Norfolk Boreas Offshore Wind Farm

Appendix 5.3

Ordtek UXO Review

Environmental Statement

Volume 3

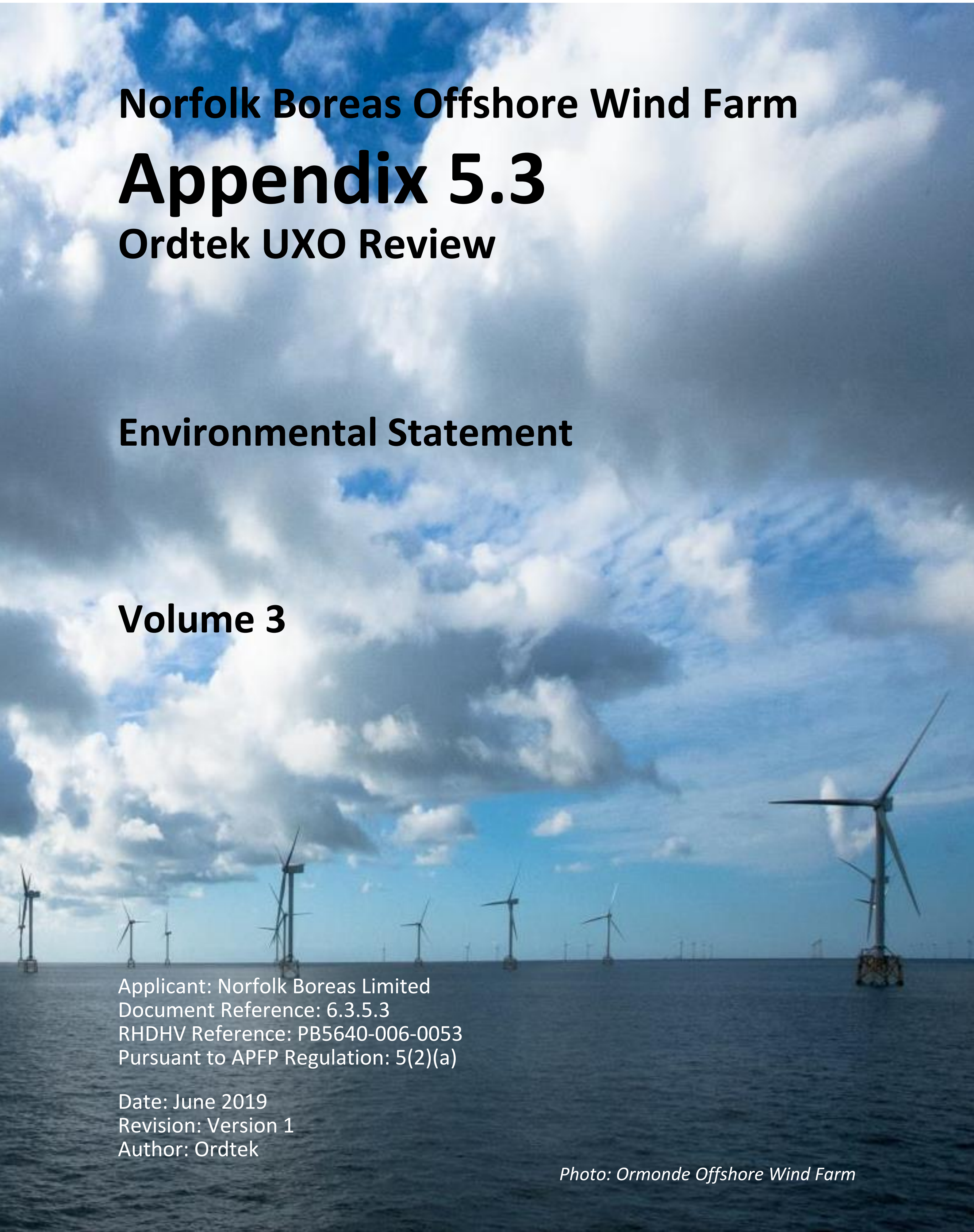

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Photo: Ormonde Offshore Wind Farm

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Unexploded Ordnance (UXO) Hazard and Risk Assessment with Risk Mitigation Strategy

Project: **Norfolk Boreas Offshore Wind Farm**

Client: **Vattenfall Wind Power Limited / Norfolk Boreas Limited**

Date: **26 September 2018**

Ordtek Project Reference: **JM5503**

Ordtek Report Reference: **JM5503_RA-RMS_V1.2**

Client	VATTENFALL

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Quality Assurance

Project Number	Status	Version	Date	Written	Technical Review	Quality Review	Released
JM5503	Final	1.2	26/09/2018	[redacted]	[redacted]	[redacted]	[redacted]
				Henry McPartland	Robin Broadley	Amber Gladwin	Lee Gooderham

Document Revisions and Amends

Version	Page	Section	Amends
V1.0	-	-	Issued as draft.
V1.1	iii - vii	ES	Executive summary refined to add clarity.
V1.2	iii, 1, 2	ES, 1.1, 1.3	Amended in line with Client comments, “NB_UXO Comments”.

Executive Summary

Introduction

Ordtek Limited (*Ordtek*) has been appointed by *Norfolk Boreas Limited* to undertake an unexploded ordnance (UXO) risk assessment for the proposed Norfolk Boreas Offshore Wind Farm (OWF), located in the North Sea approximately 73km off the Norfolk coast.

The Norfolk Boreas Offshore Wind Farm covers an area of approximately 725km^2. The export cable will connect the wind farm to the shore, making landfall near Happisburgh, Norfolk. This report also covers the project interconnector cable, connecting Norfolk Boreas with Norfolk Vanguard. In addition to the main array, export cable and interconnector cable, this report also covers a wider Study Area that takes in the surrounding region to a distance considered relevant to any particular issue under examination.

UXO presents a potential risk to the installation and continued operation of offshore projects in UK waters, principally due to the UXO residue from World War One (WWI) and World War Two (WWII).

This “risk assessment” is primarily concerned with Health and Safety risk. The level of “Project risk” that is tolerable is to be determined by the Client in consultation with relevant vessel/equipment owners and contractors. While the H&S risk is ALARP, additional costs related to vessel/equipment insurances and/or Project delays should also be considered.

Military History

The east coast of the UK saw a considerable amount of military action during WWI and WWII. The principal hazards to the wind farm are from bombs dropped targeting shipping, dumped munitions (including bombs jettisoned by both Allied and Axis aircraft), naval artillery and projectiles and British buoyant mines from the extensive mine barrier.

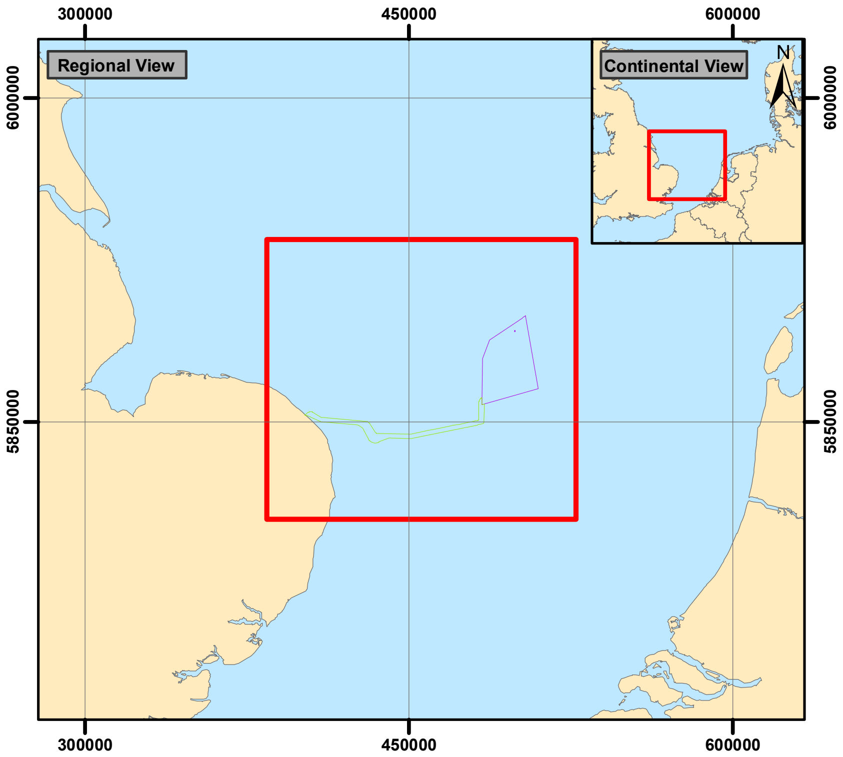
A large number of high net explosive quantity (NEQ) items of UXO have been found on wind farms on the East coast of the UK, principally 500lb and 1000lb Allied bombs, as well as smaller NEQ items such as incendiary units.

An overview of the possible UXO contamination sources is presented in the chart overleaf (Norfolk Boreas Offshore Wind Farm; All UXO Contamination Sources).

Burial of UXO

UXO may be buried up to 5.0m below current bed level in places, due to up to 4.5m high sand dunes in combination with scour burial and sediment accretion. However, clearance of the entire depth is not practical given current equipment limitations. Therefore, in line with the ALARP principle a risk horizon is assessed to which mitigation should aim to cover.

For the Norfolk Boreas OWF, this risk horizon is assessed as 2.0m below the seabed, based on practical detection depths. Given the anticipated burial and observed seabed features (sand waves/ megaripples), UXO migration into the area is unlikely. While a high-energy storm event may have sufficient power to move items of UXO on or near the surface, outside this event UXO migration is very unlikely throughout the life of the wind farm. This is explored further in Annex E.



UXO Hazard Item	Probability			UXO Hazard Item	Probability		
	MA	OEC	NEC		MA	OEC	NEC
British WWI Mines	1	2	1	HE Bombs and Rockets	4	5	4
German WWI Mines	1	2	2	Artillery and Naval Projectiles	2	3	3
Allied WWII Mines	4	3	2	Land Service Ammunition	1	1	2
German WWII Mines	3	3	3	Practice Munitions	1	1	1
Depth Charges and Torpedoes	2	2	1				

Legend for Site View

Infrastructure

▭ Main Array
▭ Offshore Cable Corridor
▭ Project Interconnector Cable Search Area

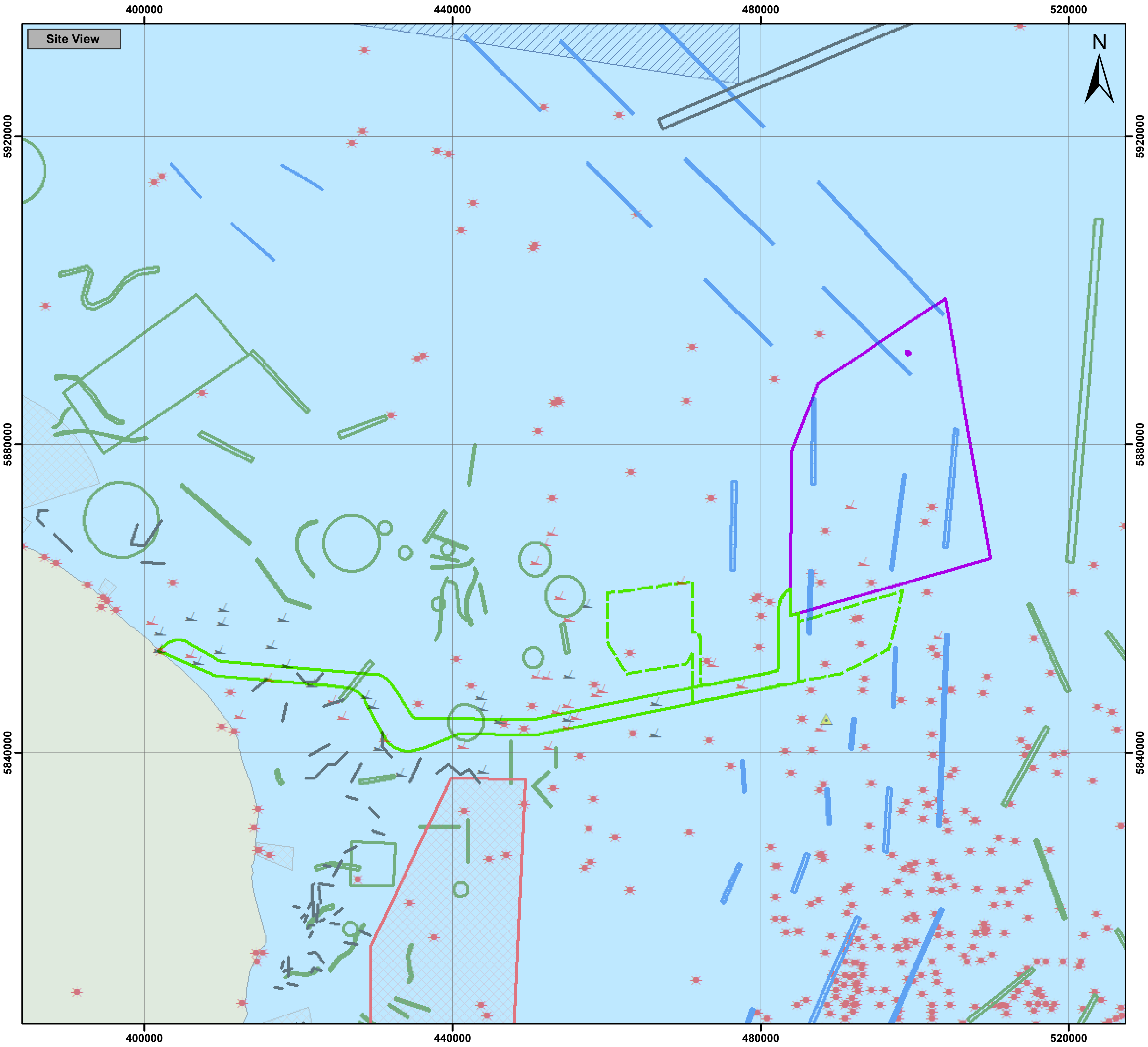
UXO Hazard

─ WWI German Mine Lay
▨ WWI British Mine Barrier
▭ WWII British Mine Lay
▭ WWII German Mine Lay
✓ WWI Wrecks of Military Interest
✓ WWII Wrecks of Military Interest
▲ OSPAR Recorded Munition Dump Site (Conventional)
● OSPAR Recorded Munition Encounters (<2014)
▨ WWII – British Armament Areas
▨ Modern Military – Air Force Training Area

Horizontal Scale(s)

Kilometers: 0, 5, 10, 20, 30, 40

Nautical Miles: 0, 2.5, 5, 10, 15, 20



Consultant

ORDTEK

Client

VATTENFALL

Drawing Title

Norfolk Boreas Offshore Wind Farm
All UXO Contamination Sources

User Notes
N/A

ISO 9001 CERTIFIED
UKAS
British Assessment Bureau

ETRS 1989 UTM Zone 31N
Projection: Transverse Mercator
Datum: ETRS 1989
False Easting: 500,000.0000
False Northing: 0.0000
Central Meridian: 3.0000
Scale Factor: 0.9996
Latitude Of Origin: 0.0000
Units: Meter

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JM5503 - Norfolk Boreas Offshore Wind Farm

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Drawing Reference: JM5503_Norfolk Boreas_DTS_09
Drawing Version: 1.1

Risk Mitigation Strategy (RMS)

While the mitigation strategy recommended within this study is based solely on the Health and Safety risk UXO presents, it is also important to consider other risks to the Project, such as the impact of delay. These other risks may need to be taken into consideration when determining the level of risk mitigation. The UXO risk can be reduced to the ALARP threshold by implementing the UXO risk mitigation strategy below.

The table below summarises the mitigation required for ALARP sign-off.

Project Phase	**Activity**	**Typical Working Area/ Survey Coverage**	**Minimum Geophysical Survey Requirement**	**Further UXO Risk Management Actions (however to be confirmed based upon specific project method statements)**
Pre-Construction Site Investigation from Floating Vessels	Grab Samples	N/A	None	➢ Residual risk management
	Geotechnical Investigations: • Cone Penetration Test • Borehole • Vibrocore	25m x 25m box	Full working area coverage with resolution to detect the smallest threat item: • Multibeam Echosounder • Side Scan Sonar Single magnetometer line centred on proposed GI locations.	➢ Relocate GI locations to survey lines ➢ Avoid potential UXO by 10m ➢ Residual risk management
Monitoring	Wave buoys and LiDAR Station anchoring	N/A	None in isolation, however where geophysical data is available, it should be utilised.	➢ Avoid potential UXO by 10m ➢ Residual risk management
	Met-Mast commissioning/ decommissioning	N/A		➢ Avoid potential UXO by 10m ➢ Residual risk management
Construction	Cable lay down	Covering working area	Full working area coverage: • Multibeam Echosounder • Side Scan Sonar	➢ Avoid potential UXO by 10m ➢ Residual risk management
	Pre Lay Grapnel Run (PLGR)	20m corridor	Full working area coverage with resolution to detect the smallest threat item: • Magnetometer • Multibeam Echosounder • Side Scan Sonar	➢ Avoid potential UXO by 15m ➢ Residual risk management
	Cable Installation: • Plough • Trenching • Jetting • Cutting	20m corridor (inter array cable) 30m corridor (export cable) – offshore, 100m corridor close to shore		➢ Avoid potential UXO by 10m ➢ Residual risk management
	Foundation Installation: • Monopile • Gravity base • Suction bucket • Multi pile	30m radius around foundations		➢ Avoid potential UXO by 15m, no potential UXO should remain within 30m of the foundation location ➢ Residual risk management

Project Phase	Activity	Typical Working Area/ Survey Coverage	Minimum Geophysical Survey Requirement	Further UXO Risk Management Actions (however to be confirmed based upon specific project method statements)
Construction	Jack-up Operations	200m radius around foundations	Full working area coverage with resolution to detect the smallest threat item: • Magnetometer • Multibeam Echosounder Side Scan Sonar	➢ Avoid potential UXO by 15m ➢ Residual risk management
	Scour protection (rock cover)	Covering working area		➢ Avoid potential UXO by 15m ➢ Residual risk management
	Dredging/pre-sweep	Covering working area		➢ Grates on dredge head ➢ Avoid potential UXO by 15m ➢ Residual risk management
	Sediment spoil disposal	Covering working area	Multibeam Echosounder/ Side Scan Sonar	➢ Avoid potential UXO by 15m ➢ Residual risk management
	Anchor Handling	Covering working area	Multibeam Echosounder/ Side Scan Sonar	➢ Avoid potential UXO by 10m ➢ Residual risk management

Table ES1 – Summary of Recommended Strategy for UXO Risk Mitigation

UXO Risk Mitigation Process

The UXO risk mitigation phases recommended for Norfolk Boreas follow *Ordtek's* proprietary framework, illustrated at Section 1 (Figure 1.1). The actions below expand on the phases of this framework.

Phase 4 and 5 – Geophysical Survey

- Establish smallest threat item and develop specification to detect item with required datasets.
    - Within water depths greater than 10m LAT, Ordtek recommends the British 500lb HE bomb.
    - Within water depths 10m LAT and lower, Ordtek recommends the British 250lb HE bomb.
- Establish survey areas.
- As part of vessel mobilisation, undertake an equipment verification test (EVT) on the project site with a deployed known test item to show all sensors are working as expected and demonstrate data transfer and processing procedures.
- Pass EVT data and report to Client and UXO Consultant for review – receive EVT acceptance report.
- Acquire geophysical data sets with Client survey representatives onboard providing data QA/QC.
- During larger campaigns or the pre-construction survey it is advised that a preliminary site block is delivered to the Client and UXO consultant to undertake a data audit ensuring data is being processed and collected within expected specifications and methods.
- Contractor to process data in accordance with the specification set by the UXO consultant.
- Send processed data to the Client and UXO consultant.
- UXO consultant to interpret data and pick "potential UXO" (pUXO) targets. The output will be a pUXO target listing.

