The new noise mitigation system ‘Hydro Sound Dampers’: history of development with several hydro sound and vibration measurements

Benedikt BRUNS[1]; Christian KUHN[2]; Philipp STEIN[3]; Dr. Jörg GATTERMANN[4];

Dr. Karl-Heinz ELMER[5]

[1,2,3,4] Technische Universität Braunschweig, Institute for Soil Mechanics and Foundation Engineering, Germany

[5] OffNoise-Solutions GmbH, Germany

ABSTRACT

For some years, a noise prevention concept for the protection of marine animals exists in Germany. Based on that, the underwater sound exposure level (SEL) due to pile driving at offshore wind farms (OWF) is required to be less than 160 dB re 1 µPa²s at a distance of 750 m. This value, however, is often exceeded so that the use of a soundproofing system is necessary. The Hydro Sound Damper (HSD) is a new, versatile method to reduce noise levels during offshore pile driving. To achieve this, elements of different sizes and materials which are fixed to fishing nets are used. The principle of operation and the effectiveness of these HSD elements were investigated in the laboratory and in situ under offshore conditions during different pile installations. During these offshore applications thorough measurements were performed which metered the propagation of the hydro sound and the vibrations of the sea floor at various distances and directions from the source. The evaluation of these data led to very promising results concerning underwater noise reduction. This article describes the theory and implementation of the HSD and focuses on the interpretation of the data from the hydro sound and vibration measurements.

Keywords: underwater acoustics, offshore pile driving, soil dynamics, wind turbines and wind farms, construction noise

I-INCE Classification of Subjects Number(s): 08.4, 12.2.3, 21.2.2, 23.1, 35.7, 41.3, 43.2.3, 43.2.4, 54.3, 65.2, 721.1, 82

1. MOTIVATION

Pile driving using hydraulic impact hammers during the installation of the foundations for offshore wind turbines (OWT) causes considerable underwater noise which spreads radially into the surrounding water. These high acoustic levels pose a threat to marine animals such as harbor porpoises, seals or gray seals. Because of this, German authorities have implemented a limiting value of 160 dB re 1 µPa²s (SEL) for the underwater sound level at a distance of 750 m to the pile driving location. This causes additional efforts for the installation of the OWF which are currently being built.

Due to an increasing economical pressure the size of the hydraulic hammers is increasing in order to shorten the time required for pile driving and also pile diameters are increased to install bigger plants at locations with higher water depth. Both lead to higher noise emissions during the pile driving process. Without any noise mitigation system (NMS) acoustic levels of up to 180 dB (SEL) are quite common so that the challenge is to reduce noise levels by up to 20 dB (SEL). Therefore, to avoid the risk of suspensions of the erection of OWF, efficient NMS are required. In the offshore sector this is the only solution to reach the goal to expand renewable energies in accordance with the protection of endangered species.

[1] b.bruns@tu-braunschweig.de
[2] c.kuhn@tu-braunschweig.de
[3] p.stein@tu-braunschweig.de
[4] j.gattermann@tu-braunschweig.de
[5] kh.elmer@offnoise-solutions.com

2. RESEARCH PROJECT 'Hydro Sound Damper'

The Institute for Soil Mechanic and Foundation Engineering at the Technische Universität Braunschweig (IGB-TUBS) developed a new noise mitigation system within a research project covering the investigation and testing of Hydro Sound Dampers for the mitigation of underwater noise during pile driving for foundations of OWF (FKZ 0325365) which is funded by the Federal Ministry for Economic Affairs and Energy (BMWi). For the development of HSD, a patent has been granted to K.-H. Elmer in 2010. It is a very promising and economical method to reduce the underwater noise and is based on the theories of dispersion, dissipation, and resonance effects. The principle of operation and the theoretical background of the HSD are explained in detail in previous publications (1) and (2).

2.1 The idea of noise mitigation with HSD

Piling, especially using hydraulic hammers, creates high frequency noise with considerable underwater sound levels (1). Depending on the type of offshore foundations, hydraulic hammers are used to drive piles and monopiles of up to 600 tons between 30 m and 40 m into the seabed. In Figure 1 (left), spectral information of pile strokes are given by third octave spectra of the SEL for two different hydraulic hammers from manufactures MENCK and IHC Merwede.

