TECHNICAL NOTE 01

Title	Strategic Unexploded Ordnance (UXO) Risk Management – Seabed Effects During Explosive Ordnance Disposal (EOD)
Client	Norfolk Vanguard Limited
Project and Number	JM5427 – Norfolk Vanguard - TN01 – V1.0
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Reference	A. 6Alpha- East Anglia One UXO Threat and Risk Assessment with Risk Mitigation Strategy, Report Number: P2825, May 2012. B. Fugro – Norfolk Vanguard Offshore Windfarm Geophysical Investigation Geophysical Site Survey, GE050/R1/Vol.2/Rev.0, 2016. C. Ministry of Defence – Handbook of Demolition and Explosives, BR338(1), May 1988 D. TetraTech – Draft Munitions And Explosives Of Concern (Mec) Desktop Study, VOWTAP, dated October 2014

Abbreviations and Acronyms

ALARP	As Low As Reasonably Practicable	**MCM**	Mine Countermeasures
CIRIA	Construction Industry Research and Information Association	**mm**	Millimetres
CW	Chemical Weapon	**NEQ**	Net Explosive Quantity
EO	Explosive Ordnance	**Nm**	Nautical Mile
EOD	Explosive Ordnance Disposal	**OWF**	Offshore Wind Farm
ERW	Explosive Remnants of War	**PLGR**	Pre Lay Grapnel Run
GC	Allied designation for German type LMB mine	**pUXO**	Potential unexploded ordnance
GG	Allied designation for German type BM1000 mine	**ROV**	Remotely Operated Vehicle
GIS	Geographical Information System	**RN**	Royal Navy
HE	High Explosive	**QA/QC**	Quality Assurance/Quality Control
HSE	Health and Safety Executive	**SOP**	Standard Operating Procedure
KHz	Kilohertz	**SSS**	Side Scan Sonar
kg	Kilogram	**SQRA**	Semi Quantitative Risk Assessment
Kv	Kilovolt	**TNT**	Trinitrotoluene
km	Kilometre	**UK**	United Kingdom
LMB	Luftmine B (German air-dropped ground mine	**UXB**	Unexploded Bomb
m	Metres	**UXO**	Unexploded Ordnance

1. Introduction

Norfolk Vanguard Limited have commissioned *Ordtek Limited* to provide guidance on blast calculations from detonations of the various types of UXO identified as potentially present within the Site; *Norfolk Vanguard Limited* will then use this data in conjunction with their environmental consultants as part of the Environmental Impact Assessment (EIA) documentation to determine the possible implications for marine mammals.

In the technical note *Ordtek* has:

- assessed typical UXO items, likely to be recommended for high order disposal.
- assumed that all items found are live and the maximum explosive content is present.
- assumed that a ~5kg donor charge will be used during the EOD phase.

The guidance provided is drawn both from practical offshore industry experience, open-source studies and principles applied by military EOD specialists. *Ordtek* considers this advice to conform to industry best practice and be in line with the recently published Construction Industry Research and Information Association (CIRIA) guide C754, “Assessment and Management of Unexploded Ordnance (UXO) Risk in the Marine Environment”.

2. UXO Types and Net Explosive Quantity

From the UXO hazard and risk assessment at Reference A and Ordtek’s experience in the area, this TN will consider the items of UXO likely to be encountered at the Norfolk Vanguard OWF. From Reference A, it can be seen that the principal UXO to consider are German and British sea mines, with German High Explosive (HE) bombs, torpedoes and depth charges a lower residual background threat. In addition, there are munitions related wrecks within the Study Site and therefore naval projectiles are also considered. From experience of UK North Sea developments, *Ordtek* consider the presence of Allied HE bombs to also be a principal UXO hazard to consider.

