BERWICK BANK WIND FARM
OFFSHORE ENVIRONMENTAL IMPACT ASSESSMENT

APPENDIX 10.1, ANNEX G: PARTICLE MOTION REVIEW

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1. INTRODUCTION

1. The Subsea Noise Technical Report (volume 3, appendix 10.1), together with the marine ecology chapters of the Offshore Environmental Impact Assessment (EIA) Report, provide an analysis of the effects of sound on marine life. However, there are uncertainties in relation to the presence of compression and interface waves at the water/ground substrate boundary during piling, and the potential effect on fish and invertebrates. Although the risk of injury to fish with and without swim bladders is addressed through the use of Sound Exposure Level (SEL) and peak pressure thresholds (Popper *et al.*, 2014), it is possible that fish are only sensitive to particle motion. These fish could experience high levels of particle motion in close proximity to piling. However, the Popper *et al.* (2014) paper primarily addresses high amplitude sounds and high dynamic pressure, rather than particle motion.

2. Whilst the source measurements used to inform the subsea noise study included both direct radiated sound from the pile into the water, as well as ground-borne radiated sound, there are uncertainties with respect to how effectively the ground borne energy couples into the sea. If measurements were taken in an evanescent (non-propagating) field then high particle motion would not be reflected in the associated dynamic pressure measurements, particularly if those measurements were taken in shallow water and the energy is below the cut-off frequency. Consequently, it is possible that the effects on bottom fauna close to the pile could be under-estimated, particularly for species primarily sensitive to vibration of the seafloor sediment.

3. To put this issue into perspective, under section 5.1 entitled “Death or Injury”, Popper *et al.* (2014) states that “*extreme levels of particle motion arising from various impulsive sources may also have the potential to injure tissues, although this has yet to be demonstrated for any source*”. It would therefore appear that there is currently a lack of criteria for (or detailed measurements of) particle motion during piling operations for this issue to be currently assessed. Thus, in terms of potential damage to fish, volume 3, appendix 10.1 has addressed the impact as far as is practicable with the existing state of knowledge, based primarily on exposure to sound pressure.

4. The purpose of this technical note is to provide an overview of the acoustic aspects of particle motion. Potential effects on marine life are dealt with in the marine ecology topic chapters of the Offshore EIA Report.

2. OVERVIEW OF PARTICLE MOTION

5. Particle motion is defined as the motion of an infinitesimally small part of the medium relative to the rest of the medium, that is caused by a sound wave (Popper *et al.,* 2014). Unlike the pressure variation caused by the wave, which is a scalar quantity and therefore has no direction, the particle motion is a three-dimensional vector quantity (i.e. directional). Particle motion can be described by the velocity, acceleration, and displacement of the particle. These are related by the following equations (Nedelec *et al.,* 2016):

$$a = u \times 2\pi f$$

$$\xi = \frac{u}{2\pi f}$$

where a = acceleration (m/s^2), u = particle velocity (m/s), 2πf = angular frequency, and ξ = displacement (m).

6. Particle motion can also be related to measured sound pressure and can be approximated from the sound pressure in simplified circumstances such as a plane wave. For a plane wave, or a wave for which a plane wave is a good approximation of its behaviour (a wave in the free-field), the following relationship holds:

$$u = \frac{P}{\rho c}$$

where P = acoustic pressure (Pa), ρ = density of the water (kg/m^3), and c = sound speed (m/s). The quantity ρc is also known as the characteristic acoustic impedance. The following relationship holds true for the near field of a point source. The source must be far from any boundaries that could lead to the wave not propagating due to cut off frequency, or reflections that could interfere with the propagation of the wave:

$$\xi = \frac{p}{2\pi f \rho c}\left[1 + \left(\frac{\lambda}{2\pi r}\right)^2\right]^{1/2}$$

where r = distance to sound source (m). All other symbols are consistent throughout the equations presented here.