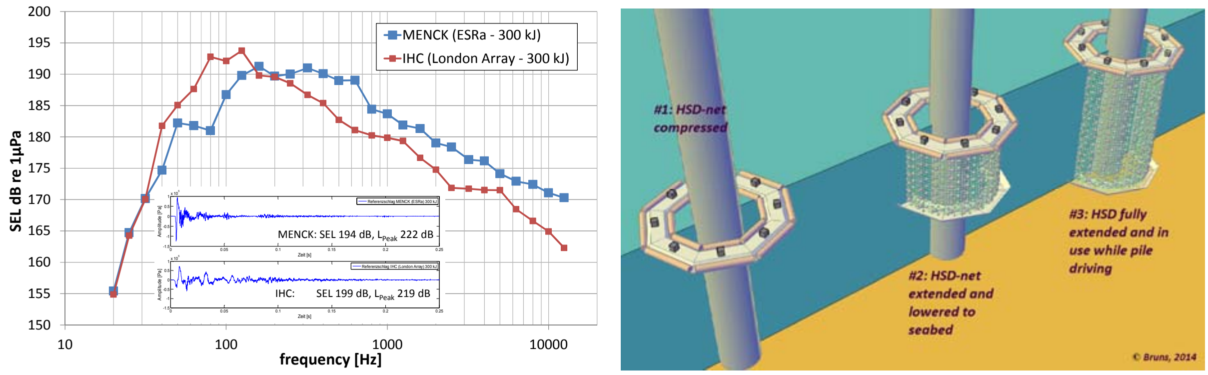


Figure 1 – ram noise spectra of hydraulic hammer (MENCK and IHC) with 300 kJ in the near field (left), HSD application in combination with a monopile (right) ©

The highest spectral levels of the measured underwater piling noise for different hammers can be detected in the frequency range between 80 Hz and 400 Hz. These spectral levels are responsible for the high noise levels of offshore piling. Therefore, these frequencies have to be reduced using effective NMS to meet the requirements established by German authorities.

The noise mitigation method of HSD is very simple and uses only small gas filled bladders and robust polyethylene (PE) foam elements of different sizes and geometries, fixed to a pile-surrounding fishing net (Figure 1, right). The figure shows the application concept with a compressed system for transport on deck (#1) which extends for use (#2) by pulling the net with a heavy weight to seabed (#3). In this stage the net is fully extended and ready for noise reduction. All HSD elements are tuned to resonant frequencies in order to get most effective noise reductions. Several laboratory tests were done to get information about the mechanical and acoustical behaviour of single elements and combinations of different elements. Steel is only used as heavy weights at the seabed to compensate the buoyancy behaviour of the HSD elements.

3. OFFSHORE APPLICATIONS AND LABORATORY TESTS

Within the development and optimization process of HSD several offshore and laboratory tests were done to proof suitability for offshore applications and to investigate noise reduction behaviour.

3.1 1st offshore application (ESRa-Test, 2011)

For a first offshore test within the ESRa project ("Evaluation von Systemen zur Rammschallminderung an einem Offshoretestpfahl, FKZ 0325307) in 2011 a self-swimming construction with hand operated winches to lower 3 different types of HSD nets to the seabed was designed as a prototype of the HSD system. The total weight of the system was about 10 t (Figure 2). The testing location was the Brodtener pile in the Baltic Sea. The pile has a diameter of about 2.35 m with a length of 79 m (embedded 65 m). The water depth is about 8.5 m

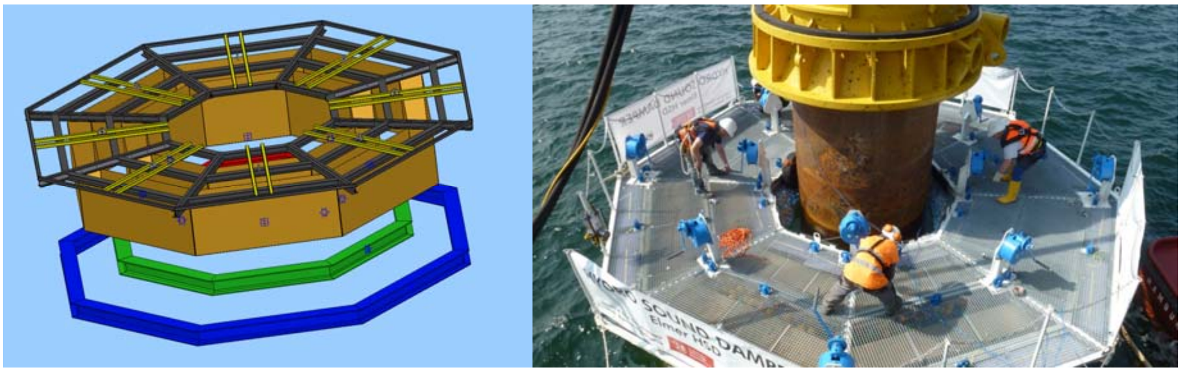
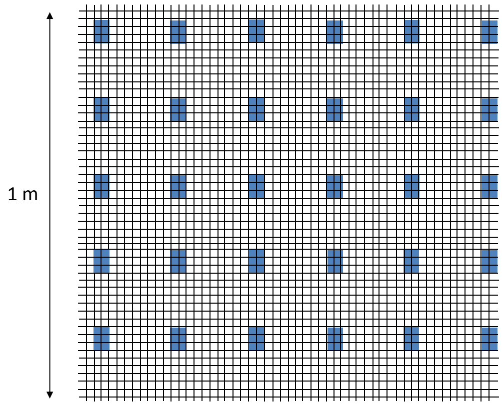


