Project title	Estimated ranges of impact for various UXO detonations, Norfolk Vanguard
Project number	E603
Author(s)	Tim Mason, Richard Barham
Company	Subacoustech Environmental Ltd.
Report number	E603R0401
Date of issue	9 April 2018

Introduction

The risk of detonation by unexploded ordnance (UXO) on the seabed, associated with the Norfolk Vanguard Offshore Windfarm (OWF), has been investigated by Subacoustech Environmental Ltd, in respect of the underwater noise produced. The range of impact in relation to marine mammals and fish injury from UXO detonation has been estimated.

A number of UXOs with a range of charge weights have been identified within the boundary of the Norfolk Vanguard OWF site. There is expected be a variety of explosive types, which will have been subject to degradation and burying over time. Two otherwise identical explosive devices are likely to produce different blasts where one has spent an extended period on the sea bed.

A selection of explosive sizes has been considered in the estimation of the underwater noise levels produced by detonation of UXO, based on the *Unexploded Ordnance (UXO) Hazard and Risk Assessment with Risk Mitigation Strategy* by Ordtek Limited (Report reference JM5427 V1.0, 5th February 2018). The potential impact has been compared to up to date impact criteria in respect of marine mammals that could be present in the area. This assessment assumes the maximum explosive charge is present.

Estimation of underwater noise levels

The noise produced by the detonation of explosives is affected by a number of different elements, only one of which, the charge weight, can easily be factored into a calculation. In this case the charge weight is based on the equivalent weight of TNT. Many other elements relating to its situation (e.g. its design, composition, age, position, orientation, whether it is covered by sediment) and exactly how they will affect the sound produced by detonation are unknown and cannot be directly considered in an assessment. This leads to a high degree of uncertainty in the estimation of the source noise level (i.e. the noise level at the position of the UXO). A worst-case estimation has therefore been used for calculations, assuming that the UXO to be detonated is not buried, degraded or subject to any other significant attenuation.

The consequence of this is that the noise levels produced, particularly by the larger explosives under consideration, are likely to be over-estimated as they are likely to be covered by sediment and degraded.

Report JM5427 V1.0 by Ordtek details UXO devices that are potentially present in the Norfolk Vanguard OWF site boundary. The Net Explosive Quantity (NEQ) of explosive material in the device is corrected, depending on the type of explosive material, to an equivalent quantity of TNT for the purpose of calculations. In this report, the following devices are identified:

UXO Item	NEQ	TNT Eq.
250lb HE Bomb (Amatol / TNT)	55 kg	55 kg
500lb HE Bomb (Amatol / TNT)	120 kg	120 kg
1000lb HE Bomb (Amatol / TNT)	250 kg	250 kg
British MK14 Buoyant mine	227 kg	261 kg
British A Mk6 Ground Mine	430 kg	525 kg
German E series buoyant mine (Wet Gun Cotton / TNT - worst case)	150 kg	150 kg
German LMB (GC) Ground Mine (Hexanite)	700 kg	770 kg

Table 1 – UXO devices potentially present at Norfolk Vanguard site

Estimation of the source noise level for each charge weight was carried out in accordance with the methodology of Soloway and Dahl (2014)[1], which follows Arons (1954)[2] and MTD (1996)[3]. These cannot take into account the range of variables noted above and thus will only provide an indication of the noise output from each detonation, assuming a freely suspended charge.

Estimation of propagation of underwater noise

The attenuation of the noise as it propagates from the source location is accounted for in calculations using geometric spreading and a sound absorption coefficient, using the methodologies cited in Soloway and Dahl (2014). This is a relatively simple calculation used to give an indication of the range of effect, which does not take into account of variable bathymetry or seabed type. However, an attenuation correction has been made for the absorption over long ranges (i.e. of the order of thousands of metres), based on measurements of high intensity noise propagation taken in the North and Irish Seas in similar depths to that present at Norfolk Vanguard.

