triad

Evaluation of the combined use of two different noise mitigation systems (HSD and BBC) during the installation of monopile foundations in the OWF Amrumbank West

Investigations on interactions between pile, soil and water

funding code 0325681

Final Report (Summary)

Technische Universität Braunschweig
Institute of Foundatioon Engineering and Soil Mechanics

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Motivation

During the installation of pile foundations for offshore wind turbines (OWT) high sound emissions can occur which are harmful for marine life. However, large diameter open ended steel pipe piles (monopiles) are the foundation method mostly used for OWT [EWEA, 2015]. Impact driving is the common installation method.

Within the research project triad the development of the sound at the driven pile, the sound propagation in sea water and subsoil as well as the effects of two sound mitigation systems (hydro sound damper, HSD and big bubble curtain, BBC) are investigated (Figure 1).

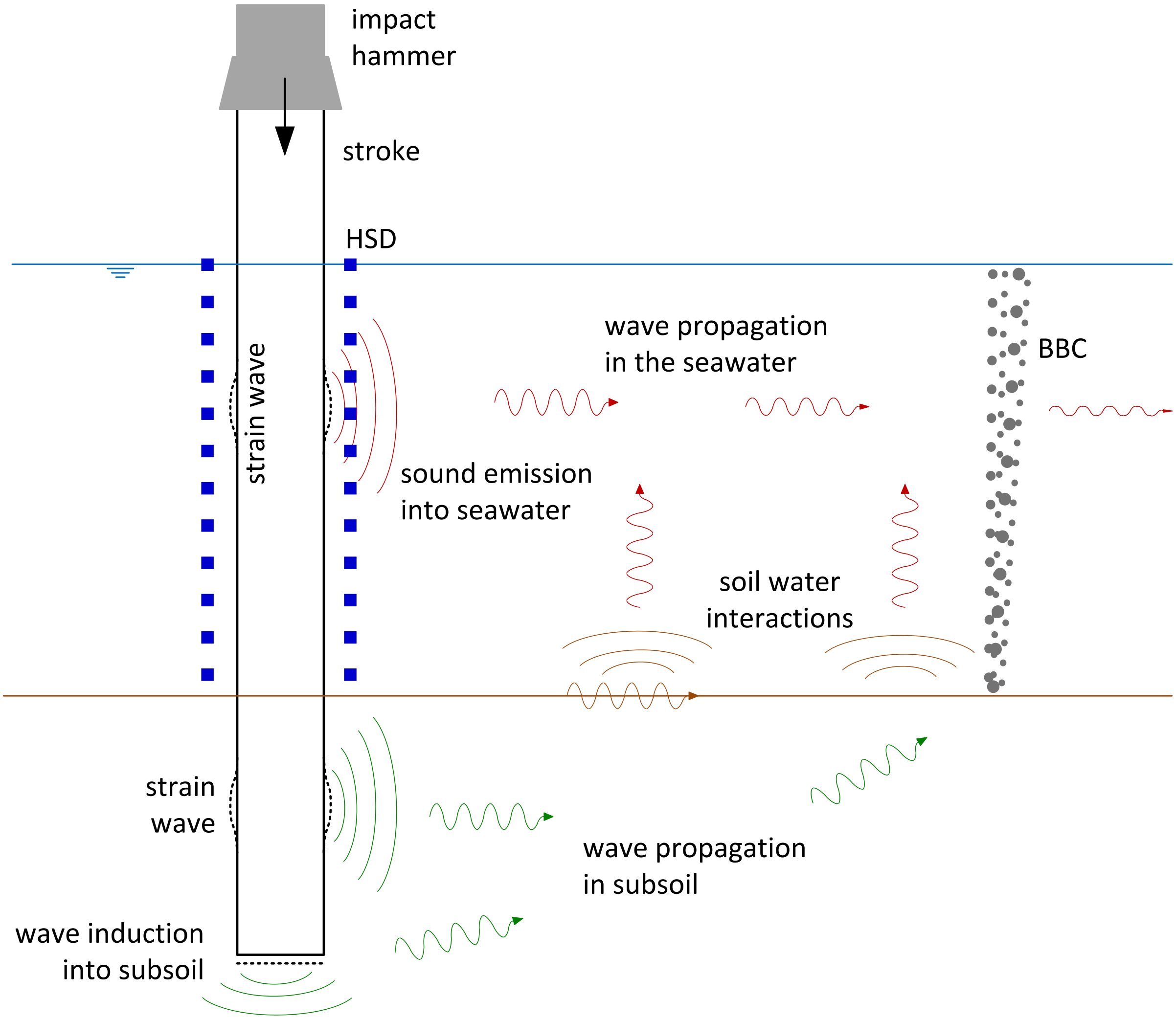

Figure 1: sound propagation in pile, soil and water with noise mitigation systems HSD and BBC [Stein et al., 2015]

OWF *Amrumbank West*

Measurements were carried out in the offshore wind farm (OWF) *Amrumbank West* which is located in the North Sea approximately 37 km west from Amrum and 35 km north from Helgoland in the German exclusive economic zone (EEZ). It consists of 80 OWT with 3,6 MW each. The turbines are founded on monopiles with a diameter of 6 m and about 55 m length in water depths of about 20 m. The soil conditions are homogenous, the subsoil consists mainly of sand. The similar conditions at the different locations in the OWF are welcome regarding the comparability of measurements at different piles.