Figure 2 – technical drawing of HSD-system with three single nets (left), HSD-system in action (right) (3)

Gas filled, thin-walled balloons were used together with robust PE foam elements of high material damping as HSD elements. Nearly 100,000 elements were attached to three nets. All elements were tuned to a resonant frequency of 120 Hz to get reduced noise transmissions within the most important frequency range. One square meter of the designed net layout with blue coloured HSD elements is shown in Figure 3 (left). It becomes clear that only every 0.2 m is one HSD element and the water can flow through the rest of the net.



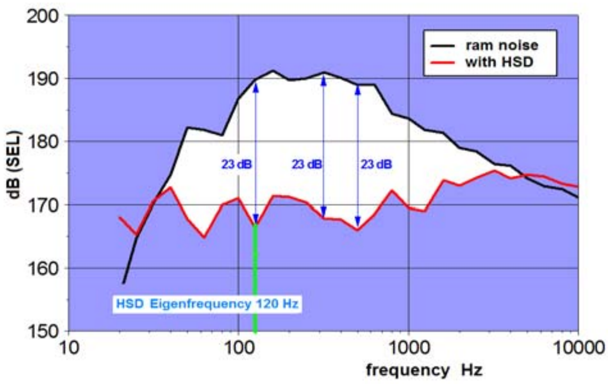


Figure 3 – HSD net layout at ESRa (left), noise reduction of the HSD net (right)

The radiated underwater sound pressure was measured 4 m above the ground at a distance of about 6 m from the pile to acquire the sound directly radiated from the source and to avoid influences of reflections from the water surface and the seabed. Figure 3 (right) shows the third octave spectrum of the SEL of the original piling noise of 300 kJ energy and the reduced SEL after applying HSD system with both, gas filled balloons and PE foam elements. For this result the energy of the hammer was 300 kJ. The effect of noise reduction is greatest near the resonant frequency of the HSD elements of 120 Hz and there is a very broad noise reduction up to 23 dB (SEL) within the most important frequency range between 100 Hz and about 600 Hz. For this test elements of one size and geometry were tested to investigate the impact of only one type.

In addition to the measurements in the water column (1.8 m above seabed) the itap GmbH, Germany carried out geophone measurements on the seabed to determine the vibrations of the ground during pile driving. Some results are shown in Figure 4. The signals of plot a) and b) are synchronized and the same blow, c) and d) results from two different blows.

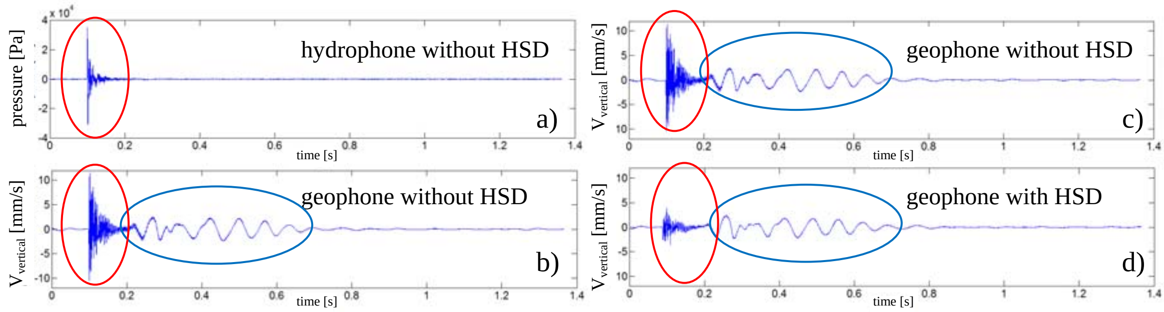


Figure 4 – different results of hydrophone and geophone measurements at 13 m distance to the pile

The signal measured in the water column 1.8 m above the seabed is shown in Figure 4, a, the associated vibration of the ground in Figure 4, b. In all plots you can see the impact of the blow. The impact in the water takes a time of about 0.1 s (a) and has a high frequency. The length of the vibration of the seabed is about 0.6 s (b – d). In these measurements a high frequency signal can be seen (red circle) followed by a low frequency signal (blue circle, only geophone). Comparing the plots c without HSD and d with HSD the high frequency signal is reduced while the low frequency signal is nearly identical, not influenced by the HSD. It is clear that the high frequency signal is a result of the sound wave propagating through the water which also erecting the geophone on the seabed and the low frequency signal shows a seismic wave propagating from the pile shaft and toe through the soil with some delay. The analysed vertical vibration velocity of the seabed for this case is about 3 mm/s at a distance of 13 m.

