Measurements of pile driving noise at the research platform FINO3

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ABSTRACT
This paper presents measurements of underwater pile driving noise recorded during the construction of the offshore wind farm DanTysk in Fall 2013. The measurements were carried out at the research platform FINO3 in the North Sea. The measurement system was specifically designed to provide simultaneous sound measurements at different heights above the sea-floor. It consisted of a bottom mounted tripod to which a vertical chain of hydrophones was attached with the top-most hydrophone being located about four meters below the sea-surface. The system was cable-connected to the research platform FINO3 which provided electric power and large data storage space. This allowed the system to be operated with relatively large sampling rates. The focus of this paper will be on the analysis of the depth dependence of the received pile driving noise. The paper furthermore presents the design of the acoustic measurement system and discusses its performance and endurance in the relatively harsh North Sea environment.

Keywords: pile driving noise, underwater sound propagation, research platform FINO3

1. INTRODUCTION

The foundations of wind turbines in offshore wind farms are often constructed by the method of impact pile driving, where steel pipes are driven deeply into the sea-floor by a hydraulic hammer. As a result of this pile driving significant levels of underwater sound are emitted into the surrounding water column. In fact, underwater sound levels caused by pile driving are among the highest of marine construction activities. It is well known that high level underwater noise can have a negative impact on marine life, like e.g. the harbor porpoise which is common in the North Sea (1). Therefore in Germany the Federal Maritime and Hydrographic Agency (BSH) together with Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) have established a limit for the underwater sound produced by wind turbine construction (e.g. 2): the sound exposure level of a pile driving strike must not exceed 160 dB rel 1µPa outside of a circle of 750 m radius and the peak level (L_{peak}) must not exceed 190 dB re 1µPa, with the sound measuring hydrophones to be placed between 2 and 3 meters above the sea-floor (2).

From numerous investigations it is well known that the observed sound-levels may exhibit significant variability both with respect to time and the location (i.e. distance from the pile and depth below sea-surface) of the receiving hydrophone. Possible reasons are variations of the hammer energy, of the performance of the sound mitigation system, of the position of the receiving hydrophones and of the manner in which sound waves propagate through the water (and also the sea-floor) from the pile to the receiver. The latter variability is a consequence of spatial and temporal variations of environmental parameters like the sound-velocity profile, the water depth (primarily because of tides), the sea-state, and the geo-acoustic properties of the sea-floor (e.g. 3). For regulatory purposes with respect to the above mentioned limits, it is important to know and/or to be able to predict the variance of the underwater sound level.

Towards this end, WTD 71 has been carrying out underwater sound measurements at the research platform FINO3 in the vicinity of the offshore wind farms DanTysk (Figure 1). Acoustic recordings took place during three different periods of time between September 2013 and March 2016. A particular design feature of the measurement system was that hydrophones were placed at up to 7 different heights above the sea-floor. The main purpose of this design was to investigate whether a single measurement 2 to 3 meters above the sea-floor would be representative for the sound level throughout the water column.

The following section 2 first describes the measurement location. Then the acoustic system will be described in some detail and its performance and endurance during three periods of deployment will be discussed. In section 3 acoustic measurements of pile driving noise will be presented but only for the first deployment during construction of the offshore wind-farm DanTysk. The paper will end with some conclusions and acknowledgements.

2. LOCATION AND SETUP

2.1 Location

The research platform FINO3 ist located in the German Bight about 80 kilometers west of the island of Sylt at coordinates 55° 11,7‘ North and 007° 9,5‘ East (Figure 1). It is very close to the offshore wind-farm DanTysk. The distance between FINO3 and the nearest wind measures only about 1,5 kilometers.

The wind-farm DanTysk consists of 80 wind turbines. The distance between the turbines measures between 800 and 1000 meters. The entire wind-farm covers an area of about 70 square kilometers over which the water depth varies between 21 and 32 meters. At the research platform FINO3 the tidally averaged water depth is about 23 meters.

