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Underwater acoustics — Measurement of radiated underwater sound from percussive pile driving — In situ determination of the insertion loss of barrier control measures underwater

Acoustique sous-marine — Mesurage de l'émission sonore sous-marine lors de l'enfoncement de pieux marins par percussion — Détermination in situ de la perte par insertion de barrières sous-marines

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Foreword

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This document was prepared by Technical Committee ISO/TC 43, *Acoustics*, Subcommittee SC 3, *Underwater acoustics*.

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Introduction

Within the scope of approval and licensing procedures for offshore wind energy farms worldwide an assessment is required of whether sound caused by the construction, operation and demolition of wind energy farms represents a possible hazard for the marine environment. To reduce the noise output effective noise abatement systems (noise control measures underwater) can be used to protect the marine environment, see References [12] to [25].

Examples of noise-generating activities are pile driving (e.g. by impact hammer) or pile extraction. Examples for noise abatement systems are bubble curtains and cofferdams whose acoustic efficiency can be demonstrated by applying the methodology described in this document.

This document describes measuring methods for the in situ characterization of the effectiveness of noise abatement systems underwater. The acoustic effectiveness of a system can be derived from measurements carried out with and without the considered noise abatement system, e.g. References [10] and [11]. This acoustic effectiveness of the system is given as insertion loss.

The principles of the method can also be applied in other cases such as construction of docks, piers, wharfs, bridge supports, etc., a procedure is described in Annex A. Sound particle motion and seabed vibration are of increasing interest in ocean acoustics and are dealt with in Annex B.

In general, in acoustic underwater measurements, the influences of the noise source and the noise propagation cannot be completely separated. For example, the soil properties have a direct influence on the noise source. Another influence is the sound propagation and sound radiation via the sea bottom.

Results acquired in accordance with this specification are necessary and useful for

— comparison with acoustical specifications, e.g. within the scope of approval procedures,

— comparison with different noise abatement systems, and

— further development and improvement of noise abatement systems.

Underwater acoustics — Measurement of radiated underwater sound from percussive pile driving — In situ determination of the insertion loss of barrier control measures underwater

1 Scope

This document specifies two procedures for the in situ determination of the insertion loss of underwater noise abatement measures (noise abatement systems). The impulsive sound of pile driving is used as the sound source for the investigation of noise abatement systems. This document does not apply to artificial sound sources and investigations under laboratory conditions.

Apart from the correct application of the respective noise abatement system, the achieved sound attenuation also depends on the installation conditions (e.g. type of hammer, driving energy, pile dimensioning) as well as on the environmental conditions (e.g. water depth, seafloor classification and bathymetry, current and wind conditions) and the flanking transmission via the seafloor.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 18405, *Underwater acoustics — Terminology*

ISO 18406:2017, *Underwater acoustics — Measurement of radiated underwater sound from percussive pile driving*

3 Terms and definitions

For the purpose of this document, the terms and definitions given in ISO 18405, ISO 18406 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

3.1
insertion loss of barriers
$D_p(f)$
difference, in sound pressure levels at a specified receiver position before and after the installation of a barrier

Note 1 to entry: $D_p(f)$ is the sound pressure level without barrier minus the sound pressure level with barrier, in one-third octave (base 10) bands. According to ISO 18405, an alternative name for one-third octave (base 10) is decidecade.

Note 2 to entry: The sound pressure level is determined over multiple pulses.

Note 3 to entry: The insertion loss can also be calculated with sound exposure level. The results are identical to the calculations with sound pressure level using the same integration time T.

Note 4 to entry: For calculation of insertion loss, see 7.3.

Note 5 to entry: Insertion loss is expressed in decibels.

[SOURCE: ISO 10847:1997, 3.5, modified — Abbreviation modified and Notes 1 to 4 to entry added.]

3.2
noise abatement system
mitigation measure that attenuates the sound output from the sound source

Note 1 to entry: There are near-pile noise abatement systems, such as cofferdams, where a pipe is built into the water enclosing the pile and the water is pumped out between the pile and the pipe. Applications away from the pile are mostly bubble curtains, see References [12] to [25].

3.3
flanking transmission
transmission of sound from a source (pile) to receiver point but not via the *noise abatement system* (3.2)

[SOURCE: IEC 60050-801-31-40:1994, modified — Term from building acoustics, changed for underwater applications.]

4 Instrumentation

4.1 General information

Clause 4 describes relevant information on instrumentation for underwater measurements. ISO 18406 provides further considerable details on the type of measurements and instrumentation.

4.2 Hydrophones and analysers

The measurement chain for hydroacoustic measurements consists of the following components:

— omnidirectional hydrophone (with preamplifier) with a constant sensitivity that deviates by less than 2 dB over the analysed frequency range;

— analogue high-pass filter (which may be integrated in the measuring amplifier) to limit the low-frequency dynamics of the measuring data;

— measuring device, including the possibility to record time raw data, consisting of low-pass filters (anti-aliasing filters), amplifiers, and A/D converters;

— cables, connecting components, etc.

Furthermore, the following test equipment, devices and recording equipment are required:

— pistonphone for checking the calibration of the hydrophone measuring chain before and after each measurement;

— distance meter (e.g. laser, GPS based);

— equipment to record the data required to determine the sound speed profile (sound speed as a function of depth). For example, CTD sensors are used to determine the temperature, conductivity and the depth below the water surface at the CTD probe. With the measured quantities the sound speed profile can be determined.

4.3 Analysis software

For data post-processing and evaluation, an analysis software is required which comprises the following methods:

— one-third octave (base 10) bands analysis, with the filters corresponding to the requirements in IEC 61260-1;

— narrow-band analysis;

— time averaging.

