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Subject Calculation of the number of porpoises potentially disturbed by offshore vibropiling noise

Date
21 December 2023
Our reference
2023 M12655
Project nr.
060.55665/01.23.01

1. Introduction

The underwater noise produced during the construction of offshore wind farms disturbs marine life [1]. To reduce the effects of such disturbance, the site decisions for offshore wind farm development include a requirement to limit the underwater noise from percussive piling for wind turbine foundations. Annex B of the Netherlands' Framework for Assessing Ecological and Cumulative Effects (KEC 4.0) [2] describes the procedure that was applied to derive these limits from the ecological standard set by the Netherlands' government to protect the harbour porpoise population on the North Sea.

The KEC 4.0 procedure focuses on the impulsive sound produced by percussive piling with a hydraulic impact hammer, which is the most used installation technique for offshore wind turbines. Various techniques are available to reduce this sound, by modifying the hammer impact force on the pile and by application of noise abatement systems such as bubble curtains [3].

Alternative installation techniques, such as vibropiling, produce a different (non-impulsive) type of underwater sound than percussive piling. Nevertheless, the risk that the underwater sound produced by vibropiling disturbs marine life cannot be excluded. The joint industry project 'Sustainable Installation of XXL Monopiles' (SIMOX)[1] aims at accelerating the development of innovative technologies for the installation of XXL monopiles, by means of knowledge development and testing. In this project, TNO has developed a proposed approach for assessing the effect of vibropiling sound on marine mammals. This proposal has been discussed in the Netherlands' working group on marine mammals and underwater sound (WZO), organized by Rijkswaterstaat[2].

Although there are large gaps in knowledge and data to support the proposed approach for assessing the effect of vibropiling sound on marine mammals, it is currently considered to be the 'best available' precautionary approach. Therefore, Rijkswaterstaat has decided to propose using this approach for assessing the potential disturbance of harbour porpoises, until better information becomes available. The criteria are formulated in terms of the maximum allowed total number of '*harbour porpoise disturbance days*', defined as the sum over all piling days of the number of porpoises disturbed per day.

This memorandum describes a staged procedure for calculating the number of *harbour porpoise disturbance days* due to the underwater sound produced by vibropiling for wind turbine foundation piles.

2. Staged procedure

The proposed staged procedure for calculating the number of *harbour porpoise disturbance days* due to the underwater sound produced by vibropiling for wind turbine foundation piles follows the same first four stages as the KEC 4.0 procedure for the impulsive noise produced by percussive piling [2]:

[1] https://grow-offshorewind.nl/project/simox
[2] See https://www.noordzeeloket.nl/publish/pages/220489/bijeenkomst-werkgroep-onderwatergeluid-en-zeezoogdieren.pdf; and https://www.noordzeeloket.nl/publish/pages/220454/presentatie-22-11-2022-simox-tno.pdf

1 Calculation of a realistic worst case for the underwater sound field resulting from vibropiling for one or more representative pile locations in the wind farm;
2 Calculation of the probability of disturbance of porpoises at all field locations, on the basis of the calculated sound level and a dose-effect relationship for the occurrence of a significant behavioural change;
3 Calculation of the number of harbour porpoises disturbed by vibropiling sound per piling day, on the basis of the calculated probability of disturbance and the local density of animals;
4 Calculation of the number of *harbour porpoise disturbance days* by summing the calculated number of disturbed porpoises per day over the disturbance days;

The different stages are discussed in more detail in the following sections.

3. Stage 1: Calculation of vibropiling sound

In KEC 4.0, the impulsive underwater sound produced by impact piling is quantified in terms of a broadband single-strike sound exposure level (SELss, expressed in dB re 1 $\mu Pa^2 s$). This measures the total acoustic energy contained in the pulse. Vibratory pile drivers produce continuous sound. The time-averaged acoustic energy in such sound is quantified in terms of a root-mean-square *sound pressure level* (SPL, expressed in dB re 1 μPa). These terms are defined by the international organization for standardization (ISO) [4].

Vibro-hammers contain eccentric rotating masses (see Figure) that transmit axial vibrations into the pile. The pile vibrations reduce the resistance of the ground surrounding the pile, enabling it to penetrate into the ground. Depending on the composition of the ground, this technique can result in a faster driving with lower peak loads on pile and sediment compared with percussive pile driving.

