophone and a single hydrophone. The self-sufficient measurements units in the remote range were set out by a separate vessel. Figure 2 displays the different position of each ML in near and remote range. The ML declaration indicates the distance between the monopile and each ML.

FIGURE 1 - Interactions in wave propagation of pile-water-soil (10)

FIGURE 2 - Measuring concept (11)
While it was possible that the setup of the near range ML were carried out in the same pattern for all measured piles, the ML in remote range varies because of different maritime safety regulations. Furthermore, the direction in which the ML in remote range were placed depended on the current wind, wave and current condition. Due to the elliptic shape of the BBC it was possible to set out on remote range ML at the same distance on of the ML in near range but outside the BBC. Figure 3 illustrates the position of the ML in near range and the ML in remote range to the pile. During the three MK the installation of eight piles were metrological monitored. Various NMS configurations were used which enables an evaluation of the different NMS. In addition it was possible to measure an officially authorized pile as a reference without NMS.

3.3 Analyses of acoustical measurements

To describe the loudness of sound and hydro sound, sound levels are usually used. Sound levels are given in a logarithmic decibel (dB) scale which refers to a reference pressure $p_0$ of 1 μPa in hydro sound acoustics (therefore the unit is dB re 1 μPa). The evaluation of underwater piling noise is regulated in (12) and (13). In the mentioned regulations the SEL (or $L_E$) and the $L_{\text{peak}}$ are of importance. The $L_{\text{peak}}$ is determined by transferring the maximum absolute pressure on $p_{\text{peak}}$ in an interval (for example a hammer blow) to the decibel scale

$$L_{\text{peak}} = 20 \log \left( \frac{p_{\text{peak}}}{p_0} \right)$$

(1)

The $L_{\text{peak}}$ gives only information about the absolute maximum amplitude of a signal. A peak value of 190 dB corresponds to a sound pressure of about 3 kPa. Due to different reference pressures and different acoustic impedances, a direct comparison of hydro sound level with common sound pressure levels in the air is not possible. The difference is about 60 dB. Also no frequency weighting is done in hydro acoustics.

If, however, the energy content of the hammer impact is of interest, its determination has to be performed over the duration of the event. The SEL takes this into account by integrating the sound pressure over a selected period of time and dividing it by the reference time $T_0=1s$:

$$SEL = L_E = 10 \log \left( \frac{1}{T_0} \int_{t_1}^{t_2} \frac{p(t)^2}{p_0^2} dt \right)$$

(2)

As the sound pressure is squared and normalized to one second, the unit of this sound level is [dB re 1 μPa²s]. The boundaries of $t_1$ and $t_2$ should be selected so that the entire sound event is detected.

In addition to the single-event level and the peak level, the composition of the signal is examined in the frequency domain. This is not done by means of a1/3-octave analysis.

4. Results of the hydro sound measurements

During the measurements at the OWF Amrumbank West a great amount of measurement data of several piles was recorded. In the following the results of hydro sound measurement are presented. Figure 4 shows the hydro sound signals of an exemplary piling blow for selected sensors in different distances to the pile and different heights above the seabed.
The sound waves propagate from the pile in radial direction in the surrounding water and are first detected by the sensors at ML25 and subsequently by the other sensors. Overall, the sound events in the water include frequencies above 100 Hz, in contrast to seismic waves. In the shown example, pressure fluctuations of more than 20 kPa occur which can increase to 100 kPa at maximum driving energy. With increasing distance to pile and increasing height above seabed the peak values decrease. Likewise, the duration of the sound event is shortened with larger distance to the sound source.

As explained, the broadband SEL and the L_{peak} in 750 m distance provides the relevant variables for the evaluation of NMS. These levels can be determined from the sound pressure curves shown in Figure 4, in accordance with the formulas described in section 3.3. Figure 5 shows the development of the SEL and L_{peak} over the pile driving process at different ML in the form of a single event analysis shown. The shown pile served as a reference measurement without noise reduction, which is why the measured hydro sound levels at 750 m distance significantly exceed the required limit by about 16 dB (SEL). The measurement was necessary to assess the effectiveness of noise reduction systems used in the context of the research project separately and in combination.
Basically, the level values are reduced due to the propagation loss with distance to the pile. In addition, sudden increases in sound emission as a result of change in the driving energy can be observed. The SEL of 176 dB re 1μPa²s (SEL) in 750 m distance matches very well with the measurements required by the authorities and carried out by itap. It turns out that for the OWF Amrumbank West a sound reduction of at least 16 dB (SEL) has to be provided reliably to meet the limiting value. This implies a reduction of energy in the water of about 97.5%.