3.2 Laboratory tests and numerical simulations within the research project

After the results of the ESRa test the research project was given to the IGB TUBS. The main scope of it was the study of the HSD elements, the proof of applicability under offshore conditions and the development to bring the HSD to a serial application.

Figure 5 – different Lab test at IGB TUBS

For the first stage several materials were investigated in the laboratory in order to get information about the damping capacity, durability, stability under hydrostatic pressure and the volume behaviour. Therefore different laboratory experiments were designed: a pressure tank, a concrete basin, a wave flume with a length of 20 m and a steel pipe as shown in Figure 5. In these lab tests investigations on single elements, combinations of different elements and HSD nets were done. For example some results recorded in the concrete basin are shown in Figure 6.

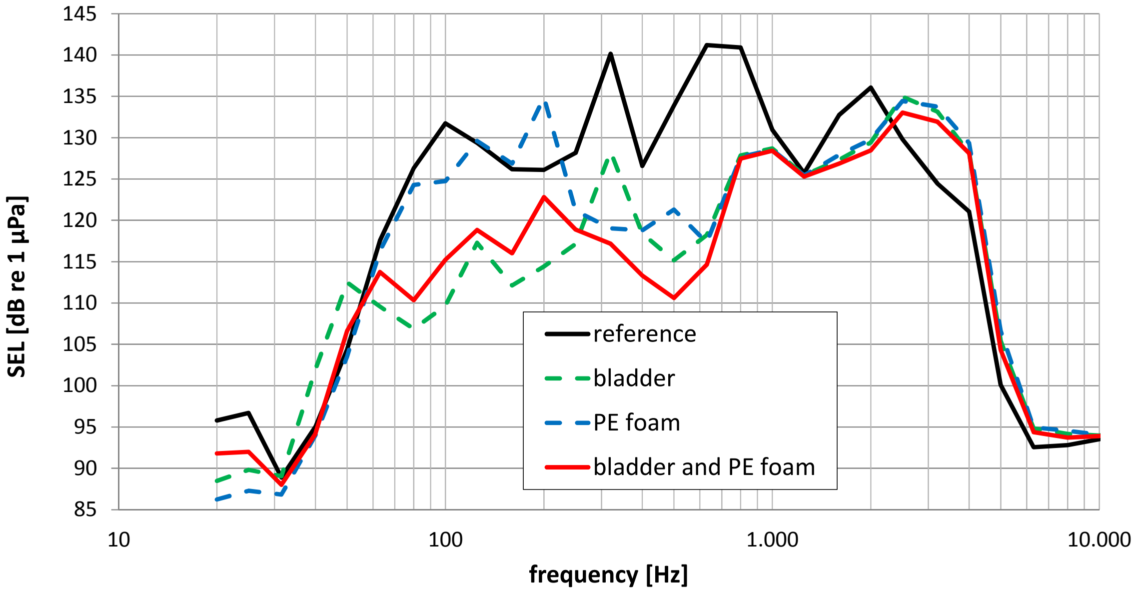


Figure 6 – results of measurements in the concrete basin

Two speakers generate a sweep of a frequency range from 10 Hz to 4,000 Hz as the source. Visualized are noise spectra of the reference sweep without any elements, single elements (bladder, PE foam) signed by the dashed lines (green, blue) and the combination of these elements (red line). The difference between the black line and the others shows the damping capacity of the material. The bladder reduces the noise in a large range between 50 Hz to 1,000 Hz while the PE foam operates mostly between 250 Hz to 1,000 Hz. Both show a maximum reduction of up to 15 dB in some frequencies. The result of the combination of these elements displays the increased noise reduction in the range between 250 Hz to 800 Hz up to 25 dB.

These and other measurements show similar effects. Summarizing the main results are as follows:

- single elements act in a larger frequency range than their resonant frequency
- stiffness, size and geometry of the material has an influence on the resonant frequency
- combination of different element types operating in a large frequency range
- no negative impact on noise reduction if the elements get in contact
- increasing noise reduction by increasing density of elements

Results of the numerical simulations are published in (7).

3.3 2nd offshoretest at wind farm London Array (2012)

In summer 2012 a 2nd in situ test at the world largest offshore wind farm 'London Array' (LA) in the North Sea was performed in cooperation with the Aarsleff Bilfinger Berger Joint Venture (ABJV). The main scopes of the test were to proof the applicability of the HSD under offshore conditions and to reach a significant noise reduction in the important frequency range between 100 Hz and 1,000 Hz. The developed HSD-system for the test met the specific site conditions. It was designed for monopiles with a maximum diameter of 5.7 m and water depths of up to 28. The HSD consists of three main parts; the buoyancy ring at the water surface, the HSD-net with the damping HSD-elements, and the ballast box, which expands the net down to the seabed. Figure 7 shows its application on site on the left and a schematic drawing of the HSD on the right.