7. A plane wave is a wave that can be considered to have a flat wavefront. This generally occurs far from both the source of the wave and any sources of reflected waves. The term ’far’ is relative to the wavelength of the sound and the size of the source as both will change the distance at which the wave can be considered a plane wave. In shallow coastal and sea-shelf habitats these far-field conditions are not often met at the acoustic frequencies relevant to fish and invertebrates. This means that there is usually not a reliable way to derive particle motion from sound pressure measurement in these habitats. Technically a relationship between particle motion and sound pressure can be derived for more complicated wavefronts (e.g. by assuming that the wavefront has an idealised geometry). However, this is not necessarily reliable, and, in most cases where plane waves cannot be assumed, the only reliable solution is to measure directly (Nedelec *et al.*, 2016).

8. In those situations where it is appropriate to assume that waves generated by a monopole are plane waves (i.e. in the acoustic far field), it is possible to approximate the magnitude of the particle motion. It is important to understand where it is appropriate to make these assumptions. Spherical spreading occurs when sound propagates from a source without any interference and the applicability of the plane wave assumption is based on the frequency of interest and the waveguide (i.e. the duct formed by the surface and bottom of the water column), which encapsulates the water depth, distance to source, source type, and the sound speed in water and sediment. The values that are key for this assumption are the wavelength of the lowest frequency of interest (λ) and the cut off frequency (f_0) based on the waveguide. These values can be calculated from the following equations (Nedelec *et al.*, 2021):

$$\lambda = \frac{c_w}{f}$$

$$f_0 = \frac{c_w}{4D\sqrt{1 - \left(\frac{c_w}{c_b}\right)^2}}$$

Where f_0 is the cut off frequency, *D* is the water depth, c_w is the sound speed in water, and c_b is the sound speed in sediment.

9. If the distance to the sound source is greater than one wavelength and the lowest frequency is greater than the cut off frequency, then it is possible to estimate the magnitude of the particle motion from a Sound Pressure Level (SPL) measurement. However, it must be noted that this only applies to a travelling plane wave and as such the signal to noise ratio must be high enough to consider other sounds negligible (Nedelec *et al.,* 2021).

3. HEARING IN FISH AND INVERTEBRATES

10. All fish, and many invertebrates, detect the particle motion of a sound wave with mechanosensory organs such as the inner ear, statocyst or lateral line (Nedelec *et al.,* 2021). The ability to hear their surroundings gives fish, and many invertebrates, an abundance of information about their environment. This ability is unaffected by light levels and is omnidirectional, allowing for the most abundant information about the environment. Of all the senses that fish, and many invertebrates, use to assess their surroundings, hearing is the most versatile in a marine environment. In particular, their hearing is able to give rapid feedback with relatively long distance 3-D information (Popper and Hawkins, 2019).

11. The detection of sound and characterisation of the immediate soundscape is something that is key to the way that fish (and many vertebrates) live. This ability allows them to detect the direction of predators, and subsequently avoid them, or detect prey and move towards them. Furthermore, this ability can be used to recognise others within their own species and select a mate. Although not all fishes, or invertebrates, produce sound for communication, they are all known to use it for awareness of their surroundings. As such any interference with this ability could impact the survival of the fish (Popper and Hawkins, 2019).

12. There have been several studies into the hearing capabilities of fish and invertebrates. However, very few of them have used conditions that are truly representative of the environment that they would encounter in open water. This is due to tank conditions or methodologies used to observe them in an offshore environment. Furthermore, few of these studies have focussed on particle motion specifically (Popper and Hawkins, 2019).

13. Taking this into account it is possible to establish a reasonable assumption for hearing range of various species. Most fish appear to be able to detect sound that falls between 10 Hz and 500 Hz. If the fish or invertebrates are capable of detecting SPL, then they may be able to detect sounds at higher frequencies up to 1,000 Hz. There are also a small number of fish that are capable of hearing between 3 Hz and 4,000 Hz due to various specialisations that they have (Popper and Hawkins, 2019). The values presented here are the upper and lower estimates of each range, there is a degree of variability in each of the values. This is in part due to the complexity of the sound field in a tank or enclosure (Popper *et al.,* 2019). Likewise, invertebrates are also typically sensitive to lower frequencies (Nedelec *et al.,* 2016).