Phase 6 – Potential UXO Avoidance and Inspection

- Any pUXO can be avoided by a suitably safe distance for any intrusive seabed interactions.

- This can be achieved through rerouting or micro-siting of seabed interactions.
- In accordance with the ALARP principle, the installation could then proceed with a de minimis risk of encountering UXO.
- Safety exclusion zones around pUXO should be respected.
- Should the pUXO targets remain a constraint to the Project, then they may need to be inspected. This may involve investigation by diver or Remotely Operated Vehicle (ROV).
- A UXO Specialist should be embarked onboard the vessel during inspection.

Phase 7 and 8 – Residual Risk Management

- Obtain ALARP sign-off certificate.
- Input geophysical contacts to be avoided into the on-board navigation system.
- Ensure the Project team are aware of their internal UXO policy, including key support numbers.
- Hold a copy of this risk assessment on-board the vessel.
- Brief all personnel on the potential UXO risk.
- Hold a UXO specialist on-call in the event of an encounter with a suspect item of UXO.

Contents

Annexes

Annex A – Supplementary Notes on Munitions Types

Annex B – Explosive Ordnance Technical Data

Annex C – Explosive Ordnance Detonation Mechanisms and Effects

Annex D – Supplementary Notes on UXO Burial

Annex E – Supplementary Notes on UXO Migration

Annex F – Seabed Effects During Explosive Ordnance Disposal (EOD)

Abbreviations and Acronyms

AA	Anti Aircraft	**M**	Metres
AEZ	Archeological Exclusion Zone	**MBES**	Multibeam Echo Sounder
ALARP	As Low As Reasonably Practicable	**MBD**	Maximum Burial Depth
AOI	Area of Interest	**MCM**	Mine Countermeasures
BL	Breech Loading	**MDD**	Maximum Detection Depth
BSH	Bundesamt für Seeschifffahrt und Hydrographie (German hydrographic office)	**MGS**	Mindestens Gleiche Sicherheit (German legislation)
CDM	Construction Design and Management (UK legislation)	**ML**	Muzzle Loading
CIRIA	Construction Industry Research and Information Association	**mm**	Millimetres
CW	Chemical Weapon	**MoD**	Ministry of Defence
EMA	German moored contact mine Type A	**MTB**	Motor Torpedo Boat
EMC	German moored contact mine Type C	**MW**	Megawatt
EMG	German moored contact mine Type G	**NEQ**	Net Explosive Quantity
EO	Explosive Ordnance	**NM**	Nautical Mile
EOD	Explosive Ordnance Disposal	**OSPAR**	Convention for the Protection of the Marine Environment of the North East Atlantic
ERW	Explosive Remnants of War	**PLGR**	Pre-Lay Grapnel Run
EU	European Union	**RAF**	Royal Air Force
GAMAB	Globalement Au Moins Aussi Bon	**RMF**	Risk Management Framework
GC	Allied designation for German type LMB mine	**RML**	Rifled Muzzle Loading
GD	Allied designation for German type LMA mine	**RN**	Royal Navy
GG	Allied designation for German type BM1000 mine	**ROV**	Remotely Operated Vehicle
GY	Allied designation for German type EMC/EMG mine	**QA/QC**	Quality Assurance/Quality Control
GZ	Allied designation for German type UMA mine	**SAA**	Small Arms Ammunition
GIS	Geographical Information System	**SBP**	Sub Bottom Profiler
H&S	Health and Safety	**SF**	Shock Factor
HAA	Heavy Anti-Aircraft Artillery	**SOP**	Standard Operating Procedure
HE	High Explosive	**SQRA**	Semi Quantitative Risk Assessment
HSE	Health and Safety Executive	**SSS**	Sidescan Sonar
HSF	Hull Shock Factor	**TNT**	Trinitrotoluene
Kg	Kilogram	**UK**	United Kingdom

KHz	Kilohertz	**UKHO**	United Kingdom Hydrographic Office
Km	Kilometre	**UMA**	German anti-submarine mine Type A
KSF	Keel Shock Factor	**UXB**	Unexploded Bomb
Kv	Kilovolt	**UXO**	Unexploded Ordnance
LMA	Luftmine A (German air-dropped ground mine Type A)	**WWI**	World War One
LMB	Luftmine B (German air-dropped ground mine Type B)	**WWII**	World War Two
LSA	Land Service Ammunition		

Definitions

Several industry specific terminologies are used in this document. However, *Ordtek* considers the following worthy of special note.

- **Explosive Ordnance (EO)** – A military munition that is designed to detonate or explode. It may contain either High or Low Explosive or both (it may also contain nuclear fissile material but this is not relevant within this document). In the context of this Desk Study with Risk Assessment, the term includes Chemical Weapons (CW).
- **Unexploded Ordnance (UXO)** - UXO is defined as military munitions, including CW, that have been primed, fused, armed or otherwise prepared for action; have been fired, dropped, launched, Projected or placed in such a manner as to constitute a hazard to operations, installations, personnel or material; and remain unexploded whether by malfunction, design or any other cause.
- **Potential UXO** (in terms of UXO survey) **–** A geophysical anomaly modelling as UXO but not yet inspected. Within this context, the term is also understood to include primarily inert practice munitions that may or may not have a low explosive element.
- **Suspect UXO** – An object inspected (usually by diver or ROV) but awaiting further confirmatory inspection or analysis.
- **Confirmed UXO** – An object that has been positively identified as UXO.
- **As Low As Reasonably Practicable (ALARP)** - The health and safety principle is that *any residual risk shall be as low as reasonably practicable.* For a risk to be ALARP it must be possible to demonstrate that the cost involved in reducing the risk further would be grossly disproportionate to the benefit gained. The ALARP principle arises from the fact that infinite time, effort and money could be spent on the attempt of reducing a risk to zero.
- ***De minimis*** - A residual risk that is deemed to be too trivial or minor to merit consideration, especially in law. It is the failure to reach the threshold level required to be actionable.
- **Exclusion Zone** – An avoidance zone placed around a potential UXO item, designed to avoid disturbance of that item.
- **Safety Zone** – An avoidance zone implemented around confirmed UXO to protect both Project and third party personnel, vessels and equipment should the item detonate.

1 Introduction

1.1 Background

Ordtek Limited (*Ordtek*) has been appointed as the unexploded ordnance (UXO) risk management consultant to *Norfolk Boreas Limited* for the Norfolk Boreas Offshore Wind Farm (OWF), situated in the North Sea approximately 73km off the Norfolk coast.

UXO presents a potential risk to the development and continued operation of offshore projects in European waters, principally due to the UXO residue from World War One (WWI) and World War Two (WWII). Explosive Ordnance (EO), both the result of military action and planned post-war dumping, is frequently encountered off the UK coast.

1.2 Purpose of this Document

The purpose of the document is to serve as a valid operational risk assessment, not as a detailed historical report. Accordingly, the research has drawn on the most convenient and reliable sources, cognisant of the need to limit cost and delay to the Project. Nevertheless, the data presented is complete and appropriate for risk assessment purposes and fully in line with current best practice.

This study is structured around five key components:

- **Project Description** – Those activities to be risk assessed.
- **UXO Hazard Assessment** – A detailed hazard assessment will be carried out and a summary of identified hazards within the Study Area will be presented.
- **UXO Interaction in the Natural Environment** – How the hazard items are likely to be found within the area.
- **UXO Risk Assessment** – Using the information above Ordtek will then assess the risk to the proposed operations.
- **UXO Risk Mitigation Strategy -** Recommendations for mitigation ahead of the proposed operations.

Charts have been embedded within the body of the report and will be referenced by their Chart Number.

1.3 Project Details

1.3.1 Background

The Norfolk Boreas Offshore Wind Farm covers an area of approximately 725km^2. The wind turbine generator (WTG) configuration has yet to be decided but up to 257 WTG could deliver up to 1800MW of electricity. This report also covers an interconnector cable, connecting Norfolk Boreas with Norfolk Vanguard. The export cable will connect the wind farm to the shore, a distance of approximately 90km, making landfall near Happisburgh, Norfolk.

1.3.2 Risk Assessment Study Area

This report will cover the Norfolk Boreas main array and export cable up to the landfall, in addition to the project interconnector cable, referred to within this report as the “wind farm”. In our assessment, we also consider a wider “Study Area” that takes in the surrounding region to a distance considered relevant to any particular issue under examination; the extent of this wider area considered is charted at JM5503_Norfolk Boreas_DTS_01.

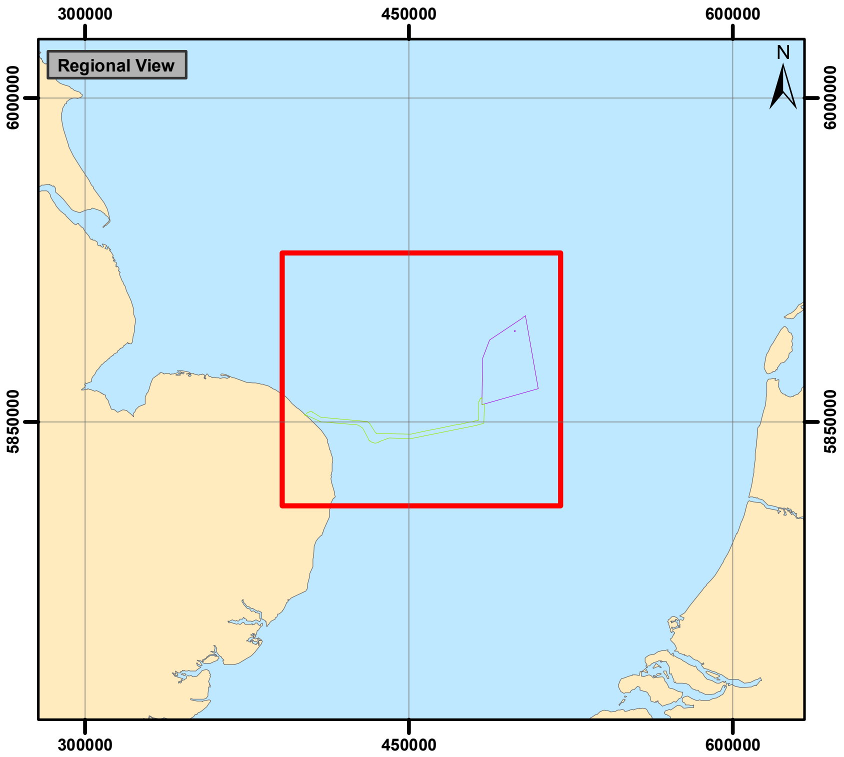
1.3.3 Proposed Work for UXO Risk Assessment

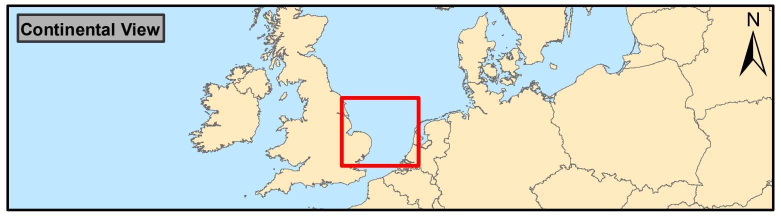
At the time of writing this study, the full scope of work (including installation methodology) has not been decided, however we understand the foundation types being considered are single steel monopiles and piled jackets are being considered in deeper water.

At this stage, we have no information on the depth at which the inter-array cables, interconnector cables or export cables will be buried but we have assumed for risk assessment purposes it is likely to be < 2m below bed level.

For the purposes of UXO risk assessment, *Ordtek* has assumed the following typical phases and activities are likely to be undertaken:

- Site Investigation
    - Geotechnical campaign (Geotech) from a Dynamically Positioned (DP) vessel along cable routes and WTG locations.
    - Geophysical survey for engineering purposes.
    - Installation of MetOcean equipment, such as Met Mast and Tide Gauge.
- WTG foundation installation
    - Site preparation - debris removal and/or dredging.
    - Jack-up barge operations.
    - Piling (hydraulic hammer).
    - Scour protection - rock/gravel dumping.
    - Boulder clearance operations.
- Inter-Array Cable, Interconnector Cable and Export Cable Installation
    - Pre Lay Grapnel Run (PLGR).
    - Cable plough / trenching / jetting / cutting.
    - Scour protection (rock cover).
    - Boulder clearance operations.





Legend for Site View

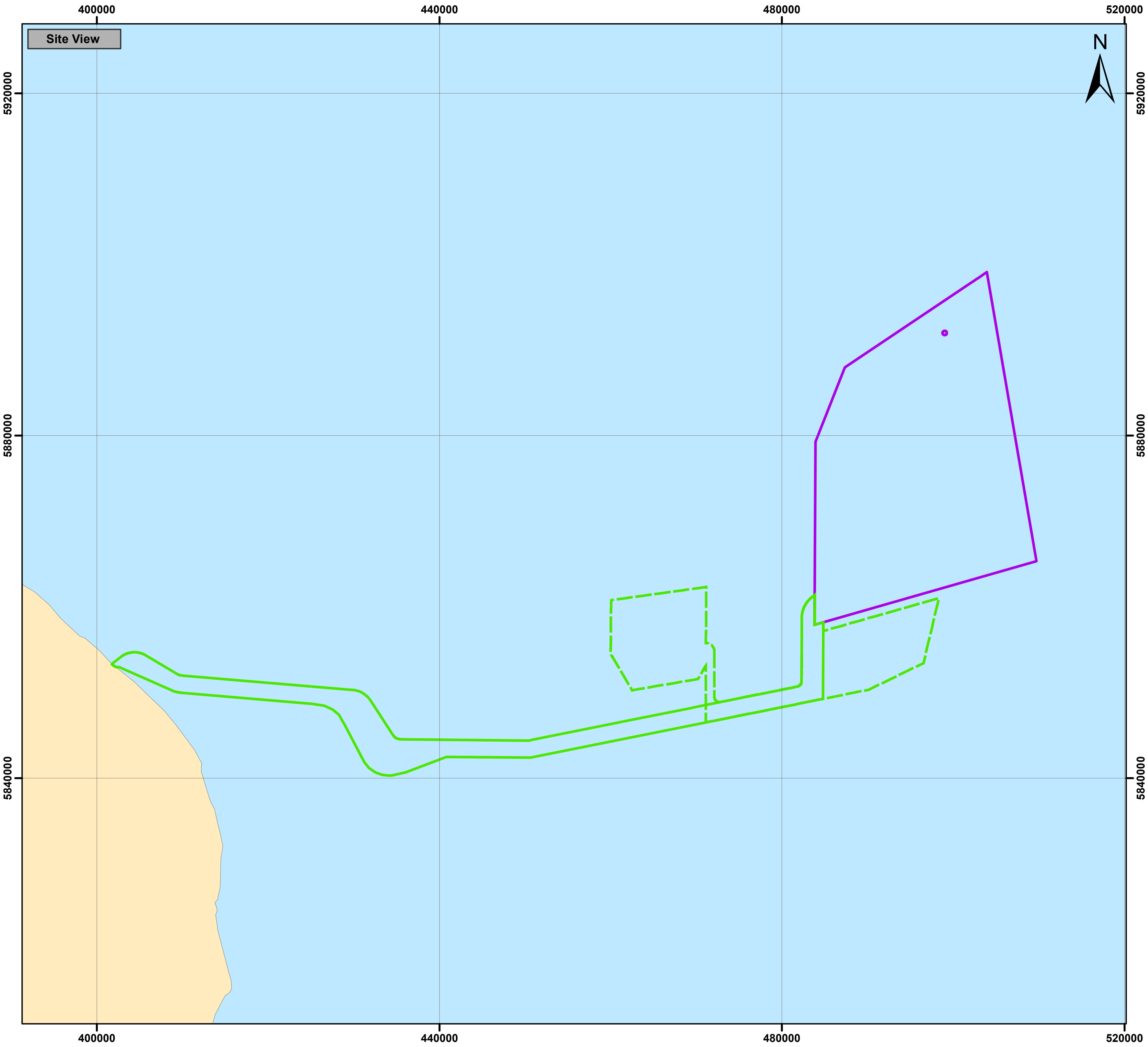
Infrastructure

🟪	Main Array
🟩	Offshore Cable Corridor
▨	Project Interconnector Cable Search Area

Horizontal Scale(s)

Kilometers: 0, 5, 10, 20, 30, 40

Nautical Miles: 0, 2.5, 5, 10, 15, 20



Consultant
ORDTEK

Client
VATTENFALL

Drawing Title
Norfolk Boreas Offshore Wind Farm
Project Overview

User Notes
N/A

ISO 9001 CERTIFIED
UKAS
British Assessment Bureau

ETRS 1989 UTM Zone 31N
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Drawn by: BB
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JM5503 - Norfolk Boreas Offshore Wind Farm

Date Drawn: 30 August 2018
Drawing Reference: JM5503_Norfolk Boreas_DTS_01
Drawing Version: 1.1

1.4 References

Key references used for this study have been listed below:

A. CIRIA, *Assessment and Management of Unexploded Ordnance Risk in the Marine Environment (C754),* dated 2015.

B. Fugro Group, *Norfolk Boreas Offshore Wind Farm – UK Continental Shelf, North Sea Geophysical Site Investigation (GE059-R1-2 (02)),* dated March 2018.

1.5 Construction Industry Duties and Responsibilities

1.5.1 European Law

In our experience, it is generally the case across Europe that there is no specific legislation covering the management and control of the UXO risk to the offshore construction industry (especially outside the 12NM boundary). In view of the lack of specific UXO legislation, our considered opinion is that European Union (EU) law concerned with the protection of workers from work-place hazards will normally apply to offshore activities. This is the subject of *Council Directive 89/391/EEC of 12 June 1989 (amended up to 21 November 2008)*, which introduces measures to encourage improvements in the safety and health of workers at work. The Directive applies to all sectors of activity, both public and private (industrial, agricultural, commercial, administrative, service, educational, cultural, leisure etc.).

Within the Directive, “Prevention” is defined as: all the steps or measures taken or planned at all stages of work in the undertaking to prevent or reduce occupational risks (Article 3 Definitions).

The Directive lays down the obligations of both employer and workers. Article 6 sets out the general principles of prevention, which include *inter alia*:

a) Avoiding risks;
b) Evaluating the risks which cannot be avoided;
c) Combating the risks at source;
d) Adapting the work to the individual …
Etc.

Article 18, directs that “Member States shall bring into force the laws, regulations and administrative provisions necessary to comply with this Directive by 31 December 1992.”

1.5.2 Relevant National Law and UXO Risk Tolerability

As noted above, there is no specific legislation covering the management and control of the UXO risk in the UK construction industry in general, or the development of an offshore wind farm in particular, but issues regarding health and safety (H&S) are addressed under a number of regulatory instruments. In practice the regulations below impose a responsibility on the construction industry to ensure that they discharge their obligations to protect those engaged in ground engineering operations from any reasonably foreseeable UXO risk.