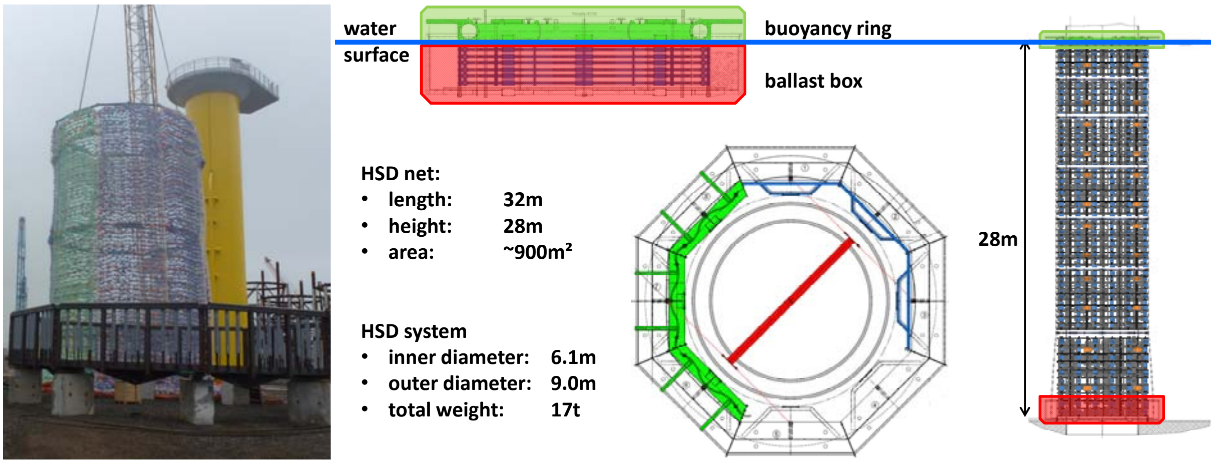


Figure 7 – designed HSD for offshore test at LA

The testing procedure was as follows. First, the pile F05 was driven without any noise mitigation system until the self-stand-criteria (penetration depth of about 20 m) was reached. Now, the HSD was installed without any complications. The pile driving process was continued until the hammer was close above the water surface. At this point, the buoyancy ring was filled with water and lowered to the sea floor as the pile had to be driven until below the water surface and a contact between the hammer and the HSD had to be prevented. Also this additional requirement was fulfilled. The handling of the HSD within this test worked very well.

To determine the efficiency of the HSD a measurement concept to meter the hydro sound propagation in the far field was planned and implemented in cooperation with the itap GmbH, Germany. For this, two hydrophones in different water depth were installed at seven different measurement positions (MP). These were located in three directions (with the current, perpendicular to it and against the current) and at distances of 240 m, 750 m and 1500 m. For additional vibration measurements in the far field measurement systems of the Christian-Albrechts-University (CAU) Kiel were used. During the test, three monopiles were installed of which the second pile (F05) was driven while using the HSD. Pile one (G10) and pile three (F04) were driven as reference piles without the use of the HSD. In addition to the hydro sound measurements in the far field by the itap GmbH further hydro sound and vibration measurements from deck of the installation vessel were conducted by the IGB TUBS. An overview of the measurements in the near and far field is shown in Figure 8.