4. EFFECTS OF SOUND AND PARTICLE MOTION

14. Potential effects of sound and particle motion on fishes and invertebrates can be summarised as follows (Popper *et al.,* 2014; Popper and Hawkins, 2018; Nedelec *et al.*, 2016):

- Death and injury:
  - Exposure to very high amplitude sounds can cause injury and death in fish and other marine life. In addition, the effect of sudden pressure changes (barotrauma) must be considered.
  - Barotrauma is the tissue injury that is caused by a sudden change in pressure. Rapid pressure changes can cause the gases in blood to come out of solution and can cause rapid movement in the swim bladder. This can damage other organs and even rupture the swim bladder.
  - Sudden changes in pressure (such as that from impulsive sounds) are more likely to cause damage than gradual ones.
  - Extreme levels of particle motion may have the potential to cause tissue damage, but this has not been proven yet.
- Effects on hearing:
  - Hearing loss can be permanent or temporary (Permanent Threshold Shift (PTS) and Temporary Threshold Shift (TTS)) with permanent being caused by damage to the tissue in the auditory pathway (including the swim bladder).
  - TTS results from temporary damage to the hairs in the inner ear or to the auditory nerves. In fish (unlike in mammals) the hairs of the inner ear are constantly added and replaced if damaged. Therefore, loss of hearing due to damage to these hairs may be mitigated over time in fishes.
  - While experiencing TTS, fish may have a decrease in fitness in terms of communication, detecting predators or prey, and/or assessing their environment.
  - Masking is an impairment with respect to the relevant sound sources normally detected within the soundscape. The consequences of masking are not fully understood for fish and sea turtles. It is likely that higher levels of masking occur with a higher sound level from the masker.
  - Masking is the inability to detect sounds due to a reduction in the signal to noise ratio of 6 dB. This level is used as it is considered that a change of less than 6 dB would be undetectable experimentally in fish or turtles.
- Effects on behaviour:
  - It is possible that anthropogenic sound will have a detrimental effect on the communication of species between conspecifics, it may also hinder their identification of predator and prey.
  - There have been a variety of behavioural reactions observed from fish, including changes in swimming patterns and startle reactions
  - These reactions may habituate over repeated exposure to the sound.

15. There has been very limited research carried out to date in relation to the effects of particle motion on marine invertebrates (Popper and Hawkins, 2018). However, they are expected to have the same types of effect even if the severity is unclear.

16. Popper *et al.* (2014) split the affected species into the following identifiable groups:

- fishes with no swim bladder or other gas chamber. These fish are less susceptible to barotrauma and only detect particle motion, however, some barotrauma may occur from exposure to sound pressure;
- fish with swim bladders in which hearing does not involve the swim bladder or some other gas volume. These species again only detect particle motion; however, they are susceptible to barotrauma due to the presence of the swim bladder;
- fish in which the swim bladder (or other gas volume) is involved in hearing. These species detect sound pressure as well as particle motion and are susceptible to barotrauma. The frequency sensitivity range of this group is higher than the other groups due to the ability to detect the pressure component of the sound signal as well as the particle motion;
- sea turtles; and
- fish eggs and larvae.

17. These groups are known to be able to detect particle motion. However, it is also likely that marine invertebrates are able to detect particle motion (Popper and Hawkins, 2018; Discovery of Sound in the Sea (DOSITS)). Furthermore, some marine invertebrates can detect the vibrations directly from the substrate. This makes them susceptible not only to the particle motion in the water but also the rolling waves, and associated particle motion, in the substrate. It has been observed that benthic marine invertebrates respond directly to anthropogenic sound that has been generated in the substrate or very close to its surface (Hawkins *et al*., 2021; Aimon *et al*., 2021). This is particularly important for construction processes like piling that generate a large amount of sound deep into the substrate. The repercussions of

this may in fact affect the benthic habitat, as many benthic invertebrates have a key role in how the substrate is structured. Considerable disturbance of these creatures for a prolonged period could result in potential habitat damage in addition to any damage caused by the source of anthropogenic noise. It has also been suggested that some species use the sound that travels through the substrate to communicate or to find food sources, loud sounds that mask these sounds could make it difficult for them to operate normally (Popper and Hawkins, 2018).

