Measurements of Construction Noise During Pile Driving of Offshore Research Platforms and Wind Farms

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Introduction

Offshore wind turbines and many offshore and port constructions are founded by means of pile driving. Impact pile drivers cause strong impulsive underwater noise that is potentially harmful to the marine environment, in particular to marine mammals. This paper discusses possible noise mitigation methods and presents measurements thereto.

Properties of underwater piling noise

Figure 1 shows a typical time function of a pile driving blow. Blow rates are usually 15 to 60 per minute. The total number of blows may vary from 500 to more than 5000, depending on the soil properties and on the required penetration depth of the pile.

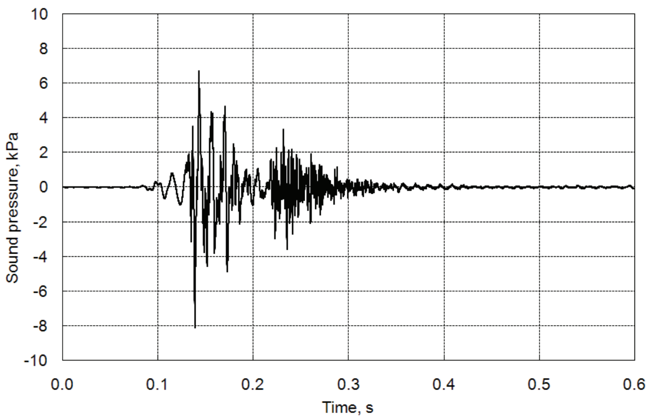

Figure 1: Underwater noise impulse caused by an impact pile driver. Distance = 700 m, pile diameter = 4 m, blow energy = 850 kJ.

Common quantities for describing pile driving noise are

- Sound exposure level SEL:

$$SEL = 10\,log\left(\frac{1}{T_0}\int_{T_1}^{T_2}\frac{p^2}{p_0^2}dt\right)\quad dB, \qquad (1)$$

  where T_1 and T_2 are the (arbitrary) time boundaries of the sound event, i.e. the pile driving blow, and T_0 is 1 s. Reference sound pressure p_0 is 1 µPa. Contrary to the L_{eq}, the SEL is independent of the blow rate (for the strike rates mentioned above, the difference between SEL and L_{eq} is 0 to 6 dB).

- Peak sound pressure p_{peak}, often expressed as peak level $L_{peak} = 20 \log (p_{peak}/p_0)$, where $p_{peak} = \max |p(t)|$, that is, the highest absolute sound pressure observed. Some authors however prefer a "peak-to-peak level".

In Figure 2, measured SELs and peak levels from a number of offshore construction sites are plotted versus pile diameter. The level increase from left to right is not only due to the increase of the radiating surface, but the diameter implicitly also includes the parameter blow energy, since larger piles require larger pile drivers. Levels were normalized to equal distance by adding $15 \log(R_{meas}/750)$, where R_{meas} is the measurement distance (only data measured in a range from 250 m to approx. 1000 m were used for this diagram. The distance of 750 metres is a reference point used in offshore windfarm construction permits in Germany).

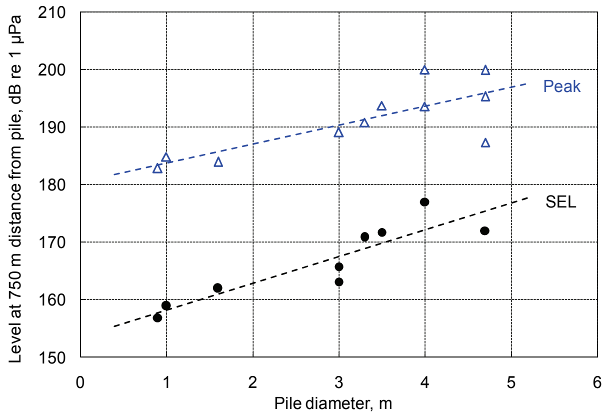

Figure 2: Measured peak levels and broadband SELs versus pile diameter from various pile driving operations [1, 2, 3, 4, 5, 6, 7]

