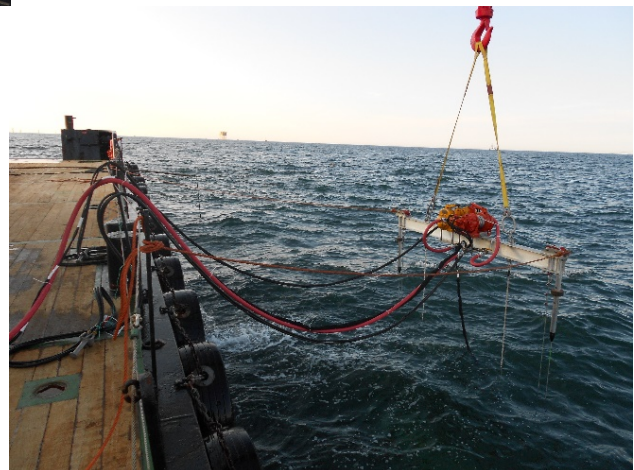


AdBm Demonstration at Butendiek Offshore Wind Farm with Ballast Nedam



Executive Summary

A demonstration of the AdBm Technologies underwater noise abatement system was conducted July 11–12, 2014 during pile driving operations for monopiles BU 32 and BU 21 in the Butendiek Offshore Wind Farm. The panel-based noise abatement system was deployed and recovered four times without incident. Acoustic testing was conducted at three locations ranging from 285 meters to 750 meters from the monopile being driven. Measurements were collected on 668 hammer strikes at a distance of 285 meters from the monopile. **Attenuation of up to 36.8 dB was realized across all hammer strikes at this location.** At 750 m from the monopile, 136 hammer strikes were analyzed and the noise radiated from the pile driving was attenuated to the level of ambient noise near the recording vessel, which ranged on average from 140–150 dB re 1 μ Pa. The results from this test strongly suggest that this system alone will be sufficient to meet the required sound exposure level of 160 dB at 750 m.

Project

Under contract from WPD, Ballast Nedam began pile driving operations for the Butendiek Offshore Wind Farm on the 1st of April, 2014. Operations were based out of the port of Esbjerg, Denmark. AdBm engaged Ballast Nedam to demonstrate our panel-based noise abatement system. Originally AdBm had planned to ship the system via surface transport; however, due to time constraints from the fact that Ballast Nedam was one month ahead of schedule AdBm shipped the system via air freight and met the accelerated schedule on time.

Key Personnel and Equipment

AdBm

Mark Coplen – Vice President of Sales, Project Manager for the demonstration

Kevin Lee – Research Scientist from Applied Research Laboratories, University of Texas at Austin (ARL:UT) and Science Advisor to AdBm

Andrew McNeese – Engineering Scientist from Applied Research Laboratories, University of Texas at Austin (ARL:UT)

Ballast Nedam Offshore

Jarko Snaar – Ballast Nedam Senior Project Engineer. Jarko championed the project inside Ballast Nedam and was instrumental in making the demonstration happen.

Arne Hartogsveld – Ballast Nedam Senior Planner/Logistics Coordinator. Arne was our main point of contact at the port and coordinated all logistics for receiving the system at the port, getting the system to and from the project site, and making arrangements for the AdBm staff for offshore accommodations.

Captain Mark Rawdon of the Multicat “Mena C” and crew were excellent hosts and extremely helpful in preparing the system for deployment, and assisting with deployment of the panel.

Captain Patrick Nowee of the HLV “Svanen” and crew provided lodging and food, and assisted with offloading gear from “Mena C” and trans-loading to the “Viking” for transport back to port.

Vessels directly involved with the demonstration

HLV “Svanen” – Ballast Nedam’s installation vessel

Multicat “Mena C” of Rhu – GSS Marine Services, under contract to Ballast Nedam

Demonstration Noise Abatement Panel

AdBm's noise abatement system consists of a modular, collapsible framework, which houses and deploys submersible air-filled acoustic resonators. When fully deployed, the framework and acoustic resonators can be designed to extend and cover the entire water column; the collapsible nature of the framework allows the system to be stored in a compact manner.