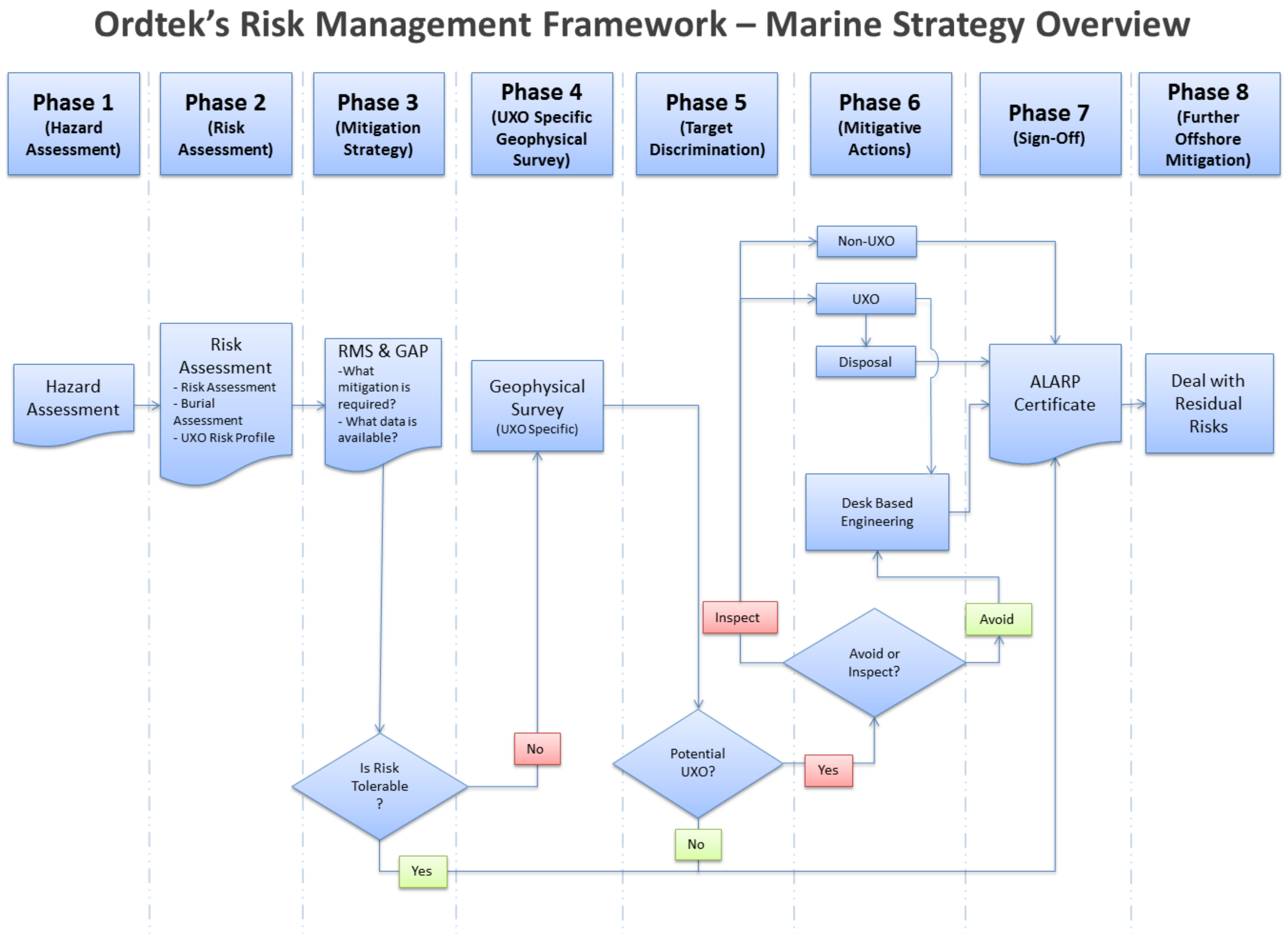
- **The Health & Safety at Work Act (1974)** places a duty of care on an employer to put in place safe systems of work to address, as far as is reasonably practicable, all risks (to employees and the general public) that are reasonably foreseeable.

- **Construction Design and Management (CDM) Regulations (2015)** defines the responsibilities of all parties (primarily the Client, the CDM Coordinator, the Designer and the Principal Contractor) involved with works.
- **Corporate Manslaughter and Corporate Homicide Act (2007)** now enables the prosecution of companies (and other organisations) where there has been a gross failing, throughout the organisation, in the management of health and safety with fatal consequences. If UXO causes a fatality and there has been a gross failing, the act will apply.

1.6 UXO Risk Management Standards and Risk Assessment

Through previous engagement on offshore projects in Europe and worldwide, *Ordtek* is acutely aware of the standards and guidance that need to be adhered to when managing UXO risk (Section 6). This includes working in line with the guidance and research provided by CIRIA *(C754*, 2015) and the relevant health and safety legislation.

Where limited official guidance exists (i.e. such as addressing risk in the offshore environment), *Ordtek* will work within its proprietary Risk Management Framework (see *Figure 1.1*) and Standard Operating Procedures (SOPs).



Ordtek's Risk Management Framework – Marine Strategy Overview

Figure 1.1 – Ordtek's risk management framework for the reduction of UXO risks.

The framework consists of 8 interrelated and sequential phases, which are specifically designed to discharge clients' legal liabilities to *de minimis* in accordance with the ALARP principle.

2 UXO Hazard Assessment

2.1 Research

In this desk based study we have considered both wider regional and, where the information is available, Project specific historical factors for the purpose of determining a baseline UXO hazard level.

Research has focussed on the following:

- Military history of the area
- Official and unofficial munitions dumping sites
- Current and historical military weapon ranges and training areas
- Potential migration of dumped munitions
- Wrecks of vessels or aircraft that may have a legacy of UXO contamination
- Protective, defensive and offensive minefields laid by both the German and British military forces
- Evidence of aerial warfare, including bombing, depth charge and torpedo deployment
- Bombing raid flight paths
- Evidence of naval surface and subsurface warfare and engagements

Information and data from a wide variety of sources have been collated to inform the study and risk assessment. The principal sources have been consulted from the following:

- UK Hydrographic Office (UKHO)
- The National Archives, London
- Royal Navy Historical Archive, Portsmouth
- The British Ministry of Defence (MoD)
- Pertinent authoritative publications
- Web based archives
- *Ordtek's* own comprehensive internal database
- Bundesarchiv-Militaerarchiv Freiburg
- Federal Maritime and Hydrographic Agency (BSH) in Hamburg
- Naval Office of the German Federal Armed Forces, Division Geo 1, Underwater Data Centre, Rostock
- British Ministry of Defence, Air Historical Branch, RAF Northolt Archive

2.2 UXO Hazard Overview

The east coast of the UK saw a considerable amount of military action during WWI and WWII. The Norfolk coast was contaminated by a wide variety of both Allied and German UXO. Over the decades since the end of the last war, fishing vessels have routinely found items of UXO that have subsequently been removed or made safe by Royal Navy Explosive Ordnance Disposal (EOD) teams. More recently, a number of items of UXO have been located, identified and disposed of on other renewable projects in the region. Consequently, the explosive remnants of war (ERW) potentially present a significant risk to the Project.

It is important to note that the positions shown on the charts may not always be accurate. Mine lays were conducted under the tension of war and with rudimentary navigation systems. Moreover, mining was not always accurately recorded and, after the war, many original records were lost. The positions of the minefields shown could be out by hundreds of metres or, in some cases, several kilometres.

2.3 World War One Sea Minefields

Both the German and British navies were very active during WWI, laying numerous minefields along the whole length of, principally, the Atlantic coast.

German and British minefields were subject to clearance operations between the end of the war and 1920. Moored mines frequently broke free from their moorings and drifted many tens, sometimes hundreds, of kilometres before sinking. Their presence anywhere within the Study Area cannot be discounted, although by now these mines will be severely corroded and the risk they present is low.

The German WWI mines laid would most likely have been type “EMA” (commonly known as “egg” mines) moored contact mines, with chemical Herz horns and with a charge weight of 160kg block-fitted Hexanite. Any British mines encountered are most likely to be Type HII. These mines are also ovoid, made of steel, have a diameter of 38 inches (0.96m) and a total weight of 295kg. The mine has a charge of 145kg of TNT and is fitted with Herz horns.

Today, if a WWI buoyant mine is encountered it is most likely be found situated on the seabed, often partially buried in the sediment. The mine casings will be heavily corroded. Chemical (Hertz) horns may still be capable of functioning but internal wiring and firing mechanisms are unlikely to be effective. Switch horn mines require power from an internal battery and these will no longer function. The explosive filling is likely to be stable if undisturbed but the mine may still detonate if appropriate criteria are met.

WWI German Minefields
German submarines laid a number of moored contact minefields in the region during WWI; in total 36 minefields were laid within the Study Area, containing on average 12 mines each. These were moored contact mines with chemical Hertz horns and with a charge weight of between 80kg to 150kg of either wet gun cotton or TNT. If they still exist, these mines will now be severely corroded and present minimal threat.

Table 2.1 – WWI German Minefields Relevant to the Project

WWI British Minefields

In 1916, 200 deep mines were laid off Lowestoft, followed by a further 1,100 in 4 deep fields extending southwards towards the latitude of Southwold.

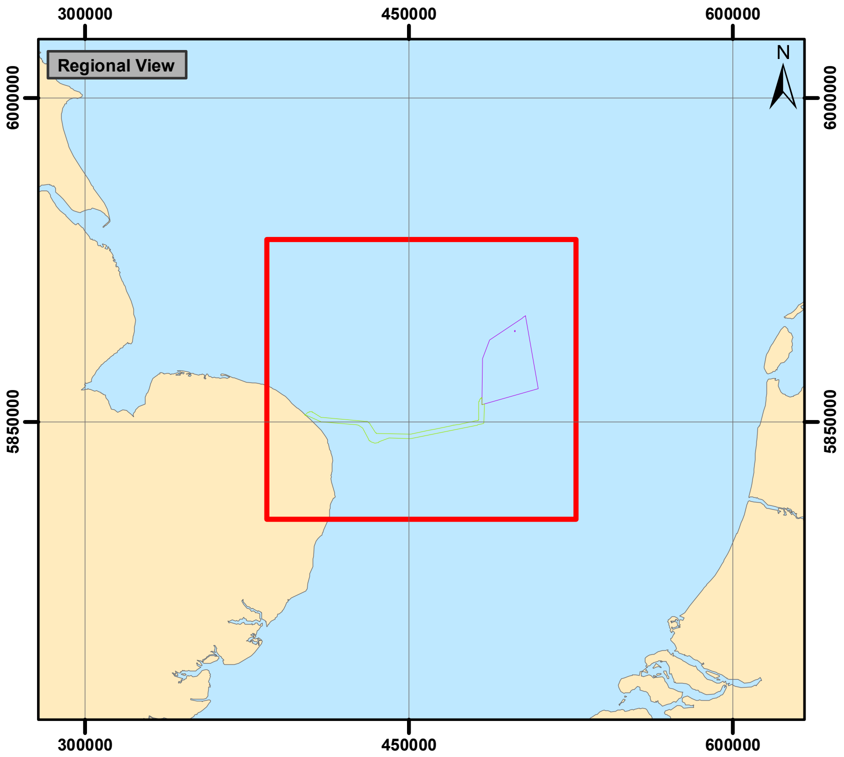
The Lowestoft shallow field was then extended by 2 large fields of 780 mines each with the objective of defending the coasts of Norfolk and Suffolk. In 1917, a large field of 416 mines was put down off Harwich, to the north of the Outer Gabbard and motor launches laid another containing 491 mines between this shoal and the Galloper. Minelaying activity continued into 1918, with a further 500 mines being laid in the Lowestoft minefield and 3 small fields, each of 20 mines, laid by the submarine E41 off the *Shipwash*.

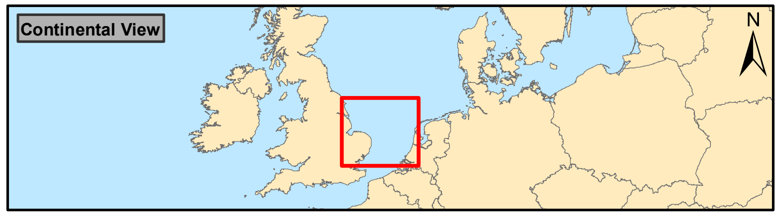
The records available show that the barrier contained a mixture of British Naval Spherical (also known as the Service mine), with a charge of 250lb (113kg) of wet gun cotton, and British Elia mines with 220lbs (100kg) of TNT. Both mines are constructed of steel and used a lever-actuated inertia firing mechanism and were very unreliable. They were replaced in 1917 by the H2, Britain’s first chemical horn mine. The H2 is spherical, with a diameter of 0.97m and a charge of 145kg of Amatol.

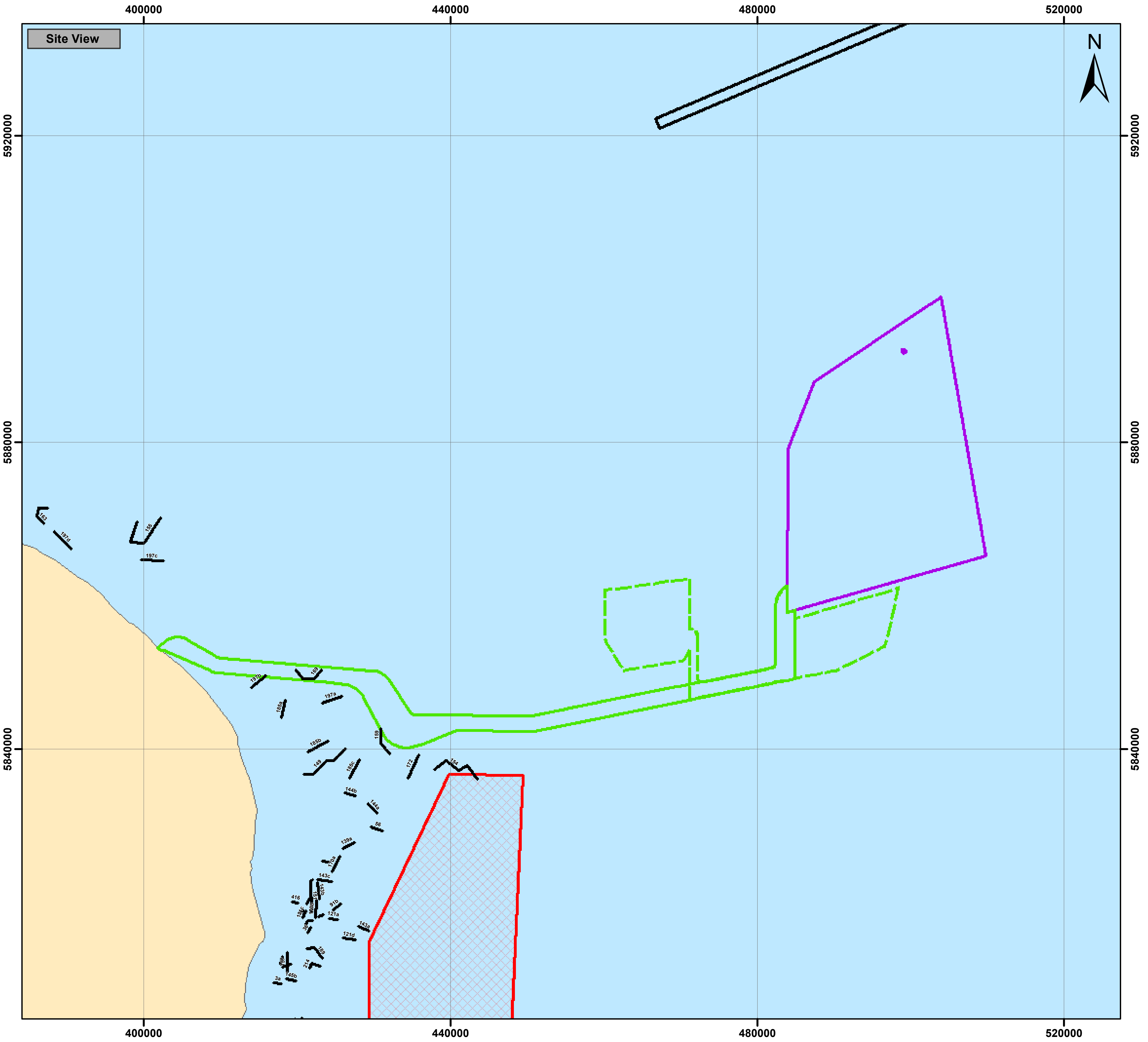
Although these mines will by now be severely corroded, the main explosive filling remains a hazard and, given the many hundreds laid, it is likely that some British mines or their sinkers are present within the Study Area.

Minefield No.	Number of Mines	When Laid	Probable Type of Mine	Distance from Project boundary (km)
Mine Barrier	4,327	1916-1918	Service, Elia and H2 Buoyant Mine	5.1km South

Table 2.2 – WWI British Minefields Relevant to the Project







Legend for Site View

Infrastructure

- 🟪 Main Array
- 🟩 Offshore Cable Corridor
- ▭ Project Interconnector Cable Search Area

UXO Hazard

- — WWI German Mine Lay
- ▨ WWI British Mine Barrier

Horizontal Scale(s)

Kilometers
0 5 10 20 30 40

Nautical Miles
0 2.5 5 10 15 20

Consultant	Client	Drawing Title	User Notes
ORDTEK	VATTENFALL	Norfolk Boreas Offshore Wind Farm WWI British and German Mine Lays	N/A

ISO 9001 CERTIFIED
UKAS
British Assessment Bureau

ETRS 1989 UTM Zone 31N
Projection: Transverse Mercator
Datum: ETRS 1989
False Easting: 500,000.0000
False Northing: 0.0000
Central Meridian: 3.0000
Scale Factor: 0.9996
Latitude Of Origin: 0.0000
Units: Meter

Drawn by: BB
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JM5503 - Norfolk Boreas Offshore Wind Farm

Date Drawn: 30 August 2018
Drawing Reference: JM5503_Norfolk Boreas_DTS_02
Drawing Version: 1.1

2.4 World War Two Sea Minefields

2.4.1 British and Allied Minefields

Experience during WWI had shown the British the advantage of offensive mine laying to restrict coastal shipping and to introduce a risk factor to German naval operations, as a result British ground mines were used mostly as an offensive weapon. However, the British laid a large number of buoyant minefields. The vast majority of these mines were Vickers T III, MK17 and MK14 buoyant contact mines (or variations). The MK14 had Herz horns while the Mk17 had switch horns (See Annex A for more explanation of horn types). In the latter case, by now, the batteries required to provide power to the detonator will have discharged and both types will have suffered significant degradation due to prolonged immersion in the water. NEQs varied depending on the precise type, but the most common NEQ was 227kg of HE.

In addition to surface laid British minefields, there were routinely re-seeded (replenished) mine “gardens” laid by the RAF. Aircrew slang for mine-laying operations was ‘gardening’ and the mines were referred to as being ‘sown’ when they were dropped at low-level into the sea.

British ground mine casings were generally made of steel and subject to corrosion over time unless they became buried in hypoxic sediment. The mines relied on batteries to power sensors and firing circuit; these will now be discharged and the mine will not function as designed. Charge weights were between 227kg-499kg, except for two specialist mines that had much smaller net explosive quantities (NEQs) of 45kg and 91kg. The British continued to develop ground mines throughout the war, starting with AMKs I-IV in the early years, finally progressing to the *AMK IX* by 1945.