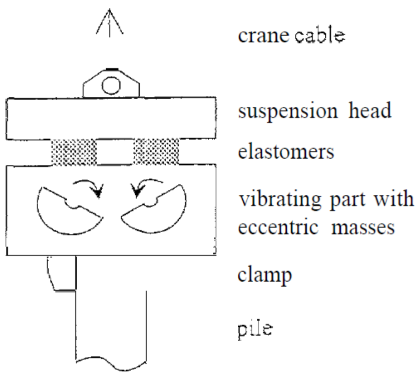


Figure 1 Schematic depiction of a vibratory hammer, from [5]

There is limited information available on underwater sound generated by vibro-piling, see the summary in Annex A. Moreover, there is no measurement standard for vibropiling sound, which makes it difficult to compare published measurement data across studies. The limited available data of underwater sound from vibropiling show that the SPL varies significantly (10-20 dB) over the course of the piling, likely due to variations in the resistance that the pile encounters when penetrating the ground, see e.g., [6]. Vibropiling sound is characterized by a series of tones, in the frequency range roughly between 10 Hz and 1 kHz, at harmonics of the rotating frequency of the eccentric masses in the vibrohammer.

No validated numerical models for vibropiling sound have been found. The presence of the large number of tones in the piling sound spectra indicates that the sinusoidal force produces by the rotating masses in the vibrohammer is distorted, likely due to details in the design of the hammer and its clamping to the pile. More research is needed to understand and quantify these effects.

3.1. Proposed estimation of vibrohammer sound spectrum

It is suggested to use an upscaled version of the vibropiling sound spectrum measured for a smaller pile as a first tentative estimation. Based on the analysis of the limited available data presented in Annex A and an evaluation of unpublished data, this is considered a precautionary worst case estimation.

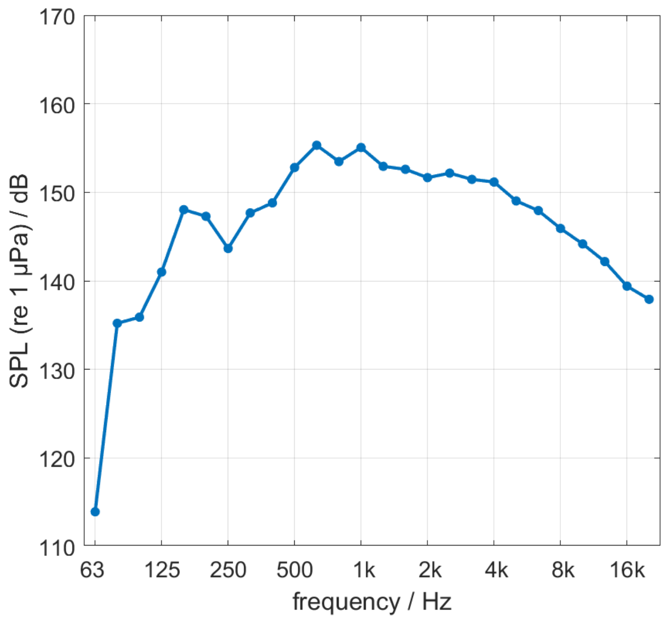
The 10% exceedance level of the SPL spectra measured at a distance of 303 m from the vibration of a truss pole in the Benelux harbour in Rotterdam [7] is proposed as a conservative estimate of vibropiling sound. This pile had a diameter of 1.7 m and was driven with a vibrohammer with an eccentric moment of 110 kg m and a maximum speed of 1350 rpm (~23 Hz). The broadband SPL is consistent with numbers given in the guidelines for estimating the effects of pile drivers (vibrators and impact hammers) on fish, issued by the California Department of Transportation [8], see Annex A.

It can be assumed that the energy of the radiated sound scales in proportion to the kinetic energy of the vibratory hammer. The kinetic energy varies in proportion to the static moment (M) and to the square of the rotational speed (Ω) of the vibratory hammer. It is therefore tentatively suggested that the SPL (with symbol L_p) at a given distance can be scaled according to:

$$L_p^{M,\Omega} \approx L_p^{M_{ref},\Omega_{ref}} + 10\, log_{10}\left(\frac{M}{M_{ref}}\right)\, dB \; + 20\, log_{10}\left(\frac{\Omega}{\Omega_{ref}}\right)\, dB \qquad (1)$$

with M_{ref} and Ω_{ref} the static moment and speed of the hammer for which data are available from previous measurements of the sound pressure level $L_p^{M_{\mathrm{ref}},\Omega_{\mathrm{ref}}}$.