The piles were installed by means of impact driving. Limiting values of 160 dB re 1 µPa²s for the sound exposure level (SEL) and 190 dB re 1µP for the peak sound level (L_{peak}) apply for such works in the German EEZ [UBA, 2011]. To meet these values, a HSD system (Figure 2, left) and one or more BBC (Figure 2, right) were used.

Figure 2: HSD system retrieved from the pile (left) and BBC fed by vessel (right) at the OWF Amrumbank West

The HSD system is mitigating the hydro sound directly at the source (= monopile) and can be put in place by the main crane of the installation vessel. The BBC is acting in a distance of about 70 m to 170 m from the pile in oval shape around pile and installation vessel. It is deployed and supplied from a separate vessel. Due to logistical reasons, the pile driving had to be carried out in two stages with the HSD system only used in phase 2.

Measuring concept

For the investigation of the wave propagation in pile, soil and water, an extensive measuring concept was developed: Three monopiles were instrumented with strain gauges and accelerometers to measure the strain wave induced by impact driving. During the installation of eight piles, the surface of the subsoil was equipped with geophones measuring the soil vibrations. Single hydrophones and hydrophone arrays were deployed to measure the sound propagation in the seawater in distances from 25 m to 1500 m. Figure 3 and Figure 4 show a sketch of the measuring equipment deployed in the offshore construction site.

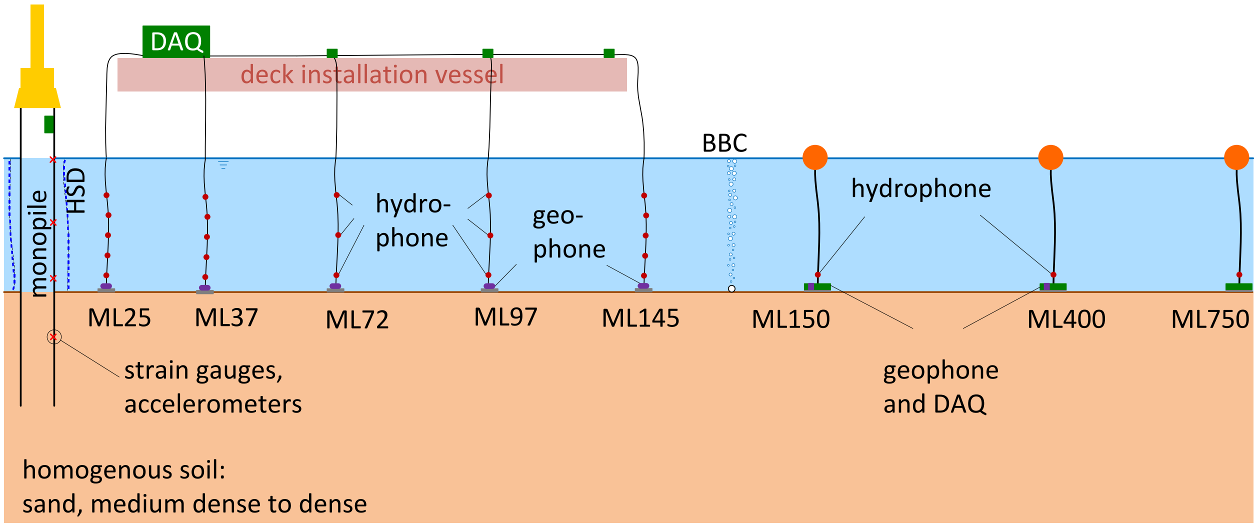

Figure 3: measuring concept (section) [Bruns et al., 2014]

In close range (up to 145 m from the pile) geophones and hydrophones could be deployed from the installation vessel. Arrays consisting of three to five hydrophones plus one triaxial geophone were used at five different measuring locations (ML). In distances of 150 m up to 1500 m autarkic measuring systems were deployed outside the bubble curtain by a separate vessel.