<table>
<tr><th colspan="5">WWII British and Allied Minefields</th></tr>
<tr><td colspan="5">The wind farm is within a section of the huge East Coast defensive mine barrier. A total of 6,715 moored mines were laid within 50km of the wind farm, with 6 of the minefields actually intersecting the main array. Although these minefields were “swept” after the conflict, a very large number were unaccounted for – having broken free from their moorings. Moreover, many of those that were swept were subsequently sunk by gunfire, leaving a legacy UXO hazard in the region.</td></tr>
<tr><th>Minefield No.</th><th>Number of Mines</th><th>When Laid</th><th>Probable Type of Mine</th><th>Distance from Project boundary (km)</th></tr>
<tr><td>QV1</td><td>100</td><td rowspan="3">1943 (anti-eboat)</td><td>Mk17(6)/17</td><td>52.8km North</td></tr>
<tr><td>QV2</td><td>120</td><td>Mk27/19</td><td>57.6km North</td></tr>
<tr><td>QV3</td><td>120</td><td>Mk27/19</td><td>62.4km North</td></tr>
<tr><td>BS18</td><td>448</td><td>1940</td><td>Mk14/17</td><td>50.8km North</td></tr>
<tr><td>BS14</td><td>399</td><td>1940</td><td>Mk14/17</td><td>43.5km North</td></tr>
<tr><td>BS32</td><td>260</td><td>1940</td><td>Mk20/17</td><td>31.9km North</td></tr>
<tr><td>BS17</td><td>448</td><td>1940</td><td>Mk14/17</td><td>29.8km North</td></tr>
<tr><td>BS12</td><td>340</td><td>1940</td><td>Mk14/17</td><td>18.4km North</td></tr>
<tr><td>BS27</td><td>250</td><td>1940</td><td>Mk20/17</td><td>Intersecting Boundary</td></tr>
<tr><td>BS16</td><td>340</td><td>1940</td><td>Mk14/17</td><td>7.8km North</td></tr>
<tr><td>BS11</td><td>340</td><td>1940</td><td>Mk14/17</td><td>Intersecting Boundary</td></tr>
<tr><td>BS36</td><td>166</td><td>1940</td><td>Mk20/17</td><td>7.2km North</td></tr>
<tr><td>BS15</td><td>454</td><td>1940</td><td>Mk14/17</td><td>Intersecting Boundary</td></tr>
<tr><td>BS5</td><td>540</td><td>1940</td><td>Mk14/17</td><td>Intersecting Boundary</td></tr>
<tr><td>BS29</td><td>164</td><td>1940</td><td>Mk20/17</td><td>Intersecting Boundary</td></tr>
<tr><td>BS9</td><td>296</td><td>1940</td><td>Mk14/17</td><td>Intersecting Boundary</td></tr>
</table>

Minefield No.	Number of Mines	When Laid	Probable Type of Mine	Distance from Project boundary (km)
BS4	180	1940	Mk14/15	9.0km South
BS30	300	1940	Mk20/17	7.9km South
BS77	100	1942	Mk17/15/17	9.0km South
BS82	100	1942	Mk17/15/17	8.8km South
BS78	100	1942	Mk17/17	14.5km South
BS3	180	1940	Mk14/15	18.6km South
BS83	100	1942	Mk17/17	21.8km South
BS79	100	1942	Mk17/15/17	22.87km South
BS31	170	1940	Mk20/17	34.7km South
BS1	500	1940	Mk 14/17	31.4km South
BS81	100	1942	Mmk1/17	41.1km South

Table 2.3 – WWII Allied Minefields Relevant to the Project

2.4.2 German Minefields

Throughout WWII the Germans continued to lay minefields, to interdict coastal convoy traffic along the length of the UK. Very early in the war, torpedo boats and destroyers laid a number of contact and ground minefields. Thereafter, the German minelaying offensive was conducted mainly by *E-Boats* and aircraft, laying influence (magnetic/acoustic/pressure) ground mines. Predominantly, type LMB (Allied designation GC) mines were dropped. Types *LMA (GD)* and *BM1000 (GG)* could also have been laid but in lesser numbers by the Luftwaffe; submarine mine lays consisted mostly of type TMB (Allied designation GS) or, though in lesser numbers, the earlier and later variant TMA (GT) or TMC (GN). Axis mines were sometimes laid randomly and minefields often went unrecorded. These ground mine fields were often supplemented with traditional moored contact mines, such as the UMB and EMC, or with sweep obstructers such as the explosive float (XpFL) or static cutter (StCtr). More information can be found at Annex B.

The LMB (GC) ground mine casing is made of aluminium and its ferrous content is limited to the dip needle sensor arrangement, which contains magnets, and a few other small components. The LMB (GC) casing is 1.74m long (without any additional fittings) and has a diameter of 0.66m. The overall weight is 988kg (NEQ is 698kg Hexanite). Type BM1000 mines (GG), could also have been laid. The BM1000 (GG) casing is made of manganese steel and its ferrous content is similar to that of a LMB mine. The BM1000 (GG) casing is 1.52m long and the diameter 0.66m. The overall weight is 986kg (NEQ is 727kg Hexanite).

The TMB (GS) was a ground influence mine laid from the torpedo tubes of U-boats. Later variants included acoustic and acoustic/magnetic fuzed types. These mines were cylindrical and constructed of an aluminium alloy. These had a NEQ of between 420kg and 560kg of hexanite, measuring 2.30m in length and had a diameter of 0.53m. The mine was normally laid in waters of 12-15 fathoms (22-27 m).

WWII German Minefields
There are two minefields intersecting the export cable, an LMB minefield (containing 20 LMB mines) and a submarine-laid TMB minefield (containing 9 TMB mines), with eight more minefields within 10km of the cable.

Minefield No.	Number of Mines	When Laid	Probable Type of Mine	Distance from Project boundary (km)
F1	36	1945	LMB	12.4km North
F2	23	1945	LMB	12.3km South
F3a	36	1945	LMB	29.36km North
F3b				26.7km North
F8	6	1944	LMB	15.7km North
F9a	6	1944	LMB	8.1km North
F10	21	1945	LMB	11.9km North
F11	12	1942	LMB	30.5km North
F12a	12	1942	LMB	13.8km North
F12b	12	1942	LMB	19.6km North
F13	18	1942	LMB	33.14km North
F14	18	1942	LMB	30.3km North
F15	42	1942	LMB	33.0km North
F16	42	1942	LMB	10.1km North
F17b	12	1942	LMB	25.5km South
F19a	24	1942	LMB	11.0km South
F19b				0.8km South
F22	18	1942	LMB	13.6km North
F23a	24	1942	LMB	19.7km North
F23b	24	1942	LMB	11.0km North
F24	18	1942	LMB	18.6km North
F25	24	1942	LMB	15.6km North
F26	24	1942	LMB	21.3km North
F27a	48	1942	UMB	32.6km South
F30	16	1943	LMB	23.6km South
F31	18	1943	LMB	19.7km South
F32	16	1943	LMB	35.2km South
F35	10, 6	1943	LMB, UMB	32.9km South
F38	24	1943	UMB	2.1km South
F39	16	1943	UMB	5.4KM South
F45	24	1944	LMB	9.5km South
F47	20	1944	UMB	18.5km North
F48	18	1944	UMB	18.1km North
F49	17	1944	BMC	6.7km North
F50	9	1944	BMC	7.7km North
F51	33	1944	LMB	13.7km North
F52	20	1944	LMB	Intersecting Boundary
F56	28	1943	UMB	19.6km North
F57	20	1943	UMB	24.9km North
F62	3, 13, 55	1939	RMA, RMB, EMC	12.3km North
F63	50, 40	1940	TMB, EMC	26.0km North
F64a	46, 111	1940	RMB, EMC	61.4km North
F64b				46.0km North

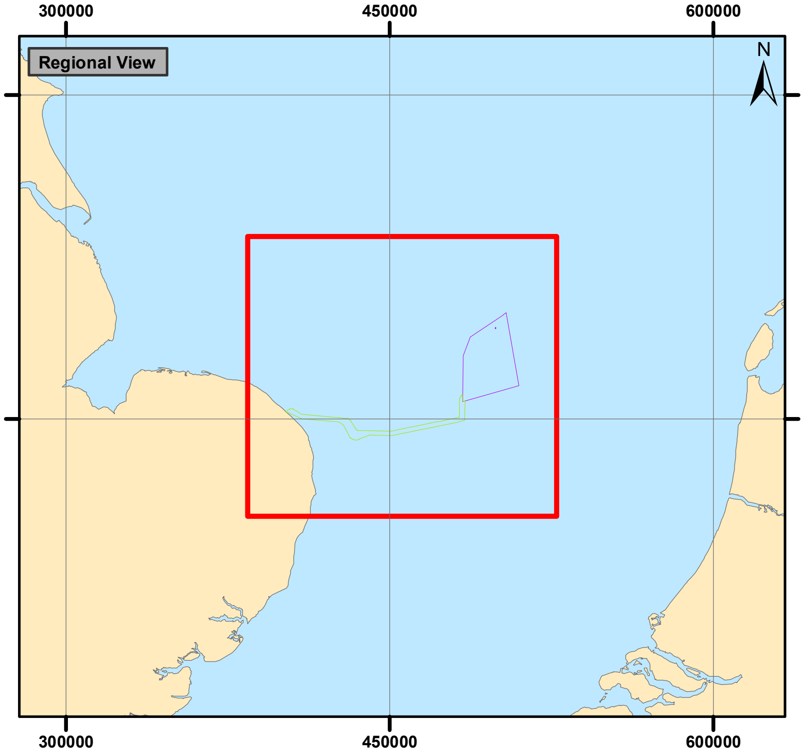
Minefield No.	Number of Mines	When Laid	Probable Type of Mine	Distance from Project boundary (km)
F65	90, 84	1940	EMC, XpFL	12.5km North
OMU14	9	1939	TMB	22.4km South
OMU18	9	1939	TMB	Intersecting Boundary
OMU20	9	1939	TMB	31.1km South
OMU26	9	1939	TMB	14.9km South
OMU27	9	1939	TMB	17.2km South
OMU29	6	1940	TMB	4.3km South
C18	112	1942	EMC	17.8km East
C19	75	1942	EMC, EE	58.1km East
C20	75	1942	EMCII	51.5km East
C21	64	1942	StCtr	53.4km East
C22	64	1942	StCtr	37.1km East
C23	64	1943	StCtr	22.9km East
C24	64	1942	StCtr	7.7km East
C27	742, 1040	1940	EMD/EMC, XpFl	10.3km East

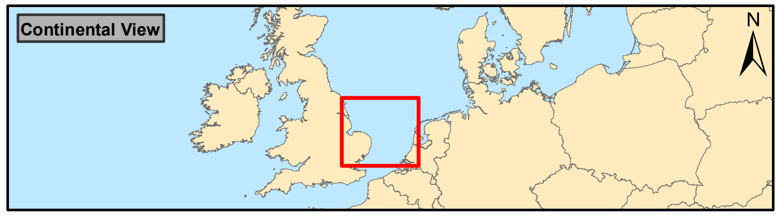
Table 2.4 – WWII German Minefields Relevant to the Project

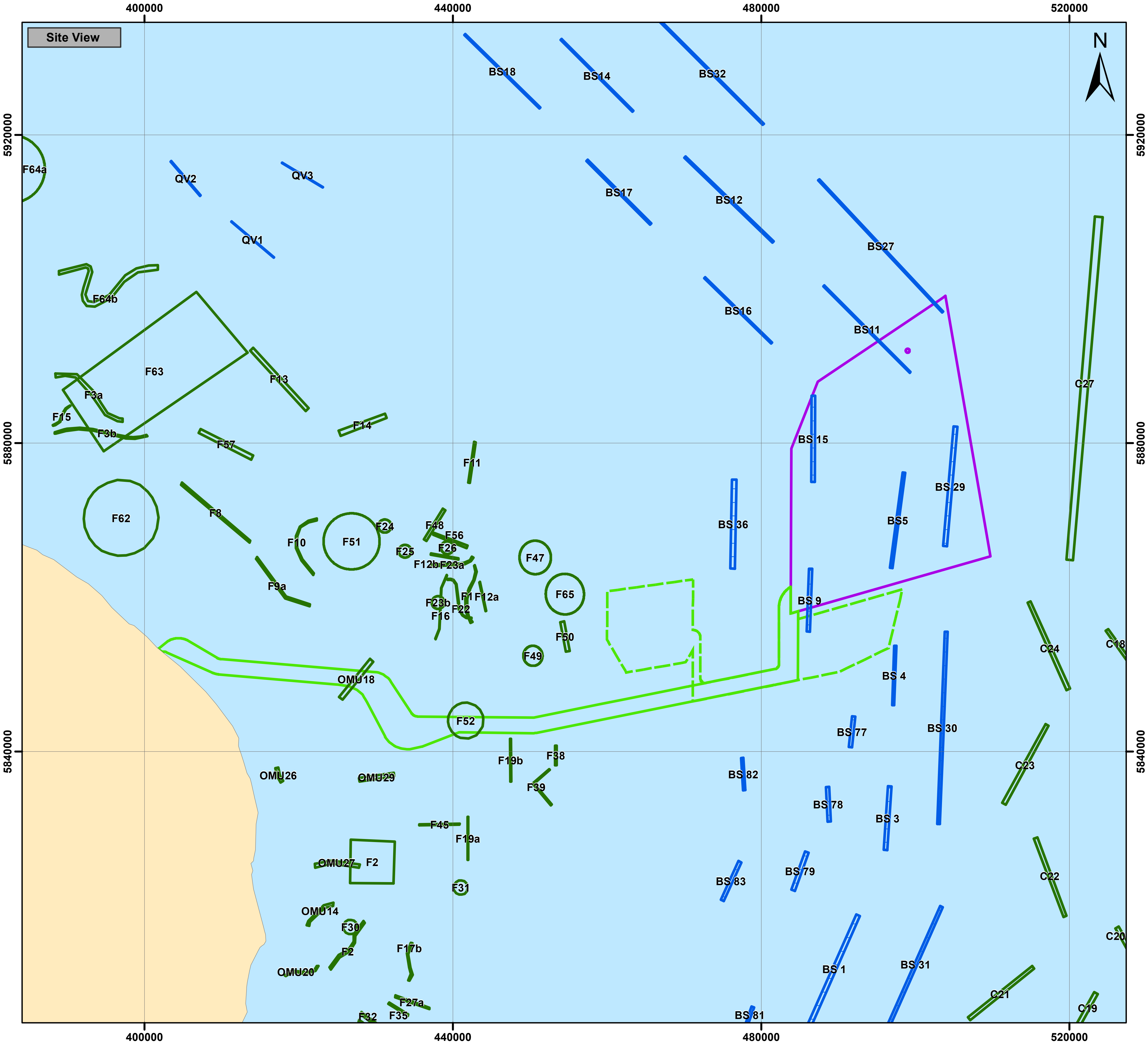
2.4.3 Minesweeping and Mine Clearance Operations

Minesweeping continued well after the armistice in November 1918 with 55 different flotillas still operating in June 1919. The British searched over 40,000 square miles until November 1919. At the end of the war when great efforts had to be made to clear the sea of mines, it was observed that about 85% of the mines laid had “disappeared” due to various causes and only a small fraction could be found and eliminated.

A similar effort was put into clearing minefields after WWII. Many reports refer to the “clearance” of barrier minefields after WWI and WWII. The term here should not be confused with what is understood by the modern usage of the word clearance, which includes removal of the UXO threat completely, usually by countermining. Minesweeping was not effective against mines that had already broken free and sunk to the seabed. And while minesweeping removed the threat for surface vessels and submarines, the practice of sinking them with gunfire has left a significant legacy hazard to modern seabed operations. The mine sinkers (anchors) also present solid targets for modern sonars and magnetic sensors that have to be identified and discounted, increasing the effort and time required for the survey of a contaminated area.







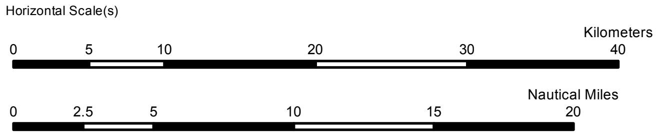
Legend for Site View

Infrastructure

- ▭ Main Array
- ▭ Offshore Cable Corridor
- ⬚ Project Interconnector Cable Search Area

UXO Hazard

- ▭ WWII British Mine Lay
- ▭ WWII German Mine Lay



Consultant	Client	Drawing Title	User Notes
ORDTEK	VATTENFALL	Norfolk Boreas Offshore Wind Farm WWII British and German Mine Lays	N/A

ISO 9001 CERTIFIED
UKAS MANAGEMENT SYSTEMS
British Assessment Bureau

ETRS 1989 UTM Zone 31N
Projection: Transverse Mercator
Datum: ETRS 1989
False Easting: 500,000.0000
False Northing: 0.0000
Central Meridian: 3.0000
Scale Factor: 0.9996
Latitude Of Origin: 0.0000
Units: Meter

Drawn by: BB
Checked by: LG

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JM5503 - Norfolk Boreas Offshore Wind Farm

Date Drawn: 30 August 2018
Drawing Reference: JM5503_Norfolk Boreas_DTS_03
Drawing Version: 1.1

2.5 Torpedoes/Depth Charges

During both WWI and WWII most surface ships were fitted with torpedoes and there were many ship to ship torpedo actions, in addition to submarine attacks on shipping; and in turn, submarines were attacked with depth charges. Consequently, large and small naval projectiles, torpedoes, depth charges and other anti-submarine weapons remain an almost universal threat.

Depth charges (and depth bombs from RAF coastal patrol aircraft) were deployed in huge numbers during WWII, often at spurious targets, as this contemporary diary account illustrates:

> *"Setting sail at 5.45 am on 27 August, Rodney headed west, bound for Plymouth, a sloop and two destroyers as escort.* ***Along the way, there was the usual enthusiastic depth-charging of submarine contacts, which were, as so often was the case, probably wrecks on the seabed****".*

Depth charges and depth bombs have an NEQ in the range of 50kg - 200kg. These all would have been thin-cased and consequently subject to severe corrosion in the intervening years. They would have fired by a hydrostatic fuse or perhaps an impact bomb fuse with a delay.

During both WWI and WWII, the Germans developed torpedoes of the "wet heater" type; steam driven, with kerosene as fuel and compressed air providing oxygen for combustion. Warheads of around 250kg were detonated by means of a direct impact or magnetic fuse. WWI torpedo fusing was often unreliable and it is quite possible that attacks took place, unrecorded, when the torpedo failed to function and sank to the seabed. WWII warheads were filled with 280kg of Hexanite and were generally much more reliable.

Torpedo/Depth Charge Contamination
German E-Boats, fitted with heavy-weight torpedoes, were a constant threat to Allied east coast shipping during WWII. German submarines operated in the area; extensively during WWI but also to a comparatively limited extent in WWII. These submarines themselves were attacked with depth charges both by surface ships and aircraft. Consequently both torpedoes, depth charges and other anti-submarine weapons potentially contaminate the study area.