Figure 2 shows the tentatively proposed estimation of the decidecade spectrum of the SPL ($L_p^{M_{\mathrm{ref}},\Omega_{\mathrm{ref}}}$ in dB re 1 µPa) at a distance of 750 m from a monopile vibrated with a hammer with $M_{\mathrm{ref}} = 2560\ \mathrm{kgm}$ and $\Omega_{\mathrm{ref}} = 23\ \mathrm{Hz}$. This can be scaled to other hammer energies using formula (1).



nominal band centre frequency / Hz	SPL (re 1 µ Pa) / dB
63	113.9
80	135.2
100	135.9
125	141.0
160	148.0
200	147.3
250	143.7
315	147.7
400	148.8
500	152.8
630	155.3
800	153.5
1k	155.1
1.25k	152.9
1.6k	152.6
2k	151.7
2.5k	152.2
3.15k	151.5
4k	151.2
5k	149.0
8k	147.9
10k	145.9
12.5k	144.2
16k	142.2
20k	139.4

Figure 2 Tentatively proposed scaled decidecade spectrum of the SPL ($L_p^{M_{\mathrm{ref}},\Omega_{\mathrm{ref}}}$ in dB re 1 µPa) at a distance of 750 m from a monopile vibrated with a hammer with $M_{\mathrm{ref}} = 2560\ \mathrm{kgm}$ and $\Omega_{\mathrm{ref}} = 23\ \mathrm{Hz}$.

3.2. Propagation of vibrohammer sound

It is proposed to calculate the distribution of vibropiling sound on the basis of a prior calculation of the distribution of percussive piling sound. The relative decay of vibrohammer sound with increasing distance from the pile is equal to the decay of percussive piling sound. Both are radiated from vibration waves travelling along the length of the pile. Hence, the single-strike sound exposure level (SELss) spectra calculated for percussive piling can be used as starting point for the calculation of the SPL-spectra for vibropiling. The model applied for calculation of the SELss due to percussive piling should take into account the radiation of sound along the length of the pile, as well as the effects of bathymetry and sediment properties on the underwater sound propagation. TNO used its Aquarius 4.0 piling sound model [9] in studies for the environmental impact assessment for offshore wind farm sites, as well as for the cumulative impact assessment of the underwater sound from percussive piling for offshore wind farm developments on the North Sea. Table 1 shows the typical environmental parameters used for these studies. Sound calculations are performed at the decidecade band centre frequencies, taking the maximum values of the sound levels over 10 receiver positions uniformly distributed over the water depth.

The frequency spectrum of the transmission loss (TL; symbol ΔL_{TL}) between the sound level field around the pile and the sound level at a reference position (x_{ref}, at 750 m from the pile) is the same for the SELss (symbol L_E) from impact piling and the SPL (symbol L_p) from vibropiling:

$$\Delta L_{\mathrm{TL}}(x,f) = L_E(x,f) - L_E(x_{\mathrm{ref}},f) = L_p(x,f) - L_p(x_{\mathrm{ref}},f) \quad (2)$$

Hence, SPL field due to vibropiling is calculated from the SELss field from the Aquarius calculations for impact piling and the scaled SPL spectrum for vibropiling at 750 m from the same pile location:

$$L_p(x,f) = L_p(x_{\mathrm{ref}},f) + \Delta L_{\mathrm{TL}}(x,f) \quad (3)$$

Table 1: Environmental parameters for sound propagation calculations

Parameter	Value
Water depth	EMODnet bathymetry, 1/8 minute resolution, http://www.emodnet-bathymetry.eu/
Seabed type	'medium sand' ([10]; Table 4.18; $\phi = 1.5$)
Sediment sound speed	1797 m/s
Sediment density	2136 kg/m³
Sediment absorption [de Jong et al, 2018]	0,88 dB/wavelength for $f \geq 250$ Hz $\left(\frac{f}{250\ \mathrm{Hz}}\right)^{0.8} \times$ 0,88 dB/wavelength for $f < 250$ Hz
Sea water sound speed	1500 m/s
Sea water density	1024 kg/m³
Wind speed (10 m height)	0 m/s

Alternative modelling approaches and model input data are acceptable, provided that these are clearly described and substantiated with evidence of model verification and validation.

