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Hydro sound measurements during the installation of large diameter offshore piles using combinations of independent noise mitigation systems

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ABSTRACT

During the installation of pile foundations for offshore wind farms (OWF) in the German North Sea, hydro sound emissions occur which are harmful to marine life. Limiting values defined by German authorities could not be met by the use of single noise mitigation systems (NMS) in past wind farm installations with large diameter monopiles. To improve noise reduction, combinations of several NMS are used in recent projects. Different NMS taking affect in different frequency ranges can reduce noise caused by impact driving more effectively. During offshore measuring campaigns at an OWF in the German North Sea, hydro sound measurements have been carried out in 7 distances from 15 m to 1500 m and in 5 depths from 1 m to 17 m over ground simultaneously. Results of these measurements will be shown in the time and frequency domain. Pile driving noise emissions with single NMS and combinations of NMS will be compared with reference measurements without NMS to evaluate different setups. The influence of the subsoil will be discussed as well as it has a significant influence on hydro sound propagation in general and the effectiveness of NMS in particular.

Keywords: underwater acoustics, offshore pile driving, soil dynamics
I-INCE Classification of Subjects Number(s): 08.4, 12.2.3, 41.3, 43.2.3, 43.2.4, 54.3, 72.1, 82

1. MOTIVATION

For the erection of offshore wind farms (OWF) in the German North Sea, foundations have to be installed which can withstand the influences of wind, wave and current and transfer them into the subsoil. The most common technique for founding offshore wind turbines (OWT) in the German North Sea are tripods, jackets and monopiles. All these have in common the need to drive tubular steel piles into the seabed. Currently, the most common method for this is driving which causes massive noise emissions in the seawater and affects marine life. To protect animals like Harbour Porpoises, limiting values for hydro sound emissions during offshore pile driving have been set by German authorities. These limits are hard to keep, especially for the driving of monopiles. (1)

In the past years, different noise mitigation systems (NMS) have been developed to lessen the impacts of offshore pile driving on marine life. Tried and tested methods like the bubble curtain as well as new techniques like Hydro Sound Dampers (HSD) or IHC NMS have been integrated into the installation processes. However, currently no single NMS is able to sufficiently lessen hydro sound emissions during installation of large monopile foundations.

Measuring campaigns during the ESRa test (2) and at the OWF London Array (3) have shown strong influence of the subsoil on hydro sound emissions even in greater distances from the driven pile. To supply better information for the further development of NMS, a deeper understanding of the wave propagation in the steel piles, subsoil and seawater as well as the interactions between them is necessary.

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2. RESEARCH PROJECT 'triad'

To evaluate the effectiveness of different NMS and to study the wave propagation in and the interactions between pile, soil and water during the installation of large diameter offshore piles, a research project funded by the German Federal Ministry of Economic Affairs and Energy is carried out by Technische Universität Braunschweig and E.ON during the monopole installation of the Amrumbank West OWF.

2.1 OWF Amrumbank West

The OWF Amrumbank West is built by the energy group E.ON in the German North Sea. The locations of the 80 turbines have water depths of between 19.5 m to 23.6 m LAT (lowest astronomical tide). All turbines are founded on monopiles with a diameter of 6 m and a length of approximately 55 m, which are driven into the sandy subsoil by a hammer of type MENCK MHU 2100. To lessen the hydro sound emissions of the pile driving and to meet the limiting values for underwater noise mentioned above, two independent noise mitigation systems are used. Around the installation vessel, a double big bubble curtain (DBBC) is laid out and fed from a separate vessel. Around the monopile, a Hydro Sound Damper (HSD) system is used to mitigate the noise emissions directly at the source. The HSD system consists of elements of foams and gas-filled bladders that are attached to a tubular fishing net which is connected to a steel box that sinks to the ground (Figure 1). For more information about the acoustical damping effects and the technical implementation refer to Elmer (4) and Bruns et al. (5)

Figure 1 – HSD system being put over monopile (left) and HSD net at the water surface (right)

Due to operational causes in the installation process of the monopiles, it is not possible to use the HSD system over the whole pile driving process. Each pile has to be driven to a penetration of about 12 m to fulfill a temporary free stand criterion, which is done with low impact energy. After that, the HSD system is placed around the monopile and the pile is driven to final penetration. This issue makes it possible to compare noise levels measured with (w/) and without (w/o) HSD system considering the used impact energy of the hammer.

