24th INTERNATIONAL CONGRESS ON SOUND AND VIBRATION
23–27 July 2017, London

# A STANDARD FOR THE MEASUREMENT OF UNDERWATER SOUND RADIATED FROM MARINE PILE-DRIVING

Stephen Robinson and Pete Theobald

*National Physical Laboratory, Hampton Road, Teddington, UK*
*email: stephen.robinson@npl.co.uk*

This paper describes a standardised method for measuring the underwater sound radiated during marine percussive pile driving. The pile-driving of marine foundations radiates substantial levels of low-frequency impulsive noise into the water column, which can propagate over large distances. Concern over the potential for impact on marine fauna often results in a regulatory requirement to measure the radiated noise level over distances which may extend to tens of kilometres. Furthermore, if the transmission loss is to be established or validated it is necessary to measure as a function of range from the pile at a number of positions. In addition, because of the variation in hammer energy during the pile-driving activity, particularly if a soft-start is employed, it is also desirable to perform the measurement at a fixed range for the duration of the pile-driving operation. The noise generation mechanisms are complex, and a number of factors influence the noise radiated into the water column, including the water depth (exposing a different amount of the surface area of the pile), the seabed properties, and the penetration depth into the seabed by the pile, the pile dimensions, and the hammer energy. In this paper, a standard method for the measurement of underwater radiated sound from percussive pile driving is described. The method includes a combination of fixed-range recordings and range-dependent hydrophone deployments. The method described was established by Working Group 3 of Technical Committee 43 (Sub-Committee 3) of the International Organization for Standardization (ISO), and is published in 2017 as ISO 18406.

Keywords: Marine Pile Driving, Ocean Noise, International Standards

## 1. Introduction

Marine pile driving is used for foundation installation in relatively shallow water, for construction of piers, bridges and offshore wind farms, activities that have typically been in water depths of a few tens of metres or less, and generally less than 50 m. Foundations are often installed using percussive pile-driving employing hammer strike energies which can be up to a few thousand kJ. This technique is widely employed in relatively shallow water and can radiate substantial levels of low-frequency impulsive noise into the water column, which can propagate large distances [1, 2]. Developers planning an offshore construction project must give consideration to the potential for an impact on sensitive marine receptors such as marine mammals and fish [2-8]. Regulatory requirements to measure the radiated noise level from such infrastructure construction activities are in place in many countries, either to validate a prediction made in an environmental impact assessment or to ensure the level does not exceed a defined threshold [9, 10].

Measurement methodologies adopted in different countries reflect the requirements of the local regulation. For example, piling noise measurements in Germany are generally performed at a distance of around 750 m, measurements in the United Kingdom and the Netherlands are generally completed at a number of distances and measurements in the USA are often reported at a distance of 10 m from the pile for shallow water inshore applications [10-13]. Range dependent measurements are generally

used to validate propagation model predictions and are also inherently useful for understanding the distances over which there is potential for impact on marine fauna. If, however, the regulatory requirements are such that a level should not be exceeded at a given distance from the source then a single measurement distance will generally be sufficient. In Germany, the Netherlands and the United Kingdom, local guidance documents exist which are compatible with the local regulatory requirements [9, 10,14]. Until now, there has been no international standard for the measurement of underwater noise from pile-driving.

The International Organization for Standardization (ISO) has been undertaking work under Technical Committee (TC) 43, Sub-Committee (SC) 3, Working Group (WG) 3 with the aim of standardizing the measurement methodology which should be followed when measuring radiated underwater noise from marine pile-driving and the metrics which are used for reporting. This paper describes the general measurement methodology outlined in the ISO standard which is published in the summer of 2017 and titled: ISO 18406: 2017 "Underwater acoustics — Measurement of radiated underwater sound from percussive pile driving".