Other items of UXO may be encountered, however the wide range of net explosive quantities (NEQ) of the items above provide a good baseline for predicting and measuring the effects of any other items encountered in the Project. The table below illustrates the NEQ of the potential types of UXO that may be encountered at the Site:

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

Figure 2.1 – UXO Types Associated With Norfolk Vanguard OWF

3. Seabed Conditions

The seabed conditions for the at Norfolk Vanguard are predominantly sandy deposits with large sand waves.

The seabed features subaqueous dunes ranging from very large (100-300 m wavelength and up to 6m high) to medium (8-10 m wavelength and up to 0.6 m high). The medium dunes blanket the seafloor across the majority of the Site. Dune crests strike approximately east to west which is indicative of north to south currents. Present on the dunes are low, flow-parallel sand ridges, and along the western perimeter of the Site rippled sand or, where the seabed veneer of Holocene sand is absent, silty clay of the underlying Brown Bank Formation.

The water depths in the proposed area varies between 25.3m and 50.8m LAT. Minimum water depth is found along the north-central edge of the Site, above a large constituent dune of the Jim Howe Bank. Maximum water depth is found the south-western corner of the Norfolk Vanguard Site.

From Reference A, the presence of large sand wave features means that there is potential for UXO burial within the Site. However, given the large size of German WWII aerial delivered sea mines, these items are likely to only become partially buried, or remain on the seabed.

4. Detonation Effects

4.1 Overview

When an item of UXO detonates on the seabed underwater, several effects are generated, most of which are localised at the point of detonation; such as crater formation and movement of sediment and dispersal of nutrients and contaminants. Surface vessels and submarine equipment are also susceptible to the rapid expansion of gaseous products known as the "bubble pulse"; in this instance damage is caused by a water jet preceding the bubble and lifting and whiplash effect that can break the back of a ship. An effect, known as "bubble collapse" can also cause severe damage. Once it reaches the surface, the energy of the bubble is dissipated in a plume of water and the detonation shock front rapidly attenuates at the water/air boundary. Fragmentation (that is shrapnel from the weapon casing and surrounding seabed materials) is also ejected but does not pose a significant hazard underwater for receptors more than ~10m away.

The effect that causes damage to the receptors considered in this TN is shock transmitted through the seabed and water column.

4.2 Shock

The principal effect that causes damage to vessels and receptors in the far field is shock transmitted through the water column and the seabed. The severity of consequence of UXO detonation will depend on many variables but principally the charge weight and its proximity to the receptor. In simple terms, the larger the UXO charge weight and the closer it is to any given receptor, the more damage it may cause.

The shock wave from a detonation consists of an almost instantaneous rise in pressure to a peak pressure, followed by an exponential decay in pressure to the hydrostatic pressure. Initially, the velocity of the shock wave is proportional to the peak pressure but is rapidly settles down to the speed of sound in water, around 1,525 metres per second (m/s). In consolidated sediments and rock this can increase to ~1,800m/s. After detonation the shock wave will expand spherically outwards and will travel towards any particular receptor in a straight line – i.e. line of sight. Therefore, unless the wave is reflected, channelled or meets an intervening obstruction, for all practical purposes, the object will not be affected by the pressure wave if it is out of line of sight.

Most studies deal with the effect of shock through the water column, which is reasonably understood and well-documented. The peak pressure and decay constant depends on the size of the explosive charge and the stand-off distance from the charge. The Peak Pressure (*Pmax*) and Impulse (*I*) (momentum) experienced by a receptor (vulnerable structure) at distance *R* from a charge *W* can be calculated (Section 5.1).

4.3 Factor of Effect

There are several types of explosives used in munitions, often with added aluminium to increase blast and enhance the Bubble Pulse effect. Most safety distance and effect tables are entered using TNT as the standard. Other high explosives (HE) are compared to TNT using a *Factor of Effect (FoE)* to calculate the relative power. For example:

Explosive Type (100kg)	Equivalent TNT (Kg)	Factor of Effect
Amatol (German bombs)	100	1.0
Hexanite (German mines)	110	1.1
RDX/TNT mix (British bombs)	120	1.2
Minol (British mines)	150	1.5
Torpex (British Torpedoes / some bombs)	150	1.5

Table 4.1 – Conversion of The Main Explosive Fillings to TNT.