Bubble curtains were used in different setups during the project. Regardless of the respective bubble curtain setup, this mitigation system could generally be used over the whole pile driving process since it does not directly interfere with any of the processes onboard the installation vessel.

2.2 Scope of research project

To contribute to the understanding of different causes of underwater noise emissions during offshore pile driving, the wave propagation in pile, soil and water shall be investigated in three measuring campaigns. The monopile itself is instrumented with strain gauges and accelerometers along the length of the pile. The data acquired by these sensors can be used to study the dynamic deflections of the pile while it is driven into the soil. These deflections emit vibrations in the soil and noise in the seawater. Geophones are placed on the seabed to measure the movements of the soil surface. At the same locations as the geophones, hydrophones are deployed to measure noise levels in different distances from the pile and in different water depths. By time synchronized data acquisition of the different sensors, travel times can be determined which enable estimates regarding ways and characteristics of the different types of waves.

This paper shall focus on the wave propagation in water and subsoil measured by one pile in the first measuring campaign. Different setups of NMS used during the installation of the monopiles and their noise damping effects will also be considered.

3. MEASURING CAMPAIGN

To evaluate the wave propagation in the seawater and the subsoil, as well as the noise mitigation of the different NMS, an extensive measuring campaign is performed. Hydrophones and geophones are deployed to the ground of the North Sea from the installation vessel and a chartered measuring vessel. Measurements have been performed during pile driving with different NMS setups.

3.1 Measurement setup

The measuring locations are divided into an immediate area in distances of up to 140 m to the pile and a remote area of 250 m to 1500 m to the pile (Figure 2). This classification is done due to the logistical boundary conditions for deploy of the measurement systems and must not be mixed up with the acoustical near-field and far-field. The exact location of the particular measuring locations depends on the logistical conditions on deck of the installation vessel and matters of marine safety on the offshore construction site.

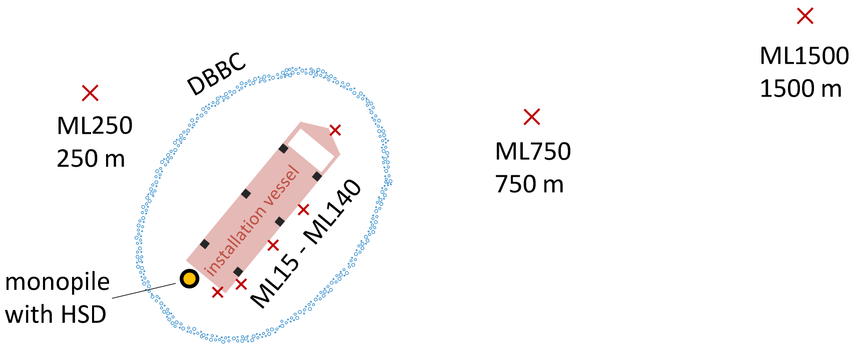

Figure 2 – Measuring locations in immediate and remote area

In the immediate area of the pile, ballasted geophones are deployed from the deck of the installation vessel. At each of the five measuring locations (ML), an array of three to five hydrophones is attached to the geophone. Signal cables from all sensors are lead to the vessel's deck and signals are acquired at a central data acquisition (DAQ) station. In greater distance to the pile, autarkic DAQ systems with geophones and hydrophones are deployed from a measuring vessel. As mentioned, Figure 3 shows a section through all measuring locations with the different sensors used to study wave propagation in water and soil with a dense matrix of hydrophones in the immediate area from the monopile.