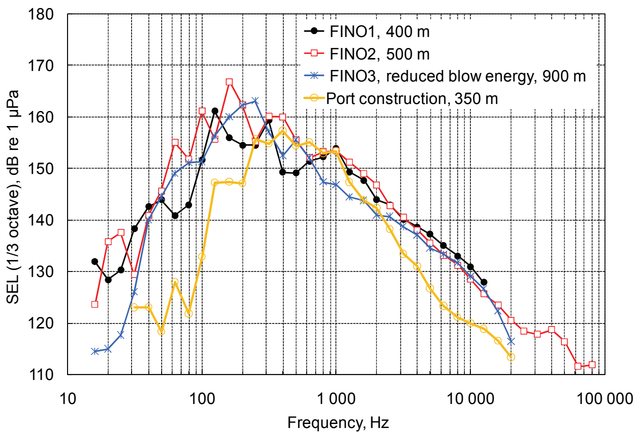

Figure 3: Acoustic spectra of pile driving blows for various measurement distances and pile diameters (FINO1: 1.6 m, FINO2: 3.5 m, FINO3 4.7 m, blow energy reduced to 30% of required value during measurement, Port construction: 1.5 m). All spectra are averages of 10 to 30 blows.

Measured spectra are shown in Figure 3. Their shapes are quite similar, with a maximum between 100 Hz and 400 Hz. The sharper cutoff at lower frequencies of the port construction spectrum is probably due to the peculiarities of sound propagation in shallow water. At 10 m water depth, propagation is limited to frequencies above 70 to 120 Hz [e.g. 8]. The other three spectra were gathered at larger water depths of 24 to 30 m.

Noise mitigation methods

At present, there is no off-the-shelf technique for reducing underwater pile driving noise. Some methods that have been proposed or tested are itemised below.

Vibration pile driver

Vibration pile driving is a proven technique in particular for sheet piles for bulkheads. An eccentric drive induces vertical vibrations of the pile with a frequency of 20 to 40 Hz. It is also possible to drive larger piles as used for offshore wind turbines, but the required penetration depth (35 m are not uncommon) can usually not be reached by means of a vibration pile driver. Furthermore, in order to verify the final stability, an impact pile driver is needed at least at the end of the pile installation process.

Under ideal conditions, only the fundamental frequency and weak harmonics are radiated as sound. Due to nonlinear coupling ("rattling"), however, vibration pile driving is often accompanied by a broad noise spectrum with fluctuating intensity (Figure 4).

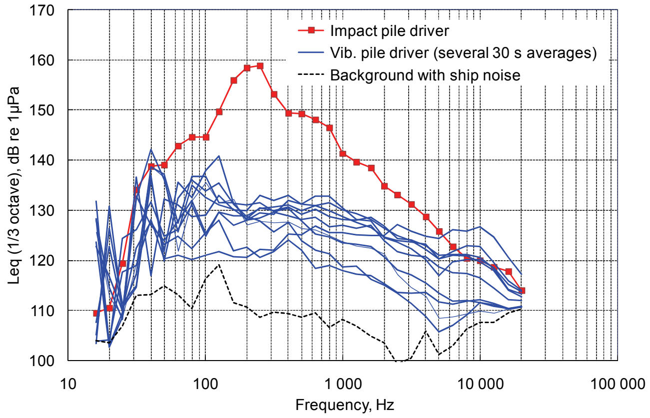

Figure 4: Impact and vibration pile driving of the same pile. Vibrator frequency was about 20 Hz. Pile diameter = 2.6 m, distance = 1200 m.

Noise barrier: Pile sleeve

The pile is surrounded by a sleeve that is made of material with an acoustic impedance that is different from that of the medium ($Z_{water} \approx 1.5 \times 10^6$ kg/m^{2}s). Hence the optimal material is air (or any other gas). Tests have been performed with foam material [9,10]. Also, air-filled double-wall structures and sleeves made of air-filled hoses have been proposed [11].