18. There have been several studies into the hearing abilities of fish for a relatively small number of species. From these studies, the upper limit of detection for particle motion was found to be between 200 Hz and 400 Hz and the lower limit was 0.1 Hz (Sigray and Anderson, 2011). It is considered likely that all teleost fish have a similar extent of ability to detect particle motion (Radford *et al.*, 2012). Elasmobranchs are also considered to have a similar range of detection for particle motion. For piling, specifically, it is currently considered that most fish would be able to detect particle motion due to piling from 750 m away (Thomsen *et al.,* 2015). Marine invertebrates are generally not considered to be sensitive to the pressure wave component of sound as they lack an air-filled space in their bodies. Much research still needs to be carried out to understand the hearing capabilities of marine invertebrates. The research that has been undertaken so far has primarily focused on crustaceans and molluscs. A need has been identified to develop species specific audiograms to improve the understanding of the detection thresholds.

19. Hammar *et al.* (2014) discussed the impact of the Kattegat offshore wind farm on Atlantic cod *Gadus morhua* in the region. Estimates of operational noise were predicted as 150 dB re 1 µPa (root mean square (rms)) at 1 m for the 6 MW turbines and 250 dB re 1 µPa (rms) for the pile driving based on measurements on the Burbo Bank offshore wind farm taken by Parvin and Nedwell (2006). Using these estimates, Hammar *et al.* (2014) established that developed Atlantic cod were likely to suffer physical injury within several hundred meters of pile driving. However, studies have shown that fish often group around operational wind turbines (Sigray and Andersson, 2011; Engås *et al.*, 1995; Wahlberg and Westerberg, 2005). This suggests that operational noise is not enough to cause them to vacate the area, however it is not clear if it results in higher stress levels in fish in the area.

5. POTENTIAL RANGE OF EFFECTS DUE TO PARTICLE MOTION AT THE PROPOSED DEVELOPMENT

20. Due to the current state of understanding and existing (validated) modelling methodologies it is not considered possible at this time to provide a quantitative assessment of the effects of particle motion on marine life for the Proposed Development.

21. Predicting the levels of particle motion from anthropogenic sound sources is difficult. There is a small amount of measured data available on which to base such predictions and some of these data are not necessarily applicable to full scale industrial procedures such as installation of wind turbine foundations. The measurements that do exist mostly come from small scale tank testing. Some of this testing has been conducted in flooded dock style locations with small scale piles. Other recordings have used play-back speakers to generate a simulated piling noise (Roberts *et al.,* 2016; Ceraulo *et al.,* 2016). There is some debate about the validity of comparing measurements from tank tests or from playback speakers to full scale piling operations, as the way that particles move within a tank or smaller scale system is different to the full scale in the open ocean. Furthermore, the way that a speaker will agitate the particles is different to that of a cylindrical pile with an exposed length in the water column. However, there is one commonality between all measurements so far: the particle motion attenuates rapidly close to the source and more slowly further from it (Mueller-Blenkle *et al.*, 2010).

22. One such experiment was studied by Ceraulo *et al.* (2016), this consisted of measurements during piling at several locations within a flooded dock that incorporated a simulated seabed layer (approximately 3.5 m thick). This allowed the piling to be measured from different ranges. Through this experiment it was found that the sound propagation was close to cylindrical in nature. The SEL for particle motion were found to be 102 dB re 1 nanometre per second (nm/s) at a distance of 2 m from the pile and this dropped to 86 dB re 1 nm/s at 30 m. There was an interesting observation that the pressure wave appeared to have a cut off frequency at 400 Hz for shallow water and 300 Hz for deep water, although the particle motion does not share this cut off. The study was able to confirm that there is a roughly linear relation between particle motion and pressure although it also found that the particle motion levels were higher than expected.