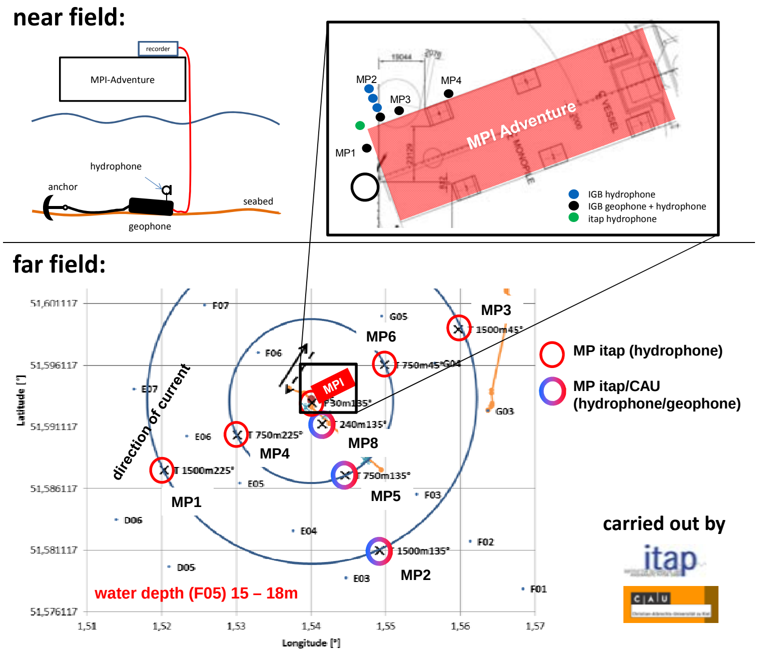


Figure 8 – performed measurement in the near and far field

The net layout of LA in Figure 9 (middle) shows the same compilation of HSD elements as used at ESRa (Figure 3). In addition to that, smaller and larger elements are applied to get a better noise reduction in the frequency range lower than 100 Hz and higher than 1000 Hz. The underwater sound mitigation was measured at 1 m above the seabed in a distance of 15 m. Figure 9 (right) shows the third octave spectrum of the SEL from the original piling noise and the reduced sound level with HSD in use. Both spectra are from different but comparable piles. The additionally applied HSD elements cause improved reductions between 20 and 100 Hz and above 1000 Hz in comparison to ESRa. Once again, a very broad noise reduction of up to 25 dB (SEL) shows the effect of the HSD.

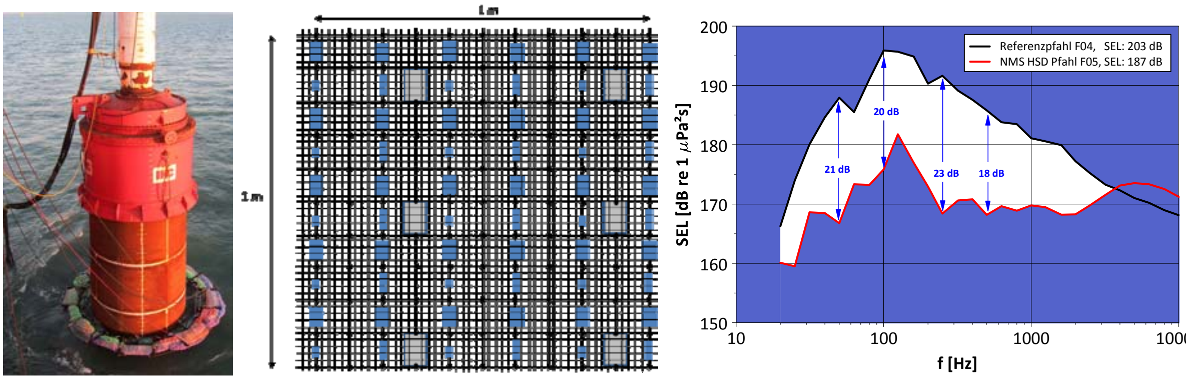


Figure 9 – HSD in use at LA (left), HSD-Net layout (middle), noise reduction of HSD-net at MP1 in the near field (right)

In the following, the results of the itap GmbH measurements in the far field are presented. Figure 10 (left) shows the difference spectra of the 1/3-octave analyses with respect to distance and direction for the piles F05 (with HSD) and F04 (without HSD) (4). Both diagrams show very good damping of up to 20 dB in the relevant frequency range between 80 Hz and 2000 Hz which mainly influences the acoustic level. Moreover, an influence of the sea current on the acoustic damping efficiency cannot be seen. The curves of the results are almost identical for all three directions. The results lead to an overall noise reduction of 9 dB (SEL) and 10 dB (L_{Peak}) in terms of single values. Further, in the diagram showing the difference spectra with respect to distance, it can be seen that at around 200 Hz (marked by the red circle) a difference in the levels of up to 8 dB exists. Evaluating the single SEL this leads to an overall noise reduction of 13 dB (SEL) at this measuring position. This difference might be caused by the sedimentary layering at the location of pile F05.

Figure 10 (right) shows the SEL trend in dependence to the distance over the piling process. In this plot the effect of HSD within the test comes clear. In the first stage (until blow 500) piling was performed without HSD. The Peak and SEL values increase because of the increasing energy of the hammer. In stage two the HSD was installed and all values drop to lower levels. In stage 3 the buoyancy ring sank down and the HSD was off use. The levels are increasing again. As expected, highest levels are measured at the closest MP (MP1) in phase 1 and 3. However this is changed in phase 2 while HSD is in action. This effect has to be caused by the influence of the ground.