![Figure 6](image.png)

**FIGURE 6 - SEL at different measuring locations while piling with noise mitigation (DBBC and HSD)**

Figure 7 has a similar structure as figure 5 but without the L peak. The SEL due to pile driving with DBBC and HSD can be seen. In phase 1 (to about 1,600 blows) only the DBBC was used. In phase 2 the HSD was additional used directly at the pile. The hydrophones at ML25 and ML72 are within the DBBC and therefore the corresponding level values are comparable to those of the reference measurement in phase 1. Between ML72 and ML250 the effect of DBBC is shown. The limit of 160 dB (SEL) in 750 m distance is almost reached at the end of Phase 1. In Phase 2 the HSD shows an additional sound reduction of about 7 dB to about 153 dB (SEL) in 750 m distance. The SEL slightly increases to about 157 dB (SEL) when it reaches the desired penetration of the monopile. This example shows the very good interaction between the two noise reduction techniques at the pile and at a greater distance. The limit was not exceeded at any point of the driving procedure. Compared with 176 dB (SEL) in the reference measurement the sound level was reduced by 19 dB (SEL).

Due to the high density of hydrophones at near range to the pile the sound emissions could be examined over the water depth and over the distance to the sound source. These relationships are shown in Figure 7 for the reference pile without sound reduction. Since the SEL is constant for a constant piling energy (cf. Figure 4), the median is taken for 500 blows with maximum piling energy. It is clear that highest levels arise very close to the pile and the noise decreases with increasing distance. Moreover, the sound level increases closer to the seabed. This relationship was observed in all measured piles in this form. Only in the direct vicinity (ML25) irregular level composition can be detected.
Apart from determining the broadband level values the frequency-dependent composition of the hydro sound signals is of great importance, as this can have an impact on the hearing organs of marine animals. Figure 8 shows the results of 1/3 octave analyses during pile driving without (reference) and with different noise reduction combinations at the same piling energy at a depth of 1 m above ground with growing distance to the pile. At the top left the reference results are shown, top right BBC only, bottom left HSD only and bottom right both systems BBC and HSD in combination.

The geometric attenuation with increasing distance from the pile occurs over the entire frequency band, but more pronounced in the low frequencies below 50 Hz, and the high frequencies above 1 kHz. The drop in intensity in the low frequency range can be attributed to the lower limit frequency in the propagation of sound in water (14), which is about 60 Hz according to the boundary conditions at the OWF Amrumbank West. Sound waves below this frequency cannot be propagated stably in the water column and are therefore dampened disproportionately high. The reduction in the upper frequency range can be attributed to the general frequency dependence of the geometrical attenuation, according to which shorter wavelengths are attenuated stronger than longer ones (15). From a distance of about 400 m a typical frequency spectrum for the pile driven monopile develops with a predominant amount of energy in a range between 100 Hz to 600 Hz. The typical frequency spectrum can vary and is dependent of the water depth, pile diameter, piling equipment, piling energy and geology.
The effects and the area of influence of the two different NMS can be taken from the comparison of the four results in Fig. 8. While the BBC (between ML150 and ML400) mostly effectively attenuates frequencies above 300 Hz due to the low maximum bubble size of 1..2 cm, the HSD (directly at the pile) acts in the frequency range between 60 to 1000 Hz due to the controllable bladder size. HSD and BBC complement one another and provided a sufficient broadband noise reduction over the entire frequency range. The attenuation causes by the HSD system is seen at ML25 and ML72, the use of the BBC results in an additional attenuation in the higher frequencies between ML145 and ML400.

5. Results of the vibration measurements

In addition to the underwater noise measurements vibration measurements were carried out at each measuring location. The seismic measurements are of particular interest to investigate a possible impact of the soil vibration to the hydro sound emissions. To examine these potential effects, triaxial geophones with ballast plates and spikes were lowered to the seabed. A camera applied at ML25 could prove that the seabed is relatively flat and the sensor's position and orientation did not change during pile driving. In the following, only the results of the vertical direction of measurement are shown, because the true orientation of the horizontal axes cannot be clearly defined.

There are few practical studies in the literature on the vibration propagation during the driving of offshore piles. Preliminary measurements during the ESRa test in 2011 have been described by (16) and show a non-negligible influence of seabed on the effectiveness of the NMS. However, these measurements are not transferable to the constraints in the installation of offshore foundation piles, because the test pile had an enormous embedment length and was joint almost rigidly to the subsoil. Further measurements were published in (17) and (18).

Figure 9 shows the measured vibrations of the seabed (red) at ML25 to ML750 during piling, as well as the corresponding sound pressure in the water at ML25 1 m above ground (blue). The first four blows of a piling sequence are shown. On the right side of the curves the corresponding frequency spectrums are shown as Fast Fourier Transformation (FFT).