The construction of the wind turbine foundations, i.e. of the steel monopiles by pile-driving, took place from March 2013 to December 2013 (4). The acoustic measurements at FINO3 of pile driving noise at DanTysk covered only the period of time from mid-September to the end of November 2013. During that time 20 foundations were constructed. Out of these the smallest distance to FINO3 was 3,2 kilometers and the largest 14,5 kilometers.

Figure 1 – Left: Chart of part of the German bight with the approximate locations of three already present (Butendiek, DanTysk and Sandbank) and one planned (Nördlicher Grund) offshore wind-farm. Only wind-farms in the vicinity of FINO3 are shown here. The research platform FINO3 is located close to DanTysk. Center: Photograph of FINO3 with two DanTysk wind-turbines in the background. Right: Aerial views of FINO3 and DanTysk during construction of the foundations in 2013.

2.2 Measurement Setup

The research platform FINO3 is operated by the Forschungs- und Entwicklungszentrum Fachhochschule Kiel GmbH which provides the necessary resources and the support for a number of research projects that are conducted on or in the immediate vicinity (i.e. a 500 meter safety zone) of FINO3. Details can be found on the FINO3 website (6). For the purposes of this study the most important features of FINO3 are that it provides electric power and space for data acquisition and data storage devices.

The underwater part of the acoustic measurement system is shown in Figure 2. It consists of a metal tripod that is placed on the sea-floor at a distance of about 200 meters from FINO3. Inside the tripod a metal pressure case is mounted which houses the electronics for analog-digital conversion of the signals from six hydrophones and one pressure sensor. The key component is the 8-channel 24Bit LTT24 data acquisition device by the company LTT Tasler. Electric power is provided by FINO3 through a cable connection. Through the same cable the data are transferred via fibre-optic cable to the data storage devices on FINO3. For the recording of pile-driving noise six hydrophones channels (later in 2014 seven channels were used) and one pressure sensor channel were sampled simultaneously with a sampling frequency of 50 kHz. For selected periods of time, when the focus was on the recording of the high frequency acoustic calls of harbor porpoises, sampling frequencies of 250 or even 500 kHz were used, but usually only for 2 to 3 acoustic channels simultaneously.