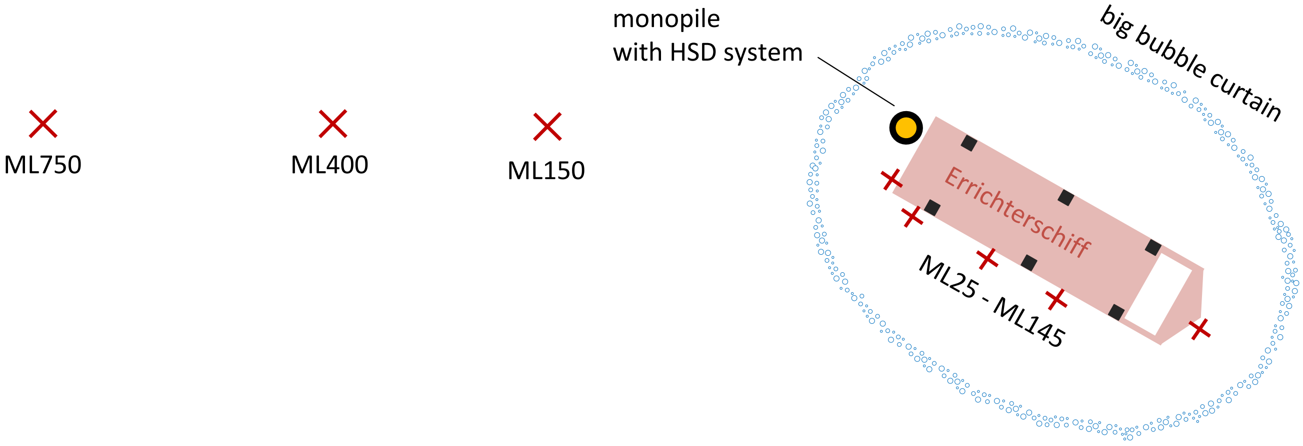

Figure 4: measuring locations in close range and remote range (top view) [Bruns et al., 2014]

The distance of ML to the pile in [m] is indicated by the denotation of the ML. In the close range within in the BBC, the particular hydrophones were located in heights of 1 m, 5 m, 9 m, 13 m and 17 m above ground. In the remote range, all hydrophones were placed 1 m above ground. The hydro sound measurements were carried out following the StUK 4 standard [BSH, 2013].

Pile instrumentation

Three piles (A22, A44, and A66) were equipped with accelerometers and strain gauges in different measuring sections (MS). Accelerations were measured in axial and radial directions while strains were measured in axial and tangential directions. Piles A22 and A66 were equipped in five and four measuring sections respectively with the upper measuring sections equipped in three axes. Pile A44 was equipped in only one measuring axis but with a larger number of measuring sections in closer distances (Figure 5).

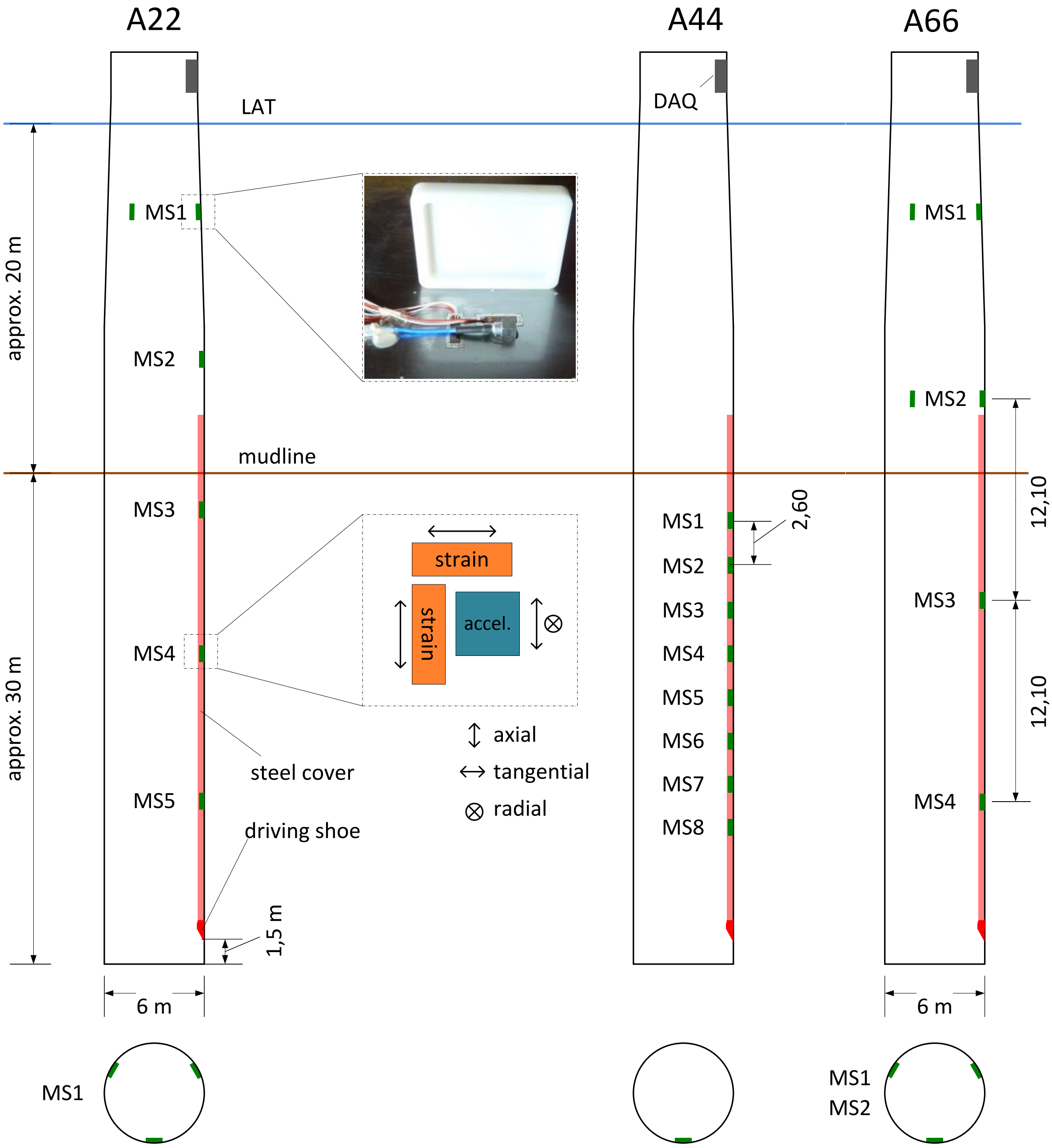

Figure 5: measuring concept of the pile measurements [Sychla et al., 2015]

No drilling and welding works were allowed on the monopiles, so all measuring equipment (including data acquisition, DAQ) was installed using adhesive technology. Strain gauges were applied by means of low energy spot welding (< 30 J). Figure 6 shows details of the encapsulation of sensors (left), protection of cables and sensors below mudline (middle) and a mounting plate for the DAQ unit (right). Details on the gluing technique can be found in Wisner et al. [2015].