Filtering may be accomplished using analogue electronic filters, but is more commonly undertaken using digital processing. The digital methods can either utilise implementations of digital filters, or may be achieved by aggregating levels in the frequency domain over the requisite bands (subsequent to a Fourier transform of the time-domain waveform).

Data processing can also be carried out within the measuring device.

4.4 Calibration

The organization performing the measurements shall make sure that the devices of the acoustic measuring chain (including hydrophones) are calibrated traceable to appropriate standards using a suitable method (IEC 60565-1 and IEC 60565-2).

The calibration interval shall be 24 months at maximum. The required calibration certificates shall be kept available for at least 10 years.

5 Methods

5.1 General remarks

Two methods are common for the in situ characterization of noise abatement systems underwater: the direct method (see 5.4) and the indirect method (see 5.5).

5.2 Comparability of measurements

Two methods are described in this document. Both have the objective to determine the in situ insertion loss of an underwater noise abatement system. The descriptions for both approaches are to ensure that excitation and conditions of the sound source as well as transmission properties to the hydrophone positions are comparable for the situation with and without noise mitigation system.

In the following, parameters are listed that could have an influence on the direct and indirect measurements:

a) configuration and pile characteristics relating to

  — pile geometry (e.g. diameter, length, wall thickness distribution),

  — material,

  — pile head design (e.g. flange), and

  — slant angle to the seabed;

b) environmental conditions:

  — water depth at pile and hydrophone location and in between pile and hydrophone (bathymetry);

  — distance between pile and noise mitigation system;

  — distance between hydrophone and noise mitigation system;

  — hydrophone depth;

  — properties and layering of the seabed, cpt (cone penetration test) values at site;

  — ocean current[27];

  — wind conditions[27];

- significant wave height[27] and direction;
- swell height[27] and direction;

c) operating conditions:

- type of pile driver (e.g. manufacturer, driving/rotational mass, maximum blow energy/operating frequency);
- type of force-conducting connecting elements between pile driver and pile (e.g. anvil);
- hammer energy;
- pulse repetition rate;
- penetration depth;
- number of blows in the noise measurement period.

Any changes in the above conditions that occur between measurements with and without the noise attenuation in place shall be determined and documented.

To ensure comparability of measurements between the unmitigated and mitigated situation, these parameters should all be sufficiently equal.

Ideal equal conditions cannot always be achieved, so quantitative minimum requirements are listed below:

- pile material should be equal, and pile and pile head geometry should not differ more than 10 %;
- flat bathymetry is required: the variation in water depth should not exceed 10 % between source and measurement site;
- measurement geometry (distance between noise mitigation measure and hydrophones to pile and hydrophone depths should not differ more than 10 %);
- hammer energy and pulse repetition rate should not differ more than 10 %.

The combined standard uncertainty should remain <20 %, so that the error in the determination of the insertion loss is <1 dB, see also 7.4 on the uncertainty of measurement according to ISO/IEC Guide 98-3.

NOTE 1 Experience shows that the background noise which includes self-noise of the hydrophone measurement device including mooring concept and measurement device can limit the validity of the determination of the in situ insertion loss. In concrete terms, this means that the noise abatement system used can have a higher insertion loss than can be verified by measurement. However, this case would be excluded if requirement 5.3. is considered.

NOTE 2 The measurements describe an in situ "insertion loss". The in situ determined insertion loss is therefore dependent on the environmental parameters and the selected measurement configuration. Thus, for each measurement report, the validity range is documented by representations of the above-mentioned parameters, see also Clause 8.

NOTE 3 The parameters water depth, wind, significant wave height and current are important for the documentation of acoustic measures such as the bubble curtain, as the properties can be/are influenced by these parameters. Up to a significant wave height (Hs) of 2 m, no relevant effects on the performance of the noise abatement systems are known from experience. For currents above ~0,75 m/s (and water depths up to ~40 m), experience has shown that the noise reduction in the direction of flow decreases significantly due to drift effects, see Reference [24].

NOTE 4 The parameter soil or soil layering is fundamentally important to document for all noise abatement systems, as this parameter can influence the properties of the insertion loss determined in situ.

5.3 Background noise

According to ISO 18406, the background noise is all sound recorded by the hydrophone in the absence of the pile driving signal for a specified pile driving signal being measured. The sound pressure level of the sound source shall be high enough to create a sound pressure level at the measuring location which exceeds – with and without the respective noise abatement system – the background noise level in the frequency bands of interest by at least 6 dB, or 10 dB ideally, (see 7.2). Background noise such as chain rattling (anchor chains), pitching noise caused by sea state, ship aggregates, or movement of crew, sea markers, buoys, etc., in the immediate vicinity of the measurement device shall be avoided. Background noise shall be recorded and documented. If additional noise is caused by the operation of the respective measure, it shall also be recorded and documented.

Background noise measurements shall be performed before and after each single measurement with and without sound mitigation measure to record the time-dependent change of the noise at least for 10 minutes.

5.4 Measurements on one single pile (direct method)

The measurement is performed on one pile and consists of two parts which are carried out in quick succession to reduce the influence of the pile penetration depth on the sound radiation. One of the measurement setups described in 6.4 is used for this kind of measurement. Firstly, the measurement is preferably performed without the noise mitigation measure while the pile driver is running (see 6.2). After these measurements, the noise mitigation measure is put into operation, and the measurement is repeated with active noise abatement system. Comparability of the conditions without and with noise control measure shall be ensured (see 5.2).

Advantage of this measuring method: For both parts of the measurement the comparability of the conditions can easily be ensured if both the penetration depth of the pile and the coupled seabed layers are comparable during both measurements.