Despite this correction, caution should also be raised over the longer range SPL_{peak} values. Peak noise levels are difficult to predict accurately in a shallow water environment (von Benda Beckmann, 2014); Soloway and Dahl (2014) only verify the calculation used for small charges and ranges of <1,000 m. At longer ranges greater confidence in calculated SELs is expected. Additionally, an impulsive wave tends to be smoothed (i.e. the pulse becomes longer) over distance (Cudahy and Parvin, 2001[4]) and so where two waves' SPL_{peak} levels may technically be at the same level, the injurious potential of the one at greater range tends to be lower. Therefore, assessment in respect of SEL is considered preferential at long range.

The calculation also does not take into account the variation in the noise level at different depths. Where animals are swimming near the surface, the acoustics at the surface cause the noise level, and hence the exposure, to be lower at this position (MTD, 1996). The risk to animals near the surface may

[1] Soloway, A. G., & Dahl, P. H. (2014). Peak sound pressure and sound exposure level from underwater explosions in shallow water. The Journal of the Acoustical Society of America, 136(3), EL219-EL223. http://dx.doi.org/ 10.1121/1.4892668
[2] Arons A. B. (1954). Underwater explosion shock wave parameters at large distances from the charge. J. Acoust. Soc. Am. 26, 343–346
[3] The Marine Technology Directorate Ltd (MTD) (1996). Guidelines for the safe use of explosives under water. MTD Publication 96/101. ISBN 1 870553 23 3
[4] Edward A. Cudahy, Stephen Parvin. 2001. *The Effects of Underwater Blast on Divers*, Report 1218 (Naval Submarine Medical Research Laboratory). #63706N M0099.001-5901

therefore be lower than indicated by the range estimate and therefore this can be considered conservative in respect of impact at different depths.

Impact criteria

Marine mammals

The selection of impact criteria uses thresholds and a simple estimated weighting based on the NMFS, 2016[5] criteria. The thresholds indicate the onset of permanent threshold shift (PTS) and temporary threshold shift (TTS) in various species of marine mammal, or the point at which there is an increase in risk of permanent hearing damage in an underwater receptor. These are simple indicators and do not take into account the spreading of underwater sound over long distances, and thus there is a greater likelihood of accuracy where the ranges are small.

The thresholds group a selection of species based on their hearing capabilities, that is their particular sensitivity to low or high frequency sound. Blast noise is fairly broadband, comprising a wide range of low to high frequency sound, although the majority is at low frequency.

The groupings as given in the results are as follows:

"LF": Low-frequency cetaceans, e.g. minke whale

"MF": Mid-frequency cetaceans, e.g. dolphin species

"HF": High-frequency cetaceans, e.g. harbour porpoise

"Pinn": Pinnipeds (in water), e.g. harbour seal

Some of the thresholds given are weighted, which adjusts the sound present at the receiver based on the sensitivity of the receiver, e.g. harbour porpoise are less sensitive to low frequency sound than minke whale. It should be noted that the weightings given for the criteria used in the older Southall *et al.* 2007 paper are different to those used in the updated NMFS, 2016.

Additionally, a criterion is included based on work by Lucke *et al.* (2009) specifically for harbour porpoise, also indicative of PTS, has been included. This is unweighted and does not make any assumptions of the receptors' hearing sensitivity. It is also derived from experiments in a confined space and is therefore likely to overestimate the impact of this level in open water. Further to this, the threshold has been identified recently by von Benda-Beckmann *et al.* (2015)[6] as the inflection point between where noise-induced PTS is "unlikely" and "increasingly likely". It is considerably lower than the point at which noise-induced PTS is judged to be "very likely". Therefore, the calculated range is expected to be highly conservative.

Please note that both Sound Pressure Level (SPL) and Sound Exposure Level (SEL) values are included, which are specific to different criteria used, and should not be confused or compared directly. All decibel SPL values are referenced to 1 µPa; all SEL values are referenced to 1 $\mu Pa^2 s$.