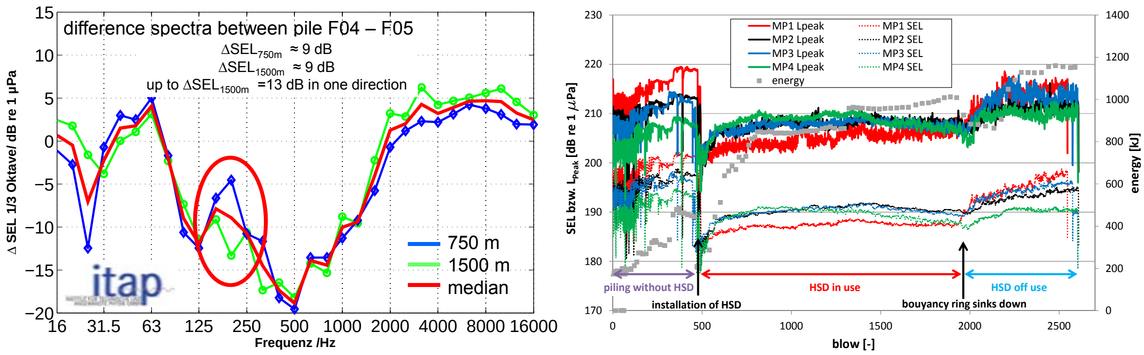


Figure 10 – Difference spectra of 1/3-octave spectra with respect to distance between piles F04 (without) and F05 (with HSD) (5) in the far field (left), result plot of SEL while using HSD at pile F05 in near field (right)

Figure 11 shows the results measured by the itap, Germany (5) and IGB TUBS. Beside the SEL trend in respect to distance with and without HSD (black lines) the deviation (red line) between the two lines is illustrated. The SEL is decreasing exponentially. Remarkable in both measurements is the decrease of the deviation from about 16 dB (SEL) close to the pile to a constant value of 8 – 9 dB (SEL) at a distance of 45 m. This effect can also be explained by the influence of the soil. The frequency-dependent damping is visualized in Figure 11 by 1/3-octave spectra (right). Because of geometrical damping there is a bigger reduction in higher (> 500 Hz) than in lower frequencies.

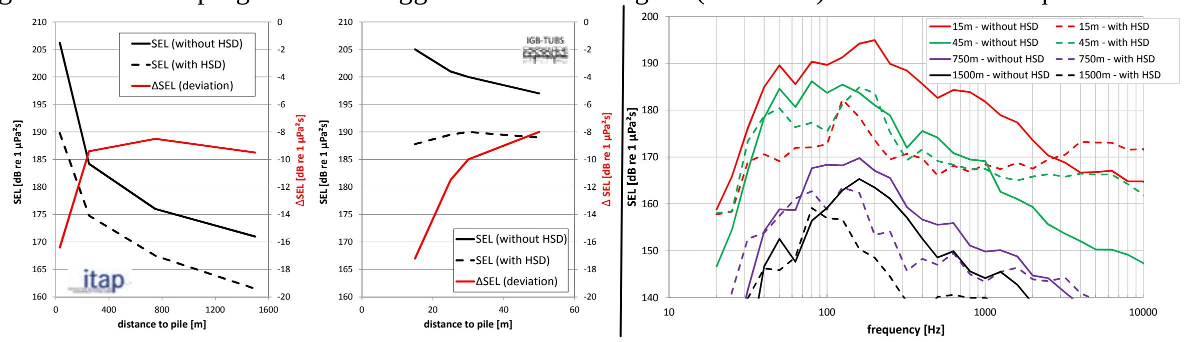


Figure 11 – SEL trend with respect to distance (left) (6), 1/3-octave spectra with respect to distance at pile F05 (right)

Examples of measurements of an hydrophone an several geophones show two blows of piling in Figure 12 (left). Similar to the results from Figure 4 all signals of one blow can be divided in two parts. The first part contains high frequencies (red cycles), the second lower frequencies (blue cycles). Here as well the influence of the hydro sound to the measurements of the geophones comes clear. You also acknowledge an increasing time delay between part one and two by increasing the distance to the pile. This might cause by different wave speeds of the water and the soil.

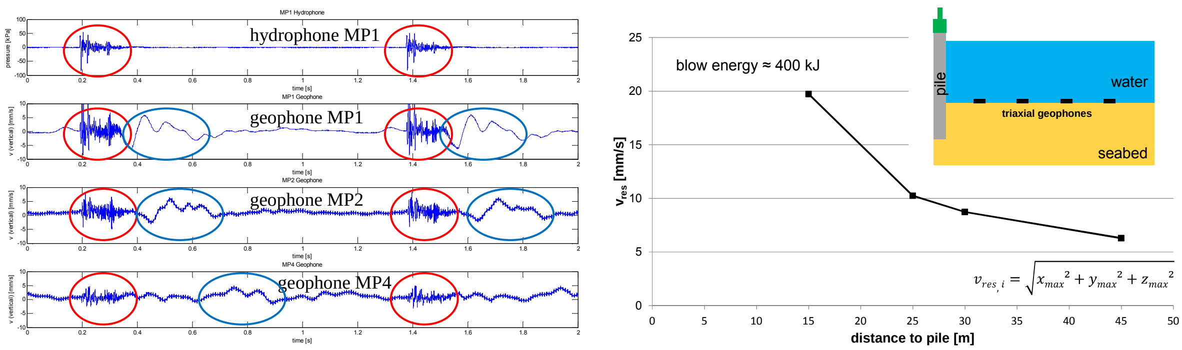


Figure 12 – time domain results from the vibration measurements on the seabed (left), seabed vibration induced by piling with respect to distance (right)

The vibrations were measured independently in three directions and the maximum amplitude of the resulting vector of the vibration velocities with respect to distance to the pile at a driving energy of 400 kJ is shown in Figure 12 (right). The maximum vibration velocity decreases from 20 mm/s at a distance of 15 m to 7 mm/s at 45 m. This is quite strong compared to ESRa-Test (Figure 4).