Disadvantage of this measuring method: Only a short period can be evaluated for each of the two measurements to be compared to fulfil the requirement of comparable penetration depth. The propagation conditions underwater before, on and after activation of the noise abatement system vary. Statements on changed flanking transmission, depending on penetration depth, soil layer, etc., can only be made if comparing measurements are carried out for different penetration depths.

5.5 Measurements on two different piles (indirect method)

This type of measurement is based on carrying out two measurements at two different piles, where both measuring positions shall have the same distance to the respective pile (6.3.3). One measurement shall be carried out at the pile without the noise abatement system (measure not applied), and another measurement is carried out at the pile with the noise abatement system (measure applied) according to one of the measurement setups described in 6.4. For this method, it is necessary that the environmental conditions and the measurement setup for both separate measurements are comparable (see 5.2).

Advantage of this measuring method: Taking into account the environmental and acoustical conditions, this method can be used to evaluate the insertion loss for the whole pile-driving process (with and without measure applied) and not only for a short period as described in 5.4.

Disadvantage of this measuring method: It is unlikely that completely identical conditions exist at the two different measuring locations. Especially the flanking transmission of sound via the seafloor can have an influence on the results and increase the uncertainty of the judgement concerning the effectiveness of the noise abatement system. Additionally, different soil conditions can lead to changed radiation characteristics of the source.

6 Measurement procedure

6.1 General remarks

The measuring positions are linked to the installation process and to the basic conditions dictated by the acoustical environment. For security reasons and to avoid a measurement in the acoustic near field, a minimum distance of the acoustic measuring system to the pile-driving location (safety zone) shall be observed. According to ISO 18406 a preferable distance to the pile is 750 m. See Annex A for minimum monitoring distance requirements for near shore applications.

6.2 Chronological order of the measurements

If the acoustic conditions can be influenced by the noise abatement system after switching it off or removing it (e.g. due to air transferred into the water in the form of bubble curtains and changing the sound propagation due to the air/water mixture (impedance)), measurements shall be taken first without and then with noise mitigation measure.

6.3 Measuring positions

6.3.1 General

The selection of the measuring positions depends on the respective task. The following compilation describes the minimum number of measuring positions and hydrophones and proposes an extension of the measurement setup. The parameters of the measuring positions shall be defined and documented. Examples for measurement setups are given in 6.4.

6.3.2 Number of hydrophones/measuring positions

First of all, it shall be checked whether a dependence on the directivity of the radiated sound (due to the source or the noise mitigation measure) is to be expected. To estimate these factors, the parameters given in 5.2 shall be verified. Such measures are, for example, bubble curtains in current, or a measurement setup with a bathymetry strongly depending on the respective measuring direction. If there is no prior knowledge about the directivity, at least two measuring directions and two different measurement depths shall be considered (see case examples in 6.4).

The measuring positions shall be kept constant during the whole measurement. For the indirect method, the hydrophones shall be installed at exactly the same geometrical positions in relation to the sound sources.

NOTE For near shore applications, it is important that any range-dependent bathymetry between the source and the hydrophone also be consistent between measurements, see Annex A.

6.3.3 Measuring distance

The preferred measuring distance is 750 m. This is the specified value in ISO 18406. However, the distance may be changed for operational reasons. The measuring distance shall not fall below 750 m and shall not exceed 1 100 m. A second hydrophone shall be installed at twice the measuring distance (at least 1 500 m and not farther than 2 200 m). See Annex A for monitoring distance requirements for near shore applications.

6.3.4 Measuring direction

For measurement setups for which a dependence on directivity is to be expected (e.g. due to non-radially-symmetric noise abatement system such as an oval, eccentric bubble curtain) at least two hydrophones shall be applied in different measuring directions but at the same distance to the sound source. If there is no other knowledge available, both hydrophones shall preferably be arranged at an azimuth angle of 90° ± 30° between the measuring directions (see Figure 2).

With respect to the section about the measuring distance above, a third hydrophone should be installed at the given aspect angle but at double measuring distance of the mentioned hydrophones. See Annex A for measuring direction requirements for near shore applications.

6.3.5 Measuring depths

Provisions shall be made so that the hydrophone depth (height above seafloor) can be kept constant during the measurements.

In accordance with ISO 18406, the measuring hydrophone shall be positioned in the lower half of the water column, between a height 2 m above the sea floor and one-half the total water depth (measured from the sea surface). It is common to install at least one hydrophone at 2 m to 3 m above the seafloor. Other hydrophone configurations are also possible, e.g. one or more hydrophones in different depths at the same distance and aspect angle to the sound source.

NOTE If the bathymetry is not flat (e.g. rocks, etc.), the position near the seafloor can be affected by shadowing effects, and measurement positions at half the total water depth are then preferred.

It is recommended to determine the influence of the measuring depth on the insertion loss (see Figure 3) to avoid misinterpretation of the measurement results, for example, due to a strong layering of water and the resulting varying sound speed profiles relating to the water depth.

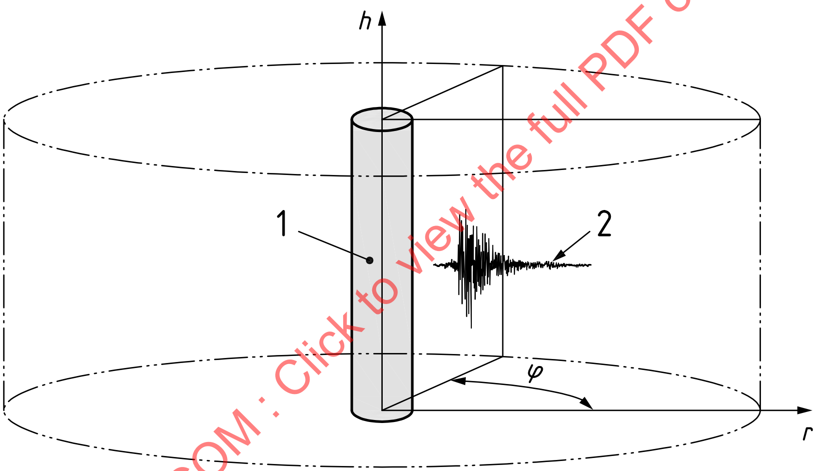
If the measuring depth of the hydrophones cannot be kept constant, the influence on the measurement results (uncertainties) shall be described separately, see 7.4.