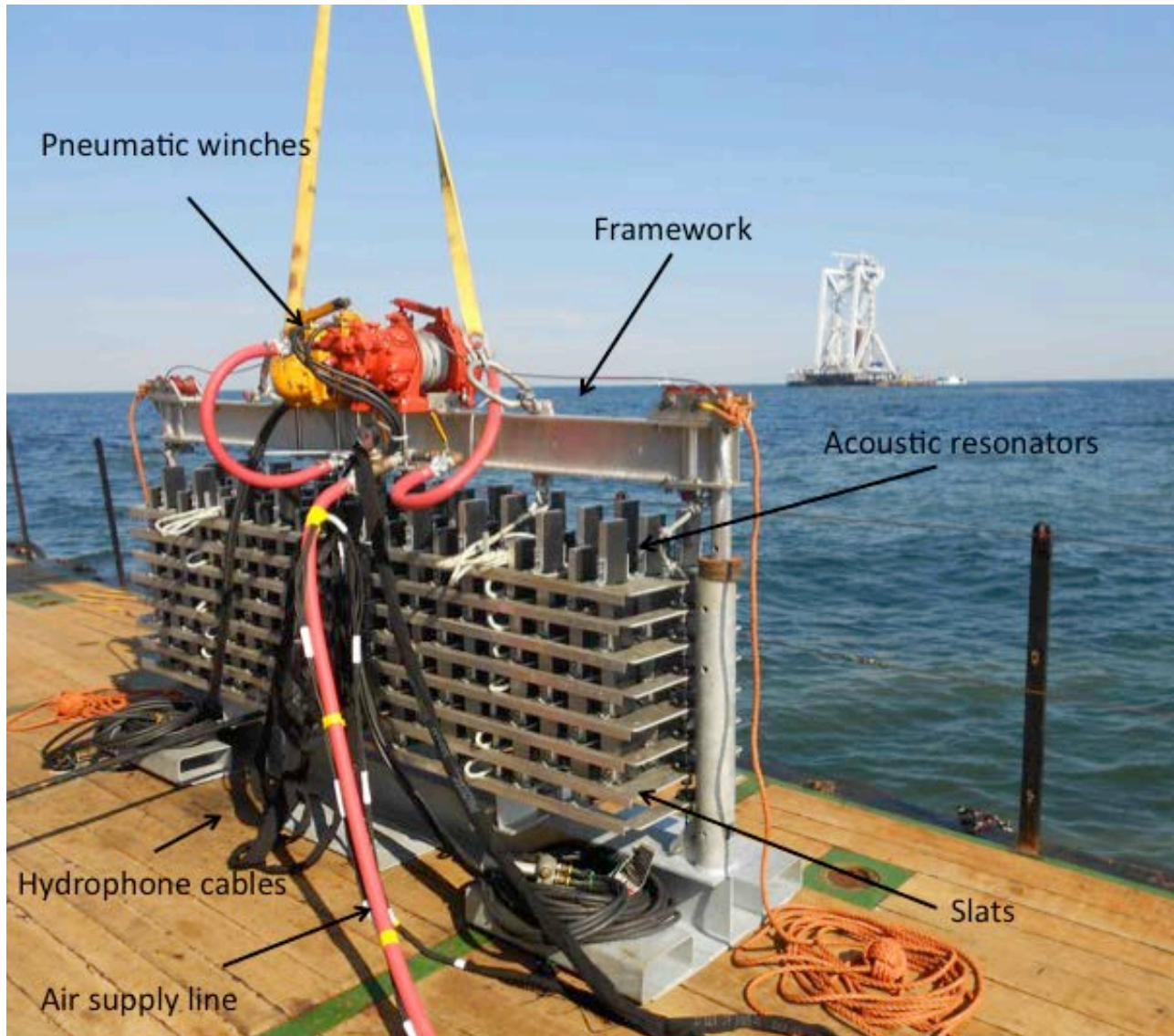


Fig. 1: Photograph of demonstration panel in collapsed state on deck of the Mena C. The various components of the system are labeled. Note that for the production version of this system, the hydrophone cables, winch control lines, and tag lines will not be present.

The demonstration noise abatement system consisted of a scaled-down, single collapsible framework populated with 240 acoustic resonators. The resonators were designed to have a resonance frequency of 100 Hz and were fabricated specifically for this demonstration. The framework consisted of eight horizontal slats, each housing 30 acoustic resonators, that could be expanded to a height of 7 meters.

When fully collapsed, the panel was less than 1.5 meters tall. A photograph of the demonstration panel in its fully collapsed state on deck of the Mena C is shown in Fig. 1. A photograph of the fully extended panel at an ARL:UT test tank is shown in Fig. 2.

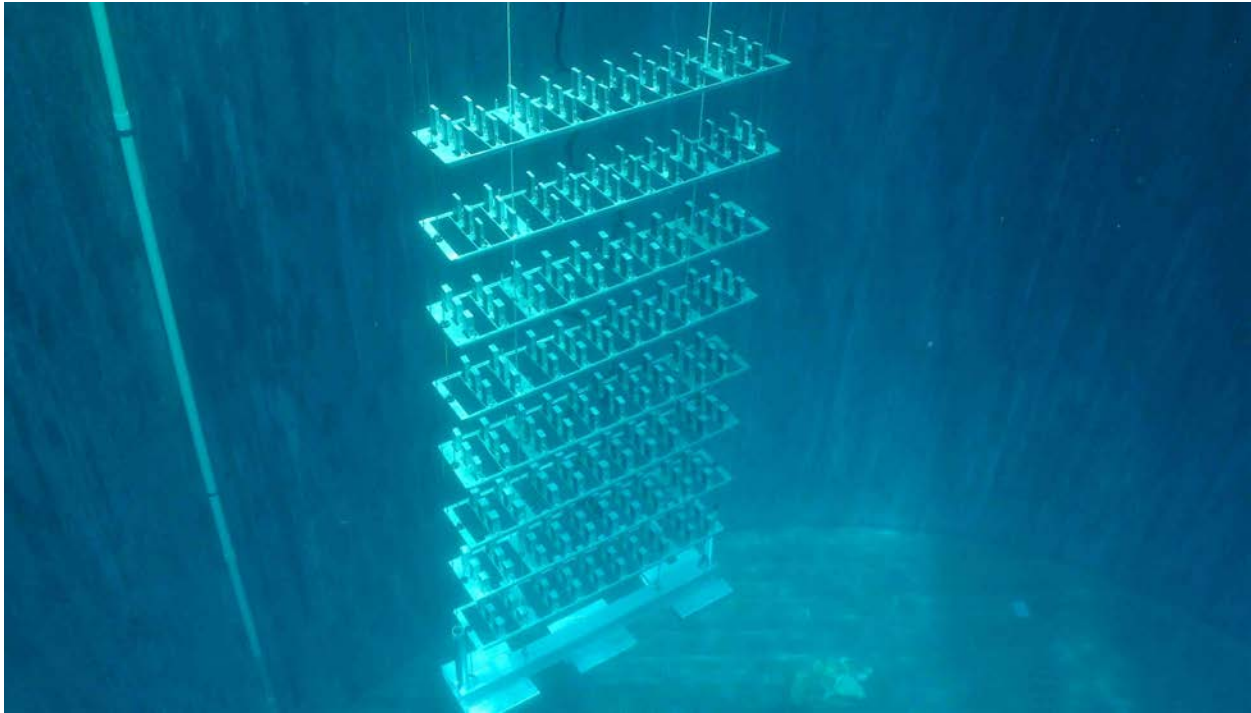


Fig. 2: Photograph of the fully extended demonstration panel in the ARL:UT test tank. Underwater photographs were made during the Butendiek demonstration; however, the test tank photo more clearly shows the system due to water clarity.