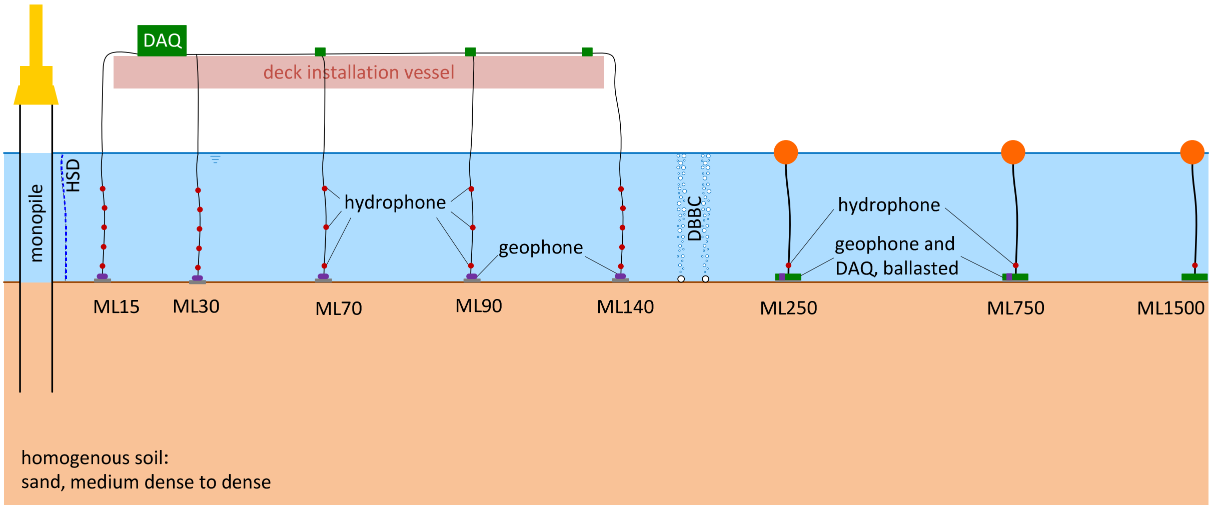

Figure 3 – Section of the measuring locations

3.2 Measurement equipment

For the measurement of hydro sound pressures and soil vibration velocities, different sensors and DAQ recorders are used. Hydro sound measurements carried out from the installation vessel are done by sensors and DAQ hardware from Brüel & Kæjr (B&K). Vibration measurements are performed with tri-axial velocity sensors and amplifiers while DAQ was realized by National Instruments hardware. Additionally, hydrophone and geophone signals are acquired by Teac/Roga data recorder for time synchronization. Measurements in the remote area were realized with systems developed by develogic containing Reson hydrophones and Sensor Nederland geophones. All systems are selected in order to keep requirements of measuring range (no clipping) and high frequency information.

4. MEASUREMENT RESULTS

The first measuring campaign including pile measurements as well as acoustic and seismic measurements in the immediate and remote area was carried out in May 2014. All data shown in this paper have been acquired during the installation of one monopile. To study the evaluation of shock waves in water and soil induced by pile driving, sound pressure signals are analysed in the time and frequency domain. Signals captured in difference distances from the source, in different water depths, at different penetration lengths of the pile and with or without particular NMS are compared.

4.1 Signal analysis

By the time-synchronised data of soil vibrations and hydro sound pressure, a two-dimensional study of the wave propagation is possible in different water depths and over the distance from the pile. Figure 4 shows the time signal of hydro sound pressures of one single blow in different heights above ground in distances of 15 m and 140 m from the monopile.

Table 1 – Overview of measuring locations

Measuring location	ML15	ML30	ML70	ML90	ML140	ML250	ML750	ML1500
Distance to monopile [m]	15	30	70	90	140	250	750	1500
Hydrophones; height over ground [m]	1; 5; 9; 13; 17	1; 5; 9; 13; 17	1; 9; 17	1; 9; 17	1; 5; 9; 13; 17	1	1	1