4. Stage 2: Calculation of porpoise disturbance

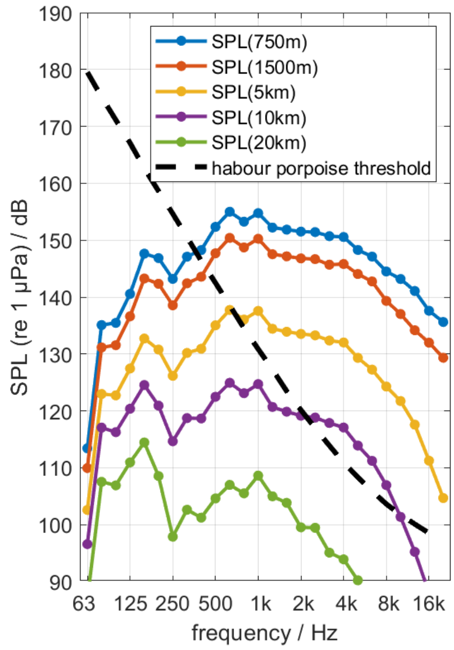
Criteria for disturbance of marine mammals by continuous underwater noise are still being developed, see [11]. In the meantime, the approach proposed by [12], see also [13], is tentatively adopted here. Based on the limited data available, it is provisionally assumed that the behaviour of a harbour porpoises is significantly disturbed when it is exposed to sound pressure levels that are 45 dB higher than the hearing threshold, in any of the bands in the decidecade frequency spectrum. Because the measurement of hearing thresholds is not standardized and published data do not always overlap, it is proposed to use the generalized audiogram from [14] for 'very high-frequency cetaceans' (VHF) plus 45 dB as preliminary disturbance threshold for harbour porpoises.

This tentative approach differs from the approach for percussive piling in two aspects:

- the proposed dose-response function for continuous sound is simpler than the S-curve derived for impact piling sound exposure. It is either zero, for sound exposure at an SPL below the threshold, or one, for sound exposure at an SPL above the threshold.
- the proposed dose-response function for continuous sound does take into account the frequency content of the sound exposure, while the dose-response function for piling sound is based on the unweighted broadband SELss.

The different approaches are mainly driven by data availability, which is extremely limited for vibropiling, and by suggestions from the peer-reviewed literature.

Figure 2 shows the spectrum of the proposed threshold for porpoise disturbance by vibropiling sound.



nominal band centre frequency / Hz	porpoise threshold SPL (re 1 μ Pa) / dB
63	179.5
80	175.2
100	171.1
125	167.1
160	162.6
200	158.6
250	154.6
315	150.6
400	146.4
500	142.5
630	138.5
800	134.5
1k	130.9
1.25k	127.3
1.6k	123.5
2k	120.2
2.5k	117.0
3.15k	113.9
4k	110.9
5k	108.3
8k	105.9
10k	103.6
12.5k	101.8
16k	100.1
20k	98.5

Figure 3 Tentatively proposed decidecade spectrum of the SPL (in dB re 1 μPa) above which harbour porpoises are disturbed by vibropiling sound (black dashed line), based on [12] and [14]. Compared with an example of calculated SPL spectra at various distances of a pile in the IJmuiden Ver area, using the SPL at 750 m shown in Figure 2.

Figure 3 provides an example of a comparison of the calculated SPL at various distances from the pile with the proposed threshold for disturbing harbour porpoises. In this example, the disturbance extends beyond 10 km from the pile, where the SPL exceeds the threshold between 2.5 and 8 kHz. At 20 km distance the SPL is well below the threshold, which suggests that the vibropiling sound does not disturb porpoises at that distance. For final application of the proposed approach for calculating harbour porpoise disturbance, the energy of the vibrohammer and the sound propagation need to be adapted to the proposed wind farm installation.

Similar to the KEC procedure for percussive piling, potential masking of the piling sound by background sound is not taken into account in the assessment. This leads to a precautionary assessment of the probability of disturbance.

5. Stage 3: Calculation of number of disturbed porpoises

This stage is the same as in the KEC 4.0 approach for percussive piling sound. The number of harbour porpoises disturbed by vibropiling sound per piling day is calculated by multiplying the calculated probability of disturbance (zero where the SPL is below the threshold and one where the SPL exceeds the threshold) map with an appropriate porpoise density map and then integrating that product over the map area.