The purpose of the Butendiek demonstration was two-fold: 1) demonstrate deployment and retrieval of the panel in North Sea conditions, and 2) demonstrate our technology's sound reduction effectiveness on pile driving noise. To enable the acoustic tests of the demonstration panel, two hydrophone arrays were used: a baseline array that measured the untreated pile driving noise and an array embedded with the demonstration panel to measure the panel effects on the noise. The demonstration is described below, followed by the key acoustic results.

Demonstration Procedure

The demonstration panel was deployed from the Mena C during the driving of two monopiles at the Butendiek offshore site: BU-32 and BU-21. The demonstration panel was deployed at a site approximately 385 m away from monopile BU-32 and at sites approximately 285 m and 750 m away from monopile BU-21. The Mena C's GPS system was used to determine the distance from its mooring location to the monopile. The panel, its embedded hydrophone array, and a baseline hydrophone array were deployed from the starboard side of the Mena C at each deployment location, and the Mena C was positioned such that its starboard side was facing the Svanen. The Mena C's thrusters were turned off during acoustic data collection to minimize the ambient noise levels at each site; however, its generators were left on. The test configuration is summarized in Fig. 3.

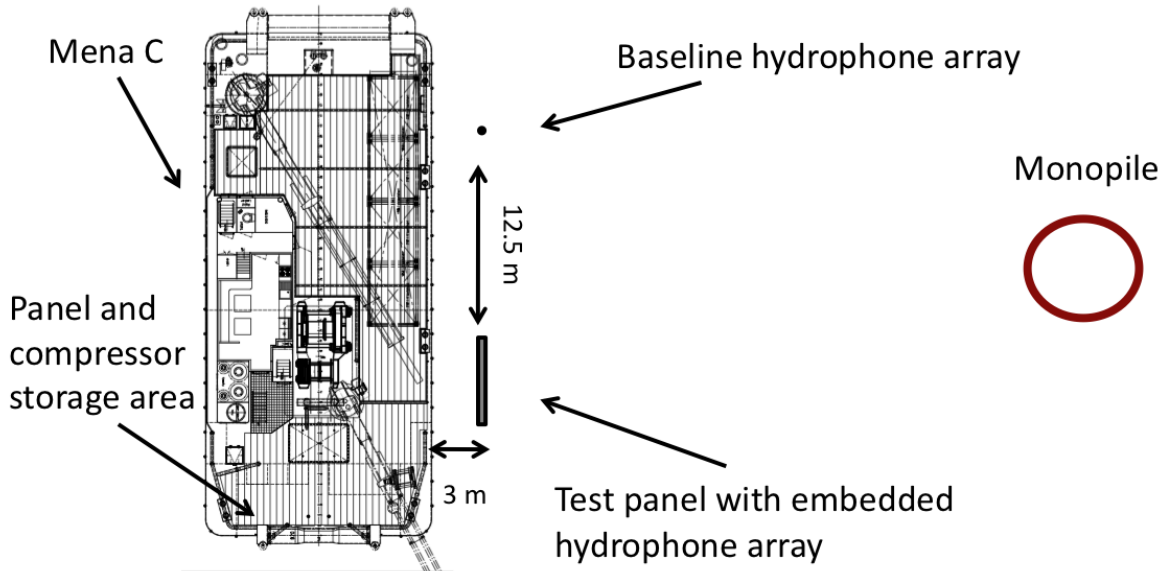


Fig. 3: Diagram depicting the deployment and test configuration for monopiles BU-32 and BU-21.

At each test location the panel and baseline hydrophone array were deployed and left in the water during pile driving events until sufficient acoustic data were collected. Acoustic data were recorded simultaneously on hydrophones from both arrays so that a direct comparison could be made between the signals recorded on the unshielded array and those recorded on the array embedded in the noise abatement panel. This comparison provided a measure of the amount of sound absorption provided by the demonstration panel. After acoustic data collection was completed at each test site, the panel and baseline array were retrieved and stowed away for transport.

Video of the system being deployed from the Mena C can be found here: <http://youtu.be/J8jLdlyrvLY>

Underwater video of the panel deployment can be found here: <http://youtu.be/QZoCqUJA8i8>

Acoustic Data Acquisition Equipment and Post-Analysis

All acoustic data were recorded using High Tech Inc. HTI-90-U dual sensitivity hydrophones. The three hydrophones on each array were spaced at 1.2 m from each other at water depths ranging from 3.6 m to 6.0 m. The hydrophones were powered using custom electronics designed and built by ARL:UT. Unprocessed hydrophones signals were digitized at a sampling rate of 10 kSamples/s in 24-bit resolution using a Data Translation DT9826 USB Data Acquisition Module and stored on a laptop computer.

Electrical interference from the ship's AC power system induced significant electrical noise into the measuring equipment via the hydrophone power supplies, which were initially connected to ship for the monopile BU-32 tests. Due to this noise, we utilized a custom-built, low-noise, two-channel hydrophone power supply, which we had brought as a backup and which minimized the electrical interference. This hydrophone power supply allowed us to collect data from two consecutive hydrophones rather than using the full array of six (three in baseline array and three embedded in the panel). During this phase of testing we collected data from four total hydrophones, two each at a time with one in the baseline array and one in the protected area of the noise abatement panel however; there was still electrical

noise present in this data. For the second monopile tested we utilized a pure-sine-wave power inverter connected to an automobile battery, which provided extremely clean power, allowing us to use our multichannel (5 channels each) hydrophone power supplies, which had been previously affected by electrical noise when connected to ship power. During this phase we collected data simultaneously from six hydrophones, three in the baseline array and three in the protected area of the noise abatement panel. For these reasons, we will focus on the data in this report from monopile BU-21, which was free of interference from non-acoustic electrical noise.