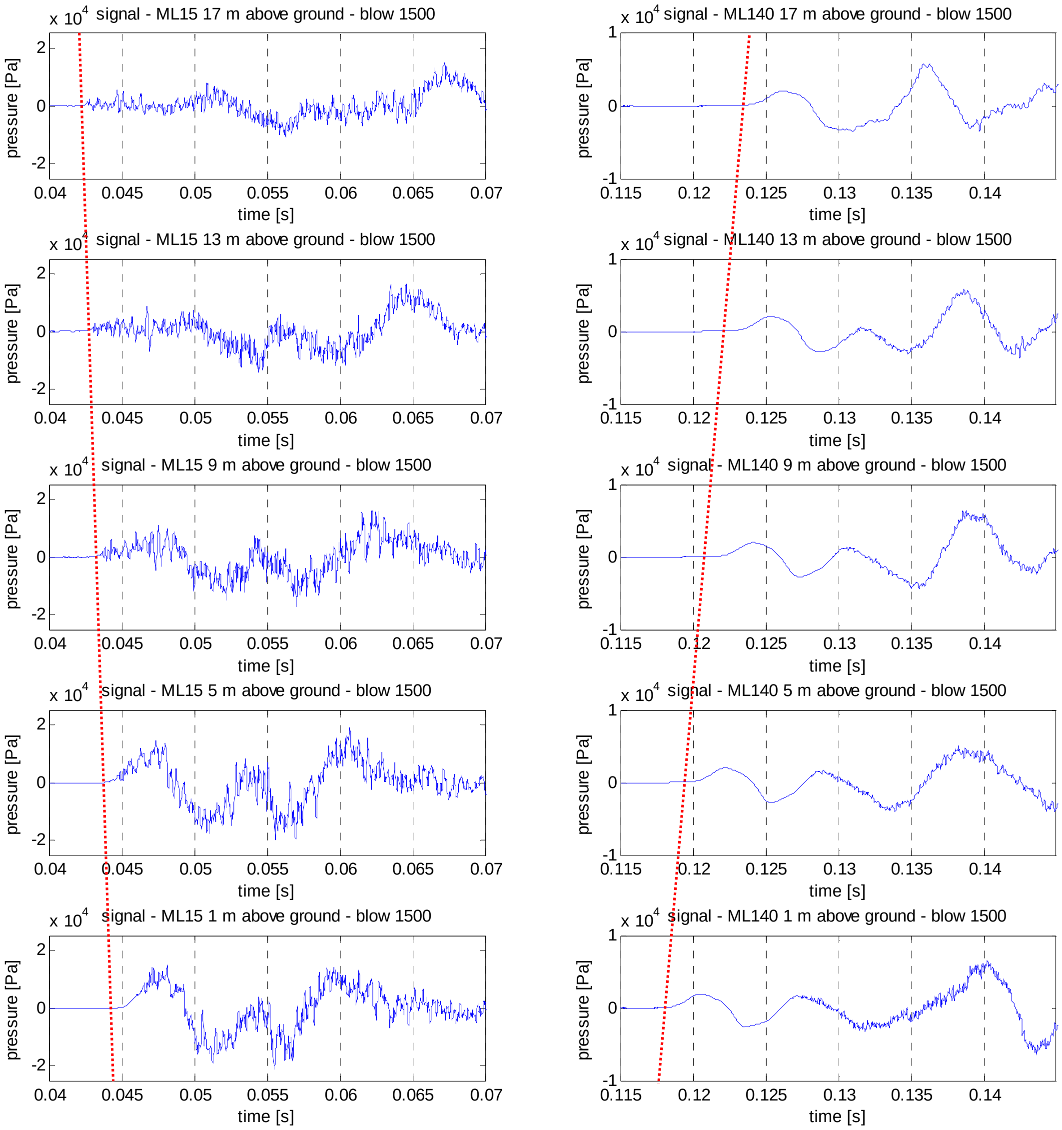

Figure 4 – Hydrophones signals of one single blow in different heights above ground (top to bottom) in 15 m distance from the pile (left) and 140 m distance from the pile (right) with 800 kJ

As indicated by the dashed line on the left side of the figure, the wave reaches the hydrophones in different heights above ground at different points in time. This can be explained by the wave propagation in the driven pile from the pile head to the pile toe causing direct noise emissions into the seawater. The angle of the wave front can be calculated by the time delay between two hydrophones at one ML multiplied by the sound velocity in water divided by the vertical distance between the hydrophones. The time delay can be picked from the figure, the wave velocity has been determined to $c_W = 1487$ m/s by a CTD probe and the vertical distance of the hydrophones can be taken from Table 1. This leads to an inclination of the wave front of about 16.6° between hydrophones in 1 m to 17 m above ground at ML15 which fits good to the cone angle of $\varphi_w = \sin^{-1}(c_W/c_S) = 16{,}9°$ described by Dahl (6) and Lippert et al (7). This angle inverts at ML140 which indicating a faster propagation near the ground which might be caused by the interaction between ground and water.

Besides hydrophone measurements in different heights above ground, seismic measurements have been carried out at the same MLs to study the wave propagation in the soil. Figure 5 shows the vertical velocities of soil movements during pile driving at ML250 in the two phases of the installation process.