Figure 6: adhesive-based pile instrumentation with encapsulation for sensors (left), steel profile covering sensors and cables (middle) and mounting plate for DAQ unit (right)

The instrumentation of the monopiles took place in the monopile storage of the wind farm in the port of Cuxhaven, Germany.

The data acquisition was performed by a customised autarkic measuring unit which was suspended by means of rubber bands to a steel plate glued to the inner surface of the pile right below the flange of the pile head. Figure 7 shows the DAQ box mounted to pile before upending and suspended to the mounting plate waiting for recovery shortly after end of pile driving.

Figure 7: autarkic DAQ unit for pile measurements before (left) and after pile driving (right)

Measuring campaigns

The first monopile was instrumented in April 2014 followed by the first offshore measuring campaign in May 2014. Based on a quick analysis of the measured data, some modifications were planned for the next measuring campaign. Two more monopiles were instrumented in September 2014 and installed in October 2014. Within the last measuring campaign, reference measurements could be carried out. In accordance with the approving authority (Federal Maritime and Hydrographic Agency, BSH) three piles were installed with HSD only, BBC only and without noise mitigation systems, respectively.

Apart from the measurements in the remote area carried out within the research project, hydro sound data from measurements within the construction monitoring carried out by *DEWI* and *itap* in 750 m and 1500 m distance were made available to the project.

Table 1: overview of measuring campaigns

	pile	date	noise mitigation	measuring locations			pile measurements
				close range	remote range	construction monitoring	
measuring campaign 1	A24	04.05.2014	DBBC + BBC + HSD	25..145 m	500 m (G) 800 m (G) 1500 m	756 m 1503 m (DEWI)	--
	A23	06.05.2014	BBC + HSD	25..145 m	250 m (G) 800 m (G) 1500 m	756 m 1503 m (DEWI)	--
	A22	08.05.2014	DBBC + BBC + HSD	25..145 m	250 m (G) 750 m (G) 1500 m	756 m 1503 m (DEWI)	yes
measuring campaign 2 + 3	A44	03.10.2014	BBC + HSD	25..145 m	150 m (G) 300 m	739 m 1662 m (itap)	yes
	A32	12.10.2014	BBC + HSD	25..145 m	Keine	766 m (itap)	--
	A77	15.10.2014	BBC	25..145 m	150 m (G) 400 m (G) 750 m	737 m, 744 m 1489 m, 1505 m (itap)	--
	A66	16.10.2014	none	25..145 m	150 m (G) * 400 m (G) * 750 m *	742 m, 760 m 1502 m, 1524 m (itap)	yes
	A20	17.10.2014	HSD	25..145 m	150 m (G) 400 m (G) 750 m	769 m 1504 m, 1506 m (itap)	--

(G) measuring locations in remote range where geophones were deployed

* at pile A66 clipping occurred on geophones in the remote range
as well as on the hydrophone in750 m distance

Hydro sound measurements

From the measured data of hydro sound pressure, the peak level (L_{peak}) and the sound exposure level (SEL) were determined. The derived values could be related to the pile driving energy or embedment depth of the monopile for each stroke based on the pile driving protocols.

Figure 8 shows the SEL (coloured lines) and the driving energy (black line) at different distances to the pile over the pile driving process for pile A22 (top) and pile A66 (bottom).