5. Receptive Entities

5.1 Peak Pressure Calculations

From the previous Section, we can see that the shock wave of a detonation produces a rise in pressure to a peak pressure, which will affect any receptors within a certain vicinity. This peak pressure is calculated using Cole's Law:

$$P_{peak} = 52.4 \times 10^{6} (R/W^{1/3})^{-1.13}$$

Table 5.1 shows the peak pressure values from a detonation's shock wave at varying distances for the items of UXO expected at the Site.

Ordnance Type (NEQ in kg)	Distance								
	50m	100m	200m	350m	500m	800m	1000m	2000m	3000m
German LMB Ground Mine (770)	7.704	3.520	1.608	0.855	0.571	0.336	0.261	0.119	0.075
British A Mk6 Ground Mine (525)	6.668	3.046	1.392	0.740	0.494	0.291	0.226	0.103	0.065
WWI German E series buoyant mine (150)	4.161	1.901	0.869	0.462	0.308	0.181	0.141	0.064	0.041
British MK14 Buoyant mine (261)	5.126	2.342	1.070	0.569	0.380	0.223	0.174	0.079	0.050
250lb HE Bomb (55)	2.851	1.303	0.595	0.316	0.211	0.124	0.097	0.044	0.028
500lb HE Bomb (120)	3.825	1.748	0.799	0.424	0.284	0.167	0.130	0.059	0.037
1000lb HE Bomb (250)	5.043	2.304	1.053	0.559	0.374	0.220	0.171	0.078	0.049

Table 5.1 – Peak Pressure (MPa) at Varying Distances from UXO Expected at Site

5.2 Shock Effect on Marine Mammals

The pressure from a shock wave, and thus the potential for impact on marine mammals depends largely on the NEQ and specific detonation velocity. Radiation and attenuation of the pressure wave depends on water depth, sediment, sea state, stratification of the water column, temperature, salinity and other variables. It is difficult to determine the precise distance at which physical injury and death would occur to mammals. However, research suggests that the shock effect on mammals, as air-breathers and with similar respiratory lung function, is akin to that of humans. The current advice to Royal Navy EOD operators is to use the Diver/Swimmer minimum danger range table. Table 5.2, below, displays these distances as they are laid out in Reference C:

Charge Weight of TNT (kg)	Distance (m)
Up to 250	1,200
250 – 500	1,500
500 – 1,000	2,000
1,000 – 2,000	2,500

Table 5.2 – Royal Navy Minimum Safe Distance for Swimmers

However, the US Army Corps of Engineers recommend much larger safe distances for the water depths expected at the Site (displayed at Table 5.3 below), recommending 6,068.5m for a bomb with a ~430kg charge weight. (Reference D)

Ordnance Type (NEQ in kg)	Distance (m)
Mk84 Bomb (429)	6,068.5
Mk83 Bomb (202)	5,262.1
Mk82 Bomb (87)	4,494.6
Mk81 Bomb (44)	3,980.9

Table 5.3 – US Army Corps of Engineers Minimum Safe Distance for Swimmers

6. Calculations on Crater Sizes

6.1 Introduction

When an item of EO detonates on the seabed (or buried within it) a crater will form. The primary cause of this event is the pressure wave resulting from the blast. However, the water jet produced vertically downward by the initial gas bubble pulse, which is comparable with the impulse in the main shockwave, also has a substantial influence on crater formation.

Therefore, while the cratering effects of a detonation are not directly applicable to marine mammals, these calculations provide an insight into the force of the blast, shockwave and other detonation effects, which may be extrapolatable when calculating safe distances for marine mammals.