Table 2.5 – Torpedo/Depth Charge Contamination Relevant to the Project

2.6 Air Dropped Bombs

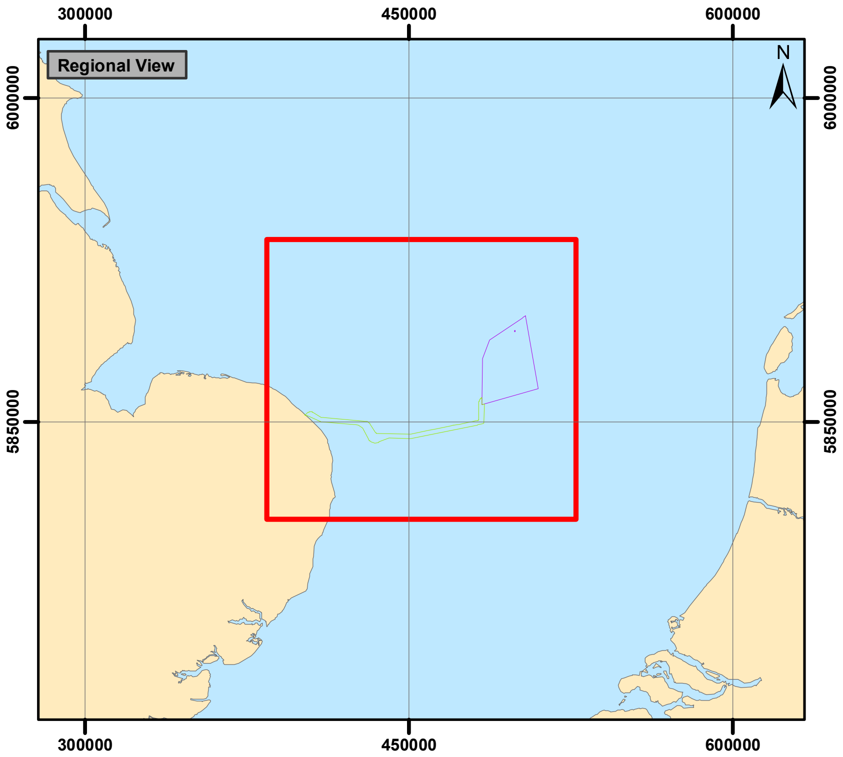
Air delivered EO is likely to come from the following sources:

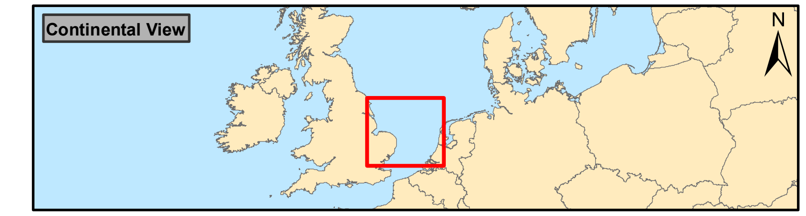
- The result of attacks on ships or submarines transitting the convoy routes, where EO missed its target. These weapons are likely to have been armed and will present a UXO risk.
- Bombs dropped in error into the sea during raids on land targets.
- Bombs jettisoned into the water by aircrew in an emergency on the way to or from an inland target. If planes had been badly damaged or were under attack, the crews often jettisoned their bomb loads to aid their evasion attempts. This was a common tactic known as "tip and run". These bombs may or may not have been armed on release. For risk assessment purposes, it must be assumed that they were armed.

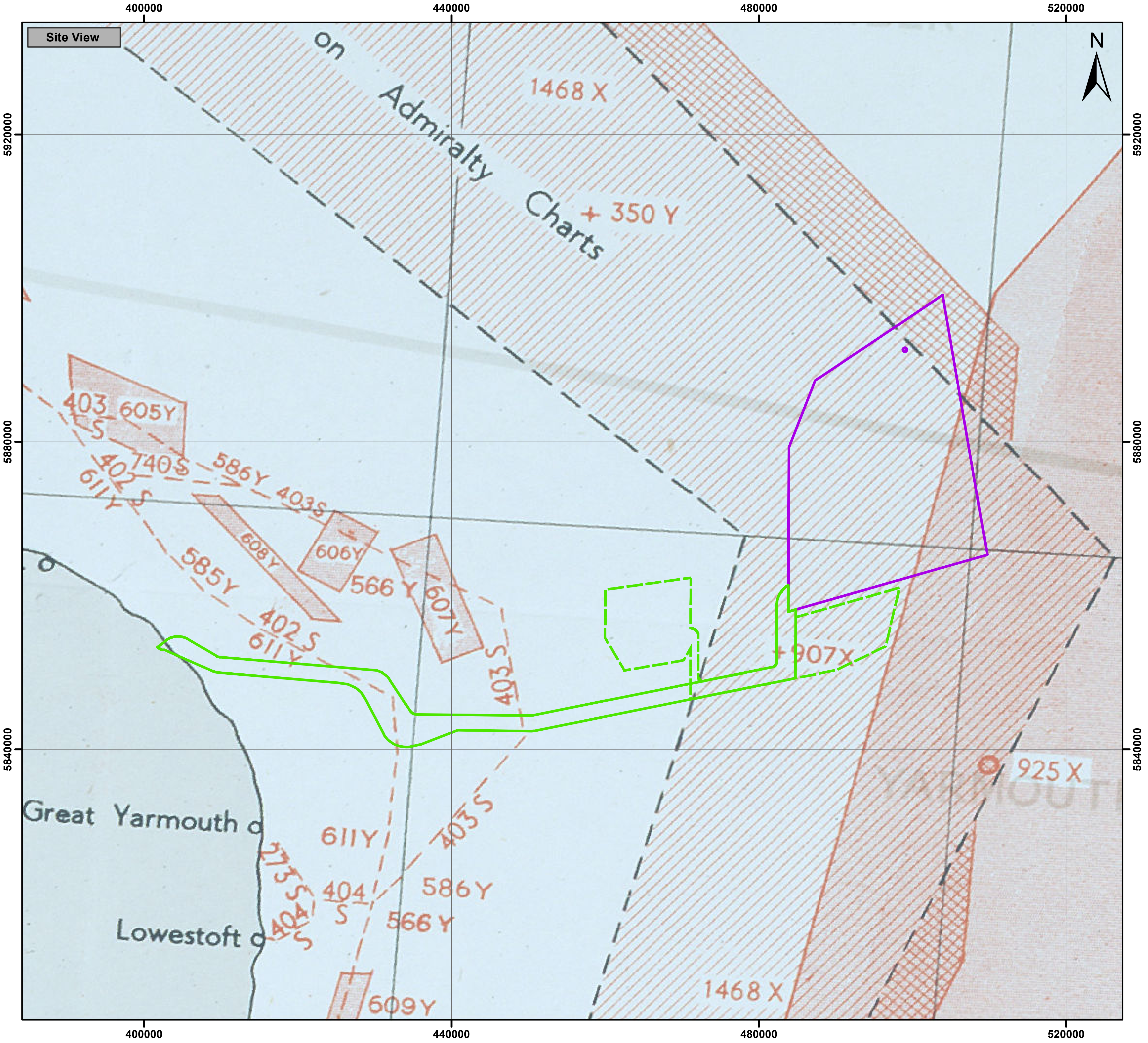
Consequently, almost any category of bomb could be present in the area. In addition to bombs, cannon shells are also very likely to be present. Bombs dropped from Luftwaffe bomber aircraft are likely to be in the region of 50kg - 500kg but in rare cases much larger bombs – up to 1800kg – could also be encountered, particularly any destined for inland raids but jettisoned over the sea. The charge to weight ratio of a general-purpose bomb is approximately 50%, giving NEQs for the examples above of 25kg, 250kg. Of interest, approximately 70% of all bombs deployed by the Luftwaffe during WWII were 50kg varieties (we do not have the statistic for attacks on ships alone).

Contamination from Air Dropped Bombs
The German Luftwaffe bombed the towns and cities surrounding the Norfolk coastline, such as Great Yarmouth, surrounding airfields and the military and industrial infrastructure of the region, sporadically during WWI and very heavily during WWII. Wreck evidence (Table 2.8) points to 6 ships sunk by air raids in proximity to the wind farm. In addition, damaged Allied aircraft returning from missions over Europe occasionally jettisoned their bombs into the sea before landing, as did the German pilots in similar circumstances.

Table 2.6 – Air Dropped Bomb Contamination Relevant to the Project







Legend for Site View

Infrastructure

- 🟪 Main Array
- 🟩 Offshore Cable Corridor
- ⬚ Project Interconnector Cable Search Area

UXO Hazard

- ▨ British Declared Danger Areas
- ▦ British Declared Minefields
- 🟥 German Minefields
- - - Searched Channels

Horizontal Scale(s)

Kilometers: 0, 5, 10, 20, 30, 40

Nautical Miles: 0, 2.5, 5, 10, 15, 20

Consultant	Client	Drawing Title	User Notes
ORDTEK	VATTENFALL	Norfolk Boreas Offshore Wind Farm WWII Mine Danger Areas	N/A

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Projection: Transverse Mercator
Datum: ETRS 1989
False Easting: 500,000.0000
False Northing: 0.0000
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JM5503 - Norfolk Boreas Offshore Wind Farm

Date Drawn: 30 August 2018
Drawing Reference: JM5503_Norfolk Boreas_DTS_04
Drawing Version: 1.1

2.7 WWI and WWII Projectiles

A wide variety of calibres of guns, up to 16in (40.6cm), were fitted to ships. Depending on their role (armour-piercing, capped, HE etc.), these shells contained between 10kg-50kg of Lyddite or Shellite (HE).

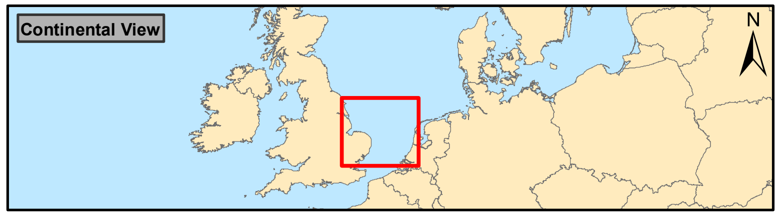
While WWII saw less big-ship surface to surface action than in WWI, there was much greater use of naval weapons in the Anti-Aircraft (AA) role, particularly in the protection of convoys. Most commonly, the guns used for AA would have been 20mm and 40mm but 4in, 6in and even 8in would also have been employed.

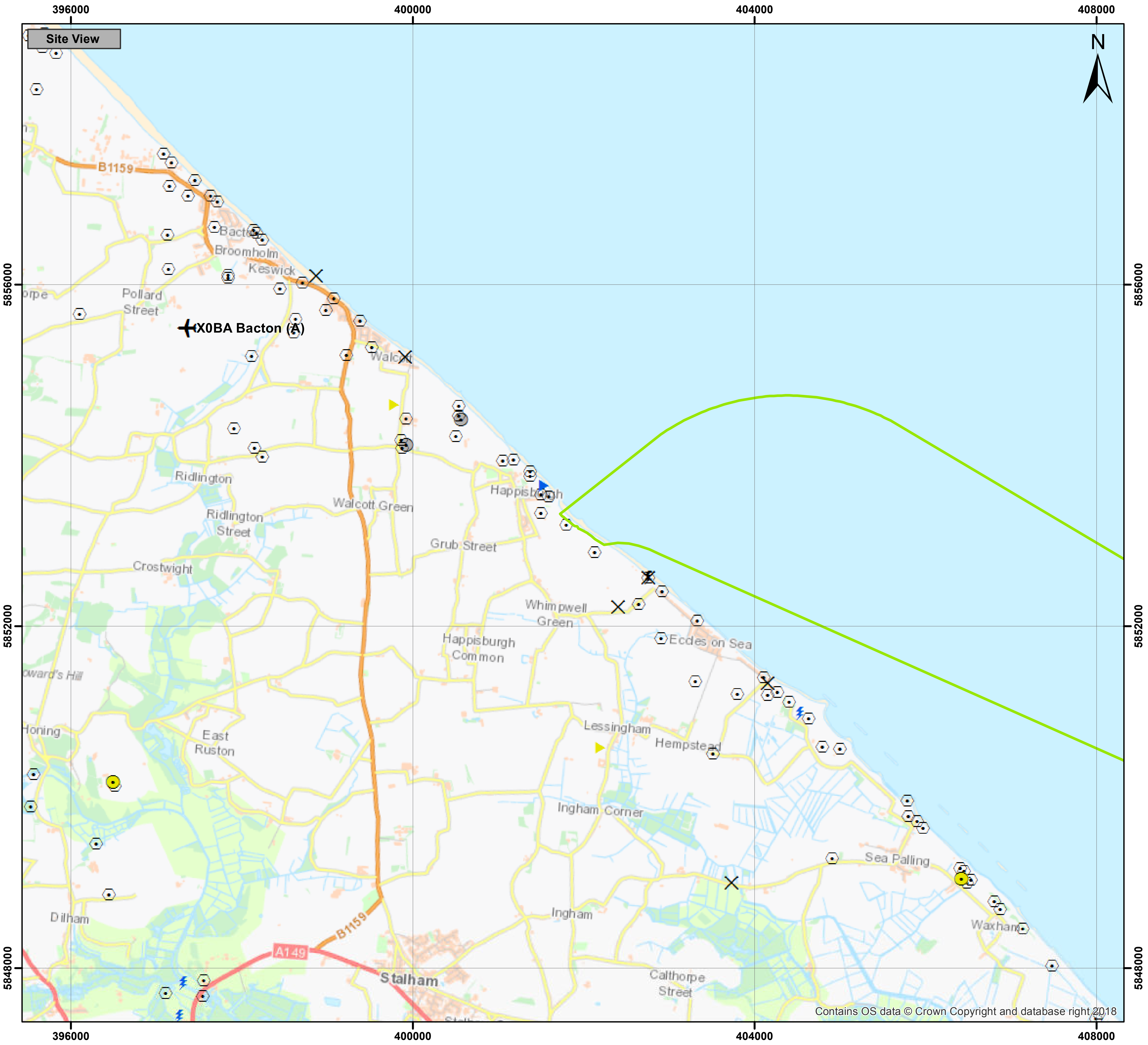
Weapon systems of the day lacked the first time strike accuracy of modern weapons and, in an exchange of fire, projectiles are likely to have missed the target in the first instance and it is entirely feasible that a number of exchanges of fire would have preceded a successful attack, with numerous rounds sinking to the seabed.

Consequently, UXO in the form of projectiles could be present anywhere in the Study Area. These are most likely to be relatively small calibre shells with an NEQ in the region of 2kg-5kg but larger projectiles could be encountered and with a slightly larger NEQ – up to 25kg of Picric acid based explosives, such as Shellite.

Projectile Contamination
Naval Projectiles
Wreck evidence shows ample evidence of shelling and naval battle in the Study Area. In addition, guns were used in defence against air attack. Consequently any size of naval projectile could be encountered but most are likely to be small; less than 5kg NEQ.
Coastal Defences
The Norfolk coast was heavily defended with passive defensive features such as pillboxes and gun batteries, in the event of an Axis invasion of the UK via Norfolk’s beaches. There are 12 pillboxes within 1km of the export cable’s landfall point and machine gun batteries, coastal artillery batteries and light anti-aircraft batteries all within range of the export cable.

Table 2.7 – Projectile Contamination Relevant to the Project





Legend for Site View

Infrastructure

- ▭ Main Array
- ▭ Offshore Export Cable Corridor

UXO Hazard

- ⊙ AA Searchlight
- ✕ Anti-Tank Defences
- ▶ Coast Artillery Battery
- ▶ LAA Battery
- ⚡ Machine Gun Post
- ⊙ Pill Box
- ● Radar Sites
- ✈ Airfields
- ⚡ Vickers Machine Gun Emplacement

Horizontal Scale(s)

Kilometers: 0 0.5 1 2 3 4

Nautical Miles: 0 0.25 0.5 1 1.5 2

Consultant
ORDTEK

Client
VATTENFALL

Drawing Title
Norfolk Boreas Offshore Wind Farm
Defense of Britain Installations

User Notes
N/A

ISO 9001 CERTIFIED
UKAS
British Assessment Bureau

ETRS 1989 UTM Zone 31N
Projection: Transverse Mercator
Datum: ETRS 1989
False Easting: 500,000.0000
False Northing: 0.0000
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Scale Factor: 0.9996
Latitude Of Origin: 0.0000
Units: Meter

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JM5503 - Norfolk Boreas Offshore Wind Farm

Date Drawn: 13 August 2018
Drawing Reference: JM5503_Norfolk Boreas_DTS_08
Drawing Version: 1.0

2.8 Military Related Shipwrecks

Many merchant as well as naval vessels sunk in WWI and WWII contained munitions. Similarly, aircraft that were shot down, or otherwise had to ditch into the sea, also had unexpended ammunition and other EO. There is evidence that munitions could spill and be thrown clear from a sinking ship or become exposed as the vessel broke-up on the seabed, and in due course migrate away from the original site. But the risk of EO contamination is generally less in the vicinity of wrecks (compared with munitions dump sites) as the ordnance typically remains contained and immobile within the structure of the sunken vessel. From a UXO threat perspective, wrecks of unknown origin should be avoided.

While some wrecks may contain ammunition, they are unlikely to be the source of any direct UXO contamination. However, the wrecks do provide clear evidence of military action and the potential for the presence of UXO from the action preceding the sinking. As noted in the previous section, wrecks are known to have been caused by torpedo and depth charge attack, but also from mines and air raids (bombs and depth bombs).

It is also possible that some aircraft were shot down and crashed into the sea in the wider area. It must be assumed, therefore, that aircraft debris, together with embarked bombs, torpedoes and ammunition, could be present anywhere within the Study Area. The circumstances of most aircraft losses offshore mean that accurate positional information of such wrecks is very rarely available.

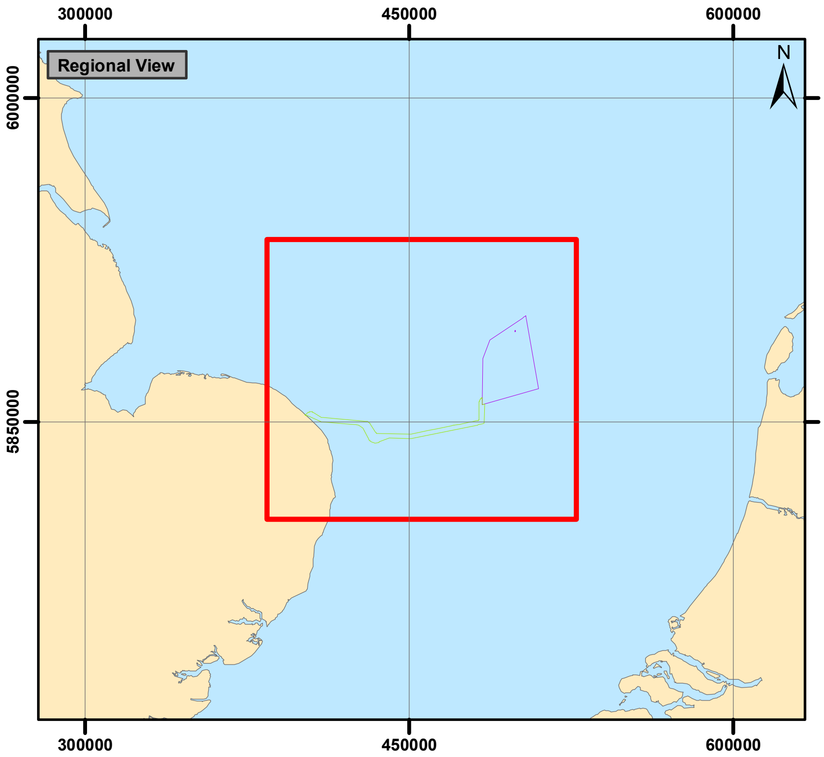
Contamination from Shipwrecks

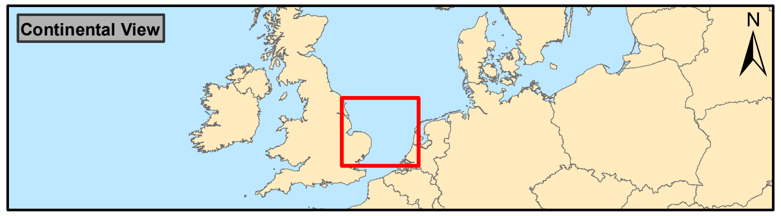
There are a very large number of shipwrecks in the Study Area, many that were sunk due to military action during WWI and WWII. Wrecks within 5km of the wind farm that were sunk by military action are outlined below and illustrated in the corresponding chart.