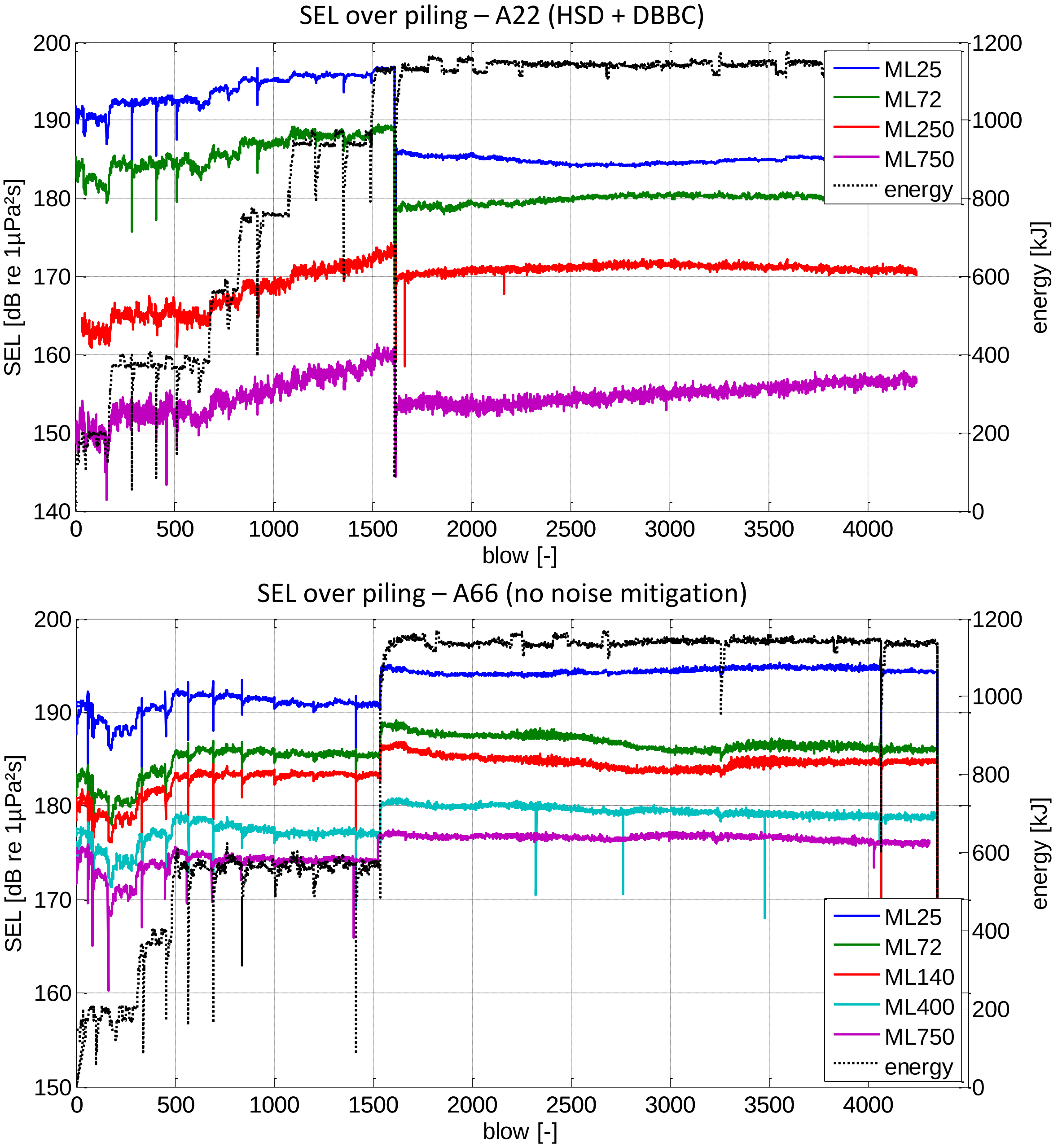

Figure 8: SEL (coloured lines) and driving energy (black line) over piling process for pile A22 with DBBC in phase 1 (top, until blow 1600) and DBBC + HSD in phase 2 (top, after blow 1600) and reference measurement at pile A66 (bottom) [Stein et al., 2015]

From these data of the pile driving process, the dependence of the hydro sound levels on distance, water depth/height over ground, energy level and pile penetration as well as the influence of the noise mitigation systems HSD and BBC can be deduced for each pile. 1/3 octave analyses give information about the frequencies of noise emissions and damping capacities of the mitigation systems in different frequencies.

From the measured sound levels in different distances to the pile at energy levels of 570 kJ and 1140 kJ the spreading loss can be determined to

$$\Delta SEL = k \cdot \log\left(\frac{R_2}{R_1}\right) \qquad [\text{dB re } 1\ \mu\text{Pa}^2\text{s}]$$

with k = 12..14. At different piles with different noise mitigation configurations the damping capacities of the noise mitigation systems could be evaluated. Both noise mitigation systems reached an attenuation of 10 dB to 11 dB (SEL). Combinations of HSD and BBC achieve damping values from 14 dB (single BBC) up to 16 dB (several BBC).

Regarding the sound level over depth it could be shown that in general the sound levels are higher closer to the seabed. Noise mitigation systems and other objects in close range to the pile (within the BBC) had a significant influence on the sound propagation.

Figure 8 also shows a dependence of the noise level on the piling energy, which can be seen at about blow 1550. The measurements carried out at OWP *Amrumbank West* confirm the estimation of an increase of about 2 dB per doubled energy. However, this relation is subject to large fluctuations.

At the beginning of the pile driving process, high SEL values occur despite low energies. Hydro sound and pile measurements together show the strain wave travelling more often down and up the pile causing a longer sound signal. This leads to a higher SEL, which is calculated by integrating the sound energy over time. More details can be found in Stein et al. [2015].

1/3 octave spectra of measurements in different distances with different noise mitigation configurations show the influences of distance and noise mitigation systems on the frequency content of the sound events. 96% of the energy content of a piling stroke lies in the range of 40 Hz to 800 Hz. Below 40 Hz, the sound propagation is inhibited by the lower frequency end of the water column which depends on water depth and sediment.