## 2. Measurement issues

The pile is unusual as an underwater source of sound in that it extends through the whole water column, extending to the boundaries and is not terminated in the water. When considered in this way, the far-field cannot be defined in the traditional sense and it is not clear that the source output can easily be represented in terms of a monopole source level [15]. Proposed approaches have included the calculation of a third-octave band sound exposure level source level, using a propagation model to propagate the sound back to the source from measurements at different distances [16, 17]. Another difficulty is that there are a number of factors which will influence the source level or noise radiated into the water column for a specific pile, including the water depth (exposing a different amount of the surface area of the pile), the seabed properties, the penetration depth into the seabed by the pile, the pile dimensions, and the hammer energy. Alternative approaches to the treatment of the source have considered modelling of the underwater acoustic radiation mechanism from a pile, using finite element modelling methods [18-20]. In terms of predictive modelling for the purposes of environmental assessments, the approach of using a "physics based" model of the pile, such as finite element modelling, could remove the reliance on a "source level" term.

An important factor which requires consideration for the measurement of the underwater noise radiating from pile-driving, particularly if determining a source output term, is that the source changes during the piling sequence. There are a number of causes for this, firstly the hammer strike energy changes, usually increasing from a soft-start, and secondly, the pile penetrates the seabed with the overall penetration depth increasing with time, with potential for seabed properties to vary with depth below the seabed [21]. In very shallow water, it is also likely that the water depth will change during the piling sequence, exposing a different surface area of the pile to the water, due to tidal variation. There is also the potential for the source to change in characteristics if the hammer enters the water column. This typically happens during the installation of pin-piles for jacket foundations, where it is common for the hammer to start above the water surface and end near the seabed. To capture these time varying factors requires a static measurement position, which provides a measurement that is independent of the variation in received level that occurs with distance, due to propagation loss. This is generally achieved with a fixed monitoring station (typically an autonomous recorder) positioned at a fixed height above the seabed for the duration of the pile-driving operation [21, 22]. The required measurement range may extend over tens of kilometres, and if the propagation loss is to be established or validated it would also be necessary to measure as a function of range from the source [2,14]. A combination of fixed autonomous recorders and vessel based hydrophone deployments are generally needed to satisfy the requirement of range dependent measurement whilst capturing time variance of the source. The vessel-based hydrophone measurements, could in this case, be obtained in a sprint

and drift fashion at a number of points along a transect, with several minutes of recording time obtained at each measurement point. The number of measurement points or the maximum distance over which measurements can be obtained, will generally depend on the duration of the piling sequence. This can vary substantially from one construction project to another and even between foundations within a given project.

It should be noted that environmental factors, which could affect the propagation path, may change during the piling sequence. Such changes would result in variation in the measured noise level even for the case of a constant source level and measurement location. In shallow water areas with large tidal variations, for example, the change in sound propagation path may be substantial. To reduce the noise level radiated into the water column, particularly when environmental impact is a concern, noise mitigation systems are sometimes employed during the pile-driving. There are a number of potential solutions which are either being developed or have been successfully employed, with the most common systems being a derivative of either a bubble curtain or a physical barrier around the pile [23]. Measurements to assess the efficacy of these noise mitigation systems may require special consideration. In Germany, guidance on how to do this is provided by the Bundesamt für Seeschifffahrt und Hydrographie (BSH) [24].