6.1 Methodology Used to Determine Likely Crater Size

To *Ordtek's* knowledge, there is very limited open-source information available on crater sizes produced by detonations underwater and we are not aware of any comprehensive figures, tables or research on this subject. Much of the research we are aware of relates to nuclear detonations, some of which, but not all, is down-scalable. Where appropriate, we have factored this into our assessment. Similarly, the results from limited small scale experiments, such as *Gorodilov et al* (see below), may not always be valid for much larger charges.

Military EOD teams use tables for calculating crater sizes on land derived from empirical data from WWII. Counter-intuitively, these tables are entered with the all-up weight of the bomb, not the amount of HE contained (NEQ).

Therefore, in order to determine the extent of any likely disturbance of the soil integrity due to the EOD operations at Norfolk Vanguard, we have calculated crater sizes for representative threat UXO items using a variety of methods and then compared the results.

In this TN, we have:

- Calculated likely crater sizes using formulae and values from experimental results (*Gordilov et al)*.
- Determined likely crater sizes using military Land tables.
- Compared empirical data from other OWF (i.e. observed craters post EOD).
- Then established a recommended table of most likely crater sizes / extent of soil disturbance for typical EOD.

7. Dimensions of Potential Craters – Gorodilov Theory

Underwater, the dynamic forces are complicated. Factors such as depth of water (particularly in relation to blast radius), charge NEQ, sediment composition etc. have an influence on the size of the crater. Unlike on land, the water will "tamp" the explosion, directing more of the force downwards and increasing the volume of the crater but, conversely, at deeper depths, gravity (the weight of the water) will resist the ejection of seabed material, thereby reducing the size of the crater. Also, as noted above, the jet of water from the bubble pulse acting vertically downwards will significantly amplify the cratering effect.

Experiments (*Gorodilov et al., 1996)* have shown that for any given charge size, the maximum crater volume occurs at around Depth/Charge Radius = 25-30. This corresponded to an optimum depth of ~9m for an NEQ of 118kg (charge radius was not presented in the paper but can be inferred as 30cm).

Thereafter, despite the rise in the total explosion impulse with increasing water depth, an increase in the water layer above the seabed surface increases the resistance of the layer to sand ejection from the explosion epicentre. At depths deeper than the optimum, the volume of the crater gradually reduces until a constant size is reached at around Depth/Charge Radius = 60. The maximum crater volume (at optimum depth) equates to approximately 1500cm^3/g and the minimum constant reached in deeper water is around 500cm^3/g. In small scale experiments, the depth of the crater (h) = 5 x R_0 (charge radius). (Note that the experimental charges were spherical).

The *Gorodilov* paper also contends that the maximum crater volume at the optimum depth under water is greater by a factor of ~4-6 than the volume in the absence of water and by a factor of ~3 than that in deep water (this is relevant when we compare crater sizes calculated with those from land tables).

Extrapolating this *very limited* data, we can surmise that maximum crater size for a large bomb/mine (300kg NEQ, R_0 = 0.45m) will occur at ~12m water depth. However, the water depth across the Site varies from about 25m – 50m LAT (for the calculations in this TN, a depth of 29m is used). At this depth, we get a value for Depth/R_0 approaching ~60, which as shown above is the value at which the crater dimensions become constant. At this depth, according to *Gorodilov* data, the crater volume will be ~150m^3.

Using the formula for the volume of a cone, this produces a crater size of ~16m x 2.25m (diameter x depth).

At Table 7.1, below, we have calculated theoretical crater sizes according to the *Gorodilov* experimental results, using a certain amount of judgement and discretion in choosing an appropriate charge radius for each item of UXO.