The acoustic data were analyzed on a strike-by-strike basis. A computer algorithm was written to automatically detect and gate individual data for further processing. The data were high-pass filtered with a cutoff frequency of 20 Hz using a zero-phase forward and reverse digital filter to minimize the presence of low frequency pressure variation in the data due purely to surface water wave motion. Quiet gaps between strikes were used to obtain estimates of the ambient noise levels (non-pile-driving noise). Two metrics are used to quantify the demonstration panel's acoustic noise-reducing performance: peak sound pressure levels and third-octave band levels. Example monopile signals are plotted in Fig. 4. The signal from a signal hydrophone on the baseline array is plotted on top while the corresponding hydrophone from the panel-embedded array is plotted on bottom. There is a clear and significant reduction of the initial impulse radiated by the monopile.

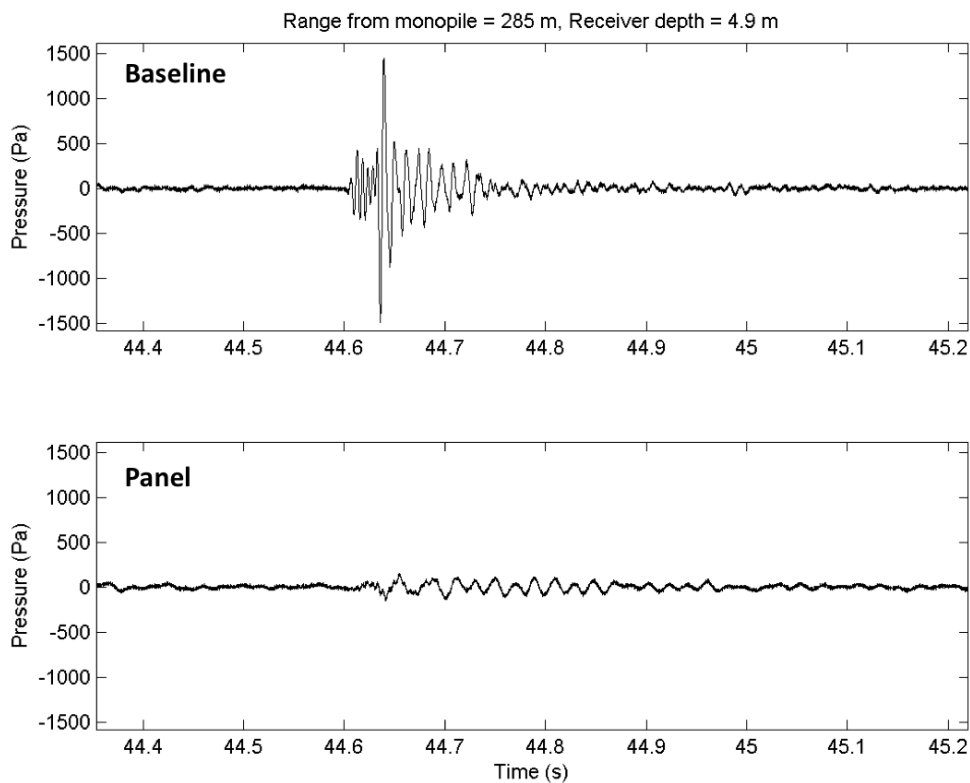


Fig. 4: Example raw acoustic data from a single event from monopile BU-21 recorded at a distance of 285 m from the monopile. The data from each hydrophone were recorded simultaneously. The acoustic signals correspond to the same hammer strike. The reduction in amplitude recorded by the panel embedded array is due to sound absorption by the acoustic resonators inside the panel.

Peak Sound Pressure Levels (SPL)

The broadband peak sound pressure levels were determined for each individual pile strike at each test location using the standard definition:

$$SPL = 20 \log_{10} (\max(p)/p_{\text{ref}})$$

where p is sound pressure and a reference pressure of 1 μPa was used. The peak SPL is expressed in dB referenced to 1 μPa . For a single measurement location peak levels for all strikes and hydrophones used were averaged to provide a degree of statistical confidence. The peak levels both inside and outside the panel are summarized in Table 1 along with the differences in levels.

Pile	Range (m)	Number of Strikes	Baseline (dB)	Panel (dB)	Difference (dB)	Max Reduction (dB)
BU-21	285	668	183.3 \pm 0.7	164.2 \pm 2.3	19.2 \pm 2.4	36.8
BU-21	750	136	157.5 \pm 0.7	146.4 \pm 2.3	11.1 \pm 2.6*	29.6*

* Reduced reduction at 750 m is because noise was fully reduced to ambient noise levels

Table 1: Summary of peak SPL values averaged over all strikes at each measurement location. The uncertainties are given by standard deviation for each data set. Also note that for 750 m the received level in the panel was at or below ambient noise levels, so the actual reduction was likely higher than could be measured.

A few comments need to be made on the BU-21 results. Only the panel hydrophone array signals recorded at 285 m were significantly above the ambient noise levels. At 750 m away from the monopile strike signal levels received inside the panel were at or below the non-piling ambient noise levels outside the panel. Hence, the apparent reduction at this location is lower than at the 285 m location, but in reality was likely comparable to the reduction measured at 285 m. Because of its high pile-signal to non-pile-noise ratio, the peak SPL values and difference computed from the data recorded at 285 m most accurately reflect the true sound reduction provided by the demonstration panel. The peak SPL values computed for the BU-32 data were severely affected by the aforementioned electrical noise issues, which had contaminated the acoustic signal, so these data are omitted here. The peak SPL data is plotted from both measurement locations along with the non-piling ambient noise levels for reference in Fig. 5.