## 3. Contents of the ISO standard

The standard, ISO 18406, defines an approach which requires measurements as a function of distance and includes at least one fixed location to capture time variance of the acoustic output of the source (it is accepted that there may also be temporal factors which effect propagation). In the case of foundation installation for offshore wind farms, there is an historic precedence to perform a measurement at a distance of around 750 m from the foundation and this is recommended in the standard to ensure a common measurement distance and also provide continuity with historic data. A fixed measurement point may also be dictated by either a regulatory requirement to determine the noise level against a predefined threshold or may be chosen based on a concern relating to the impact of the noise on a sensitive area. This approach is generally compatible, without significant additional effort, with the measurement methodologies of those countries which currently require such measurements for regulatory purposes. At each measurement location it is recommended that the hydrophone be in the lower half of the water column and that ideally two hydrophones (vertical array) are used where possible. As well as placing certain requirements on the measurement system performance, the standard will require the hydrophone to be calibrated over the full frequency range of interest, in accordance with IEC 60565:2006 [25]. Importantly, field calibration checks will be required using an appropriate method, for example, using a commercially available hydrophone-calibrator which provides a signal of known amplitude at a single frequency. Pile-driving generally results in a broadband sound field with spectral peaks between around 100 Hz and 500 Hz. A measurement frequency range of 20 Hz to 20 kHz is therefore considered sufficient to capture most of the acoustic energy and this is the minimum requirement of the standard.

An area of significant inconsistency within the field of underwater acoustics is the use of metrics and the reporting of sound or noise levels. A number of different quantities and metrics have been used including peak-to-peak pressure level, peak pressure level, root mean square sound pressure level over the duration of the pulse, the equivalent continuous noise level, and sound exposure level of a single pulse. The sound exposure level for each pulse is also often summed up for the entire piling sequence to give the cumulative sound exposure level.

The standard requires calculation of each of these metrics to provide consistency and comparability, whilst maintaining compatibility with different regulatory requirements for reporting of specific metrics. ISO 18406 requires the use of terms and reporting of metrics to be consistent with ISO 18405:2017, the new standard on ‘Underwater acoustical terminology’.

Additional reporting are specified relating to pile characteristics, with a broad range of foundation types, pile sizes, and hammer sizes typically used. Auxiliary and metadata are also be required for parameters which are important to the measurement process, or which may influence the measurement or data in some way. Measurements of piling noise generally have a requirement to measure the background or ambient noise in the area. This requirement usually exists to assess the piling noise in the context of the existing environment to determine an effective "signal-to-noise ratio". To measure ambient noise effectively requires a different procedure and equipment to pile driving noise. Therefore, in ISO 18406, the background noise is required only for the purposes of determining the signal-to-background-noise ratio. It is anticipated that there will be future work within ISO TC43 SC3 on measurement standards for ambient noise.

## 4. Limitations on the scope of the standard

Generally, the method adopted for measuring the sound radiated from pile-driving is consistent with good measurement practice for measuring underwater sound radiated from other sound sources. However, the measurement of percussive pile-driving does require consideration of a number of factors which may not be common to other sound sources and has some requirements which are specific to the characteristics of the source. For example, the output is of high amplitude and this may place specific demands on the sensitivity of the hydrophone, the dynamic range of the measurement system and the distance at which a measurement should be performed. One limitation on the scope of the standard is to restrict it to percussive piling only, excluding vibro-piling. Whilst the general approach to the measurement of the underwater noise radiated from pile-driving using a percussive hammer and a vibro-hammer might be the same, the amplitude of the radiated noise levels from a vibro-hammer would be expected to be less [26]. Furthermore, the sound resulting from percussive pile-driving requires reporting in different metrics to a source which is considered to be continuous in nature. Similarly, sheet piling, which is routinely used for construction of harbour walls, is also excluded due to the difference in the nature of the source and the differences in the type of environment in which such measurements would be required.

The points considered relating to water depth and the use of subsea pile-driving also requires the scope to be limited to "shallower" water measurements, to exclude the use of subsea piling in hundreds of metres or more, where the source characteristics may be substantially different.

Finally, an important point to note is that the scope has been limited to consider only the sound in the water column and only the pressure component of this sound. Particle motion in the water column and vibration of the seabed are potentially very important sensory indicators for many species, particularly for crustaceans and fish [28]. Particle motion may therefore be an important measurement parameter for acoustic measurements carried out in relation to establishing the potential for impact on marine fauna, particularly for percussive piling. However, during the preparation of the standard, there was insufficient understanding regarding the specifications for such a measurement and very limited experience in performing such measurements, and it was therefore not possible to standardise the methodology to carry out such a measurement.