Both noise mitigation systems show sound damping of up to 15 dB over a wide frequency range. The damping of the HSD system is stronger in frequencies up to 250 Hz while the BBC has even higher damping (> 20 dB) in frequencies above 500 Hz. Measurements in different direction on one pile showed greater variations of the sound levels using a BBC then with HSD or no noise mitigation at all. When both systems are used in combination, the main damping effect in low frequencies is caused by the HSD system which is located directly at the pile while additional damping by the BBC is created in higher frequencies. Figure 9 shows frequency spectra of hydro sound measurements carried out in different distances with different noise mitigation configurations.

Measurements with CTD probes showed constant wave velocities in the seawater over the water depth at all measuring campaigns.

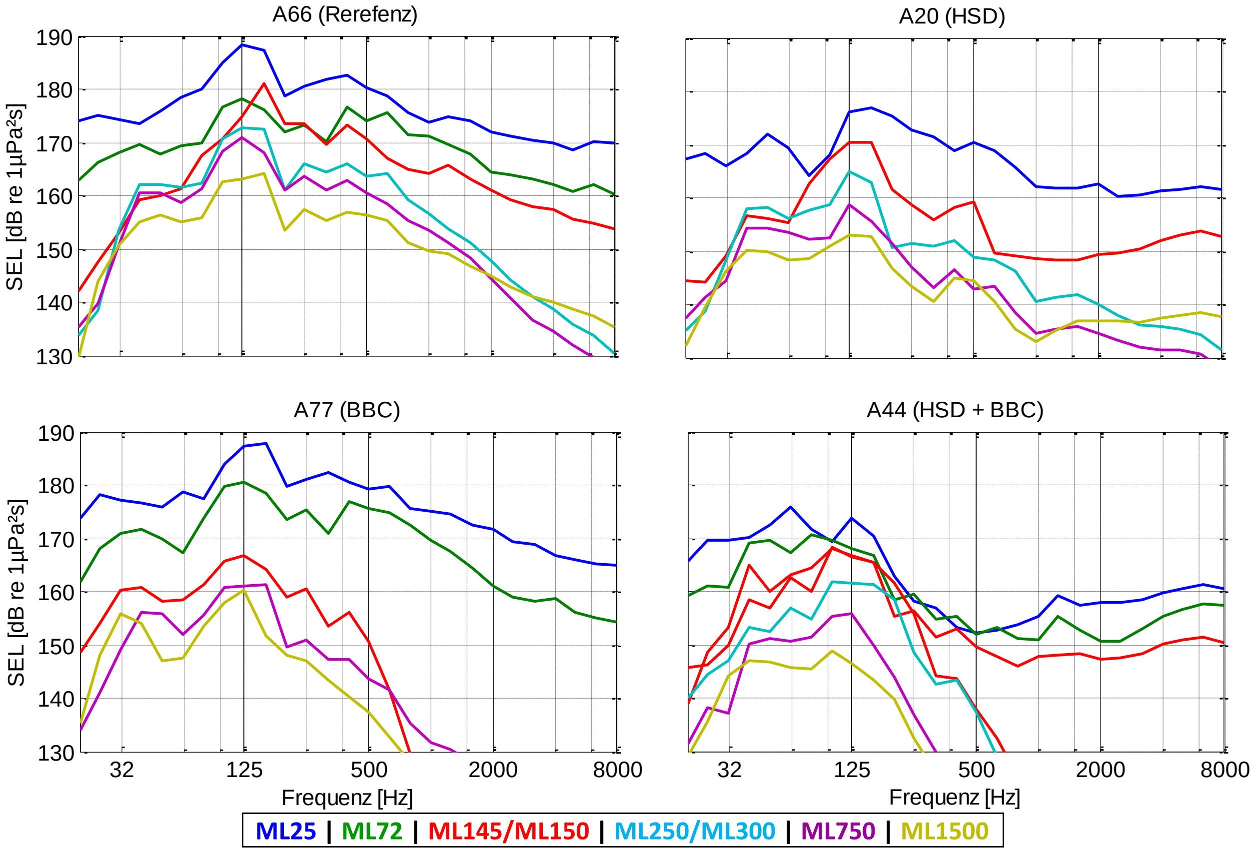

Figure 9: 1/3 octave spectra of piling events in different distances with different noise mitigation configurations

Seismic measurements

Due to the geometry of the geophones, not only soil vibrations but also sound waves acting on the sensor housing were measured. Figure 10 shows a high-frequency hydro sound signal (blue circle) before the main event of low-frequency soil movements. To exclude the hydro sound from the measurement, the signals were low pass filtered (green).

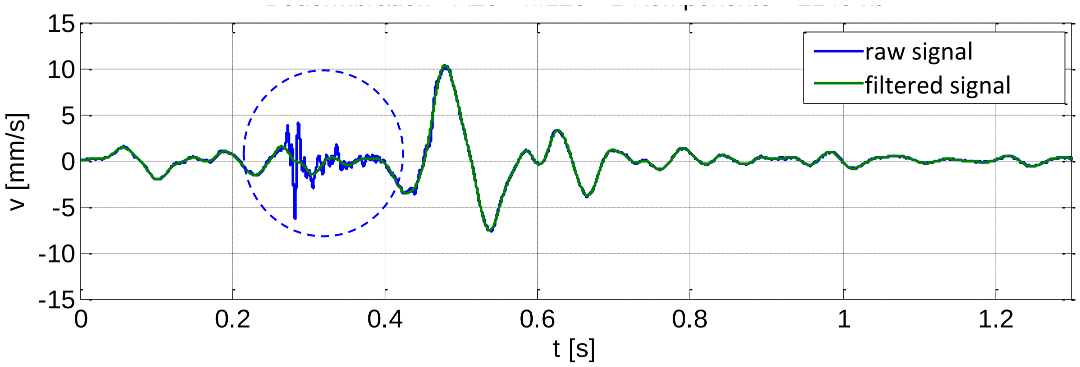

Figure 10: raw signal (blue) and filtered signal (green) of soil vibrations in horizontal direction at ML25 during the installation of Pile A23 at 1140 kJ piling energy