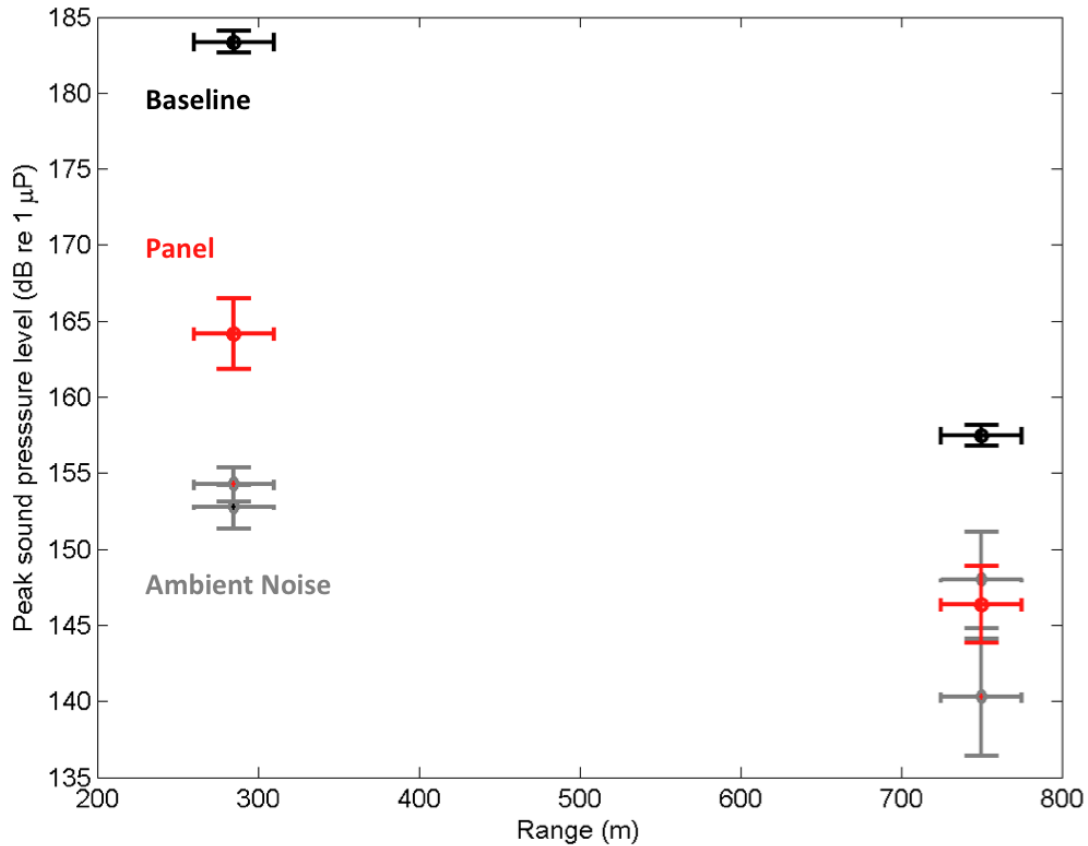


Fig. 5: Peak sound pressure levels average over at least 100 pile strikes at each measurement location vs. range from the monopile. The 285 m and 750 m peak values come from data collected on BU-21. The error bars indicate the standard deviation in the measurements. Non-pile-driving ambient noise measurements are indicated by the grey diamonds with error bars for levels recorded outside the panel (black faces) and inside the panel (red faces). For the 750 m case, it can be seen that the measured levels inside the panel were at the level of ambient noise.

One-Third-Octave Band Levels and Reduction

To determine the frequency dependence of the sound attenuation provided by the panel, one-third-octave band levels were computed from the acoustic data for each pile strike. The raw hydrophone data was sent through a bank of digital filters each with one-third octave bandwidth and center frequencies specified by the most recent ANSI standard¹, and the peak pressure in each band was determined. Ambient noise bands levels were also computed from the quiet gaps in between the pile strikes. All of the third-octave band levels are plotted in Figs. 6 and 7 to show the amount of variation in the recorded data.

From the baseline data, the noise radiated from the monopile has a broad peak in approximately the 50 Hz to 300 Hz frequency range, with a particularly sharp peak at 200 Hz, and without much acoustic energy observed above the non-piling ambient noise levels at frequencies of 1 kHz and higher. It is assumed that the relatively low band levels at 1 kHz and above is due to the effect of the noise

¹ ANSI S1.11-2004, "Specification for Octave Band and Fractional Octave Band Analog and Digital Filters" (2004)

abatement treatments already in place at the installation site, while the energy below about 250 Hz is mostly untreated noise. The sharp peak at 200 Hz, which is seen in all of the data during an impact event but not between strikes, is indeed from pile driving and not from other sources such as electrical noise or ship noise, but the tonal characteristics of it are not yet understood. In addition, given this source condition in which the pile driving noise at frequencies above 300 Hz is only about 10 dB above the ambient noise, only 10 dB of noise abatement can be demonstrated. In this data it is apparent that indeed the levels above 300 Hz have been reduced to the ambient noise, but the demonstrated performance of the system could have been higher given a louder source condition.

As demonstrated at the 285 m measurement location (Fig. 6), the demonstration panel reduced the sound levels at all frequencies above approximately 50 Hz. At 750 m away from the monopile (Fig.7), the received pile driving signal is essentially reduced to the non-piling ambient noise levels by the demonstration panel, which is the most reduction possible. Again it is believed that given a louder source condition, demonstrated noise reduction could have been greater.