KEC 4.0 proposes using the harbour porpoise density map compiled by ITAW for Rijkswaterstaat, see [15]. This is an update of an earlier summer density map, supplemented with data from the 2016 SCAN-III survey and annual summer censuses from Belgium, the Netherlands (by WMR), Germany and Denmark for the period 2014 – 2019. Due to the lack of current maps for the other seasons, it to follow KEC 4 and tentatively use the average summer density map from [15] for the entire year. The same map will have to be used as used in the project-specific site decision and the EIA.

6. Stage 4: Calculation of porpoise disturbance days

The total number of porpoise disturbance days resulting from the construction of a wind farm is the sum of the number of disturbed porpoises for each of the calendar days on which foundation-installation takes place. If each foundation installation is done on a different calendar day and produces the same amount of (mitigated) noise, then the total number equals the number of monopiles times the number of disturbed porpoises per installation day.

7. Concluding remarks

This memorandum presents a proposed approach for calculating the cumulative effects of the underwater noise produced by offshore vibropiling on harbour porpoises, taking into account the site decision and the specific requirements for this installation technique. Although there are large gaps in knowledge and data to support the proposed approach, it is currently considered to be the 'best available' precautionary approach. Data gathered during future vibropiling for wind turbine foundation installations will enable further research, that may lead to an updated approach.

8. References

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Annex A: Estimation of vibropiling sound levels

Limited information on vibropiling sound has been found in the literature.

1. In 2014, [16] published a study of the underwater noise measured during vibrating foundation piles for the Hong Kong-Zhuhai-Macao bridge with the (then) largest vibratory hammer in the world (OCTA-KONG). It was made up of 8 APE 600 hammers with a static moment of 199 kg m each and a maximum speed of 1350 rpm (~23 Hz). This involved driving steel cylinders with a diameter of 22 m into a riverbed (water depth about 8-9 m). In this study, a broadband SPL of 140 – 150 dB re 1 μPa² was measured at a distance of 60 to 80 m from the pile.

2. In 2015, the California Department of Transportation issued guidelines for estimating the effects of pile drivers (vibrators and impact hammers) on fish, see [8]. This includes an overview of previously measured sound pressure levels at 10 m distance from vibrated piles with diameters up to 1.8 m, see Table A-1. These numbers give a first impression of the sound produced by vibratory driving of relatively small piles in shallow water. The tables in [8] do not provide information on the type and size of the vibrohammer.

Table A-1: Underwater sound levels at 10 m distance from vibrated piles, after [8].

Pile type	approximate diameter	Water depth	SPL re 1 μPa
Steel pipe pile	0.3 m	<5 m	155 dB
Steel pipe pile (typical)	1 m	~5 m	170 dB
Steel pipe pile (loudest)	1 m	~5 m	175 dB
Steel pipe pile (typical)	1.8 m	~5 m	170 dB
Steel pipe pile (loudest)	1.8 m	~5 m	180 dB

3. In 2018, TNO carried out underwater noise measurements during the vibration of a truss pole in the Benelux harbour in Rotterdam [7]. This pile had a diameter of 1.7 m and was driven with a PVE-110M vibrohammer, with an eccentric moment of 110 kg m and a maximum speed of 1350 rpm (~23 Hz). The water depth in the Benelux harbour varies from about 10 meters close to the source and to about 20 meters in the Calandkanaal. Figure A-1 gives an overview of measured decidecade spectra of the underwater sound (SPL).