6.4 Examples of measuring setups

6.4.1 General

The objective is to determine the in situ insertion loss of the noise abatement system. It may be required to define measurement positions in different directions and depths. Thus, the task of the acoustician is to find a suitable measuring setup with representative measuring points prior to the measurements.

Firstly, a coordinate system shall be defined. One possible coordinate system is shown in Figure 1.



Key

r	radial direction	1	sound source
h	vertical direction	2	acoustic pulse (time response)
φ	azimuth angle		

Figure 1 — Coordinate system

Before the measuring setup is determined, several criteria shall be checked, which can describe the respective measuring situation. For example, the acoustician should verify in advance if the sound source and the sound abatement measure have a radially-symmetric propagation characteristic. For verification measuring setup 1 (see 6.4.2) can be used.

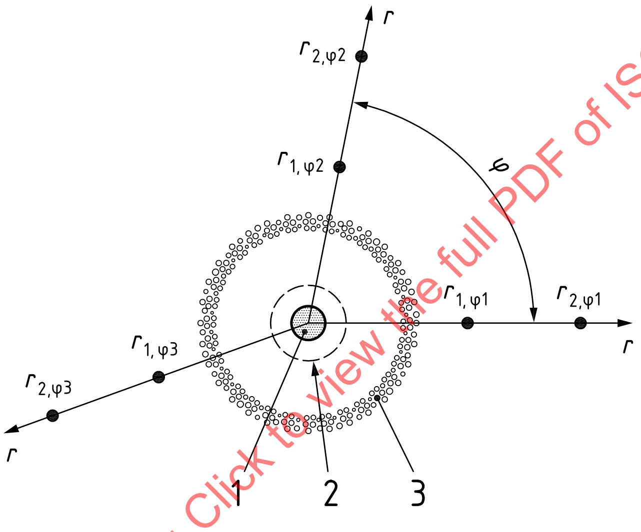
Furthermore, it is to be clarified whether the sound radiation of the sound source and the sound propagation behind the sound mitigation measure depend on the vertical position of the hydrophone in the water column. Potential depth-dependent acoustic effects of a sound abatement measure and of the sound source respectively can be verified by using the measuring setup 2 (see 6.4.3).

If the effectiveness of the sound mitigation measure and the sound radiation of the sound source are depth-independent and radially-symmetric, using measuring setup 3 (see 6.4.4) is sufficient.

In some cases, these criteria have already been verified for previous measurements. If no knowledge about the three mentioned criteria can be gained prior to the planned campaign, measurements for verifying these criteria shall be carried out in any case before sound mitigation measures can be deployed. These preliminary measurements shall be carried out on at least one pile without having taken any sound abatement measures to exclude a potential directivity of the sound source (e.g. pile driver). Only if the sound level and the sound propagation characteristics of the sound source are comparable for each pile, statements on the effectiveness of a sound abatement measure can be made. Furthermore, in order to guarantee comparability of the measurements to be taken, it is indispensable to know how the respective sound levels of the sound source (e.g. pile driver) depend on the driving energy, the pile penetration depth, the soil conditions and the other conditions listed in 5.2.

6.4.2 Measuring setup 1 — Checking for a radially-symmetric effect

A radially-symmetric effect of a sound abatement measure can be assumed for a measure which is not influenced by current and if the bathymetry near the pile can be estimated to be radial-symmetric, additionally. If there are uncertainties concerning an existing situation, the following measuring setup (Figure 2) can be used to check the propagation conditions and the directivity.



Key

φ azimuth angle
r radial direction
1 sound source (pile)
2 cofferdam, sound mitigation measure example
3 bubble curtain, sound mitigation measure example

$r_{1,\varphi1}$ hydrophone 1
$r_{1,\varphi2}$ hydrophone 2
$r_{1,\varphi3}$ hydrophone 3
$r_{2,\varphi1}$ hydrophone 4
$r_{2,\varphi2}$ hydrophone 5
$r_{2,\varphi3}$ hydrophone 6

Figure 2 — Measuring setup 1— Checking for dependence on directivity

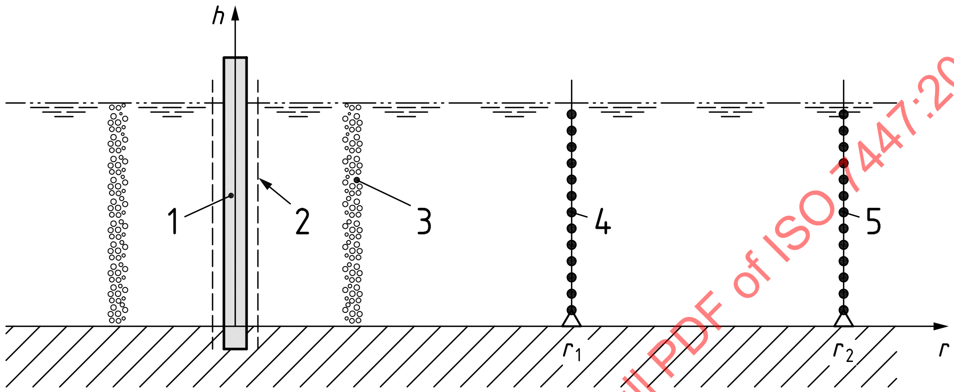
Figure 2 shows a measuring setup with hydrophone measuring points in different directions. The efficiency of a noise abatement measure can be checked by installing hydrophones in different directions. Typically, with this approach only the existence of a directional behaviour can be shown, but not the complete distribution of the directivity. The choice of measuring points depends on the application and shall be described by the user. For noise mitigation measures that are influenced by the ocean current, e.g. bubble curtains, measuring points should be selected in the direction of ocean current (azimuth angle φ_1) and perpendicular to it (angle $\varphi_2 = \varphi_1 + 90° \pm 30°$). A further measuring point can be freely selected and could be 180 degrees to the direction of the ocean current (angle $\varphi_3 = \varphi_1 + 180° \pm 30°$).