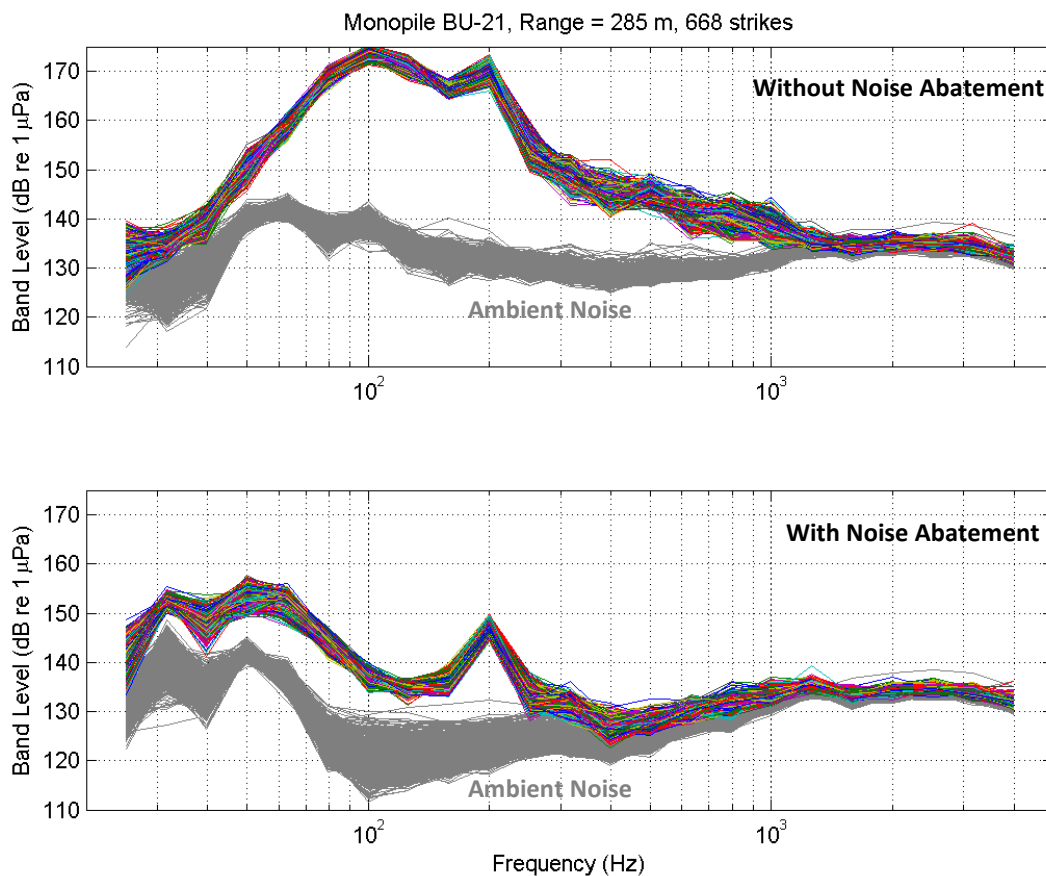


Fig. 6: One-third-octave band levels for all monopile strikes recorded at the location 285 m away from monopile BU-21. The colored lines are the band levels corresponding to each pile strike. The grey lines are non-pile ambient noise band levels from the quiet sections of data between pile strikes. The horizontal axis is frequency, given in a logarithmic scale.

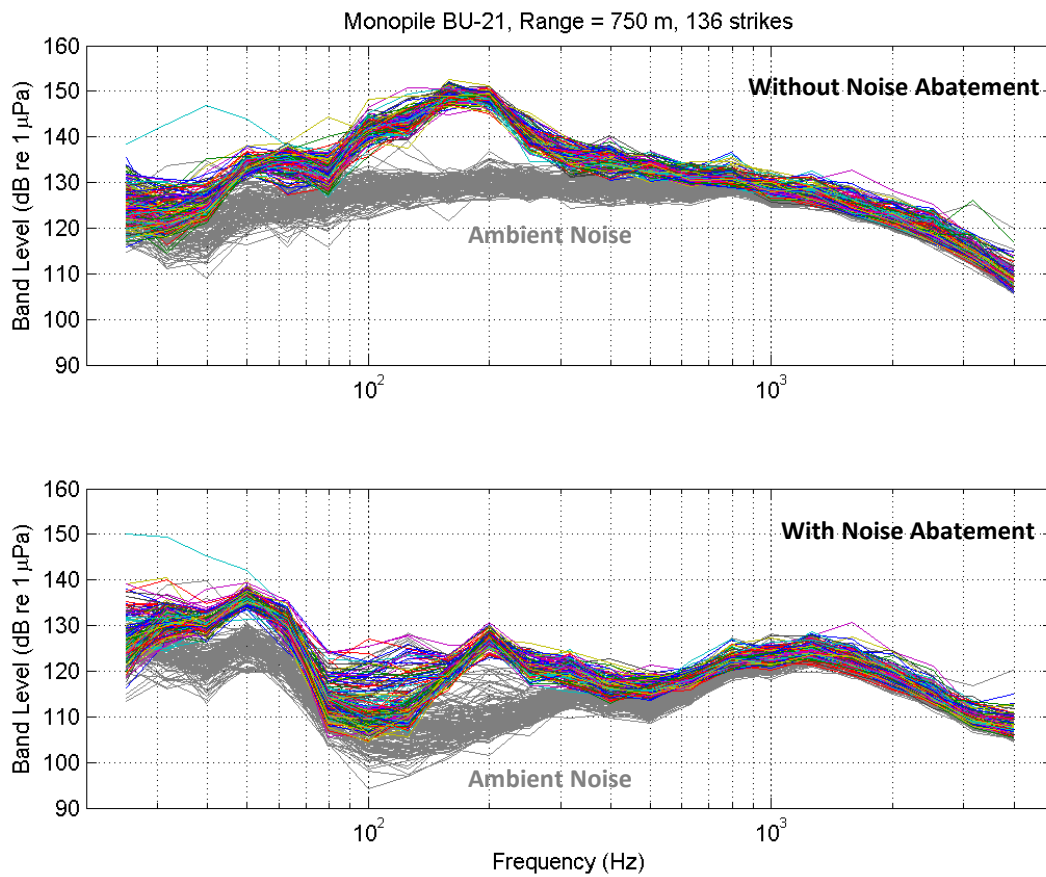


Fig. 7: One-third-octave band levels for all monopile strikes recorded at the location 750 m away from monopile BU-21. Radiated noise from the monopile was reduced to the local ambient noise levels by the demonstration panel.