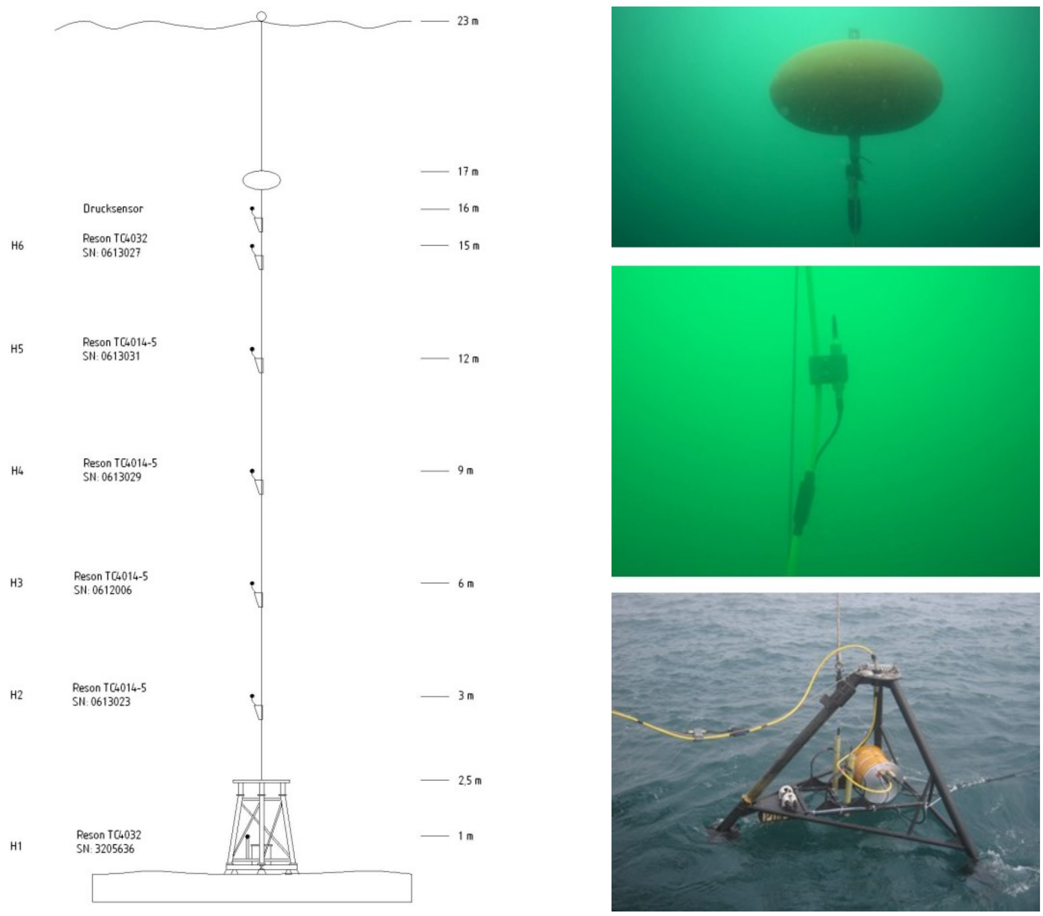

Figure 2 – Left: Schematic of the acoustic measurement system. The hydrophone inside the tripod was a Reson TC4032 with sensitivity -164 dB re 1 V/µPa. The other hydrophones were of type Reson 4014-5 with sensitivity -180 dB re 1 V/µPa. The height of hydrophones H1 to H6 above the sea-floor was 1, 3, 6, 9, 12 and 15 meters. Right: Photographs of the float for the hydrophone chain, one of the underwater hydrophones and the metal tripod which is placed on the sea-floor. Photographs are from the second deployment in 2014 when two hydrophones instead of only one were placed inside the tripod.

Hydrophones were placed at heights of 1, 3, 6, 9, 12 and 15 meters above the sea-floor. As the hydrophone chain is bend sideways by currents, heights may vary somewhat. Of course, it would have been desirable to have the chain extend all the way to the surface. However, in order to limit the risk that the chain would be hit by vessel traffic or be subjected to severe mechanical strain due to surface-wave action, it was necessary to place the float 4 to 5 meters below the sea-surface.

The bottom hydrophone H1 was of type Reson TC4032 and the hydrophones H2 to H2 of type TC4014-5. The TC4032 has a higher sensitivity but a smaller maximum frequency than the TC4014-5. For details see (7). The use of the TC4014-5 hydrophones was primarily motivated by the need to capture the high-frequency clicks of harbor porpoises. All hydrophones were manufacturer calibrated to an accuracy of 1 dB.

2.3 Remarks about the performance of the acoustic measurement system

The use of a hydrophone chain at significant distance from FINO3 has advantages and disadvantages which were weighted against each other during the design phase.

An obvious disadvantage is that the chain will not be perfectly stationary. It will be moved by currents and wave action and hence will be subject to some mechanical strain and also to some self-created structure-born noise. A second disadvantage is that the larger the distance to FINO3, the greater the risk that it might be hit by a passing vessel.

The alternative would have been to somehow place the hydrophones directly onto the FINO3 pile or onto some existing steel wires very close to FINO3. However, the concern was that known noise from FINO3 (diesel generators, wave action against the foundation, and moving parts inside and outside of the FINO3 pile) would acoustically contaminate the measurements. This could be avoided only by placing the hydrophones at a sufficient distance to FINO3. As a compromise a distance of about 200 meters from FINO3 was chosen. This was well within the 500 meter safety zone inside which vessel traffic is prohibited.