While the method is simple in principle, the installation and removal of a pile sleeve is difficult to integrate into the working procedure at sea. Once the pile is adjusted in the piling gate, it is hardly feasible to impose a sleeve on it. The ballast needed to compensate for the buoyancy of the air-filled structures makes the sleeve quite heavy; for a system that can be used at 25 m water depth, a weight in air of at least 60 tons has been estimated [11]. Finally, for tripod and jacket foundations – framework structures with three or four legs, that are "nailed" to the sea bottom with piles –, a closed screen without acoustic leakage is difficult to apply.

Noise barrier: Bubble curtain

Sound propagating in water with gas bubbles is subject to a stronger sound attenuation than in pure water. The effect is caused by scattering from resonant bubbles. At the resonant frequency, a bubble appears much larger than its actual geometrical size to an incident wave. The resonance frequency is approximately given by

$$f_R = \frac{3.25}{r}\sqrt{1 + 0.1\,h}\,, \tag{2}$$

where r is the bubble radius and h the water depth in metres. Sound attenuation values for bubbly water computed according to [12] are shown in Figure 5. A parameter that is difficult to assess is damping of the bubble oscillation; hence actual resonance curves may be wider. In addition, common theories of sound propagation in bubbly water make a number of simplifications, e.g. spherical bubble shape (only true for very small bubbles) and widely spaced bubbles (no interaction effects).

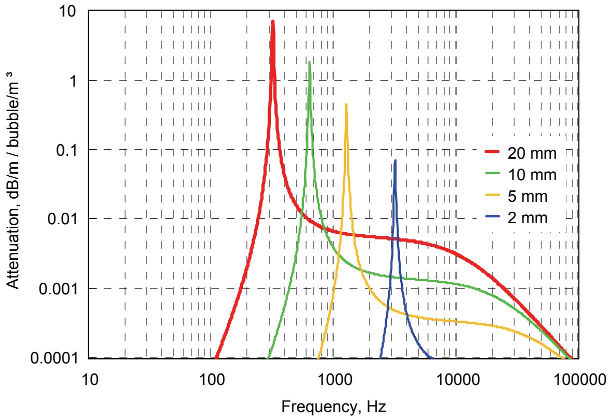

Figure 5: Theoretical sound attenuation in bubbly water near the surface (hydrostatic pressure ≈ 10^5 Pa); values in dB per metre propagation path and for a concentration of one bubble per m^3. Parameter: Bubble diameter.

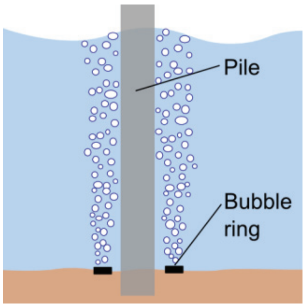

Figure 6: Bubble curtain.

The sound attenuation due to gas bubbles can be utilised for building noise barriers. The principle of such a bubble curtain is sketched in Figure 6. Practical problems include the control of bubble size distribution and the production of a sufficient number of large bubbles (several cm), which are necessary to achieve efficacy at low frequencies. The major difficulty is to avoid acoustic leakage due to bubble drift, especially because of tide current. In the North Sea, currents of up to 1 m/s are not uncommon, while the rise velocity of the bubbles is typically 0.3 m/s.

Gravity foundation

This is an example for an entirely different installation method that does not require pile driving. Pre-manufactured concrete structures are placed on the sea bottom. The technique has been used for e.g. the Nysted wind farm in Denmark, but in general it has been disregarded in favour of steel constructions. Now it is apparently undergoing a revival; at least one construction company is currently erecting facilities for building gravity foundations for offshore wind turbines.

Offshore test of a bubble curtain

In July 2008, a bubble curtain has been established during pile driving operations for the FINO 3 research platform [13]. In order to avoid problems with bubble drift due to water currents, the bubble line was installed at a radius of 70 m around the pile position. The system was set up by Hydrotechnik Lübeck GmbH and used 9 compressors, delivering approx. 0.4 m^3/s of air per metre bubble curtain length. Water depth at the construction site was about 25 m.