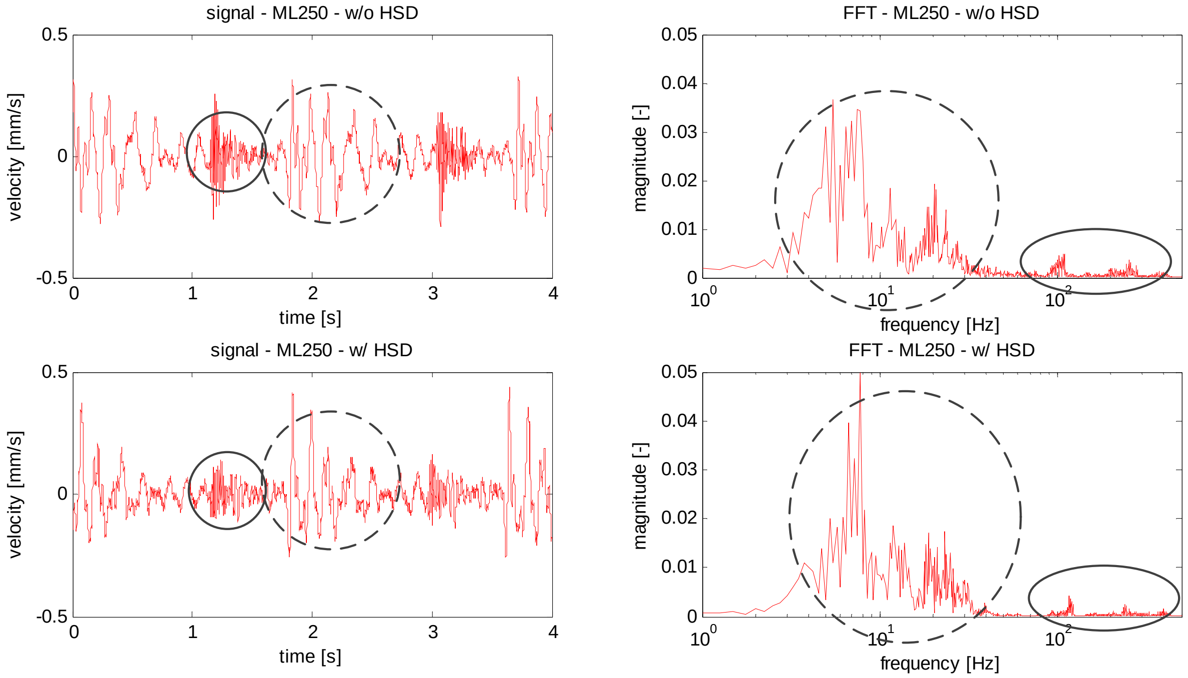

Figure 5 – signals of vertical vibrations of the ground of blows with HSD (top) and without HSD (bottom)

The upper and lower parts of the figure show soil velocity signals and corresponding FFT plots for series of blows in the first phase of the installation process without use of HSD system and in the second phase with HSD in use respectively. Each blow consists of one part with a higher frequency (solid-lined circle) following another part with a lower frequency (dashed-lined circle). While the low-frequency parts of the signals show similar amplitudes, the high-frequency signal is reduced in phase 2. This confirms findings of Bruns et al. (8) based on measurements carried out by itap GmbH, Germany, during the ESRa test indicating that high-frequency signals in geophone measurements during offshore pile driving is caused by a shock wave in the seawater which is exciting the geophones.

Looking at a single blow in a sequence of blows, it is not clear which high-frequency hydro sound pressure wave belongs to which low-frequency seismic wave. Single blows with pauses of up to 1 minute at the beginning of the pile driving show that the high-frequency hydro sound wave reaches the geophone before the low-frequency seismic wave (Figure 6).

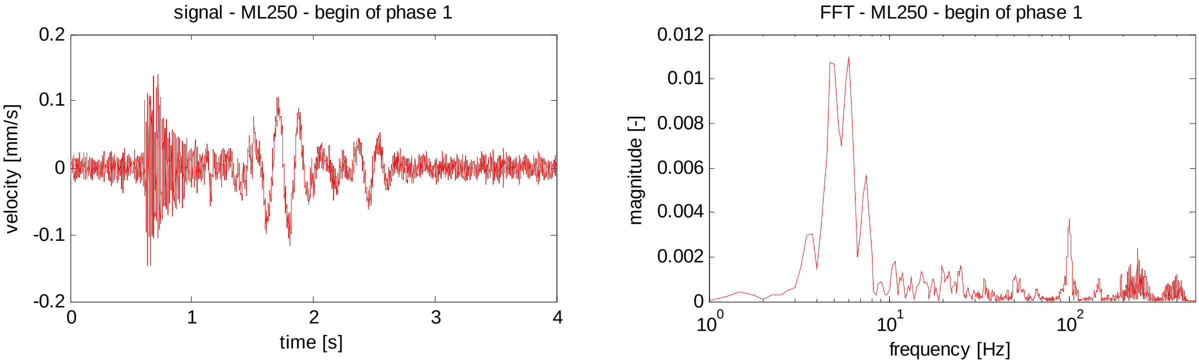

Figure 6 – Geophone signals of one single blow at the beginning of pile driving (800 kJ)