Acoustic measurements were carried out during three periods of time between September 2013 and April 2016. The measurement system was deployed the first time in September 2013. It performed well until the first of two severe storms, called CHRISTIAN and XAVER, hit it at the end of October 2013. Significant wave height reached 5,5 meters and the maximum wave height was 8 meters. The system survived but the electrical wiring of some of the hydrophones became intermittently faulty. On December 6th the second storm caused significant wave heights of 9 meters and maximum heights of 14 meters (5). According to (5) CHRISTIAN and XAVER were the two heaviest storm events since 2007. During the second storm the hydrophone chain was ripped off the tripod. It goes without saying that the system was never designed to withstand such heavy wave action.

The system was also not designed to withstand being trawled by a fishing vessel which is what happened to a second system (deployed in September 2014) in November or December 2014 despite the fact that fishing is not allowed within the FINO3 500 meter safety zone.

A third system was deployed in July 2015 and operated without any problems until its recovery in April 2016 despite the occurrence of some winter storms.

Regarding the impact of severe wave action, it is unclear whether the acoustic system would have survived the two major storms in 2013 had it been somehow rigidly mounted directly to FINO3. What is clear, however, is that the second system would not have been damaged by trawling. In retrospect, we think that the system was designed well and performed according to expectations. Protecting it against all possible kinds of maritime danger is almost impossible or at last prohibitively expensive.

3. RESULTS

3.1 Example of raw data recording of pile driving noise

For illustration purposes Figure 3 shows a 15 second record of pile driving noise from a pile at a distance of 4,5 kilometers from FINO3.

The number of hits necessary to drive a pile into the sea-floor is about 5000 with an interval between hits of about 1,3 seconds. Depending on the type of sediment, the length of the steel pipe and the hammer energy these numbers might vary considerably. The shape of the pressure signal caused by pile driving has been discussed in detail in various publications and shall not be the topic of this paper.

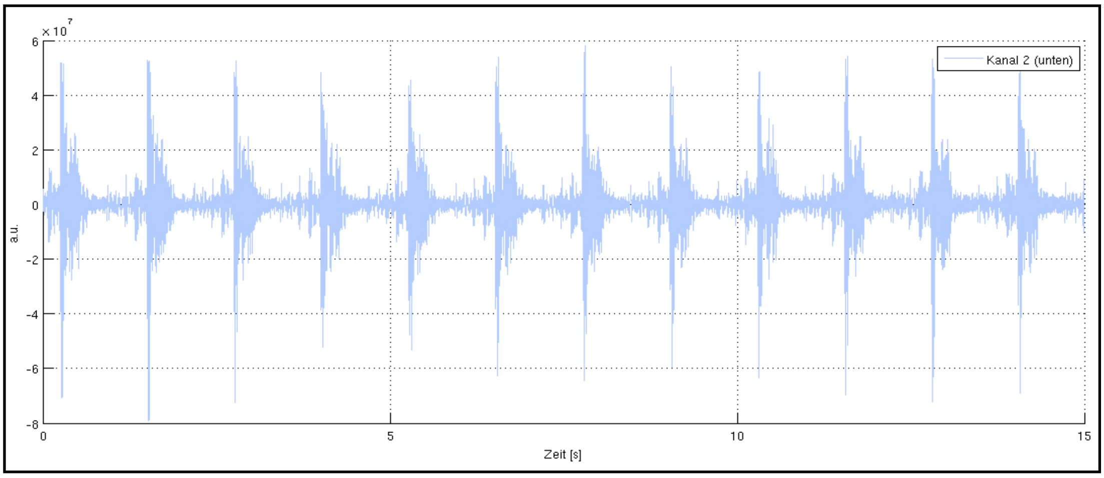

Figure 3 – Pressure recording on hydrophone 2 versus time over a period of 15 seconds during pile driving at a distance of about 4,5 kilometers from FINO3. During this period the hydraulic hammer hit the pile 12 times. The signal amplitude is shown here in arbitrary linear units.