Sound levels were measured simultaneously from two points, position A at 900 m from the pile and position B at 270 m and in a different direction. At A, an autonomous recording buoy was used, while measurement B was done from board a ship. At the end of the installation process, some experiments with and without bubbles could be made with reduced strike energy (160 kJ in this case). Broadband levels a shown in Figure 7, corresponding spectra in Figure 8. The broadband level was reduced by the bubbles by 7 to 12 dB depending on the direction, which indicates some inhomogeneities of the bubble curtain.

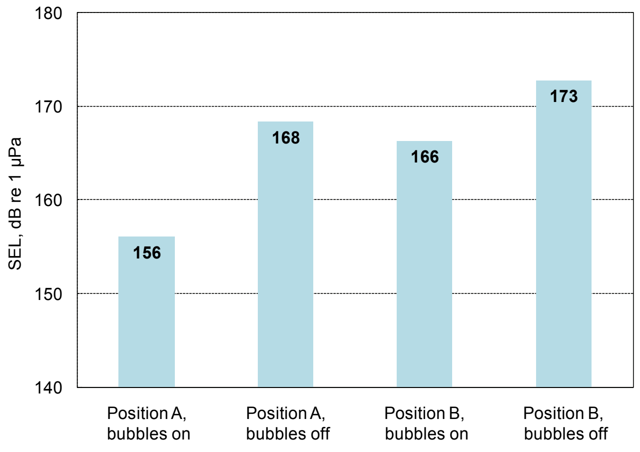

Figure 7: Broadband SEL with and without bubbles at two positions (average levels from 20 strikes)

Not much literature exists on the acoustic efficacy of other bubble curtain installations. In Figure 9, the noise reduction versus frequency at FINO3 is compared to some of the available data. Würsig et al. [14] used a similar air supply of 0.25 m^3/s per metre bubble curtain, while air flow at the other installations was 3.6 m^3/s to at least 14 m^3/s. A further difference is that Reyff [16] and Rodkin & Reyff [17] used vertically stacked constructions of two or five bubble rings, respectively.

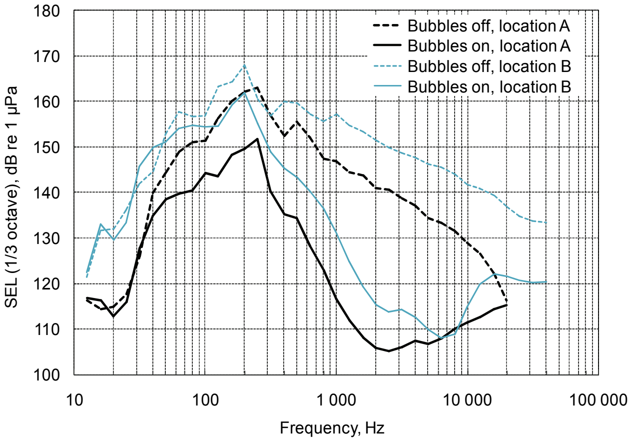

Figure 8: Spectra with and without bubbles at two positions (average levels from 20 strikes)

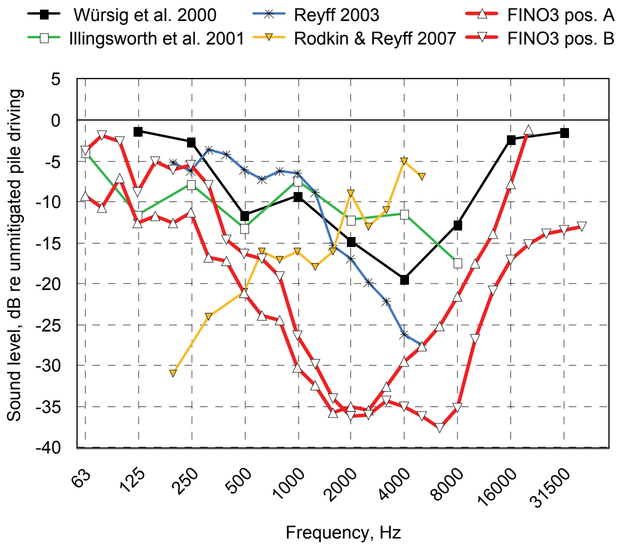

Figure 9: Spectral efficacy of bubble curtain at FINO 3 compared to some literature data [14, 15, 16, 17]

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