6.4.3 Measuring setup 2 — Checking for dependence on depth

If a depth dependence of the effectiveness of the sound mitigation measure cannot be excluded, the following measuring setup (see Figure 3) should be used to verify this situation.

An example for depth dependence of the measuring results is bubble curtains in deep water. Due to the forces affecting them, the ascending bubbles have different sizes, forms and densities, etc. depending on the respective depth. To assess these effects, at least two hydrophones at different measuring depths shall be used at the respective measuring point (see Figure 3). The distance of the hydrophone to the seafloor should be 2 m to 3 m.

Further hydrophones should be positioned at half of the water depth and/or at one third of the water depth from seabed.



Key

1	sound source (pile)	*h*	vertical direction
2	cofferdam, sound mitigation measure example	*r*	radial direction
3	bubble curtain, sound mitigation measure example	r_1	distance 1
4	hydrophone chain 1	r_2	distance 2
5	hydrophone chain 2		

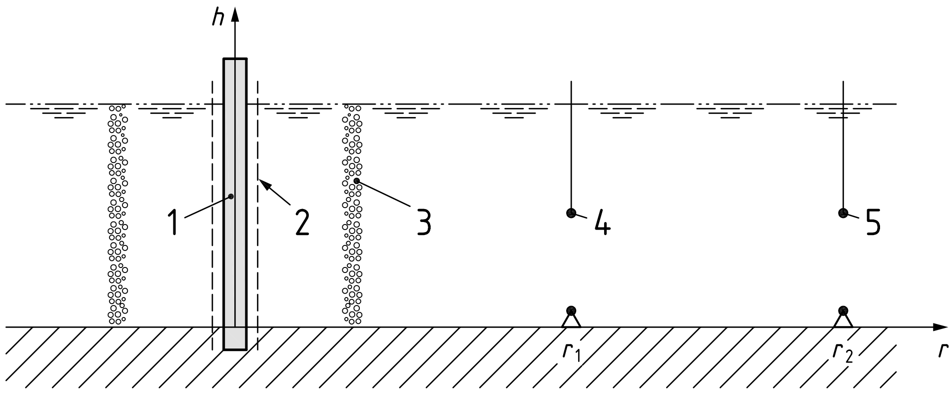
NOTE At least two hydrophones at each distance.

Figure 3 — Checking for dependence on depth

6.4.4 Measuring setup 3 — Measurement with radially-symmetric effect, independent of the respective depth

If the radial-symmetric effect of a sound mitigation measure and the independence of the measuring results from depth have been determined by means of another method, it is sufficient to perform the measurement at two measuring points at different distances to the sound source. The data at both measuring points shall be recorded simultaneously. The measuring point at the distance r_2 to the sound source serves for checking the level differences to be expected between the measuring positions r_1 and r_2. In case the sound mitigation measure is independent of depth and directivity, the measuring results in both measuring distances shall be convertible into each other.

Figure 4 shows the measuring setup 3 where the hydrophone is positioned near the ground or in the middle of the water column.



Key

1	sound source (pile)	h	vertical direction
2	cofferdam, sound mitigation measure example	r	radial direction
3	bubble curtain, sound mitigation measure example	r_1	distance 1
4	hydrophone 1 (ground system or middle of water column)	r_2	distance 2
5	hydrophone 2 (ground system or middle of water column)		

Figure 4 — Measurement with radially-symmetric effect, independent from the respective depth

6.5 Functional test and measuring conditions

The function of the hydrophone measuring chain shall be checked before and after the measurements with a suitable pistonphone. The pistonphone signal shall be recorded for the purpose of documentation and further analysis.

While installing the hydrophones, it shall be ensured that disturbing structure-borne noise transmission during the measurements is avoided as far as possible.

If noisy work or events which are not associated with the present project take place at the same time as the measurements, the background noise caused by this shall be recorded and documented.

6.6 Measuring quantities and accompanying parameters

The time raw data of the unweighted sound pressure shall be recorded at the single measuring positions.

The sample rate shall be chosen according to the frequency range to be evaluated, see 7.1.

NOTE High-pass filters are usually applied with a cut-off frequency between 1 Hz and 3 Hz.

The measurement duration for each setup shall be chosen long enough to be representative for the respective measuring setup and noise. The measurement shall be carried out under environmental conditions which are as steady as possible. Deviations and changes during the measuring period shall be documented.

The following accompanying parameters according to 5.2 shall be documented:

— geographic coordinates;

— seafloor classification;

— water depth;

— pile dimensions (length, diameter, wall thickness) and pile mass;

— pile driver (manufacturer, type, technical data);

— type of force-conducting connecting elements between pile driver and pile (e.g. anvil);

— driving protocol (hammerlog) including self-penetration, pile blow count, blow frequency, pile penetration depth and pile driving energy per 25 cm soil penetration;

— deterrence protocol;

— wind speed and direction;

— water depth;

— significant wave height and direction;

— swell height and direction;

— current velocity and direction (only relevant if this quantity influences the directional efficiency of the noise abatement system, e.g. for a bubble curtain).