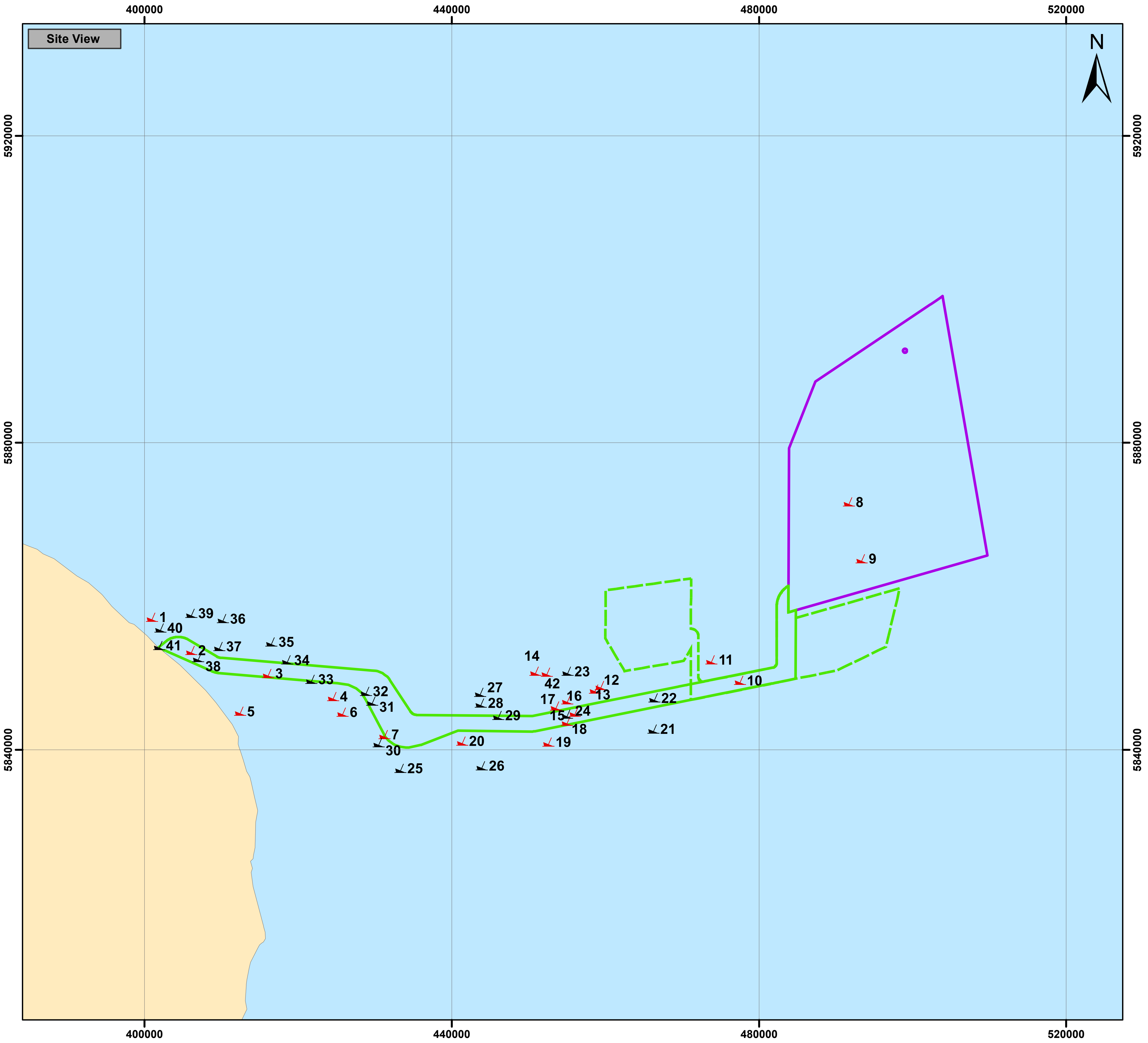
No. on Chart	Date	Vessel	How Sunk	Distance from Project (km)
World War One Wrecks				
1	1917	SS Ole Bull	Mine	3.2km North
2	1915	SS Fulgens	Torpedo	Within Export Cable
3	1916	SS Excellenz Mehnert	Mine	Within Export Cable
4	1915	FV Alert (LT 1102)	Gunfire - Shelled	2.1km South
5	1918	SS Kirkham Abbey	Torpedo	5.2km South
6	1916	unkn. steamer	Mine	3.7km South
7	1916	HMS Fair Maid	Mine	0.3km South
8	1918	PSS Koningin Regentes	Torpedo	Within Main Array
9	1915	FV Boy Ernie (LT 282)	Scuttled	Within Main Array
10	1915	FV Golden Oriole	Mine	Within Export Cable
11	1915	FV Humphrey	Charges/Explosives	2.1km North
12	1917	UB-27	Depth Charge	1.7km North
13	1916	FV Superb (LT 938)	Scuttled	1.5km North
14	1916	FV Our Boys	Gunfire - Shelled	5.1km North
15	1915	FV Strive (LT 70)	Charges/Explosives	Within Export Cable
16	1917	FV Emerald (LT 296)	Gunfire - Shelled	0.8km North
17	1916	FV Loch Lomond	Gunfire - Shelled	0.3km North
18	1915	FV Quest (LT 1080)	Charges/Explosives	Within Export Cable
19	1915	UB-4	Naval Battle	2.0km South
20	1917	FV Rosary	Charges/Explosives	1.7km South

Contamination from Shipwrecks				
No. on Chart	**Date**	**Vessel**	**How Sunk**	**Distance from Project (km)**
42	1917	De Tien Kinders	Scuttled	4.7km North
World War Two Wrecks				
21	1943	S-119	Collision	3.1km South
22	1940	HMS Dunoon (J-52)	Mine	Within Export Cable
23	1944	S-128	Collision	4.4km North
24	1943	S-88	Gunfire - Shelled	Within Export Cable
25	1941	SS Nereus (Du)	Torpedo	3.2km South
26	1940	SS Portelet	Torpedo	4.9km South
27	1942	SS Charlwood	Collision	2.7km North
28	1941	SS Virgilia	Torpedo	1.2km North
29	1944	SS Philipp M.	Torpedo	Within Export Cable
30	1941	SS Effra	Torpedo	1.5km South
31	1941	SS Rye	Gunfire - Shelled	Within Export Cable
32	1941	MV Trevethoe	Torpedo	Within Export Cable
33	1941	SS Montferland	Air Raid	0.2km South
34	1941	HMT Force	Air Raid	Within Export Cable
35	1941	SS Barrhill	Air Raid	2.1km North
36	1941	SS Norman Queen	Torpedo	4.3km North
37	1942	SS Ilse	Torpedo	0.8km North
38	1942	SS Sheaf Water	Torpedo	Within Export Cable
39	1941	SS Artemisia	Air Raid	2.7km North
40	1941	HMT Francolin (Frankolin)	Air Raid	1.5km North
41	1940	HMT Dungeness	Air Raid	Within Export Cable

Table 2.8 – Military-Related Shipwrecks Relevant to the Project







Legend for Site View

Infrastructure

🟪 Main Array
🟩 Offshore Cable Corridor
▨ Project Interconnector Cable Search Area

UXO Hazard

WWI Wrecks of Military Interest
WWII Wrecks of Military Interest

Horizontal Scale(s)

Kilometers
0 5 10 20 30 40

Nautical Miles
0 2.5 5 10 15 20

Consultant	Client	Drawing Title	User Notes
ORDTEK	VATTENFALL	Norfolk Boreas Offshore Wind Farm WWI and WWII Wrecks of Militray Interest	N/A

ETRS 1989 UTM Zone 31N
Projection: Transverse Mercator
Datum: ETRS 1989
False Easting: 500,000.0000
False Northing: 0.0000
Central Meridian: 3.0000
Scale Factor: 0.9996
Latitude Of Origin: 0.0000
Units: Meter

Drawn by: BB
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JM5503 - Norfolk Boreas Offshore Wind Farm

Date Drawn: 30 August 2018
Drawing Reference: JM5503_Norfolk Boreas_DTS_05
Drawing Version: 1.1

2.9 Exercise Areas and Firing Practice

Naval vessels and aircraft carry out exercises, day and night, off all points of the coast and it very probable that some *ad hoc* training evolutions have taken place over a period of several decades outside designated areas, particularly during the war years; including live firing of small arms, naval gunfire (typically up to 105mm) and possibly larger anti-submarine weapons.

As a rule, live firing of HE munitions for practice is only conducted in designated exercise areas; however, from experience, naval ships and aircraft commonly conduct firings, as convenient, outside formal practice areas using *“clear range procedure”*.

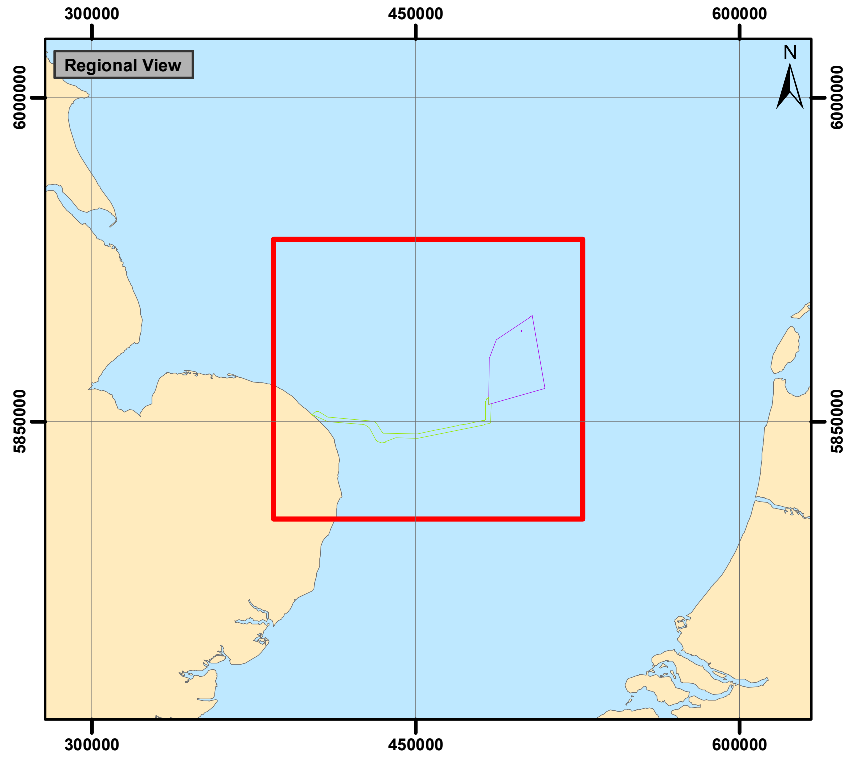
In such exercises, ships, submarines and aircraft would have used a wide variety of munitions, including flares, smoke and starshell. It is impossible to determine the detail of precisely what activities might have been conducted over so many years but it is very possible that a combination of both HE and “practice” ammunition contaminate the area. Practice munitions usually contain a Low Explosive spotting charge and/or a pyrotechnic element. These present a minimal risk to Project activities. However, given the corrosion that will have occurred in the intervening years, it is unlikely that practice munitions will be readily distinguish from similarly shaped HE versions. We have seen on other projects that it is usually necessary to dispose of “inert” items of UXO using high-order methods (counter-mining with a HE charge).

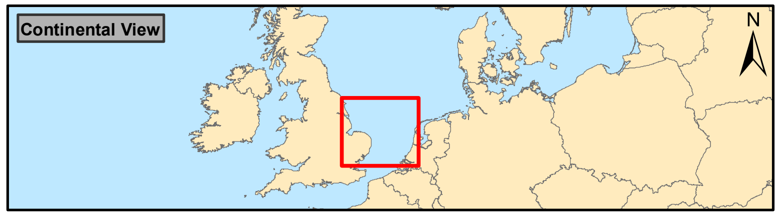
Contamination from Exercise Areas

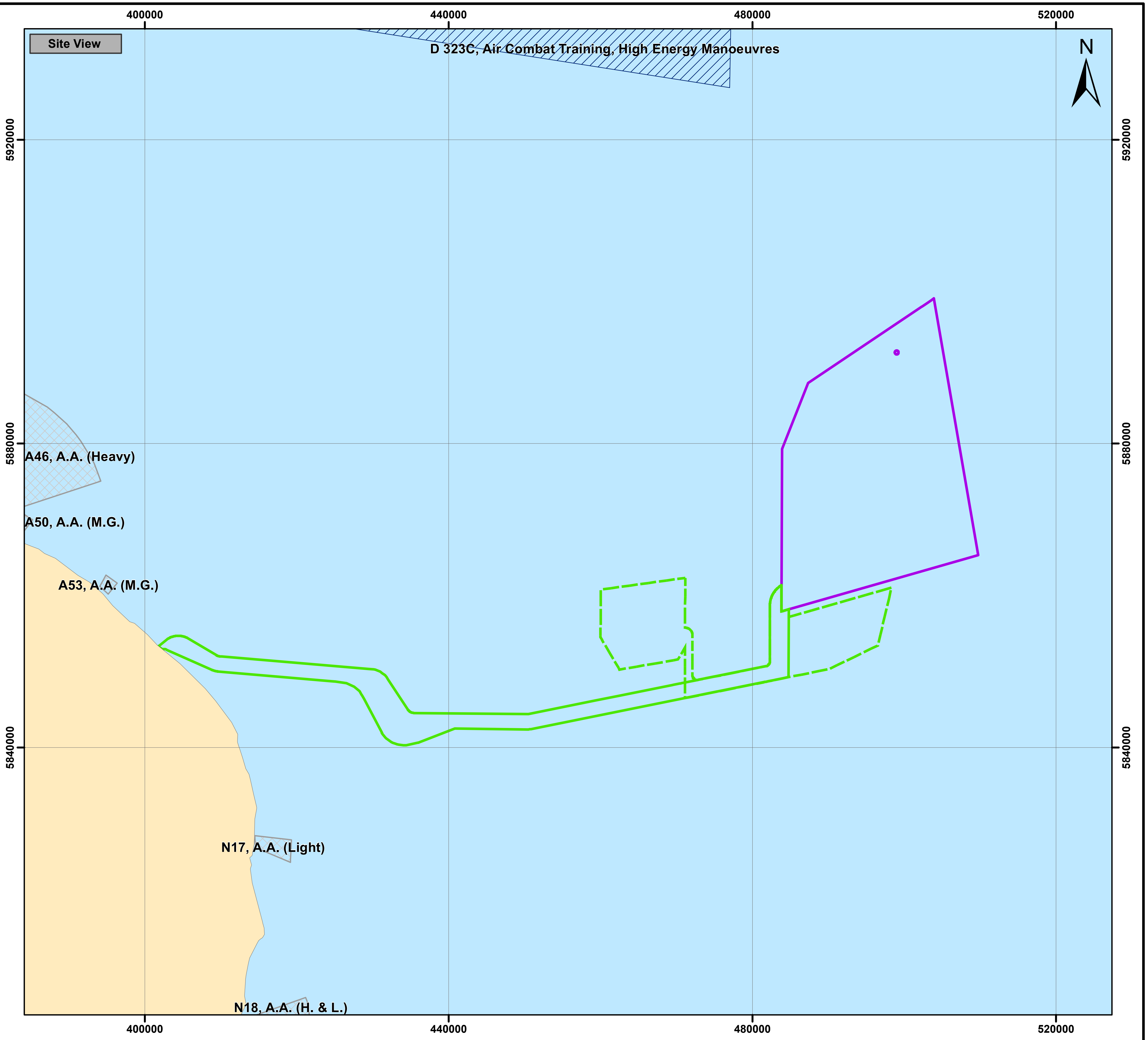
There are 5 historic training areas and 1 modern military training area within the Study Area.

- D 323C, used for air combat training and high energy manoeuvres, lies 39km North of the wind farm
- N17 was a light anti-aircraft artillery armament area, 19km South
- N18 was a heavy and light anti-aircraft artillery armament area, 36km South
- A46 was a heavy anti-aircraft artillery armament area, 22km North
- A50 and A53 were machine gun armament areas, 24km and 9.6km North

Table 2.9 – Military Exercise Areas Relevant to the Project







Legend for Site View

Infrastructure

🟪 Main Array

🟩 Offshore Cable Corridor

⬚ Project Interconnector Cable Search Area

UXO Hazard

▨ WWII – British Armament Areas

▨ Modern Military – Air Force Training Area

Horizontal Scale(s)

Kilometers: 0 5 10 20 30 40

Nautical Miles: 0 2.5 5 10 15 20

Consultant
ORDTEK

Client
VATTENFALL

Drawing Title
Norfolk Boreas Offshore Wind Farm
Military Practice and Exercise Areas

User Notes
N/A

ISO 9001 CERTIFIED
UKAS MANAGEMENT SYSTEMS
British Assessment Bureau

ETRS 1989 UTM Zone 31N
Projection: Transverse Mercator
Datum: ETRS 1989
False Easting: 500,000.0000
False Northing: 0.0000
Central Meridian: 3.0000
Scale Factor: 0.9996
Latitude Of Origin: 0.0000
Units: Meter

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JM5503 - Norfolk Boreas Offshore Wind Farm

Date Drawn: 30 August 2018
Drawing Reference: JM5503_Norfolk Boreas_DTS_07
Drawing Version: 1.1

2.10 Munitions Dump Sites and UXO Finds

2.10.1 Overview

For several decades after the World Wars, large volumes of chemical and conventional munitions were disposed of at sea. At the time, with public safety as a guiding principle, such disposal was considered best practice. The Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (London Convention, 1972), ratified by many countries, now prohibits the disposal at sea of wastes, including munitions. These discarded munitions can be a significant hazard to offshore projects.

The two World Wars left a legacy of enormous quantities of munitions requiring disposal. The process had to be completed quickly and safely. Given the technical limitations of the time, sea dumping was the only practical method of disposing of the bulk of the munitions. It became the internationally accepted method of munitions disposal. Sea dumping continued until 1972 when the UK and other European nations adopted the London Convention on the Disposal of Wastes at sea.

The Oslo-Paris Convention (OSPAR), a collaborative agreement between European countries for the Protection of the Marine Environment of the North-East Atlantic, was open for signature in Paris in 1992 and entered into force on 25 March 1998. Since the end of the 1990s, the Oslo-Paris (OSPAR) Convention has systematically recorded the munitions dumping sites of the Eastern Atlantic Ocean and the North Sea. Both dumping areas and subsequent EO finds have been recorded and the distribution of activities leading to the discovery of EO plotted. Fishing vessels have found more than 50% of EO.