## 5. Acknowledgements

This production of this paper has been funded by National Measurement Office of the United Kingdom Department for Business, Energy, and Industrial Strategy.

The authors acknowledge the support of the member of ISO TC43 SC3 WG3, and especially Christ de Jong (TNO), Andreas Müller (Müller-BBM), Michael Bellmann (ITAP), and Peter Dahl (Applied Physics Laboratory, University of Washington).

## 6. References


1. F. Thomsen, K. Lüdemann, R. Kafemann, and W. Piper, Effects of offshore wind farm noise on marine mammals and fish, biola, Hamburg, Germany on behalf of COWRIE Ltd, 2006.
2. H. Bailey, B. Senior, D. Simmons, J. Rusin, G. Picken, and P. M. Thompson, "Assessing underwater noise levels during pile-driving at an offshore windfarm and its potential effects on marine mammals," Marine Pollution Bulletin, vol. 60, pp. 888-898, 2010.
3. M. Wahlberg and H. Westerberg, "Hearing in fish and their reactions to sounds from offshore wind farms," Mar.Ecol. Prog. Ser., vol. 288, pp. 295-309, 2005
4. J. Tougaard, J. Carstensen, and J. Teilmann, "Pile-driving zone of responsiveness extends beyond 20 km for harbour porpoises (Phocoena phocoena (L.)) (L)," J. Acoust. Soc. Am., vol. 126, pp. 11-14, 2009.
5. A. Hawkins, "The impact of pile-driving upon fish," Proc. Inst. Acoustics, vol.31. pt.1, p. 72-79, 2009.
6. A. N. Popper and M. C. Hastings, "The effects of anthropogenic sources of sound on fishes," Journal of Fish Biology, vol. 75, pp. 455-489, 2009.
7. P. M. Thompson, D. Lusseau, T. Barton, D. Simmons, J. Rusin, and H. Bailey, "Assessing the responses of coastal cetaceans to the construction of offshore wind turbines," Mar. Pollut. Bull., vol. 60, pp. 1200-1207, 2010.
8. M. Brandt, A. Diederichs, K. Betke, and G. Nehls, "Responses of harbour porpoises to pile-driving at the Horns Rev II offshore wind farm in the Danish North Sea," Marine Ecology Progress Series, vol. 421, pp. 205-216, 2011.
9. C. A. F. De Jong, M. A. Ainslie, and G. Blacquière, Standard for measurement and monitoring of underwater noise, Part II: procedures for measuring underwater noise in connection with offshore wind farm licensing, TNO Report TNO-DV 2011 C251, 2011.
10. A. Müller and C. Zerbs, Offshore wind farms - Measuring instruction or underwater sound monitoring, Report/protocol for Bundesamt für Seeschifffahrt und Hydrographie, Germany, 2011. S. P. Robinson, P. A. Lepper, J. Ablitt, G. Hayman, G. A. Beamiss, P. D. Theobald, and S. Dible, "A methodology for the measurement of radiated noise from marine piling," Proceedings of the 3rd International Conference & Exhibition on Underwater Acoustic Measurements: Technologies & Results, Napflion, Greece, ISBN; 978-960-98883-4-9, 2009.
11. C. A. F. de Jong and M. A. Ainslie, "Underwater radiated noise due to the piling for the Q7 offshore windfarm park," J. Acoust. Soc. Am., v123, pp. 2987, 2008. [Proceedings of the 9th European Conference on Underwater Acoustics (ECUA2008), ed. M. Zakaria, pub. Société Française d'Acoustique, July 2008].
12. J. A. Reyff, "Underwater Sounds from Marine Pile-driving", Proceedings of Inter Noise 2009, Ottawa, Canada, 2009.
13. S. P. Robinson, P. A. Lepper, and R. A. Hazelwood, Good Practice Guide for Underwater Noise Measurement, National Measurement Office, Marine Scotland, The Crown Estate, 2014.
14. R. J. Urick, Principles of Underwater Sound, Peninsula Publishing, New York, 1983.
15. A. J. Duncan, R. D. McCauley, I. Parnum, and C. Salgado-Kent, "Measurement and Modelling of Underwater Noise from Pile-driving", Proceedings of 20th International Congress on Acoustics, ICA 2010, Sydney, Australia, August 2010.
16. M. A. Ainslie, C. A. F. de Jong, S. P. Robinson, P. A. Lepper, "What is the source level of pile-driving noise in water?," 2nd International Conference on The Effects of Noise on Aquatic Life, 2010 [Advances in Experimental Medicine and Biology, 730, pp.445-448, DOI: 10.1007/978-1-4419-7311-5_100, 2012].
17. P. G. Reinhall and P. H. Dahl, "Acoustic Radiation from a Submerged Pile during Pile-driving," Proceedings of IEEE OCEANS 2010, 978-1- 4244-4333-8/10, 2010.
18. P. G. Reinhall and P. H. Dahl, "Underwater Mach wave radiation from impact pile-driving: Theory and observation," J. Acoust. Soc. Am., Vol 130, (3), pp. 1209-1216, 2011.
19. M. Zampolli, M. J. J. Nijhof, C. A. F. de Jong, M. A. Ainslie, E. H. W. Jansen, and B. A. J. Quesson, "Validation of finite element computations for the quantitative prediction of underwater noise from impact pile-driving," J. Acoust. Soc. Am., vol. 133, (1), pp. 72-81, 2013.
20. S. P. Robinson, P. A. Lepper, and J. Ablitt, "The measurement of the underwater radiated noise from marine piling including characterisation of a "soft start" period," Proceedings of IEEE Oceans 2007, IEEE cat. 07EX1527C, ISBN: 1-4244-0635-8, 061215-074, Aberdeen, June 2007.