Factors which might have an influence on the noise measurements shall be documented and assessed in measuring reports, if they can be determined. These are, for example:

— ship traffic;

— noise input by jack-up/sounding/support vessels;

— possible acoustic shadowing, for example, through the jack-up vessel itself;

— weather induced environmental noise (in particular rain);

— other sound sources such as fish (schools of fish, in particular in case of acoustically active swim bladders), acoustically active mammals, etc.

6.7 Data recording

Data which is documented for the purpose of determining the effectiveness of sound mitigating measures shall always be recorded in an uncompressed high-resolution format, such as PCM Wave 24 bit. Any measuring data (time raw data) as well as the processed and evaluated data shall be kept available for further investigations.

7 Data processing and calculation of acoustic metrics

7.1 Data processing steps

The recorded hydrophone data shall be processed in accordance with the processing steps described in ISO 18406:2017, 6.4.1.

The acoustic metrics to be calculated are one-third octave (base 10) band spectra of sound pressure level for an averaging period that includes multiple comparable pulses, meeting the comparability requirements detailed in 5.2. Typically, this could be a period of 30 s, covering about 15 piling strikes. The frequency range should ideally cover the bands from 10 Hz and 20 kHz. The background noise level shall be computed as one-third octave (base 10) band of sound pressure level spectra over averaging periods of the same duration as selected for the piling sound spectra.

7.2 Background noise correction

If the difference of the sound generated by the sound source and the background noise is between 6 dB and 10 dB, the measured sound pressure levels shall be corrected.

If the difference exceeds 10 dB, no correction is required. If the difference is less than 6 dB, the environmental conditions are not acceptable.

The correction of the measured sound pressure levels of the sound source with and without active sound mitigation measure respectively shall be carried out as follows:

$$L_{p,i} = 10\lg\left[10^{L_{pSO,i}/10\,dB} - 10^{L_{pBG,i}/10\,dB}\right] dB \quad (1)$$

where

$L_{p,i}$ is the corrected sound pressure level with or without noise mitigation measure in the i^{th} one-third octave (base 10) band;

$L_{pSO,i}$ is the sound pressure level in the i^{th} one-third octave (base 10) band, measured with active sound source and with or without noise abatement measure;

$L_{pBG,i}$ is the sound pressure level in the i^{th} one-third octave (base 10) band, measured without sound source (background noise), with or without noise abatement measure, respectively.

7.3 Determination of the insertion loss

7.3.1 General

According to 3.1, the insertion loss D_p in one-third octave (base 10) bands for one measuring point can be calculated with the following equation:

$$D_p = L_{p2} - L_{p1} \quad (2)$$

where

L_{p1} is the sound pressure level at the place of immission with a barrier;

L_{p2} is the sound pressure level at the place of immission without a barrier.

To ensure comparability, several periods with and without noise mitigation measure shall be investigated for one measuring position. For this purpose, it is helpful to consider level-time diagrams of the sound pressure levels L_{p1} and L_{p2} in dependence of the accompanying parameter, such as pile length, penetration depth into the soil, hammer energy and pulse repetition, in advance to determine suitable time ranges for calculation of the insertion loss.

The insertion loss shall be determined for each measuring position. For all positions, the minimum and maximum insertion loss values that can be achieved shall be determined. For this purpose, their range shall be given in one-third-octave bands (base 10).

The obtained insertion loss values shall be compared for positions of the same aspect angle at different distances to the source to ensure that the determined level difference characterises the respective measure.

The insertion loss depends primarily on the acoustic characteristics and technical implementation of the noise abatement system and then of course on environmental and acoustic conditions. For both measuring setups, a flanking transmission via the seafloor is possible.

7.3.2 Case 1 — Measurement on one pile

For several periods with comparable conditions, the minimum and maximum insertion loss values that can be achieved shall be determined at each position, and their range shall be given in one-third octave (base 10) bands.

7.3.3 Case 2 — Measurement on two different piles

The minimum and maximum insertion loss values that can be achieved shall be determined, and their range shall be given in one-third octave (base 10) bands. With this method, it is possible to consider the flanking transmission of the measure over time. Thus, for representative conditions of the pile-driving process the insertion loss can be shown depending on the pile-driving/penetration depth into the seabed and for all seabed layers at testing site.

7.4 Uncertainties

7.4.1 General

In general, the effectiveness of a measure shall be described independently of acoustic source properties and environmental conditions. Measuring uncertainties can be subdivided into uncertainties caused by

— the measurement chain,

— variation of data (e.g. source excitation), and

— the environment (transmission in the form of structure-borne noise).

Uncertainties which can be quantified shall be recorded.

7.4.2 Measurement uncertainty

Measurement uncertainties are caused by the measurement chain. Measurement uncertainties are discussed in the ISO/IEC Guide 98-3 and should be observed. Sources of uncertainties are:

— the calibration of measuring equipment,

— the position of source and receiver, and

— noise introduced by the deployment (flow noise, cable strum, additional background noise from vessel, etc.).

7.4.3 Characterization of noise abatement systems

The quality of the measured insertion loss for characterising a certain noise abatement system depends on the following factors:

— variance of the insertion loss, i.e. the achievable minimum and maximum insertion loss in the one-third octave (base 10) bands determined at two positions with the same aspect angle and during one single period (see Figure 3);

— signal-to-noise ratio (in one-third octave (base 10) band) for the configuration with active sound source and without noise abatement system;

— flanking transmission via the seafloor;

— variation of the sound radiation with the progressing installation (dependence on depth);

— sound characteristics of the noise abatement system itself (and signal-to-noise ratio with active measure).