2.10.2 Condition of Dumped Munitions

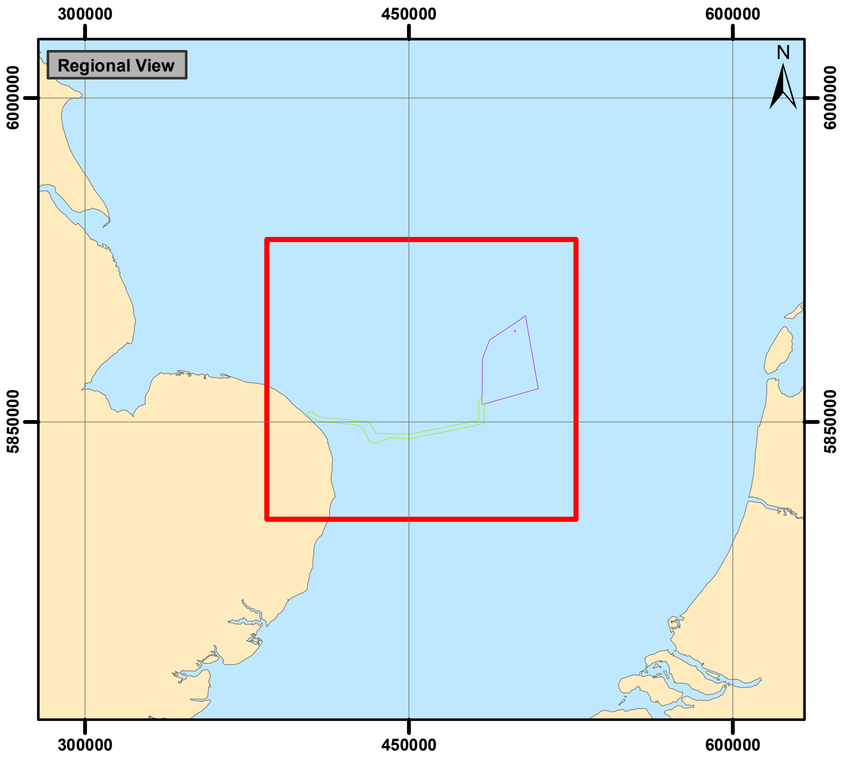
It can generally be assumed that most of the munitions deposited at post-war dump sites were packaged robustly and dumped unfused. There is no reason to believe, therefore, that they will become unstable or present a hazard even if accidently disturbed. However, the state of corrosion of all munitions could vary from very little to completely degraded and therefore it is not possible to predict the condition of all types of EO in and around the dumping areas.

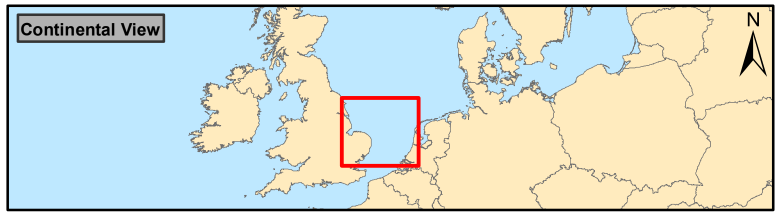
Anecdotal evidence has recorded occasional unexplained explosions in the vicinity of dump sites. No definite evidence of spontaneous detonation of dumped conventional munitions exists, but any EO which contained Shellite or Lyddite (highly sensitive picric acid based explosives) is far more likely to spontaneously detonate when disturbed than, for example, TNT filled munitions. This could arise if they were subject to an impact when the structure of a container collapsed or if they were struck by other items of ordnance falling onto them.

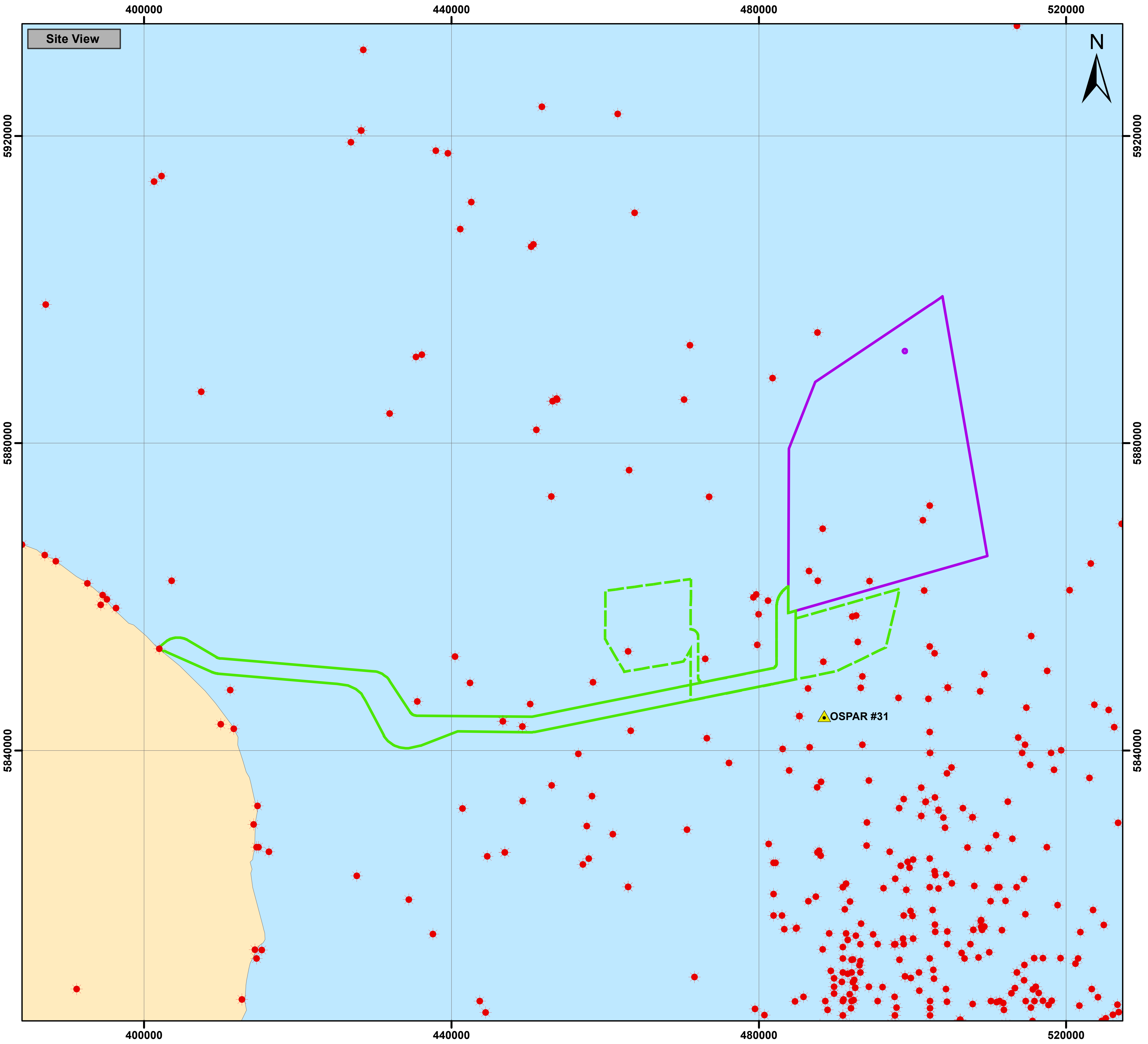
Picric acid is known to have an ageing problem through which metal picrates form, e.g. iron picrate. Such metal picrates are extremely sensitive energetic materials that can be initiated very easily. Shellite and Lyddite were a common WWI filling for large shells, including naval projectiles.

Contamination from Dumping
A recorded munitions dump site is located 6km to the South of the export cable, close to the main array. This is recorded as a conventional munitions dump site and is one of many sites off the coast of the UK where WWII munitions were disposed via dumping. OSPAR munitions finds indicate 9 items of UXO have been recovered within the wind farm boundary. Principally as a result of entanglement in fishing nets.

Table 2.10 – Munitions Dumping Relevant to the Project







Legend for Site View

Infrastructure

- ▭ Main Array
- ▭ Offshore Cable Corridor
- ⬚ Project Interconnector Cable Search Area

UXO Hazard

- ⚠ OSPAR Recorded Munition Dump Site (Conventional)
- ● OSPAR Recorded Munition Encounters (<2014)

Horizontal Scale(s)

Kilometers: 0 5 10 20 30 40

Nautical Miles: 0 2.5 5 10 15 20

Consultant	Client	Drawing Title	User Notes
ORDTEK	VATTENFALL	Norfolk Boreas Offshore Wind Farm OSPAR Recorded Munition Encounters and Dumpsites	N/A

ISO 9001 CERTIFIED
UKAS MANAGEMENT SYSTEMS
British Assessment Bureau

ETRS 1989 UTM Zone 31N
Projection: Transverse Mercator
Datum: ETRS 1989
False Easting: 500,000.0000
False Northing: 0.0000
Central Meridian: 3.0000
Scale Factor: 0.9996
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JM5503 - Norfolk Boreas Offshore Wind Farm

Date Drawn: 30 August 2018
Drawing Reference: JM5503_Norfolk Boreas_DTS_06
Drawing Version: 1.1

2.11 Probability of UXO Contamination

The UXO items we consider most likely to be *encountered* within the Project Area are shown in Table 2.12 below. Note that this table shows the probable *encounter* of generic UXO types within the Study Area based on the evidence we have gathered about potential UXO sources. The assessment has been split between the main array (MA), offshore export cable (OEC), greater than 10m water depth, and nearshore export cable (NEC), 10m water depth and lower.

It is important to recognise that the probability of *encounter* (i.e. a positive interaction with the UXO during a specific Project activity) will generally be less than the probability of items of that particular UXO type being *present* across the whole Project Area; given that the actual Project activity footprint will be significantly less than the total Project Area. Among other factors, the probability of *encounter* will depend on the Project activity being undertaken and the potential for burial.

Level	"Probability" Term	Meaning
1	Very Unlikely	Very unlikely to encounter this type of EO within an area but it cannot be discounted completely.
2	Unlikely	Some evidence of this type of EO in the wider region but it would be unusual for it to be encountered.
3	Possible	Evidence suggests that this type of EO could be encountered within the area.
4	Likely	Strong evidence that this type of EO will be encountered within the area.
5	Very Likely	Indisputable evidence that this type of EO will be encountered within the area.

Table 2.11 – Probability of UXO Encounter

UXO Hazard Item	Probability			Comments
	MA	OEC	NEC	
British WWI Mines	1	2	1	Extensive mine barrier, containing 4,327 buoyant mines, located 5.1km South of the export cable.
German WWI Mines	1	2	2	Over 94 mines located in the Study Area in 15 minefields, likely containing EMA mines.
Allied WWII Mines	4	3	2	6 minefields intersecting the main array, with 6,715 mines laid within 50km of the wind farm.
German WWII Mines	3	3	3	2 minefields intersecting the wind farm, with 8 more minefields within 10km of the wind farm.
Depth Charges and Torpedoes	2	2	1	12 vessels recorded as sunk by torpedoes within 5km of the wind farm.
HE Bombs and Rockets (Including live bombs used for training)	4	5	4	The German Luftwaffe conducted bombing raids of the UK and Allied vessels in the water; 6 ships were sunk by air raids within 5km of the wind farm. In addition, damaged Allied aircraft returning from missions over Europe occasionally jettisoned their bombs into the sea before landing, as did the Axis forces.
Artillery and Naval Projectiles	2	3	3	Evidence of ship-to-ship action within the Study Area, in addition to possible live firing during exercises.
Land Service Ammunition	1	1	2	No evidence found for LSA contamination in proximity to the wind farm, however military practice at the beach is possible.

UXO Hazard Item	Probability			Comments
	MA	OEC	NEC	
Practice Munitions (We consider practice munitions as inert ordnance)	1	1	1	No exercise areas intersecting the wind farm, these are unlikely to be a source of UXO contamination.

Table 2.12 – Likelihood of UXO encounter at Norfolk Boreas – based on both historical data and ground truth from neighbouring sites

3 UXO and Interaction in the Natural Environment

3.1 UXO Burial Processes

3.1.1 Overview

Over a period of several decades, the seabed level within an area can change due to the process of sediment accretion (also sometimes referred to as “deposition”) or erosion. It is an important factor that must be taken into consideration when determining the potential for UXO burial. The movement of sandy bedforms (ripples, mega-ripples, sand waves, etc.) also has the potential to bury (or expose) items of UXO over time and therefore the seabed sediment composition, morphology and mobility must also be considered. Bedforms in shallow water migrate and change shape due to forcing by tides and currents. Most active bedforms are those formed of sand, although where currents are strong, particularly in the nearshore, gravel can also be mobilised; this is particularly prevalent during high-energy storm events.

UXO burial in the offshore environment, as opposed to the nearshore/intertidal environment, is not affected by the conditions of initial impact or liquefaction (usually), as the force of the UXO impact is dissipated in depths >5m (i.e. the offshore environment), and liquefaction likewise does not occur offshore in consolidated sediments. Therefore, only the processes of self-burial and bedform migration are considered in the offshore environment.

- **Initial impact** – within water depth <5m LAT
- **Liquefaction** – within shallow and nearshore sands/silts or tectonic activity
- **Self-burial by scour, sinking and backfill** – within sands and silts
- **Bedform migration** – within areas of sandwaves and mega ripples

3.2 Further Reading

More information and expansion on the above processes can be found at Annex A and B.

3.3 Project Specific Seabed Conditions

Project Specific Seabed Conditions
Water depths range from approximately 20m to 43m LAT. The primary topographic features are five elongate sand banks, with heights up to 19m above surrounding seafloor. At a more local scale the seafloor is uneven due to the presence of very large to small subaqueous dunes. The seafloor comprises slightly gravelly fine to coarse SAND or, slightly gravelly silty fine to medium SAND. Gravelly SAND is present locally. The gravel fraction is due to shells and shell fragments. Subaqueous dunes range from very large (up to 4.5m high) to medium (up to 1.1m high) with small dunes having heights of up to 0.2m at the time of geophysical site investigation.

Table 3.1 – Project Specific Seabed Conditions

3.4 Project Specific Burial Assessment Conclusions

Burial Assessment

Initial impact in water depths below 10m LAT is possible to depths of 4.0m. However, at water depths greater than 10m, initial impact is not considered a factor in UXO burial.

Across the wind farm bedforms can be seen to range from 0.1m-0.5m (megaripples) to 4.5m (sand dunes); the majority are considered mobile and therefore UXO burial is possible to the full height of the bedform.

Within sands and sandy gravels self-burial through scour is also likely to have occurred to a depth of approximately half of the UXO's diameter.

Based on the Fugro report at Reference B, quantifying the effects of deposition or erosion at the wind farm is not currently possible. However, based on projects in proximity, we'd anticipate a net accretion across the site of ~1.0m since WWII.

An individual or combination of burial mechanisms may be at play across the site, and it is likely that the majority of UXO are buried. While it is possible for UXO to be buried up to 5.0m below current bed level in places, the probability of an item of UXO being covered to this depth combined with the reduced consequence should a UXO detonation occur, mean clearance of the entire 5.0m is not required to reduce the risk to ALARP. A risk horizon is assessed to which mitigation should aim to cover. For the Norfolk Boreas OWF, this risk horizon is assessed as 2.0m below the seabed, based on practical detection depths.

From the information in Table 3.1, the conclusions on the potential for ordnance burial are presented below. Please note the burial depth shown is to the bottom of the item of ordnance, i.e. for an item 1m in diameter, a burial depth of 1.1m will mean the item is covered by 0.1m of sediment (according to this calculation).

UXO Burial Calculations

Burial Factors	Burial Possibilities
UXO Type	500lb HE Bomb
UXO Diameter (m)	0.33
Initial Impact (m)	0
Sediment Type	Sand/Soft sand
Sediment Action	0.6
Scour Calculation	0.198
Bedform/Accretion (m)	4.5
Burial Depth Below Seabed Level (m)	4.698

Table 3.2 – Project Specific Burial Assessment

3.5 Ordnance Migration Conclusions

UXO Migration Conclusions

It is often a misconception that UXO movement is equal or similar to sediment migration, i.e. is caused by it. The probability of an item of UXO migrating along the seabed due to water flow (tidal stream/current) is a function, among others, of seabed composition, firmness and morphology (slopes, ripples, troughs, boulders etc.); the current strength, duration and persistence of direction; and the weight, shape (particularly of protrusions, such as lifting lugs) and orientation of the UXO.

Some smooth, cylindrical types of UXO, such as ground mines and torpedo warheads, have been known to roll along the seabed when conditions are favourable; i.e. if the seabed is flat and without obstruction, if it is firm and if the current is strong enough and predominantly uni-directional. If the UXO is laid in shallow water, storm

UXO Migration Conclusions
surges etc. can also produce the conditions necessary to move UXO from its original position. The following factors make UXO migration unlikely: • The presence of sand waves/megaripples mean the potential for 'rolling' is significantly reduced. • Soft sediment mean any UXO present will be buried appreciably by scour.

Table 3.3 – Project Specific Migration Conclusions

4 UXO Encounter and Detonation

4.1 General

It is important to consider the baseline UXO hazards to the Project prior to any works and before any mitigative measures being implemented. Generic information about the potential causes of inadvertent detonation and typical mechanisms and causes of damage and injury are provided. This is then tailored to the specific activities associated with the Project to permit a detailed risk assessment and recommendations for mitigation to be formulated.

The risk that UXO poses to a Project activity is the product of three key elements:

- The likelihood of encountering an item of ordnance.
- ***If*** that encounter happens, the likelihood of the UXO detonating.
- ***If*** the UXO detonates, the severity of the consequence to vulnerable receptors (people and equipment).

4.2 Likelihood of Encounter

Likelihood of encounter, the first element, is a function of the density of UXO items and the total area of intrusive engineering interaction as a proportion of the total area of the Project (to be accurate: by volume to the maximum intrusive depth). It is rarely possible to know precisely how many items of UXO are potentially present within an area (if any) but we make a judgement call based on the results of our historical search, our experience and our knowledge of the types of project activities to be undertaken.

The factors to consider for the Study Area in relation to each other are:

- Likelihood of UXO burial
- Likely density of UXO by type
- Areas covered
- Project activities
    - Intrusive (deep)
    - Intrusive (shallow)
    - Non-intrusive

The Likelihood of Encounter is only one factor of the risk calculation and a relatively high Likelihood of encounter of a particular UXO type does not necessarily mean that the overall risk to all Project activities will necessarily also to be high.

4.3 Likelihood of UXO Detonation

The second element, *Likelihood of the UXO detonation*, we cannot know with any accuracy: most UXO that has been in the ground for a long time is relatively stable, even if subjected to unintended vigorous stimuli but, if the explosive ordnance is for any number of reasons particularly sensitive, or it is hit hard or crushed, it could detonate. However, the risk of detonation can be reduced by the adoption of certain mitigation measures, considered later in this report.

Before a weapon can detonate, a sequence of events must happen, called the Explosive Train (also known as the Firing Train), which starts with the removal of any safety measures and culminates in the detonation of the main charge of high explosive.

Although it may not actually be the case, when UXO is encountered, it must always be assumed that the explosive train is intact: that is, all safety measures have been removed and the detonator is in contact with the main charge.

Nevertheless, the main filling is inherently stable and such a detonation is a rare event, even when UXO has been subjected to robust handling, for example when a bomb is caught up in a dredger head or ship's anchor. Most UXO – particularly EO that has lain on the seabed for several decades – will have been the subject of significant corrosion to its casing and to any mechanical moving parts. It is extremely rare for UXO found on the seabed to function as intended; detonation will almost always be the result of unusual and vigorous kinetic stimuli.

4.4 Effects and Consequences of UXO Detonation

Severity of consequence of detonation, the third element of the risk calculation, is a multifaceted issue depending on a wide range of variables – sensitivity of receptor (e.g. robustness of the vessel/equipment) and protection (are deck crew below the water line, on deck, under hard cover etc.), range from UXO, type of weapon (casing, filling type, charge weight, orientation), depth of water, depth of burial, sediment/ground consistency etc. Quantifying the precise damage that may occur to a vessel or equipment from a specific item of UXO will depend on how its construction reacts to the shock and impulse generated. *Ordtek* can therefore only offer generic advice. The equipment manufacturer and naval architects are best placed to make this calculation.