The maximum soil vibration velocities at each blow show a general decrease over distance and change with advancing pile penetration. The characteristics of this behaviour are different for horizontal and vertical soil movements. The superposition of different wave types (compression waves, shear waves, Scholte waves) as well as the change of the geometry of the system (due to progressing penetration) during pile driving can be an explanation for these phenomena. The dependence on the piling energy is limited, as shown in Figure 11.

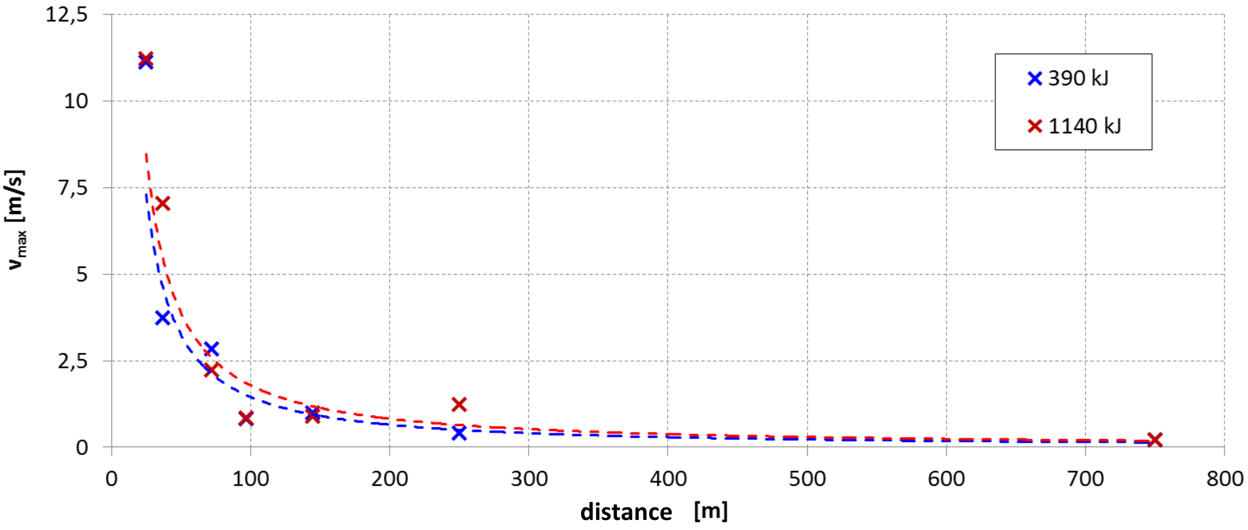

Figure 11: maximum vertical soil vibrations over distance for different energy levels

Looking at the unfiltered signals in different distances to the pile, the time gap between high-frequency hydro sound and low-frequency soil vibration signals becomes larger. This leads to the conclusion that the seismic wave measured on the soil surface is slower than the hydro sound.

Pile Measurements

By integration of the force (calculated from measured strain and axial stiffness) and velocity (integrated from measured accelerations) the energy in the pile can be determined. The measured energy in the pile was about 20% lower than the hammer energy towards the end of pile driving, which means lower damage to the pile and better conditions for fatigue calculations. From measurements at pile A44 (with 8 measuring sections in different heights) the decrease of maximum velocities in the driven pile over the penetration depth could be visualised.

Looking in detail at strains and accelerations of a single blow, the upwards and downwards travelling waves as well as the relations between axial and radial deflections can be seen. A compression of the pile in axial direction causes an elongation in tangential direction and vice versa (Figure 12, top). The axial movement in downward direction, however, is accompanied by an inward and following outward movement in radial direction (Figure 12, bottom).