Based on these findings, time delays between hydro sound and seismic signals in geophone measurements can be used to study wave propagation in soil and water. Figure 7 shows such signals of geophone measurements of the first blow of the second phase of the installation process captured at measuring locations in different distances from the monopile. It has to be considered that the high-frequency hydro sound part in the signals is damped by the HSD system (all measuring locations) and the DBBC (at ML250 and ML 750). However, the time delay between the high-frequency hydro sound signal and the low-frequency soil vibration signal can be detected. At ML15, the hydro sound signal overlays the seismic signal while in greater distances to the pile the delay between the signals increases. Knowingly that the sound speed in the water is 1487 m/s, the wave speed at the interface of the ground can be determined to about 500 m/s which fits well to the Rayleigh wave speed as mentioned in (9).

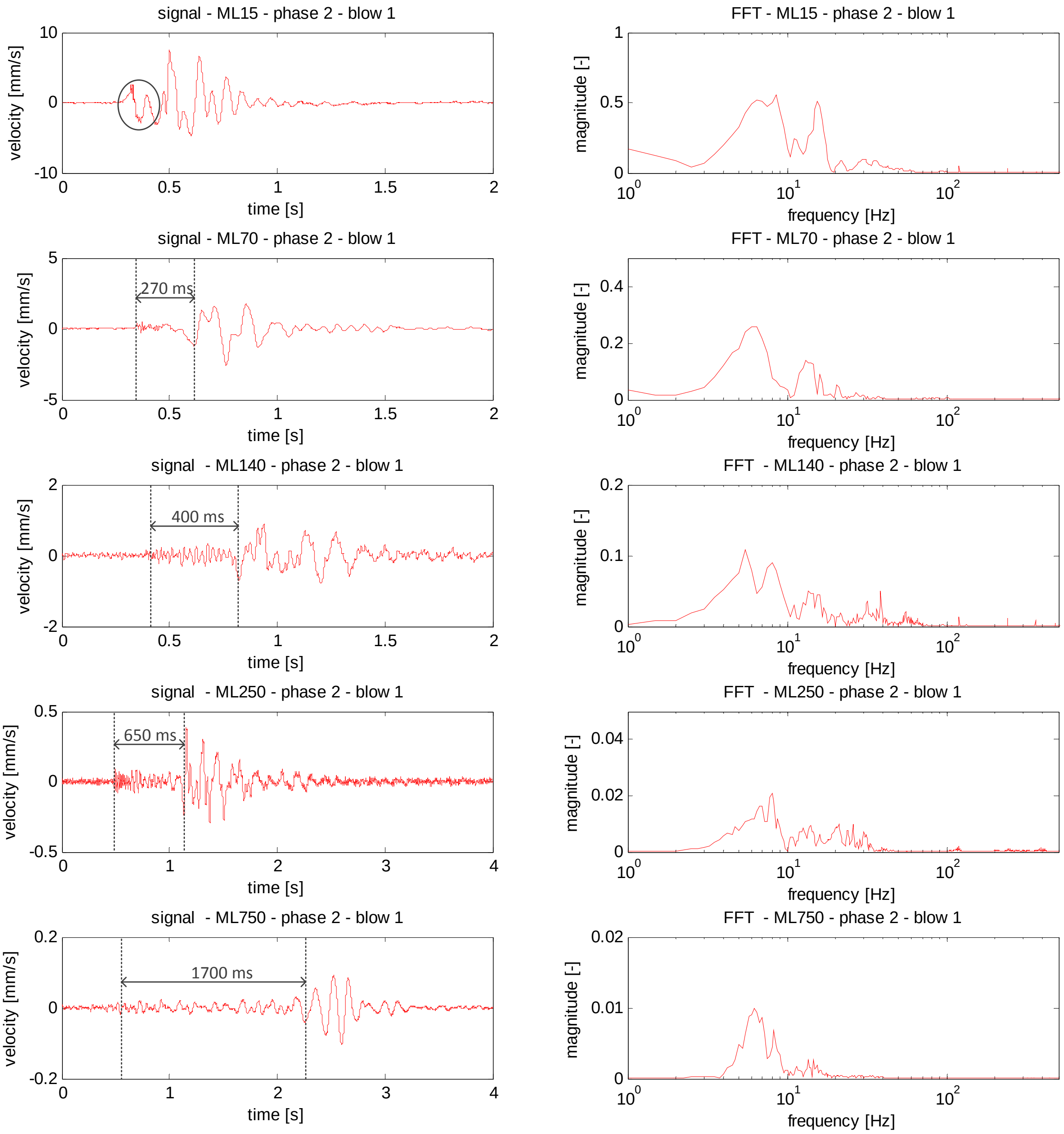

Figure 7 – Geophone signals of one single blow at the beginning of phase two in different distances from pile driving (800 kJ)