[5] National Marine Fisheries Service (NMFS) (2016). Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing: Underwater Acoustic Thresholds for Onset of Permanent and Temporary Threshold Shifts. U.S. Dept. of Commerce., NOAA. NOAA Technical Memorandum NMFS-OPR-55, 178 p

[6] Alexander M. von Benda-Beckmann, Geert Aarts, H. Özkan Sertlek, Klaus Lucke, Wim C. Verboom, Ronald A. Kastelein, Darlene R. Ketten, Rob van Bemmelen, Frans-Peter A. Lam, Roger J. Kirkwood, and Michael A. Ainslie. Assessing the Impact of Underwater Clearance of Unexploded Ordnance on Harbour Porpoises (*Phocoena phocoena*) in the Southern North Sea. Aquatic Mammals 2015, 41(4), 503-523, DOI 10.1578/AM.41.4.2015.503

Fish

The vast variation between fish species, and the little study that has been done on the impacts of noise to them, makes an assessment challenging. Criteria for marine mammals have been simplified by categorising them according to the hearing sensitivity of a species group; for fish Popper *et al*. have proposed criteria for species divided into three groups[7]:

- Fish with no swim bladder (e.g. dab and other flatfish)
- Fish where a swim bladder is not involved in hearing (e.g. Atlantic salmon)
- Fish where a swim bladder is involved in hearing (e.g. Atlantic cod and herring)

However, in consideration of explosives and potential mortality, all species groups are considered equivalent and there is no frequency weighting to account for variations in hearing sensitivity.

It is also considered that there is insufficient data for a quantitative calculation of impact ranges for recoverable injury or hearing impairment. The risk of the effect is therefore considered as either 'low', 'moderate' or 'high' at range.

[7] Popper, A. N., Hawkins, A. D., Fay, R. R., Mann, D. A., Bartol, S., Carlson, T. J., Coombs, S., *et al*. 2014. Sound Exposure Guidelines for Fishes and Sea Turtles: A Technical Report prepared by ANSI-Accredited Standards Committee S3/SC1 and registered with ANSI, pp. 33–51. Springer, New York

Calculated results

Marine Mammals

	TNT Equivalent	55 kg	120 kg	150 kg	250 kg	261 kg	525 kg	770 kg
UNWEIGHTED THRESHOLDS	SOURCE LEVEL, SPL_{PEAK}	287.4 dB	290.0 dB	290.7 dB	292.4 dB	292.5 dB	294.8 dB	296.1 dB
NMFS PTS SPL_{peak} (LF)	219 dB re 1 µPa	1,100	1,350	1,450	1,700	1,750	2,200	2,500
NMFS PTS SPL_{peak} (MF)	230 dB re 1 µPa*	350	450	480	570	580	730	820
NMFS PTS SPL_{peak} (HF)	202 dB re 1 µPa	5,400	6,800	7,300	8,400	8,500	10,400	11,500
NMFS PTS SPL_{peak} (Pinn)	218 dB re 1 µPa*	1,200	1,500	1,600	1,900	1,900	2,400	2,700
NMFS TTS SPL_{peak} (LF)	213 dB re 1 µPa	1,900	2,400	2,600	3,100	3,100	3,900	4,400
NMFS TTS SPL_{peak} (MF)	224 dB re 1 µPa	630	820	880	1,050	1,100	3,500	1,500
NMFS TTS SPL_{peak} (HF)	196 dB re 1 µPa	9,200	11,400	12,100	13,900	14,000	16,800	18,400
NMFS TTS SPL_{peak} (Pinn)	212 dB re 1 µPa	2,100	2,700	2,900	3,400	3,400	4,300	4,800
Lucke SEL (HF)	179 dB re 1 $µPa^2s$	6,700	9,000	9,800	11,700	11,900	15,000	17,000

Table 2 – Calculated impact ranges (metres) for species groups – unweighted criteria

* Note that unweighted NMFS 230 dB SPL_{peak} is identical to the Southall *et al.* 2007 cetacean (all groups) threshold, and 218 dB SPL_{peak} thresholds are identical to the Southall *et al.* 2007 pinniped threshold.

All tabulated results are ranges in metres from the blast location.