4. CONCLUSIONS

The successful implementation of an HSD system during two offshore applications was described. Besides demonstrating the applicability of the HSD under offshore conditions, acoustic reductions of the single event levels of 9 dB (SEL) on average and maximal 13 dB (SEL) as well as up to 15 dB (L_{Peak}) were determined. In the frequency range between 100 Hz and 2000 Hz, which mainly influences the SEL, reductions of up to 19 dB were reached. Further, the evaluations did not indicate an influence of the direction of the sea current on the HSD's acoustic damping efficiency. Moreover, vibration measurements were evaluated which still showed vibration velocities of 7 mm/s at a distance of 45 m to the pile.

Since the offshore tests at ESRa and LA the HSD system was further optimized. Besides using additional damping elements to attain a better noise reduction in the frequency range below 100 Hz and above 1000 Hz, concepts were developed which allow a serial implementation of the HSD from the first until the last blow of the pile driving process. Currently an optimized HSD-system is in commercial use at the wind farm “Amrumbank West” in the North Sea (8). The first results are even better than those from ESRa and LA.

Once the noise spectra of different hydraulic or vibratory hammers are identified it is possible to tune the HSD net to the required frequency range with a correspondent number, stiffness and geometry of HSD elements so that you get noise reductions as desired.

ACKNOWLEDGEMENTS

The measurement data presented in this paper have been (excepted the ESRa-Test) acquired within the research project 'Untersuchung und Erprobung von Hydroschalldämpfern (HSD) zur Minderung von Unterwasserschall bei Rammarbeiten für Gründungen von Offshore-Windenergieanlagen' ('HSD', FKZ 0325365) which is funded by the German Federal Ministry of Economic Affairs and Energy on the basis of a decision by the German Bundestag. The project is carried out by the Institute for Soil Mechanics and Foundation Engineering of Technische Universität Braunschweig together with ABJV. Our thanks also go to the crews of the measurement vessel 'Reykjanes' and the installation vessel 'MPI Adventure' Last but not least, we would like to express our appreciation to the team of Projektträger Jülich for the good cooperation in all administrative matters concerning the research project.

Supported by:
Federal Ministry for Economic Affairs and Energy
on the basis of a decision by the German Bundestag

REFERENCES

1. Elmer K-H. New hydro sound dampers to reduce underwater pile driving noise emissions, Internat. Conf. DEWEK2010, Bremen, 17-18 Nov. 2010.
2. Elmer K-H. Pile driving noise reduction using new hydro sound dampers, BSH-workshop on pile driving, ESC 2010, Stralsund, March 21, 2010
3. Wilke F, Kloske K, Bellmann M. ESRa – Evaluation von Systemen zur Rammschallminderung an einem Offshore-Testpfahl - Technischer Abschlussbericht. FKZ 0325307. 2012.
4. Bruns B, Kuhn C, Stein P, Gattermann J, Elmer K-H, Imhorst F. Underwater noise reduction from measurements and offshore tests using systems of hydro sound dampers (HSD). Proc 11. Deutsche Windenergie-Konferenz DEWEK 2012; 7-8 November 2012; Bremen, Germany 2012.
5. Bellmann M. Gerke P. Untersuchung und Erprobung von Hydroschalldämpfern (HSD) zur Minderung von Unterwasserschall bei Rammarbeiten für Gründungen von Offshore-Windenergieanlagen, Bericht Auswertung der Hydroschallmessungen im OWP London Array, Oldenburg, 2013.
6. Bruns B. Evaluation of hydro sound and vibration measurements during the use of the Hydro-Sound-Damper (HSD) at the wind farm “London Array”. Proc 166th Meeting of the Acoustical Society of America; 2-6 December 2013; San Francisco, USA 2013. 2pPA4.
7. Kuhn C. Numerical simulations of hydrosound and ground vibrations during pile driving. Proc 166th Meeting of the Acoustical Society of America; 2-6 December 2013; San Francisco, USA 2013. 2pPA4.
8. Elmer K-H, Savery J. New Hydro Sound Dampers to reduce underwater noise. Proc Internoise 2014; 16-19 November ; Melbourne, Australia 2014.