Three different oscillations due to the second hammer blow with different wave propagation velocities are marked by dotted lines: I (black), II (blue), III (red). Similar signals have been measured at each pile driving. The high-frequency impulse (II) in water can be recognized at the same time at the corresponding geophone at ML25. Later, the same signal appears at the measurement positions in greater distances according to the wave propagation velocity in water of about 1500 m/s. It can be concluded that this high-frequency oscillation of the geophones results from compression waves in the sea water (hydro sound) acting on the hull of the upright sensors on the sea floor surface and is not due to ground movements.

The events I and III oscillate at frequencies of 1..40 Hz and are clearly visible at the geophones. In the vicinitix, they occur before or after the hammer blow (II). Event I begins at ML25 about 0.1
seconds before the hammer impulse. Due to the close proximity to the pile it can be interpreted as an activity of the hammer (e.g. lifting of the drop weight). The event III, however, is caused by the Scholte wave propagating on the seafloor at a lower speed than the hydro acoustic wave. The amplitude of this signal component can be clearly seen decreasing with increasing distance. At the same time the duration between the high frequency hydro sound pulse and the low-frequency Scholte wave increases. The propagation velocity of this seismic wave is about 250 m/s. At a greater distance (ML250 and 750) it is passed by the hydro sound wave of the following blow. The circled signal components highlight the related ground vibration of one hammer blow at different locations.

In consideration of these findings and in comparison with figure 4 it is clear that the low-frequency soil vibration is detected by the hydrophones near the seabed as well. They can be clearly identified in the sensors at ML25 and ML72 in 1 m and 9 m above ground (cf. figure 4). To determine the impact of these oscillations on the SEL, all signals have been high-pass filtered with a cutoff frequency of 40 Hz and compared with the output level. The resulting level differences (ΔSEL) are shown in figure 10. An impact of up to 1 dB SEL can be seen in the vicinity of the pile penetrating into the soil. The ground coupling effect decreases at a greater distance to the pile and a greater distance to the seabed. From about 70 m, the influence of low-frequency seabed vibration almost disappears.

The waveforms of the geophones were evaluated in a single blow analysis in order to gain information on the energy content. For this purpose first the high-frequency portion of the event II was eliminated by low-pass filtering. The sum level SEL \(_{Geo}\) was calculated after (19) analogous to the hydro sound exposurer level with a reference value of \(v_0 = 1\text{nm/s}\). The result of this evaluation for different distances to the pile is shown in Figure 11.

First, the level values of the SEL \(_{Geo}\) increase with progressing pile driving and remain largely constant after blow 500. With increasing distance, the levels decrease. The insertion of HSD (at about blow1600) has no influence on the soil vibrations.

FIGURE 10 - Influence of the low frequency soil vibration on the SEL of the hydro sound

FIGURE 11 - SEL \(_{Geo}\) at different locations during pile driving with noise mitigation (DBBC and HSD)
6. CONCLUSIONS

For the protection of marine life in the North and Baltic Sea and particularly the harbor porpoise, the use of NMS is imperative during the installation works for OWT in order to meet the required noise values set by UBA and BSH. To improve the design of NMS, to optimize their application and to reduce the costs of noise reduction, a better knowledge of the wave propagation in the overall system of pile, soil and water is necessary. For that reason, the research project triad was conducted by Technische Universität Braunschweig during the installation works at the OWF Amrumbank West in the North Sea. Measurements of pile dynamic, hydro acoustics and seismic vibrations have been carried out in the context of the research project.

The measurements of the hydro sound pressures over the water depth and distance to the pile showed rising noise levels with increasing water depth and decreasing distance to the sound source. In the vicinity of the pile, pressure fluctuations of more than 100 kPa were measured. The attenuation effects of the noise reduction measures BBC and HSD could be analyzed individually and in combination, in particular in the frequency domain. The BBC gives good attenuation in the high frequency range, while the HSD is stronger in the low frequency range. These two systems complement each other very well and were able to achieve attenuations of up to 19 dB (SEL) in 750 m distance. This result could be excelled in another serial use of HSD with a DBBC at the OWF Sandbank by a system optimization to up to 25 dB SEL (20).

The vibration measurements showed low-frequency ground vibrations between 1 and 40 Hz, which propagate considerably slower than the hydro acoustic waves with about 250 m/s. The low-frequency seismic waves cause an increase of the hydro sound values of about 1 dB (SEL) in close proximity to the pile. The piling energy has only minor influence on the soil vibrations.

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