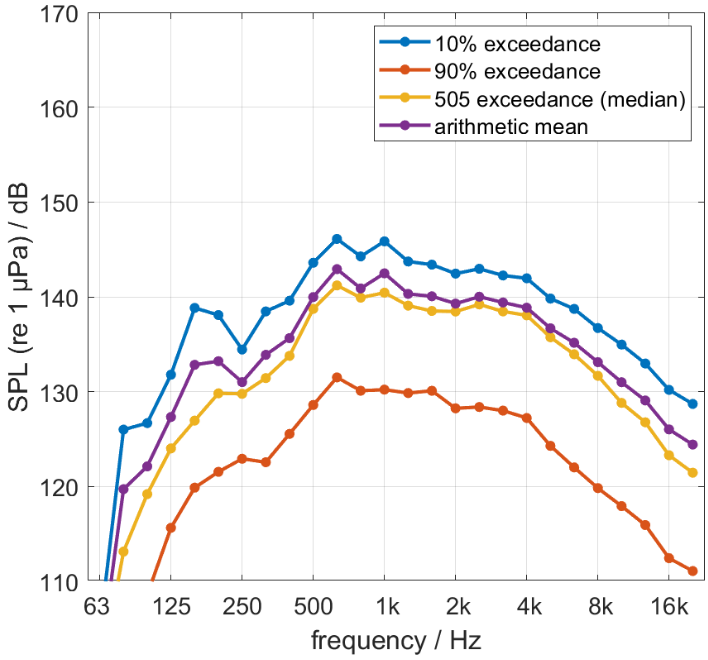

Figure A-1: Overview of the measured underwater noise (SPL, Δt=0.2482 s) at a distance of 303 m from the vibration of a mooring pole in water in the Benelux harbour in Rotterdam, from [7]. The broadband $SPL_{10\%}$ (the sound level that was exceeded no more than 10% of the time) is 155 dB re 1 µPa.

How these data translate to the larger pile diameters foreseen for the wind turbine foundations for the IJmuiden Ver wind farm is not clear. A first estimation is given on the basis of the assumption that the energy of the radiated sound scales in proportion to the kinetic energy of the vibratory hammer. That energy varies with the eccentric moment (M) and the square of the speed (Ω) of the vibratory hammer. It is therefore tentatively suggested that the SPL (with symbol L_p) at a given distance could be scaled according to:

$$L_p^{M,\mathrm{W}} \approx L_p^{M_{\mathrm{ref}},\Omega_{\mathrm{ref}}} + 10\log_{10}\left(\frac{M}{M_{\mathrm{ref}}}\right)\,\mathrm{dB} + 20\log_{10}\left(\frac{\Omega}{\Omega_{\mathrm{ref}}}\right)\,\mathrm{dB} \qquad \text{(A-1)}$$

with M_{ref} and Ω_{ref} the eccentric moment and speed of the hammer for which the SPL has been measured previously.

The Caltrans guidelines suggest a typical SPL of 170 dB re 1 µPa at 10 m when vibrating a 1.8 m diameter pile. The measurements in the Benelux harbour (Figure A-1) were for a similar pile diameter (1.7 m) but measured at a lager distance (303 m).

The SPL decreases with increasing distance from the pile, due to geometrical spreading and interaction with seabed and water surface. The damped cylindrical spreading model proposed by [17] provides a useful scaling for the SPL measured at distance r_1 to distance r, for distances up to about 4 to 5 km from the pile:

$$L_p(r) = L_p(r_1) - 10\log_{10}\left(\frac{r}{r_1}\right)\mathrm{dB} - \alpha(r - r_1) \qquad \text{(A-2)}$$

Based on data in [Lippert et al, 2018] the absorption term α can be estimated at α≈1.5 dB/km for North Sea locations.

Using equation (A-2), the SPL at 10 m of a typical 1.8 m diameter pipe pile according to [8], see Table A-1, is predicted to be SPL ≈ 155 dB re 1 µPa at 303 m. This agrees well with the broadband SPL measured at 303 m from the pile in the Benelux harbour [7]. This gives confidence in the transmission loss prediction by the damped cylindrical spreading model as well as in the representativeness of the measurements in the Benelux harbour.

The scaling with hammer energy is tested by the comparison with the measurement data for the Hong Kong vibropiling. The total static moment of the OCTA-KONG (8×199 kg m) is approximately 14 times greater than that of the vibratory hammer on the pile in the Benelux harbour. Applying formula (A-1) to tentatively scale the SPL measured in the Benelux harbour to the configuration in Hong Kong leads to an estimated broadband SPL at 300 m from the pile of approximately 166 dB re 1 µPa. Using equation (A-2), the SPL at 60 to 80 m from the pile, the measurement distance in Hong Kong, is estimated at 172 to 173 dB re 1 µPa. According to [16], the broadband SPL measured in Hong Kong is significantly (more than 20 dB) lower than this estimate. The difference cannot be explained from the limited available information. One source of uncertainty is that the estimation does not account for differences in the SPL spectra for these two cases. Due to the relatively shallow water in which these spectra have been measured, where the sound at low frequencies does not propagate well, the data do not include the low frequency (below ~100 Hz) sound emitted by the vibropiling. This is considered acceptable because harbour porpoises are insensitive to such low frequency sound.

Hence, the proposed estimation of the SPL from vibropiling based on scaling with the hammer energy is uncertain. There is a clear need for measurement data of underwater sound from vibropiling of wind turbine foundation piles. Nevertheless, as long as no better data are available, the Rotterdam piling data are proposed as a tentative worst-case approximation for vibropiling sound levels, for precautionary environmental impact assessment.