7.5 Sound insulation for broadband level quantities

This document requires calculating the insertion loss in one-third octave (base-10) bands. This can be applied to a sound pressure spectrum in absence of the barrier to determine the resulting sound pressure spectrum after installation of the barrier. The insertion loss spectrum is considered independent of the source spectrum.

Insertion loss can also be directly calculated as the difference of broadband sound pressure (or exposure) levels at a specified receiver position before and after the installation of a barrier.

For the case of near shore pile driving, the peak pressure level is an important metric for assessing potential for acoustic injury to marine mammals and fish or potential fish mortality[22][23]. Annex A discusses the use of a broadband level quantity to quantify the effectiveness of a noise abatement measure for reducing peak pressure levels.

These broadband insertion loss calculations are only valid for the specific source spectrum for which they are measured.

8 Test report

8.1 Formal information in the reports

8.1.1 Front page

The front page shall include at least the following information:

— title (also stating the respective project);

— report number;

— name of the company;

— date of the report, with state of revision (if required);

— name and address of the client;

— date of the measurements;

— location of the measurements;

— names of the employees involved in the project;

— total number of pages of the report including appendix;

— if the appendix has its own numbering of pages, the total number of pages of the appendix shall also be stated on the front page.

8.1.2 Recurring information on the following pages

All following pages shall include the following information:

— name of the company;

— report number;

— date;

— numbering of pages.

Indication of the total number of pages is not required on the following pages.

8.1.3 Signatures

The report should be signed by the author.

8.2 Contents of the reports

8.2.1 Structuring of contents

The report should have the following structure:

— information on the investigations performed;

— information on the results;

— if required, assessment of the results in comparison to limit values (in the form of levels).

8.2.2 Description of the measurements

If tests are made according to specified methods, the text shall contain at least the following information:

— name and description of the measuring setup;

— a reference to the document used, i.e. ISO 7447:2024;

— description of the measuring object such as types of foundation (monopile, jacket, ...), piling methods and piling periods;

— detailed description of pile (identifier and location for pile, pile dimensions (overall length, diameter, wall thickness), pile material type (e.g. steel, ...);

— description of the pile driver used (manufacturer, type, construction year of hammer, technical data like ram mass, oil flow rate, power packs used, special configurations like PULSE-unit or others);

— description of the force-conducting connecting elements between pile driver and pile (anvil of the hammer and configuration, type of pile head);

— description of the noise abatement system with the focus on the system test setup, test name, test type, etc.; e.g. for BBC (big bubble curtain) systems:

  — compressor types used;

  — number of compressors;

  — used amount of compressed air;

  — BBC nozzle hose lengths and layout;

  — day of deployment and operation;

  — used pressure of compressed air;

  — age of the used nozzle hoses;

— description or reference to the applied test method; Indicate operation mode of construction vessel (jack up, DP (dynamic positioning), anchor);

— environmental parameters a) site specific: water depth, cpt-profile, description of soil layers per penetration depth, calculation method, embedded depth, surface sediment (for describing soil layers and surface sediments use published classifications), b) sound speed profile, c) weather conditions during test whereas wind and significant wave height are considered indispensable;

— operation parameters: penetration depths considered in the analysis, hammer energy/pulse repetition rate at the analysed segments (hammerlog of the entire pile driving process showing self penetration and up to embedded depth);

— documentation of deviations from the procedure described in this document;

— documentation of any unusual features observed;

— information which is important for the test or the reproducibility of the test;

— information on the measurements and investigations carried out as well as the results derived from that; this data is usually complemented by tables, diagrams, sketches and photos;

— information on the applied test equipment (name, manufacturer, type, serial number) and software (name, producer, type, revision/correction state);

— serial numbers of the measuring equipment and the revision number of calculation programs to be able to retrace the effects of test equipment which turned out to be faulty after the measurements;

— calibration certificates;

— information on verification of the measurement chain;

— information on the measurement uncertainty.

8.2.3 Presentation of the results

In the diagrams, the following information shall be given:

— measuring object, measuring position;

— reference quantities;

— type of method (direct or indirect);

— information on the respective analysis, e.g. one-third octave (base 10) band/narrowband, with statement of the respective bandwidth, information on bandwidth conversion, etc.;

— information on the averaging period;

— number of pile blows in the averaging period;

— accompanying parameters according to 6.6 (sea state, flow characteristics, wind speed, etc.);

— time and duration of pile driving as well as driving energy from the pile driving records, time and duration of the soft start, time, duration and type of the noise mitigation measures;

— reference quantities (in the form of levels);

— for the presentation of frequencies, a format according to DIN 13320:1979-06, 3.1, is recommended: on the Y-axis, 20 mm corresponds to 10 dB; on the X-axis 15 mm corresponds to 1 octave.

Annex A
(informative)

Considerations for near shore piling applications

A.1 General

The procedures in this document are generally intended for pile driving at far-offshore locations. Often there is a desire to characterize the insertion loss of barrier control measures underwater for near-shore pile driving projects (for example for the construction of docks, piers, wharfs, bridge supports, etc.). This Annex points out some special points of consideration where the standard, as described, may not be directly applicable to near shore pile driving applications.

A.2 Bathymetry considerations

Near shore environments typically have sloping seafloors, with water depth increasing in the offshore direction from the pile. In these cases, radial symmetry is rare and measurement setup 3 is not adequate to characterize the performance of the barrier control measure in all directions. Measurement setup 1 would be required for the insertion loss measurement itself, not just for performing validation of radial symmetry. As such, the resulting insertion loss shall be reported as a directional quantity, at minimum quoted for an along shore and an across shore aspect.

For the indirect method of determining insertion loss for near shore applications, the bathymetry need not be flat but the bathymetry between the pile and the barrier control measure and hydrophone(s) shall be consistent between measurements (e.g. seafloor slope is within 10 % between measurements). To the extent practicable, the hydrophones shall be placed in a direction that avoids shielding of the pile driving noise caused by irregular seafloor features such as hills and sills, or from other structures and vessels.