WEIGHTED THRESHOLDS	Charge weights	55 kg	120 kg	150 kg	250 kg	261 kg	525 kg	770 kg
NMFS PTS LF SEL	183 dB re 1 μPa²s	3,000	4,100	4,500	5,600	5,700	7,500	8,700
NMFS PTS MF SEL	185 dB re 1 μPa²s	<20	25	30	40	40	55	65
NMFS PTS HF SEL	155 dB re 1 μPa²s	1,200	1,700	1,900	2,400	2,400	3,300	3,900
NMFS PTS Pinn SEL	185 dB re 1 μPa²s	560	820	910	1,200	1,200	1,700	2,000
NMFS TTS LF SEL	168 dB re 1 μPa²s	21,600	26,500	28,000	31,700	32,000	37,300	40,400
NMFS TTS MF SEL	170 dB re 1 μPa²s	350	510	570	730	740	1,000	1,250
NMFS TTS HF SEL	140 dB re 1 μPa²s	11,500	14,900	16,000	18,700	18,900	23,000	25,500
NMFS TTS Pinn SEL	170 dB re 1 μPa²s	6,500	8,800	9,500	11,400	11,600	14,700	16,600

Table 3 – Calculated impact ranges (metres) for species groups – weighted criteria

All tabulated results are ranges in metres from the blast location.

Fish

All species are considered by Popper *et al.* to be at risk of mortality or potential mortal injury at a peak SPL of 229 dB re 1 µPa. The range at which this noise level could occur is as follows:

Charge weights	55 kg	120 kg	150 kg	250 kg	261 kg	525 kg	770 kg
229 dB re 1 µPa	390	500	530	570	580	800	910

Table 4 – Calculated mortal and potential mortal injury impact ranges (metres) for any fish species

The risk of recoverable injury (including PTS) and TTS is assessed qualitatively by Popper *et al*. The following table is provided, but is based on small charges, such as used to dismantle in-water structures:

Fish species group	Recoverable injury (inc. PTS)
No swim bladder	(N) High (I) Low (F) Low
Swim bladder not involved in hearing	(N) High (I) High (F) Low
Swim bladder involved in hearing	(N) High (I) High (F) Low

Table 5 – Qualitative risk of injury for fish species groups from small charges. (N)ear, (I)ntermediate, (F)ar, equivalent to tens, hundreds and thousands of metres respectively

A greater risk should be assumed for larger charges, especially in light of the results in Table 4.

Conclusions

The impact ranges for a selection of charge weights have been presented. The calculations are based on a simple methodology; the large number of unknown variables that will affect the output of UXO located for an extended period on the seabed lead to a great degree of uncertainty. It is expected that the presented ranges overestimate the actual ranges of impact that would occur in practice, both from physical sound propagation and biological perspective.

The calculation parameters are all chosen to be conservative, leading to an upper estimate for source noise levels, and the risk of impact will be reduced over increasing range as the initial shock wave dissipates.

The sound levels have been converted to impact ranges using sets of criteria from Southall *et al*. 2007, Lucke *et al*. 2009 and NMFS, 2016, which, although describing nominally the same injury to the hearing of a species, use different criteria, leading to multiple estimates of the range of impact. No one set of criteria can be assumed to be definitive or 'correct'. It is worth noting also that the criteria refer only to the 'onset' of injury risk. More research into the effects of noise on marine species to increase confidence in the impacts in real open water circumstances is required.

The greatest PTS range was calculated at 17 km for onset of harbour porpoise, based on criteria derived from Lucke *et al.* (2009). It is worth noting that this is derived from a correction to TTS onset in a single harbour porpoise at close range in an enclosure and is likely to overestimate the actual risk in open water. Data presented in von Benda-Beckmann *et al.* (2015) show a level of 179 dB SEL re 1 µPa^{2}s will be reached, in depths of 10-20 m of water, at a range of the order of 6 to 7 km for a charge weight of approximately 700 kg. This suggests that the simple calculation methodology overestimates the noise propagation at long range.

There is little data available for the impact of different sized charges on fish species. However, calculated ranges for the risk of mortal injury to individuals have been provided. The risk of potential mortal injury to fish is predicted to be within 1,000 m of the UXO location, for the largest charge weight.