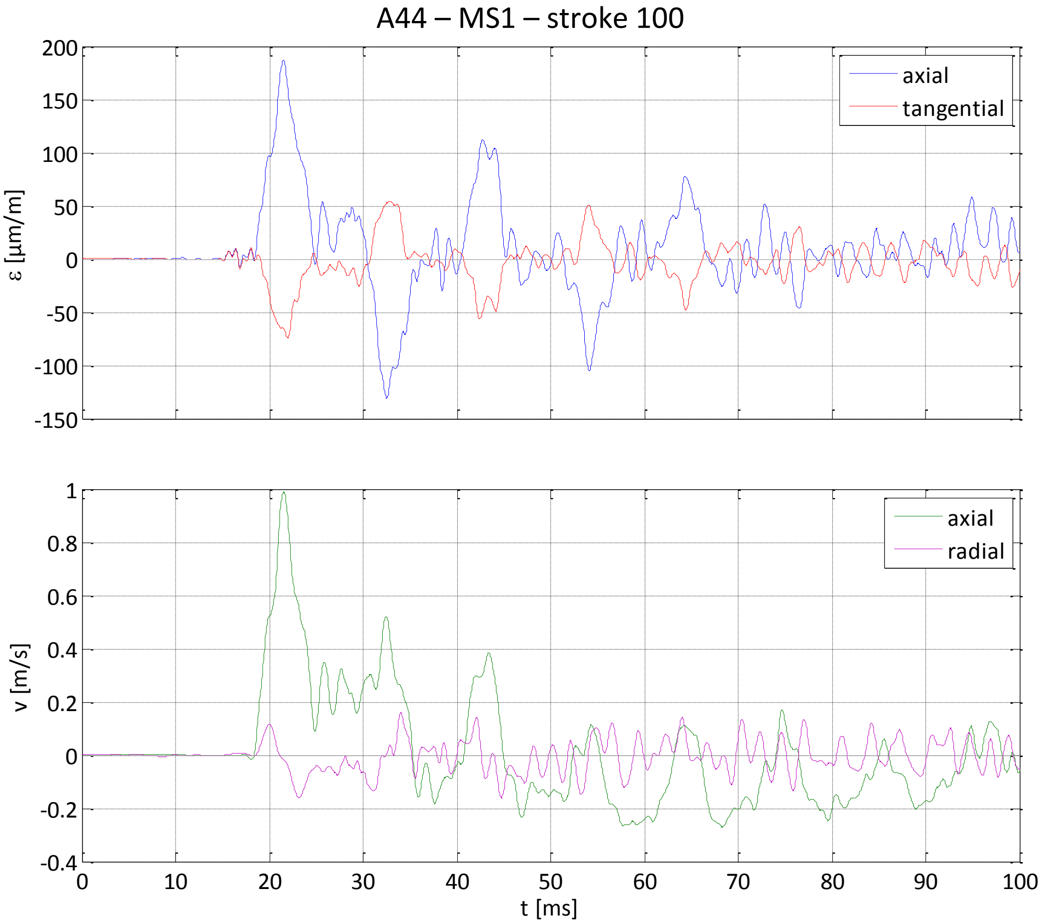

Figure 12: strains (top) and velocities (bottom) of a piling stroke at low penetration

Apart from the dynamic behaviour of the pile, the elastic damping capacities of the adhesive joint could be checked. Figure 13 shows the damping of a glued component by a factor > 2.

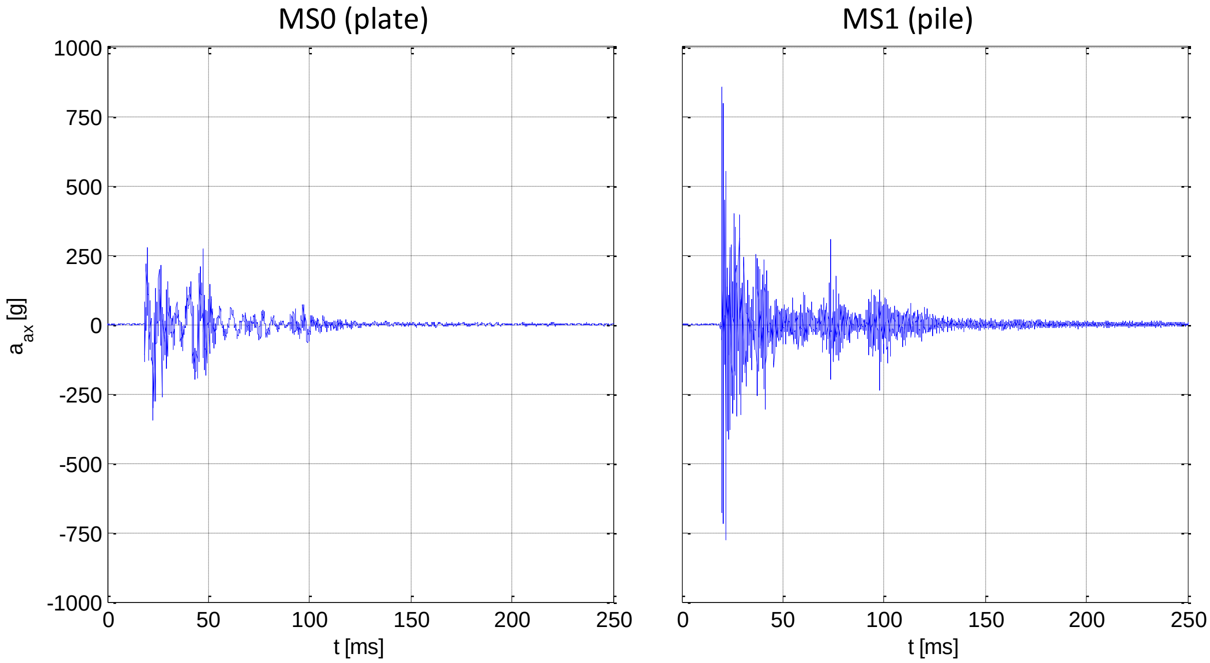

Figure 13: axial accelerations of the glued mounting plate (left) and the pile (right)

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