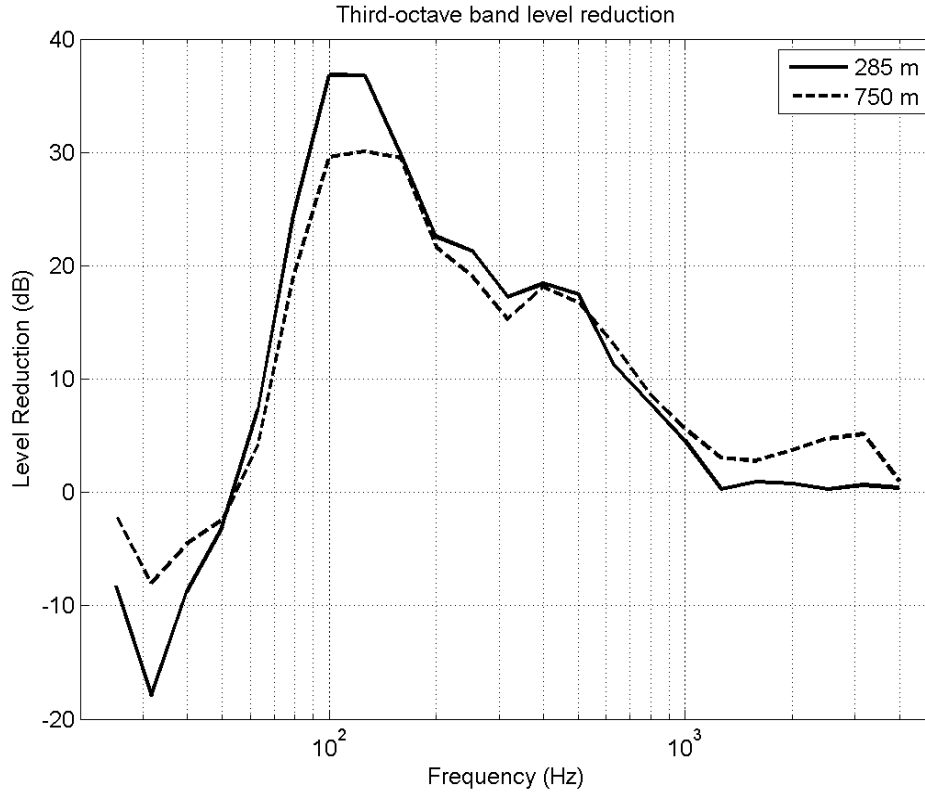


Fig. 8: Average one-third-octave band level reduction measured at each of the test locations for monopile BU-21. The slightly reduced noise abatement levels at 750 m were due to the fact that the noise was fully reduced to the ambient noise level.

Average band level reduction values were computed from the one-third-octave bands to further quantify the attenuation provided by the demonstration panel. These reduction values were calculated for the data taken at 285 m and 750 m away from monopile BU-21 and were averaged over all pile strikes recorded at each location. Band level reduction was computed by subtracting the average band levels measured by the panel array from the average band levels measured by the baseline array, and it is plotted in Fig. 6. Positive values of this quantity correspond to a reduction in sound by the demonstration panel. The peak reduction occurs at in the band centered near 100 Hz, indicating that the part of the pile noise signals at this frequency were reduced on average by 36.8 dB at the 285 m measurement location. The peak reduction occurs at this frequency because the acoustic resonators used in the demonstration panel were designed to resonate near 100 Hz and provide the most attenuation here. As seen in Fig. 6, the peak noise radiated by the pile also occurs near 100 Hz, coinciding with the highest reduction levels. The resonators were designed to target the peak frequencies associated with a pile driving noise source. The peak reduction calculated at the 750 m location was limited to 29.6 dB; however, this is an artifact of the pile driving signal being buried in the ambient noise at these frequencies at this measurement location, as can be seen in Fig. 5. At the lowest frequencies the calculated band level reduction becomes negative, indicating a level increase. This can also be seen as the low frequency oscillation in the panel hydrophone signal in Fig. 4. Below the resonance frequency of the individual acoustic resonators in the demonstration panel, a collective

resonance of the entire panel is excited and the incoming sound wave can be coherently scattered, resulting in a net increase in sound pressure. This is a well-known phenomenon from the field of bubble acoustics². Fortunately, there is not much sound energy in the pile driving noise spectrum below 50 Hz so there is very little noise at low frequencies to be amplified. Furthermore, a full-sized panel would be much larger than the demonstration panel, and since the collective panel resonance scales inversely with panel size, that mode would be shifted to much lower frequencies where no sound energy would be present to excite it.

Sound Exposure Level

The total SEL measured at 285 m and 750 m was not reported here because the pile driving noise had already been treated by two noise abatement systems before it reached our test setup and the resulting SELs would be extraordinarily low. In the case of 750 m, it would be down to or even below the ambient noise level of the North Sea, and we decided that this information did not reflect the system's actual performance.