3.2 Processing steps

Data analysis was performed for a total of 20 pile drivings. The data were screened for technical problems. As mentioned before, after the first storm some hydrophones channels showed intermittently spurious signals. Often a 102 Hz tonal signal was observed on the hydrophones channels H2 to H6. This tonal signal was easily identified and was probably caused by some electrical disturbance in the system.

The observed sound levels were also compared to the varying magnitude of the tidal currents. As expected hydrophones at the top recorded higher noise levels during strong currents than the bottom hydrophone. It has not yet become clear whether this was caused by the fact that currents might have been stronger at the surface than at the sea-floor or by the fact that vibrations of the hydrophone chain might have been stronger at the top or by a combination of both.

The 102 Hz tonal disturbance and the current induced self-noise of the hydrophone chain are significant only during periods without pile driving. During pile driving sound levels were usually so high that the two disturbances were of little or no signifance for the calculated acoustic quantities.

The acoustic quantities presented here are the equivalent continuous sound level L_{eq} (also called average level), the single sound event level (also called sound exposure level) SEL and the peak level L_{peak}. All quantities were calculated according to the instructions given in (2).

3.3 Results for pile driving at DanTysk foundation DT29

The following Figures 4, 5 and 6 show results obtained for pile driving at DanTysk foundation DT29. The distance between this pile and FINO3 and hence the hydrophone chain was 3,8 kilometers. The duration of the pile driving was about 1,5 hours and the number of hits about 4200.

Figure 4 shows the frequency content of the pile driving noise received at FINO3. In the frequency range below 500 Hz pile driving noise has levels that are clearly above background noise level. It is worth noting that background noise level was relatively high during almost all measurements. The reason is most likely that even in the absence of pile driving there was significant ship noise emitted by a number of vessels that were present at almost all times in the area of the offshore wind-farm. The little peak at 102 Hz in the dashed-line curves (background noise) in Figure 4 is caused by the electric disturbance mentioned before. The rather erratic behavior of the background noise spectra for frequencies below 20 Hz is believed to caused by current induced vibrations of the hydrophones or the entire hydrophone chain.

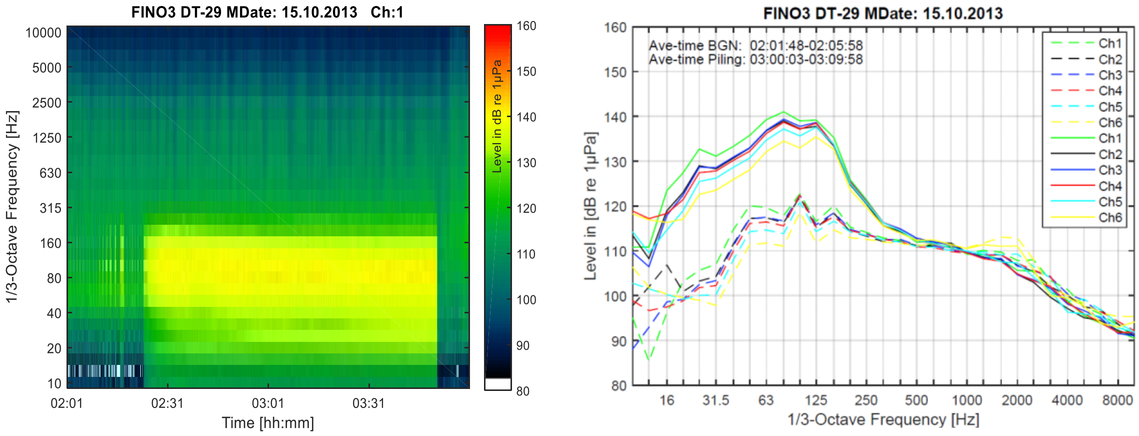

Figure 4 – Left: 1/3-octave frequency spectrogram of the acoustic recording of hydrophone H1. Right: Averaged 1/3-octave frequency spectra for hydrophone H1 to H6. The dashed lines represent times without pile driving (called BGN in the legend) and the solid lines times with pile driving. The averaging times are given in the legend at the top-left corner of the figure.