23. An added complication in predicting particle motion is the propagation of sound through the substrate. This is particularly prominent in piling operations as the pile being driven into the ground will generate considerable waves through the substrate. This particle motion can impact the benthic species in the area due to behavioural reactions and potential injury. This has been identified as an area that requires more research and should be monitored alongside particle motion within the water column itself. Furthermore, the waves passing through the substrate can add to those in the water column, making the sound field in the water more complex (Mueller-Blenkle *et al.*, 2010).

24. A study by Thomsen *et al.* (2015) investigated particle motion around the installation of piles at offshore wind sites. The study found that higher hammer energies elicited higher levels of particle motion and that particle motion levels at 750 m from the pile were higher than baseline ambient levels throughout the frequency spectrum, except at very low frequencies. Thomsen *et al.* (2015) showed that with mitigation (a bubble curtain) turned on however, particle motion levels reduced considerably. It should be noted that the range cited of 750 m was likely due to the regulatory requirement for monitoring at 750 m from a pile and this number is therefore somewhat arbitrary in terms of the potential range of effect for particle motion (i.e. it is the most common measurement range for sound pressure rather than being the range over which particle motion effects were thought likely to occur).

25. Nevertheless, the study concluded that, for most fish, particle motion levels at 750 m are high enough to be detected during pile driving of even a mitigated pile. However, for elasmobranchs, the study concluded that detectability of mitigated piles is likely restricted to relatively short ranges from the source depending on the ambient noise in the area. For invertebrates the study concluded that there is even less information on how they perceive particle motion, but the Thomsen *et al.* (2015) study would indicate that some invertebrates should be able to detect the piling noise at a distance of 750 m, whether mitigated or not.

26. Another study by Sigray *et al.* (2022) showed a reduction of 12 dB of the broadband level with an external bubble curtain in place and an additional 14 dB when used in combination with an air Isolated Steel Barrier mounted with an Internal Bubble Screen. It suggests that mitigation decreased the magnitude of the radiated particle motion and the potential range of effects on receptors and is dependent on the type of mitigation used.

27. Taking the above into consideration, it is thought likely that particle motion will be detectable for many fish and invertebrates within the order of 750 m from piling at the Proposed Development, although it is not possible to quantify this further at this stage. Furthermore, it is not possible at this time to determine whether the detection of sound by these species at this range is likely to result in an effect, such as behavioural disturbance or injury. Likewise, it is not possible at this time to define the requirements for, or potential effectiveness of mitigation for particle motion. However, it is likely that potential injury due to particle motion will be confined to a smaller range than disturbance and detectability. Ultimately, until such a time as considerably more data becomes available, both in terms of measured particle motion during full

scale piling and effects on marine life, it is considered that the assessment of effects as set out in volume 3, appendix 10.1 represents a robust assessment based on the current state of knowledge.

6. REFERENCES

Aimon, C, Simpson, S., Hazelwood, R., Bruintjes, R. and Urbina, M. (2021). *Anthropogenic Underwater Vibrations Are Sensed and Stressful for the Shore Crab Carcinus Maenas*. Environmental Pollution 285: 117148.

Ceraulo, M., Bruintjes, R., Benson, T., Rossington, K., Farina, A. and Buscaino, G. (2016). *Relationships of Sound Pressure and Particle Velocity during Pile Driving in a Flooded Dock*. In Proceedings of Meetings on Acoustics 4ENAL, 27:040007. Acoustical Society of America.

Discovery of Sound in the Sea (DOSITS). Available at: Discovery of Sound in the Sea (dosits.org). Accessed on: 04 May 2022.

Engås, A., Misund, O.A., Soldal, A.V., Horvei, B. and Solstad, A. (1995). *Reactions of Penned Herring and Cod to Playback of Original, Frequency-Filtered and Time-Smoothed Vessel Sound*. Fisheries Research 22 (3–4): 243–54.

Hammar, L., Wikström, A. and Molander, S. (2014). *Assessing Ecological Risks of Offshore Wind Power on Kattegat Cod*. Renewable Energy 66: 414–24.

Hawkins, A., Hazelwood, R., Popper, A. and Macey, P. (2021). *Substrate Vibrations and Their Potential Effects upon Fishes and Invertebrates*. The Journal of the Acoustical Society of America 149 (4): 2782–90.