If the bathymetry is not flat, changes of the bathymetry can influence the propagation of some frequencies more than others (e.g. mode stripping). The influence of the bathymetry on the propagation of individual frequency bands could be quantified by comparing measurements in the offshore (sloping) aspect with those in the along-shore (flat) aspect.

A.3 Monitoring distances

The minimum monitoring distance recommended in this document is 750 m, though acoustic monitoring for near shore pile driving applications is often conducted at much shorter distances. For near shore applications, it is recommended that the nearest monitoring distance be no less than the maximum of 20 m or three times the local water depth at the pile location. The restriction to three times the water depth at the pile is consistent with ISO 18406, to reduce the influence of the vertical variation of the sound field nearer to the pile. The restriction to 20 m is recommended for applications where the water depth at the pile is less than 7 m, so that the measurements will be made at a distance that is large relative to the pile diameter (assuming most piles for near shore applications have diameter of 2 m or less). For consistency with the recommendations in this document for offshore projects, a second hydrophone shall be installed at twice the measuring distance (i.e. at least six times the local water depth at the pile or 40 m, whichever is greater).

A.4 Peak sound pressure level insertion loss

For near shore pile driving projects, it is often a requirement to report peak sound pressure levels, defined in ISO 18406, as this metric is used to assess potential for acoustic injury to marine mammals and, notably, fish that can occur near to the piles. Given that peak sound pressure levels are an instantaneous quantity, they are quantified as broadband levels. While insertion loss values for SPL and SEL are frequency dependent, and consequently they are reported for multiple frequency bands, the insertion loss for peak sound pressure level is referred to as the "peak sound pressure level insertion loss" with symbol $D_{p,pk}$, is a single number representing the reduction of broadband peak sound pressure level resulting from the barrier. The peak sound pressure level insertion loss is calculated with the following Formula (A.1):

$$D_{p,pk} = L_{p,pk2} - L_{p,pk1} \tag{A.1}$$

where

$L_{p,pk1}$ is the peak pressure level at the measurement location with a barrier;

$L_{p,pk2}$ is the peak pressure level at the measurement location without a barrier.

Characterization of the insertion loss in one-third octave (base 10) band sound pressure levels or sound exposure levels shall also be computed to fully characterize the insertion loss of the barrier control measure. The measurements and signal analyses are carried out in accordance with ISO 18406.

A.5 Pile slant angle

Near shore pile driving projects can include installation of both vertical as well as piles that are installed off-vertical (i.e. battered piles). Consistent with ISO 18406, in the case of battered piles, because the sound propagation angles differ depending on the direction relative to the slant of the pile, the effectiveness of the barrier control measure shall be assessed based on sound measurements in three directions: in the pitch direction, in the opposite direction, and in the perpendicular direction. In each direction, the monitoring distances from the pile shall follow the recommendations in A.3. For the indirect method of determining insertion loss, the pile slant angle shall be consistent (within 10 %) between measurements.

Annex B
(informative)

Sound particle motion and seabed vibration

B.1 Requirements

For the purposes of this document, measurement of sound particle motion or seabed vibration is not required for characterizing the in situ performance of noise abatement barriers such as bubble curtains. The acoustic metrics used in the normative parts of this document may be derived solely from measurements of sound pressure using hydrophones.

However, because sound particle motion is of increasing interest in ocean acoustics, in particular with regard to marine pile driving, some general guidance is provided in this annex on the topic.

B.2 Background

Sound waves comprise fluctuations in both pressure and particle motion in the medium. All fish species and many aquatic invertebrates respond to particle motion with few responding to sound pressure. There is a growing body of evidence that underwater anthropogenic noise can be detrimental to the health and survival of fishes and aquatic invertebrates, but the importance of sound particle motion in the exposure of these marine fauna remains unclear, partly because until recently very few sound particle motion measurements have been undertaken in the ocean[32][37]. Thus, there is a need to measure sound particle motion to establish the levels at which aquatic life can detect sound, and at which adverse effects from anthropogenic noise can occur. This is particularly true for physical conditions where sound pressure cannot easily be used to predict sound particle motion.

Additional waves may also be generated along the seabed boundary, particularly by sources such as marine pile driving which make a percussive contact directly on the seabed. In general, these seabed surface waves propagate more slowly than the sound waves in the water column and do not radiate efficiently into the water column, but they can have an evanescent component close to the seabed, and they may have a direct impact on benthic creatures which live on or close to the seabed[40][33][42].

Currently, exposure thresholds for marine fauna cited by regulation are mostly restricted to those based on sound pressure measurement (for example, peak sound pressure level and sound exposure level), but work has begun to define exposure guidelines for fish and turtles[39]. Because of the nature of marine pile driving, it is a source of both water-borne sound and seabed vibration, and it is frequently conducted in relatively shallow water where the seabed properties strongly influence the acoustic radiation. Therefore, optional measurements of sound particle motion and seabed vibration may be desirable to provide the additional data which are currently lacking, and which may inform new research and assist with formulation of future regulatory guidance.

Until recently, there has been a lack of commercially-available instrumentation and a lack of guidance on how to make measurements of sound particle motion and seabed vibration in the ocean, but there have been important recent developments to establish good practice[35] and appraisals of the research priorities in the field[38].

B.3 Sound particle motion in the water column

The sound particle motion may be expressed in terms of one of several vector acoustic field quantities, most commonly sound particle acceleration, velocity or displacement.

The most commonly available sensor for measuring sound particle motion is an accelerometer, typically embedded within a neutrally-buoyant polymer sphere (often along with a hydrophone to make a co-located