The sound exposure level L_E and the peak level L_{peak}, for which maximum values (at 750 meter distance from the pile) have been established, are shown in Figure 5. Note that these values are broadband values without any frequency weigthing (2) and that they are shown for hydrophone H1 only. The values are relatively constant during the pile driving except at the beginning of the procedure. During this so-called soft-start phase hammer energies are usually much lower than during the main phase. From the histogram the 50% percentile levels can be derived (Explanation: $L_{50,30s}$ indicates the 30 seconds percentile level which is exceeded in 50% of all measurements over the total measuring period). For the peak level L_{peak} the 50% percentile level is 165 dB and for the sound exposure level SEL it is 148 dB.

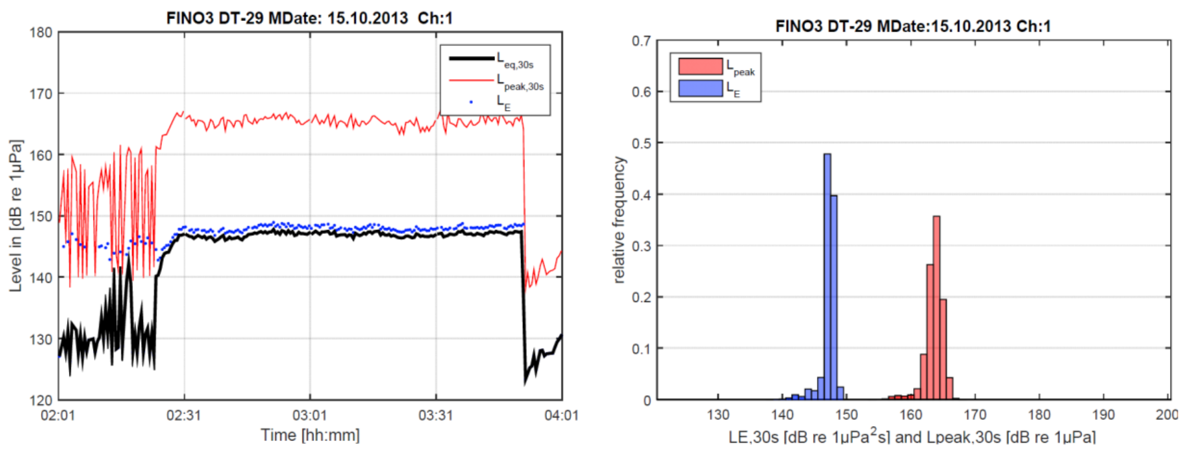

Figure 5 – Left: Equivalent continuous sound level L_{eq} (averaging time 30 seconds), peak level L_{peak} and sound exposure level L_E for data from hydrophone channel H1. Right: Histogram of peak level and sound exposure level for data from hydrophone channel H1.

Figure 6 compares the equivalent continuous sound levels L_{eq} for the 6 different hydrophones. For the left panel an averaging time of 5 seconds was used and for the right panel 60 seconds. The difference in levels between the hydrophones is obvious. During pile driving the level is highest at the bottom hydrophone and lowest at the top hydrophone. The average difference is 5,5 dB and the maximum difference is 5,8 dB. Considering the calibration accuracy of the hydrophones of about 1 dB this is a significant difference. On the other hand, the level difference between hydrophones 3 and 4 is not significant.

It is worth noting that a similar depth dependence is observed before pile driving (between 02:01 and 02:20). On the other hand, after the pile driving the depth dependence is completely different. So the conclusion is that sound received at FINO3 shows a significant depth dependence in the frequency range between about 30 Hz and 500 Hz (Figure 4); during pile driving it is clear that the main source is the pile driving. Before the pile driving the acoustic source is unclear. It could be simply vessel noise or the noise emitted from the sound-mitigation system. It is planned to investigate this in more detail.