Crater Calculation for Typical Norfolk Vanguard UXO using *Gorodilov et al* Experimental Data							
UXO Item	**NEQ (kg)**	**Factor of Effect (FoE)**	**TNT Equivalent (kg)**	**Water Depth (m)**	**Crater Volume**	**Likely Diameter of Crater (m)**	**Likely Depth of Crater (m)**
German LMB (GC) Ground Mine (Hexanite)	700	1.10	770	~29m	385m^3	21.11	3.30
British A Mk6 Ground Mine	430	1.22	525	~29m	262m^3	21.09	2.25
WWI German E series submarine-laid buoyant mine (Wet Gun Cotton) / TNT - worst case)	150	1.00	150	~29m	75m^3	12.61	1.8
Buoyant mine (British MK14)	227	1.15	261	~29m	130m^3	15.75	2.0
250lb HE Bomb (Amatol / TNT)	55	1.00	55	~29m	27m^3	8.91	1.3
500lb HE Bomb (Amatol / TNT)	120	1.00	120	~29m	60m^3	11.97	1.6
1000lb HE Bomb (Amatol / TNT)	250	1.00	250	~29m	125m^3	14.56	2.25

Table 7.1 - Crater Calculation for Typical Norfolk Vanguard OWF UXO using Gorodilov et al. Experimental Data

8. Dimensions of potential craters from Military Land Tables (WWII data)

On land, rough crater sizes for the size of bomb can be determined from military tables (based on WWII empirical evidence).

The tables consider the total weight of the bomb and that a bomb or UXO is assumed "buried" when it is buried to at least 2.5 x its length. On *Norfolk Vanguard* it is likely that medium capacity bombs were assumed when the tables were formulated and the charge to weight ratio for these is approximately 50%.

So when using the tables for underwater weapons, where charge to weight ratio is generally higher – for example for the German LMB (GC) ground it is ~70% - we have adjusted the value entered into the table accordingly.

We have assumed that the UXO will be buried to <1.0m, which for large UXO is less than a depth of at least 2.5 x length of the bomb, and on land is when a bomb is considered to be buried for the purposes of entering the table. However, given the tamping effect of the incompressible water above the detonation, underwater, the "buried" values are the most likely to give meaningful results.

The results shown in Table 8.1 below were obtained:

Crater Calculation for Typical Norfolk Vanguard UXO using Military (Land) Tables						
UXO Item	**NEQ (kg)**	**Factor of Effect (FoE)**	**TNT Equivalent (kg)**	**Crater Volume**	**Average Diameter of Crater (m)**	**Average Depth of Crater (m)**
German LMB (GC) Ground Mine (Hexanite)	700	1.10	770	378m^3	17.0	5.0
British A Mk6 Ground Mine	430	1.22	525	260m^3	15.3	4.3
WWI German E series submarine-laid buoyant mine (Wet Gun Cotton) / TNT - worst case)	150	1.00	150	73m^3	12.61	2.8
British MK14 Buoyant mine	227	1.15	261	128m^3	12.0	3.35
250lb HE Bomb (Amatol / TNT)	55	1.00	55	27m^3	8.91	1.3
500lb HE Bomb (Amatol / TNT)	120	1.00	120	78m^3	10.0	3.0
1000lb HE Bomb (Amatol / TNT)	250	1.00	250	181m^3	13.7	3.7

Table 8.1 – Estimated crater size following UXO detonation using land tables

9. Comparison of Table 1 (Gorodilov) and Table 2 (Military Land)

A comparison of the two sets of results shows that there is generally a close correlation for the calculated crater volume. However, the *Gorodilov* crater diameter value we have calculated is generally greater than that derived from the land table.

Using *Gorodilov,* the crater volume is worked out as 500cm^2/g of charge weight. Then depth of the crater is calculated as 5 x the charge radius R_o and, finally, the diameter is worked out by entering the other two values into the formula for a cone.

The *Gorodilov* experiments used spherical charges, whereas the UXO charges for the most part are cylindrical. In the calculations, we applied the UXO diameter for cylindrical EO and the approximate diameter of the internal charge case for spherical mines. This slightly skewed the results for crater diameter. Using the length of the UXO items produces a value for the diameter that is much too big. Clearly, there is an intermediate value that is correct and depends on both the shape and size of the actual UXO HE charge. However, the fact that the crater volume is closely aligned in both methods gives confidence that the calculation for overall volume of sediment disturbed in the detonation is reasonable.