Mueller-Blenkle, C., Peter K., McGregor, A.B., Gill, M.H., Metcalfe, A.J., Bendall, V., Sigray, P., Wood, D and Thomsen., F. (2010). *Effects of Pile Driving Noise on the Behaviour of Marine Fish*. COWRIE technical report. 31st March 2010. Ref: Fish 06-08.

Nedelec, S.L., Campbell, J., Radford A.N., Simpson S. D. and Merchant N.D. (2016). *Particle Motion: The Missing Link in Underwater Acoustic Ecology*. Methods in Ecology and Evolution 7 (7): 836–42.

Nedelec, S.L., Ainslie, M.A., Andersson, M.C., Sei-Him, M., Halvorsen, B., Linné, M., Martin, B., Nöjd, A., Robinson, S.P. and Simpson, S.D. (2021). *Best Practice Guide for Underwater Particle Motion Measurement for Biological Applications*. Technical Report, University of Exeter, IOGP Marine Sound and Life Joint Industry Programme.

Parvin, S. J. and Nedwell, J. R. (2006). *Underwater Noise Survey during Impact Piling to Construct the Burbo Bank Offshore Wind Farm*. Subacoustech Ltd, 5.

Popper, A.N. and Hawkins, A.D. (2018). *The Importance of Particle Motion to Fishes and Invertebrates*. The Journal of the Acoustical Society of America 143 (1): 470–88.

Popper, A.N. and Hawkins A.D (2019). *An Overview of Fish Bioacoustics and the Impacts of Anthropogenic Sounds on Fishes*. Journal of Fish Biology 94 (5): 692–713.

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, Løkkeborg, S., Rogers, P.H., Southall, B.L., Zeddies, D.G. and Tavolga, W.N. (2014). *ASA S3/SC1.4 TR-(2014) Sound Exposure Guidelines for Fishes and Sea Turtles: A Technical Report Prepared by ANSI-Accredited Standards Committee S3/SC1 and Registered with ANSI*. Springer.

Popper, A.N., Hawkins, A.D., Sland, O. and Sisneros, J.A. (2019). *Examining the Hearing Abilities of Fishes*. The Journal of the Acoustical Society of America 146 (2): 948–55.

Radford, C.A., John C. M, Caiger, P. and Higgs, D.M. (2012). *Pressure and Particle Motion Detection Thresholds in Fish: A Re-Examination of Salient Auditory Cues in Teleosts*. Journal of Experimental Biology 215 (19): 3429–35.

Roberts, L., Harry, R., Harding, I.V., Bruintjes, R, Steven, D., Simpson, A., Radford, N., Breithaupt, T. and Michael, E. (2016). *Exposure of Benthic Invertebrates to Sediment Vibration: From Laboratory Experiments to Outdoor Simulated Pile-Driving*. In Proceedings of Meetings on Acoustics 4ENAL, 27:010029. Acoustical Society of America.

Sigray, P. and Andersson M.H. (2011). *Particle Motion Measured at an Operational Wind Turbine in Relation to Hearing Sensitivity in Fish*. The Journal of the Acoustical Society of America 130 (1): 200–207.

Sigray, P., Linné, M., Andersson, M.H., Nöjd, A., Persson, L.K.G., Gill, A.B. and Thomsen, F. (2022). *Particle motion observed during offshore wind turbine piling operation.* Marine Pollution Bulletin 180: 113734.

Thomsen, F.A., Gill, M., Kosecka, M., Andersson, M., Andre, S., Degraer, T., Folegot, J., Gabriel, J., Judd, A., Neumann, T., Norro, A., Risch, D., Sigray, P., Wood, D. and Wilson, B. (2015). *MaRVEN–Environmental Impacts of Noise, Vibrations and Electromagnetic Emissions from Marine Renewable Energy*. Final Study Report, Brussels, Belgium.

Wahlberg, M. and Westerberg, H. (2005). *Hearing in Fish and Their Reactions to Sounds from Offshore Wind Farms*. Marine Ecology Progress Series 288: 295–309.

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