4.2 Frequency analysis

Due to the high number of hydrophones deployed within a radius of about 150 m from the pile along the length of the installation vessel, the sound propagation can be examined with a high resolution within the immediate area of the source. Figure 8 shows averaged 1/3 octave analyses for blows in the first part of the installation process without the HSD in different distances from the pile and different heights over ground.

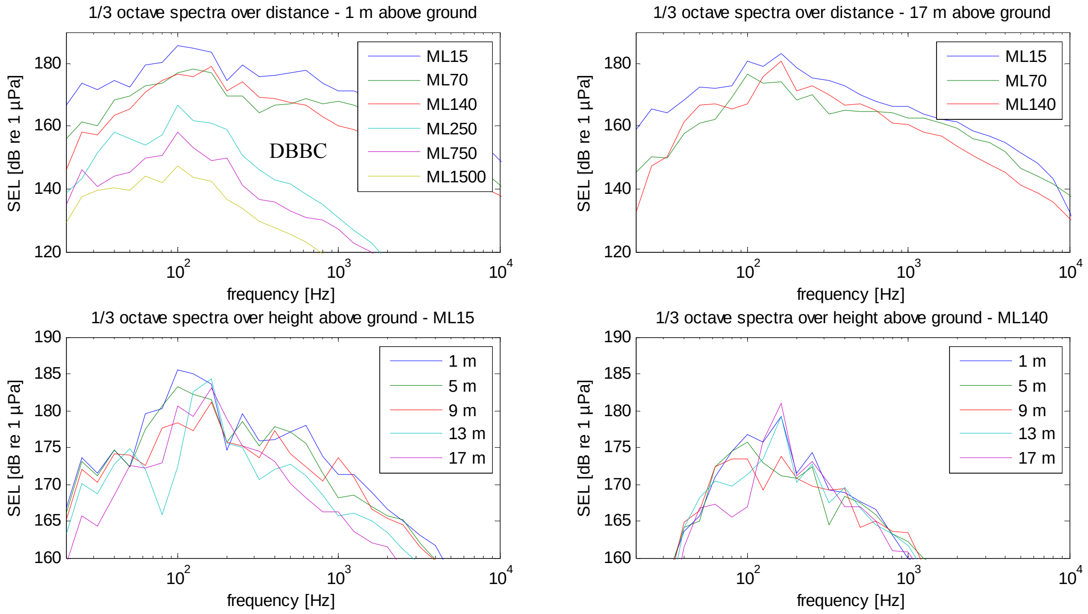

Figure 8 – 1/3 octave analyses for measuring locations in immediate area from pile driving (800 kJ)

As shown in the upper left and upper right part of the figure, noise levels decrease with greater distance from the source across the frequency range of the blows. For the spectra in the top left diagram it has to be mentioned that a DBBC was in action between ML140 and ML250 during the whole installation process. This explains the large gap between the spectra of ML140 and ML250, especially in higher frequency ranges where bubble curtains are most effective. On the lower part of the figure one can see how the sound pressure levels increase closer to the ground. This effect declines further away from the pile (right).