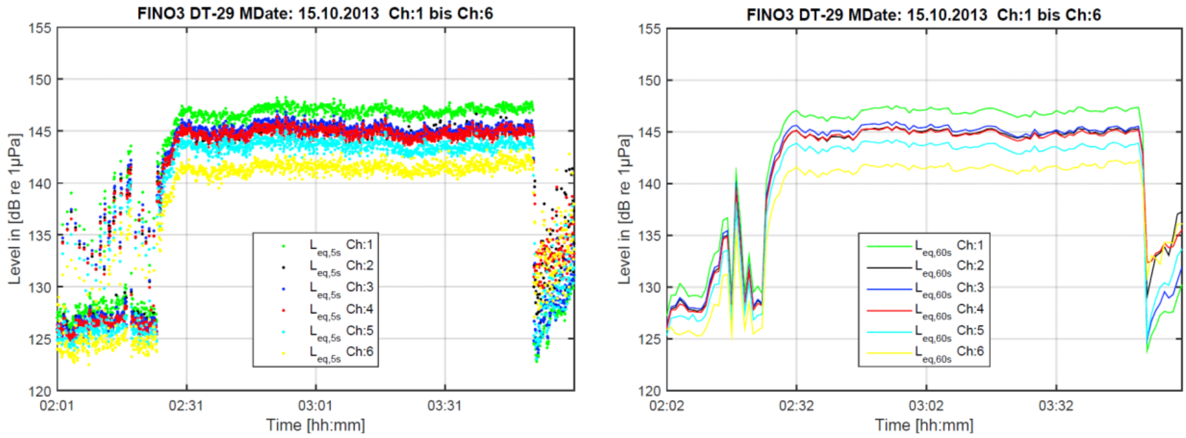

Figure 6 – Calculated equivalent continuous sound levels L_{eq} for pile driving at DanTysk foundation DT29. The values in the left figure were calculated for an averaging time of 5 seconds and the ones in the right figure for an averaging time of 60 seconds.

3.4 Other pile drivings and sound propagation experiments

For the 5 pile drivings that took place after the hydrophone chain was damaged it was difficult to reliably separate electric disturbances from real signals (only hydrophone H1 was OK). Therefore the above analysis could only be performed for 14 other pile drivings. The findings are similar to those reported for DT29. In all cases the sound level was larger at the bottom than at the top. However, the average level differences varied between 0 dB and 7dB. There appears to be a slight tendency for the level difference to decrease with increasing distance between pile driving and FINO3. However, with only 15 measurements the statistical significance is weak. Also note that the top hydrophone was not at the surface but rather about one third of the total water depth below the surface.

For the distances covered in this study which range between 3,8 and 14,6 kilometers it is fair to say that pile driving noise showed a depth dependence at the receiver. The equivalent continuous sound level was higher at the bottom than at the top hydrophone.

It is beyond the scope of this paper to analyse the physical reasons for this observation. This analysis is ongoing. However, we would like to point out that the hydrophone chain at FINO3 was also used as receiver for sound propagation experiments (8,9). The experiments that used acoustic signals that were emitted by an electric underwater transducer and an air-gun also showed a depth dependence of the received sound levels. However, the depth dependence was not identical to the one reported here, but varied significantly with time and the frequency of the signals.

4. PRELIMANARY CONCLUSIONS

One part of the ongoing research project carried out by WTD 71 at the research platform FINO3 was to investigate the depth dependence of the received pile driving noise. To this end an acoustic measurement system was designed. The system performed well but was damaged twice by events that could not be prevented and against which the system could not have been protected.

15 pile drivings at the offshore-wind farms have been analysed with respect to the question at hand. In all cases a depth dependence was observed with the highest sound levels being recorded at the bottom hydrophone. Again note that there were no measurements in the top third of the water column.

The next step is to analyse and perhaps even reproduce the measurements with sound propagation simulations. Furthermore it would be very helpful to compare our measurements with those carried out as part of the required sound monitoring at a distance of 750 meters from the pile. Also we are comparing the recordings of pile driving noise with sound produced by an air-gun which turned out to be very similar in frequency content (9).

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