21. P. A. Lepper, S. P. Robinson, J. Ablitt, and S. Dible, "Temporal and Spectral Characteristics of a Marine Piling Operation in Shallow Water," Proc. NAG/DAGA Int. Conference on Acoustics, Rotterdam, March 2009.
22. S. Koschinski and K. Lüdemann, Development of Noise Mitigation Measures in Offshore Wind Farm Construction 2013, Report Commissioned by the Federal Agency for Nature Conservation (Bundesamt für Naturschutz, BfN), Original Report (in German): published July 2011, update February 2013.
23. A. Müller and C. Zerbs, Measuring Specification for the Quantitative Determination of the Effectiveness of Noise Control Systems, Report/protocol produced on behalf of the Federal Maritime and Hydrographic Agency (BSH), Hamburg, 2013.
24. IEC 60565:2006, Underwater acoustics – Hydrophones – Calibration in the frequency range 0.01 Hz to 1 MHz, International Electrotechnical Commission, Geneva, 2006.
25. R. Matuschek and K. Betke, "Measurements of construction noise during pile-driving of offshore research platforms and wind farms," Proceedings of NAG/DAGA 2009, Rotterdam, 2009.
26. A. N. Popper and R. R. Fay, "Rethinking sound detection by fishes," Hearing Research, vol. 273, pp.25-36, 2011.
27. ASA S3/SC1.4 TR-2014. *Sound exposure guidelines for fishes and sea turtles*, ANSI Technical Report, authored by Popper, A.N, Hawkins, A.D., Fay, R.R, Mann, D.A., Bartol, S, Carlson, T.J., Coombs, S. Ellison, W.T., Gentry, R.L., Halvorsen, M.B., Lokkeborg, S., Rogers, P.H., Southall, B.L., Zeddies, D.G., Tavolga, W.N. Springer Briefs in Oceanography, 2014.