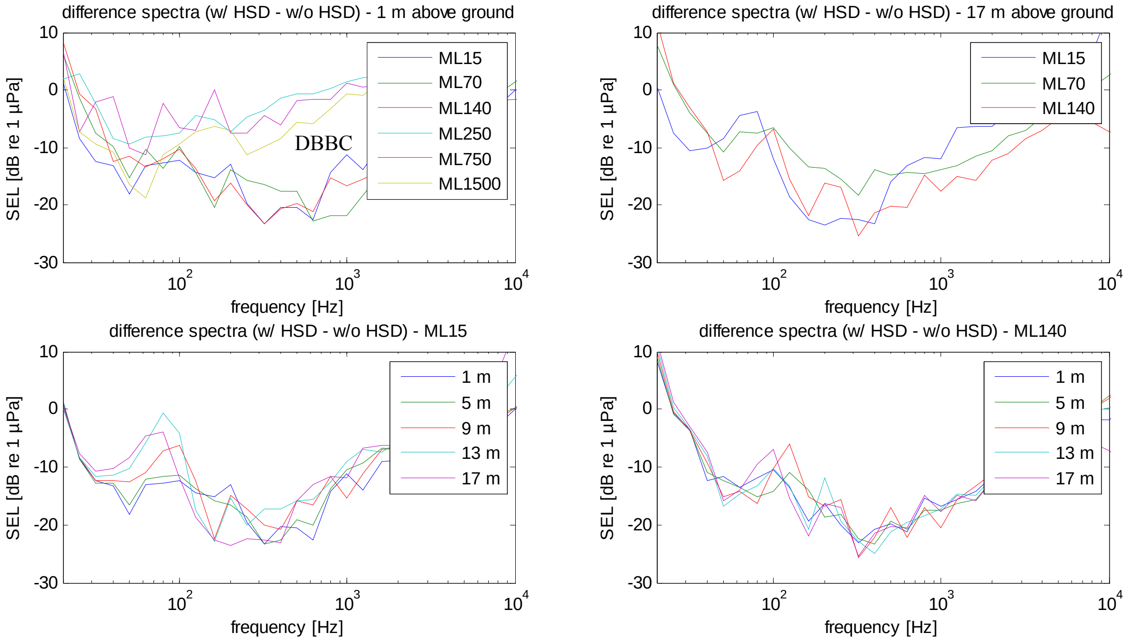

Figure 9 – difference spectra of pile driving without and with HSD (both with 800 kJ)

To evaluate the effectiveness of the HSD system, the spectra of blows at the end of the first part of the pile driving process (without HSD, 800 kJ) are compared to those of the second part (with HSD, 800 kJ) for a number of blows with similar penetration of the pile and comparable impact energy of the hammer. To visualise the damping effect of the HSD system, averaged 1/3 octave analyses for blows without HSD system are subtracted from such with HSD. The resulting difference spectra are shown in Figure 9 for different water depths and distances analogue to Figure 8.

Again, the use of the DBBC between ML140 and ML250 has to be considered for the interpretation of the upper left diagram. The upper diagrams show that no clear link can be recognised between damping of the HSD system and distance to the pile. The upper left diagram shows relatively low damping effects of the HSD system for higher frequencies at measuring locations outside the DBBC. This indicates either a tunnelling of the HSD by seismic waves that induce hydrosound emissions into the water in a greater distance from the pile (between 140 m and 250 m) or the fact that damping levels of combined NMS cannot simply be added up. Difference spectra in different heights show very similar damping of the HSD system in some distance from the source (bottom right). Close to the pile, better damping effects can be identified in greater depth especially for low frequencies (bottom left). This might be caused by the fact that the layout of the HSD net with HSD elements is not uniform over the water depths and the damping effects of HSD elements depends on hydrostatic pressure. Overall there is a very good effect of the HSD of more than 20 dB noise reduction in the range between 100 - 800 Hz.

5. CONCLUSIONS AND OUTLOOK

Within the research project 'triad' the underwater sound and soil vibration propagation induced by pile driving is investigated. To keep the German limiting values for hydro sound emission the construction of the Amrumbank West wind farm in the German North Sea uses two noise mitigation systems (DBBC and HSD) in combination. Performed hydro sound and vibration measurements during the first measuring campaign lay in the immediate area of 140 m from piling inside the DBBC in different height above ground and outside the DBBC to a distance of 1,500 m.

The hydro sound measurements show an increasing sound pressure by increasing water depth. The determined inclination of the wave front of the hydro sound fits very well to other literatures. The vibration measurements with geophones show for one blow a signal with a high frequency part caused by the hydro sound and a lower frequency part from the ground movement. Based on the time delay between these two parts, wave velocities can be estimated which indicate Rayleigh waves at the interface of water and ground. This will be evaluated further by the comparison with soil velocities in horizontal directions and hydrophone data which is directly time-synchronized with the geophones.

The influences of the two NMS are shown in frequency analyses. The HSD reduces the hydro sound in the most important frequency range between 100 – 800 Hz of more than 20 dB and works also in frequencies higher than 1 kHz. It becomes clear, that higher frequencies are stronger reduced than lower frequencies. This effect is on the one side caused by geometrical damping and on the other side because of the NMS.

To confirm the findings presented in this paper, two more measuring campaigns will be carried out in the wind farm at the end of 2014.

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