Instead, sound pressure level reduction was our focus since we wanted to focus on just the effects of our noise abatement system. In doing so we determined the instantaneous level reduction as a function of frequency, which is a result that can be widely applied to predictions of future performance. For example, once it's known how the system "filters" the sound from the pile, that effect can be applied to any signal and propagated to a set distance using standard propagation models. At that point, the resulting SEL can be calculated.

For future demonstrations in which the pile is untreated, source measurements will be taken very near the pile and we will produce estimated SEL levels at both 285 m and 750 m, as well as any other distances of interest.

Conclusions

A demonstration of the AdBm Technologies underwater noise abatement system at the Butendiek Offshore Wind Farm was described and the acoustic results were analyzed. The panel-based noise abatement system was deployed and recovered four times without incident in the North Sea. The acoustic data collected from the tests showed peak attenuation of up to 36.8 dB when measured at 285 m and 29.6 dB at 750 m. In both cases however it is expected that the actual overall reductions could have been larger given higher source levels, since in many cases the panel reduced the noise as much as possible, i.e., to the ambient levels, which at frequencies above 300 Hz were only 10 dB above the ambient noise at the most. The results from this test strongly suggest that this system alone will be sufficient to meet the required sound exposure level of 160 dB at 750 m.

² A. Prosperetti, "Bubble-related ambient noise in the ocean", *J. Acoust. Soc. Am.* **84**, 1042 (1988).; W. M. Carey, "Low-frequency noise and bubble plume oscillations", *J. Acoust. Soc. Am.* **82**, 78 (1985).

Lessons Learned from Demonstration Deployment

1. For the demonstration panel we are limited to 2 meter sea swells: since the demonstration panel does not extend all the way to the sea floor it is subject to heaving up and down as the ship's crane moves due to wave action. This will not be an issue with production units as they will extend to and be anchored on the sea floor, yet still in this environment the panel was able to handle the extra stresses. Excess cable payed out at the surface will prevent the panel from being yanked up and down during swells. This issue will be completely eliminated when jack-up vessels are utilized for pile driving as the line will be under tension from the ballast all the way to the vessel mount.
2. Panel design needs to be slightly modified to improve "stacking" of panel slats when recovering system. When recovering the panel for the second time a large swell hit the panel just as it was being lifted out of the water. The swell picked up all of the slats and the seventh and eighth slats did not nest with each other properly when the swell lowered the slats. Ship heave occurred at the same time as the swell, which amplified the effect of the swell on the panel retrieval. The panel was still easily recoverable, and once on deck we manually lifted the top seven slats and nudged them to nest with the bottom slat.
3. Design of system for maintaining slat separation can be improved. We currently utilize rope to maintain 2 ft. (0.6 m) separation between slats in the panel. In photographs of the panel this is the white rope approximately 1/3rd of the way in from each end of the panel. Currently the rope is free floating during recovery of the panel and it could potentially wrap around a resonator causing damage on subsequent deployments. After each deployment we manually dressed the rope to ensure it was not entangled inside the panel and didn't see this issue occur. This post-deployment procedure was intended for the low-cost, small-scale demonstration panel, which was easily accessible by the research crew on the deck of the deployment vessel; however, the full-scale panel design will avoid the need to redress lines after each deployment.
4. Electrical interference from the ship's AC power system induced significant electrical noise into the measuring equipment. Remedy: for the first monopile we utilized a custom-built, low-noise, two-channel hydrophone power supply, which we had brought as a backup and which minimized the electrical interference. This hydrophone power supply allowed us to collect data from two consecutive hydrophones rather than using the full array of six (three in baseline array and three embedded in the panel). During this phase of testing we collected data from four total hydrophones, two each at a time with one in the baseline array and one in the protected area of the noise abatement panel. For the second monopile tested we utilized a pure-sine-wave power inverter connected to an automobile battery, which provided extremely clean power, allowing us to use our multichannel (5 channels each) hydrophone power supplies, which had been previously affected by electrical noise when connected to ship power. During this phase we collected data consecutively from six hydrophones: three in the baseline array and three in the protected area of the noise abatement panel.
5. Contrary to automobile batteries in the US, those purchased in the EU are not initially charged. We were unable to utilize the inverter/battery arrangement during the testing of the first monopile because the battery we procured from a local store was not initially charged. We were able to fully charge the battery and utilize it throughout the testing on the second monopile. The battery shall be fully charged prior to setting out on any future demonstrations.
6. The winches used for deploying and recovering the panel did not feed/recover cabling at the same rates, requiring monitoring by operators to ensure the panel was deployed evenly on each side. The pneumatic winches used on the panel were not the ideal solution. Going forward we will use hydraulic winches.

7. The brake from one of the pneumatic winches partially released while repositioning the panel from the Mena C to the Svanen, allowing one side of the panel to lower slightly. In the future panels should be secured using cargo straps to prevent unintentional unfurling when moved from one location to another.

Lessons Learned/Observations for Full-Scale Utilization

1. When utilizing monopiles with lifting “ears” as utilized for this project, care needs to be taken to ensure that the AdBm panels do not become entangled with the ears. If monopiles were to be installed while the HLV Svanen were heaving, or if sea currents existed once the ears were under the surface the panel could make contact with the sides of the monopile during deployment, operation, or recovery. Contact with the large ears could result in damage to the noise abatement system. Potential solution: a plastic cap over the ears that prevented the panel from snagging would eliminate the opportunity for entanglement.
2. Engineering work is required for mounting the AdBm system to the Svanen. We looked at the template currently used on the Svanen for potential mounting options. Some mechanical engineering design work is needed to create an optimal deployment method. The current assumption is that a panel designed for 40 meter depth would stack to approximately a 4.5 meter height when fully collapsed, and that a total of five panels would be used: three that are either 10 meters or 12 meters in width, and two that are 6 meters.
3. Pneumatic winches are not ideal for our solution. Based on feedback from vessel personnel we will use hydraulic winches on future designs.

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