Comparison of Table 7.1 (Gorodilov) crater dimensions and Table 8.1 (Military Land)						
UXO Item	**Gorodilov**			**Military Land Tables**		
	Crater Volume (m^3)	**Average Diameter of Crater (m)**	**Average Depth of Crater (m)**	**Crater Volume (m^3)**	**Average Diameter of Crater (m)**	**Average Depth of Crater (m)**
German LMB (GC) Ground Mine (Hexanite)	385	21.1	3.30	378	17.0	5.0
British Ground Mine	262	21.1	2.2	260	15.3	4.3
WWI German E series submarine-laid buoyant mine (Wet Gun Cotton) / TNT - worst case)	75	12.6	1.8	73	12.61	2.8
Buoyant mine (British MK14)	130	15.7	2.0	128	12.0	3.3
250lb HE Bomb (Amatol / TNT)	27	8.9	1.3	27	8.91	1.3
500lb HE Bomb (Amatol / TNT)	60	12.0	1.6	78	10.0	3.0
1000lb HE Bomb (Amatol / TNT)	125	14.6	2.2	181	13.7	3.7

Table 9.1 – Comparison of Table 7.1 (Gorodilov) crater dimensions and Table 8.1 (Military Land)

10. Comparison with Empirical Results from the Field

Ordtek has a dataset from other OWF, of crater sizes measured post-detonation. The following table compares an example of the calculated crater sizes for typical UXO with values observed under similar conditions on other offshore projects. In all cases, the bombs will either have been on the surface or at <1m, exposed by dredging for the demolition.

Observed crater sizes for detonations underwater				
UXO Type	**Water Depth (m)**	**Sediment**	**Crater Diameter**	**Crater Depth**
500 lb bomb	14.7 m	Sand	5.1	0.9
500 lb bomb	14.7 m	Sand	6.3	0.9
500 lb bomb	14.7 m	Sand	5.3	1.0
500 lb bomb	14.7 m	Sand	3.6	0.9
500 lb bomb	14.7 m	Sand	6.1	1.0
500 lb bomb	14.7 m	Sand	11.0	1.5
500 lb bomb	14.7 m	Sand	6.1	0.7
500 lb bomb	14.7 m	Sand	10.0	1.7
500 lb bomb	13.0 m	Sand	6.0	0.9
500 lb bomb	13.0 m	Sand	7.6	1.3
500 lb bomb	13.8 m	Sand	6.3	1.1
500 lb bomb	14.9m	Sand	4.5	0.6

UXO Type	Water Depth (m)	Sediment	Crater Diameter	Crater Depth
500 lb bomb	13.8m	Sand	8.0	2.1
Average (500lb)			**6.6**	**1.1**
1000lb bomb	13.0m	Sand	6.2	0.9
1000lb bomb	20.9 m	Sandy Gravel	7.5	1.2
1000lb bomb	21.1 m	Sandy Gravel	8.5	1.2
1000lb bomb	20.7 m	Sandy Gravel	8.2	1.0
1000lb bomb	35.3m	Sandy Gravel	7.0	1.0
Average (1000lb)			**7.5**	**1.0**
LMB (GC) Mine	21.0m	Sand	10.0	3.7

Table 10.1 – Observed crater sizes for detonations underwater

It is immediately evident looking at the sample detonations in similar conditions that there is apparently very little consistency in the sizes of craters that are produced, even for the same type of bomb. It is also evident that the observed dimensions of the craters are significantly less than those calculated at Tables 7.1 and 8.1 above.

The wide variation is most likely because the precise state of each bomb was not known, the measurements were taken by ROV, which are usually only approximate, and by at least 2 different contractors, and the time elapsed after the detonation and before measurement probably varied significantly – from a few hours to several days. In all cases, the process of backfill due to tidal movement had almost certainly begun prior to measurement.

Therefore, determining the size of the initial crater – i.e. immediately after a detonation – and then the full extent of the sediment that has been deformed / influenced can only be a very rough estimate using these observed values.