4.5 Further Reading

More information and expansion on the above processes can be found at Annex C.

5 UXO Risk Assessment (Baseline Pre-Mitigation)

5.1 Key Terms

"Hazard" is a source of potential harm or a situation with the potential to harm or damage. For the purposes of this report the hazard will be termed as “UXO”. This is an overarching term which may include all munitions and/or explosive items that have been dumped, fired or unfired (“fired” in this sense also includes dropped, launched, thrown etc. as a means of deploying a weapon).

"Risk" is the calculation of two principal elements:

(1) The likelihood that a hazard may occur (= probability of encountering UXO x probability of detonation).

(2) The consequence (severity) of the hazardous event.

5.2 Risk Assessment Data

Important Data For Risk Assessment Purposes	
Source - Main Hazards	• British WWI Mines • German WWI Mines • Allied WWII Mines • German WWII Mines • Depth Charges and Torpedoes • HE Bombs and Rockets • Artillery and Naval Projectiles • Land Service Ammunition • Practice Munitions
Pathway - Classification of Work Activities	• Geotechnical Investigation • Jack-up Operations • Foundation Installation: Suction Bucket, Gravity Base, Monopile • Dredging • Pre Lay Grapnel Run (PLGR) • Cable plough / trenching / jetting / cutting • Scour protection (rock cover) • Anchor Handling
Seabed conditions	• Sand • Gravelly sand
Receptor - Entities at Risk	• Personnel, equipment, vessels and project program
Tolerability of Risk	• Risk level should be reduced to ALARP
Inherent Risk Controls by the Project	• Follow best practice and Project H&S plan • In-house UXO Risk Management procedure followed and benchmarked against other projects in the region • Specialist UXO risk assessment conducted • All known obstacles to be avoided or investigated • Avoid wrecks by a suitable distance

Table 5.1 - Key Factors to be used in the Risk Assessment

5.3 Risk Assessment Matrix

Ordtek uses the following matrix to quantify the risk. Each generic UXO hazard is assessed for severity and likelihood of occurrence. This model is generally considered best practice for assessing risk in the marine environment, although it has been modified where required to ensure it is UXO centric.

		Hazard Severity				
		1 = Negligible Negligible injury or impact on equipment with no lost work	**2 = Slight** Minor injury or damage requiring treatment or repair	**3 = Moderate** Injury leading to lost time incident and moderate damage to equipment	**4 = High** Involving single death and serious damage to equipment	**5 = Very High** Multiple deaths and/or sunk vessel, equipment totally destroyed beyond repair
Likelihood of Occurrence (Encounter *and* Detonation)	**1 = Very Unlikely** A freak combination of factors would be required for a UXO initiation to result	**1 = L**	**2 = L**	**3 = L**	**4 = L/M**	**5 = L/M**
	2 = Unlikely A rare combination of factors would be required for a UXO initiation to result	**2 = L**	**4 = L/M**	**6 = L/M**	**8 = M**	**10 = M/H**
	3 = Possible Could happen if sensitive UXO exists but otherwise unlikely to occur	**3 = L**	**6 = L/M**	**9 = M**	**12 = M/H**	**15 = H**
	4 = Likely Not certain to happen but sensitive UXO may exist and density may be above average resulting in an accident	**4 = L/M**	**8 = M**	**12 = M/H**	**16 = H**	**20 = H**
	5 = Very Likely Almost inevitable that an UXO initiation would result due to the type and density of UXO	**5 = L/M**	**10 = M/H**	**15 = H**	**20 = H**	**25 = H**

Table 5.2 - UXO Risk Assessment Matrix

5.4 UXO Risk Assessment

5.4.1 Overview

Ordtek sees the purpose of the risk calculation table at the pre-mitigation stage of the risk management process mainly to produce a relative order of merit that will inform the Risk Mitigation Strategy. The risk assessment can be found after Section 5.4.2.

5.4.2 Important Considerations

In assessing the UXO risk to offshore projects, *Ordtek* uses a semi quantitative risk assessment (SQRA) process widely considered as best practice in the offshore industry and in line with the Construction Industry Research and Information Association (CIRIA) guidance.

We have shown that the risk that UXO poses to any particular Project activity is the product of three key elements:

- The probability of encountering an item of ordnance;
- *If* that encounter happens, the probability of the UXO detonating; and
- *If* the UXO detonates, the severity of the consequence to vulnerable receptors (people, marine life, vessels and equipment) and company reputation.

UXO risk is generally considered a low probability but very high consequence event and it is the latter factor that usually dictates the overarching risk score. The potential consequence of a UXO detonation is by far the dominant factor in the calculation.

Consequences apply to the specific equipment, vessel or personnel and in the circumstances that may lead to detonation for a particular activity. The SQRA calculation may therefore produce resultant similar risk levels for dissimilar activities that could appear counter-intuitive. For example, although the probability of encounter may be greater for one type of UXO over another, the likelihood of detonation for a particular activity may be less. The values assigned to each factor in the risk calculation are subjective and based on many variables, which themselves are difficult or impossible to quantify. Moreover the data for a statistical analysis is not available. **The risk calculation results must be treated with caution and an understanding of their origin.**

The risk factor values assigned in the *Ordtek* SQRA are determined by our UXO specialist experts and are consequently subjective and open to different interpretation. The values assigned cannot be absolute or based upon statistical data (for example, of previous occurrences) because the data is not generally available and there are a great many permutations of the factors involved. A wholly statistical analysis is not possible and a “pseudo” statistical analysis should be treated with caution.

Scoring probability requires a qualitative and informed judgement to be made based upon the limited facts available. It is rarely possible (almost never when dealing with UXO in the offshore environment) to present a purely quantitative and statistically accurate measure of UXO probability factors, simply because the base data is largely qualitative i.e. it is drawn from a variety of different historical and environmental sources. The UXO specialist provides a professionally informed judgement based upon empirical, qualitative and anecdotal evidence employed in a consistent approach.

Nevertheless, despite its limitations, our view is that the risk assessment matrix as currently used is suitable for adequately assessing and grading Health and Safety risk, which is generally mandated by legislation as well as individual company policy. It is also a robust tool for assessing Project risk tolerability. In the risk calculation tables below, for risk assessment purposes, a number of generic ordnance classifications have been grouped. This is justifiable as the probability of encounter, potential for initiation and NEQ are sufficiently similar.

Unless otherwise stated, the consequence (hazard severity) level shown is for the typical vessel or equipment used for a particular development stage. The tables also contain a separate section that shows the likely consequence of UXO detonation to exposed personnel. This section will always assume the worst case scenario.

It is also important to note that the severity of consequence figures in the tables are predicated on the assumption that there is a reasonable degree of separation (water) between the UXO and receptor on detonation. The figure, therefore, primarily considers the effect of a detonation on vessels afloat and embarked personnel. The exception to this is the calculation for Jack-Up barge operations, where detonation of a relatively small NEQ UXO has the potential to initiate collapse of a spud leg, resulting in the vessel capsizing *(note, we have no trials data to support this view but we consider it prudent to take a cautious approach)*.

Equipment in direct contact or immediately adjacent to the detonation may receive substantial, or even catastrophic, damage from even a small item of UXO (e.g. 3.7in projectile). However, (apart from jack-up) we consider this a Project risk, while the tables are predominantly concerned with presenting H&S risk.

Detailed Risk Assessment Results		Norfolk Boreas OWF: Main Array		
Development Stage	Generic Ordnance Category	Likelihood of Occurrence (Encounter *and* Detonation)	Severity of Consequence	Result
Deployment of Monitoring Equipment and Low Energy Ground Investigation (e.g. CPT from a Dynamically Positioned Vessel or grab sampling)	**WWI Buoyant Mines**	1	4	4
	Allied WWII Mines	1	4	4
	Axis WWII Mines	1	5	5
	Depth Charges and Torpedoes	1	4	4
	HE Bombs and Rockets	1	4	4
	Artillery and Naval Projectiles	1	2	2
	Land Service Ammunition/ Small Arms Ammunition	1	2	2
	Practice Munitions	1	1	1
High Energy Ground Investigation (borehole from a Dynamically Positioned Vessel or jack-up barge)	**WWI Buoyant Mines**	1	4	4
	Allied WWII Mines	1	4	4
	Axis WWII Mines	1	5	5
	Depth Charges and Torpedoes	1	4	4
	HE Bombs and Rockets	1	4	4
	Artillery and Naval Projectiles	1	2	2
	Land Service Ammunition/ Small Arms Ammunition	1	2	2
	Practice Munitions	1	1	1
Cable Jetting, water jet via ROV	**WWI Buoyant Mines**	1	4	4
	Allied WWII Mines	2	4	8
	Axis WWII Mines	1	5	5
	Depth Charges and Torpedoes	1	4	4
	HE Bombs and Rockets	2	4	8
	Artillery and Naval Projectiles	2	2	4
	Land Service Ammunition/ Small Arms Ammunition	1	2	2
	Practice Munitions	1	1	1
Rock Dumping / Scour Protection	**WWI Buoyant Mines**	1	4	4
	Allied WWII Mines	3	4	12
	Axis WWII Mines	2	5	10
	Depth Charges and Torpedoes	1	4	4
	HE Bombs and Rockets	2	4	8
	Artillery and Naval Projectiles	1	2	2
	Land Service Ammunition/ Small Arms Ammunition	2	2	4
	Practice Munitions	1	1	1
Cable Trenching, using a tracked vehicle	**WWI Buoyant Mines**	2	4	8
	Allied WWII Mines	2	4	8
	Axis WWII Mines	2	5	10
	Depth Charges and Torpedoes	1	4	4

Detailed Risk Assessment Results		Norfolk Boreas OWF: Offshore Export Cable		
Development Stage	Generic Ordnance Category	Likelihood of Occurrence (Encounter *and* Detonation)	Severity of Consequence	Result
Deployment of Monitoring Equipment and Low Energy Ground Investigation (e.g. CPT from a Dynamically Positioned Vessel or grab sampling)	**WWI Buoyant Mines**	1	4	4
	Allied WWII Mines	1	4	4
	Axis WWII Mines	1	5	5
	Depth Charges and Torpedoes	1	4	4
	HE Bombs and Rockets	1	4	4
	Artillery and Naval Projectiles	1	2	2
	Land Service Ammunition/ Small Arms Ammunition	1	2	2
	Practice Munitions	1	1	1
High Energy Ground Investigation (borehole from a Dynamically Positioned Vessel or jack-up barge)	**WWI Buoyant Mines**	1	4	4
	Allied WWII Mines	1	4	4
	Axis WWII Mines	1	5	5
	Depth Charges and Torpedoes	1	4	4
	HE Bombs and Rockets	2	4	8
	Artillery and Naval Projectiles	1	2	2
	Land Service Ammunition/ Small Arms Ammunition	1	2	2
	Practice Munitions	1	1	1
Cable Jetting, water jet via ROV	**WWI Buoyant Mines**	1	4	4
	Allied WWII Mines	2	4	8
	Axis WWII Mines	1	5	5
	Depth Charges and Torpedoes	1	4	4
	HE Bombs and Rockets	2	4	8
	Artillery and Naval Projectiles	2	2	4
	Land Service Ammunition/ Small Arms Ammunition	1	2	2
	Practice Munitions	1	1	1
Rock Dumping / Scour Protection	**WWI Buoyant Mines**	1	4	4
	Allied WWII Mines	2	4	8
	Axis WWII Mines	2	5	10
	Depth Charges and Torpedoes	1	4	4
	HE Bombs and Rockets	2	4	8
	Artillery and Naval Projectiles	1	2	2
	Land Service Ammunition/ Small Arms Ammunition	2	2	4
	Practice Munitions	1	1	1
Cable Trenching, using a tracked vehicle	**WWI Buoyant Mines**	2	4	8
	Allied WWII Mines	2	4	8
	Axis WWII Mines	2	5	10
	Depth Charges and Torpedoes	1	4	4

Detailed Risk Assessment Results		Norfolk Boreas OWF: Nearshore Export Cable		
Development Stage	Generic Ordnance Category	Likelihood of Occurrence (Encounter *and* Detonation)	Severity of Consequence	Result
Deployment of Monitoring Equipment and Low Energy Ground Investigation (e.g. CPT from a Dynamically Positioned Vessel or grab sampling)	**WWI Buoyant Mines**	1	4	4
	Allied WWII Mines	1	4	4
	Axis WWII Mines	1	5	5
	Depth Charges and Torpedoes	1	4	4
	HE Bombs and Rockets	1	4	4
	Artillery and Naval Projectiles	1	2	2
	Land Service Ammunition/ Small Arms Ammunition	1	2	2
	Practice Munitions	1	1	1
High Energy Ground Investigation (borehole from a Dynamically Positioned Vessel or jack-up barge)	**WWI Buoyant Mines**	1	4	4
	Allied WWII Mines	1	4	4
	Axis WWII Mines	1	5	5
	Depth Charges and Torpedoes	1	4	4
	HE Bombs and Rockets	2	4	8
	Artillery and Naval Projectiles	1	2	2
	Land Service Ammunition/ Small Arms Ammunition	1	2	2
	Practice Munitions	1	1	1
Cable Jetting, water jet via ROV	**WWI Buoyant Mines**	1	4	4
	Allied WWII Mines	1	4	4
	Axis WWII Mines	1	5	5
	Depth Charges and Torpedoes	1	4	4
	HE Bombs and Rockets	2	4	8
	Artillery and Naval Projectiles	2	2	4
	Land Service Ammunition/ Small Arms Ammunition	1	2	2
	Practice Munitions	1	1	1
Rock Dumping / Scour Protection	**WWI Buoyant Mines**	1	4	4
	Allied WWII Mines	1	4	4
	Axis WWII Mines	1	5	5
	Depth Charges and Torpedoes	1	4	4
	HE Bombs and Rockets	2	4	8
	Artillery and Naval Projectiles	1	2	2
	Land Service Ammunition/ Small Arms Ammunition	2	2	4
	Practice Munitions	1	1	1
Cable Trenching, using a tracked vehicle	**WWI Buoyant Mines**	2	4	8
	Allied WWII Mines	1	4	4
	Axis WWII Mines	1	5	5
	Depth Charges and Torpedoes	1	4	4

Detailed Risk Assessment Results		Norfolk Boreas OWF: Main Array		
Development Stage	**Generic Ordnance Category**	**Likelihood of Occurrence (Encounter *and* Detonation)**	**Severity of Consequence**	**Result**
Cable Trenching, using a tracked vehicle	HE Bombs and Rockets	3	4	12
	Artillery and Naval Projectiles	2	2	4
	Land Service Ammunition/ Small Arms Ammunition	1	2	2
	Practice Munitions	1	1	1
Dredging	WWI Buoyant Mines	2	4	8
	Allied WWII Mines	2	4	8
	Axis WWII Mines	2	5	10
	Depth Charges and Torpedoes	1	4	4
	HE Bombs and Rockets	3	4	12
	Artillery and Naval Projectiles	2	2	4
	Land Service Ammunition/ Small Arms Ammunition	1	2	2
	Practice Munitions	1	1	1
Anchor Deployment & Handling (this could be for cable or foundation installation)	WWI Buoyant Mines	1	4	4
	Allied WWII Mines	2	4	8
	Axis WWII Mines	1	5	5
	Depth Charges and Torpedoes	1	4	4
	HE Bombs and Rockets	2	4	8
	Artillery and Naval Projectiles	1	2	2
	Land Service Ammunition/ Small Arms Ammunition	1	2	2
	Practice Munitions	1	1	1
Foundation Installation (Typically piling)	WWI Buoyant Mines	2	4	8
	Allied WWII Mines	3	4	12
	Axis WWII Mines	2	5	10
	Depth Charges and Torpedoes	1	4	4
	HE Bombs and Rockets	3	4	12
	Artillery and Naval Projectiles	2	2	4
	Land Service Ammunition/ Small Arms Ammunition	1	2	2
	Practice Munitions	1	1	1
Jack-up Leg Placement	WWI Buoyant Mines	2	4	8
	Allied WWII Mines	2	4	8
	Axis WWII Mines	2	5	10
	Depth Charges and Torpedoes	1	4	4
	HE Bombs and Rockets	3	4	12
	Artillery and Naval Projectiles	2	2	4
	Land Service Ammunition/ Small Arms Ammunition	1	2	2
	Practice Munitions	1	1	1

Detailed Risk Assessment Results		Norfolk Boreas OWF: Offshore Export Cable		
Development Stage	**Generic Ordnance Category**	**Likelihood of Occurrence (Encounter *and* Detonation)**	**Severity of Consequence**	**Result**
Cable Trenching, using a tracked vehicle	HE Bombs and Rockets	3	4	12
	Artillery and Naval Projectiles	2	2	4
	Land Service Ammunition/ Small Arms Ammunition	1	2	2
	Practice Munitions	1	1	1
Dredging	WWI Buoyant Mines	2	4	8
	Allied WWII Mines	2	4	8
	Axis WWII Mines	2	5	10
	Depth Charges and Torpedoes	1	4	4
	HE Bombs and Rockets	3	4	12
	Artillery and Naval Projectiles	2	2	4
	Land Service Ammunition/ Small Arms Ammunition	1	2	2
	Practice Munitions	1	1	1
Anchor Deployment & Handling (this could be for cable or foundation installation)	WWI Buoyant Mines	1	4	4
	Allied WWII Mines	2	4	8
	Axis WWII Mines	1	5	5
	Depth Charges and Torpedoes	1	4	4
	HE Bombs and Rockets	2	4	8
	Artillery and Naval Projectiles	1	2	2
	Land Service Ammunition/ Small Arms Ammunition	1	2	2
	Practice Munitions	1	1	1
Foundation Installation (Typically piling)	WWI Buoyant Mines	N/A	N/A	N/A
	Allied WWII Mines	N/A	N/A	N/A
	Axis WWII Mines	N/A	N/A	N/A
	Depth Charges and Torpedoes	N/A	N/A	N/A
	HE Bombs and Rockets	N/A	N/A	N/A
	Artillery and Naval Projectiles	N/A	N/A	N/A
	Land Service Ammunition/ Small Arms Ammunition	N/A	N/A	N/A
	Practice Munitions	N/A	N/A	N/A
Jack-up Leg Placement	WWI Buoyant Mines	N/A	N/A	N/A
	Allied WWII Mines	N/A	N/A	N/A
	Axis WWII Mines	N/A	N/A	N/A
	Depth Charges and Torpedoes	N/A	N/A	N/A
	HE Bombs and Rockets	N/A	N/A	N/A
	Artillery and Naval Projectiles	N/A	N/A	N/A
	Land Service Ammunition/ Small Arms Ammunition	N/A	N/A	N/A
	Practice Munitions	N/A	N/A	N/A

Detailed Risk Assessment Results		Norfolk Boreas OWF: Nearshore Export Cable		
Development Stage	**Generic Ordnance Category**	**Likelihood of Occurrence (Encounter *and* Detonation)**	**Severity of Consequence**	**Result**
Cable Trenching, using a tracked vehicle	HE Bombs and Rockets	3	4	12
	Artillery and Naval Projectiles	2	2	4
	Land Service Ammunition/ Small Arms Ammunition	1	2	2
	Practice Munitions	1	1	1
Dredging	WWI Buoyant Mines	2	4	8
	Allied WWII Mines	1	4	4
	Axis WWII Mines	1	5	5
	Depth Charges and Torpedoes	1	4	4
	HE Bombs and Rockets	3	4	12
	Artillery and Naval Projectiles	2	2	4
	Land Service Ammunition/ Small Arms Ammunition	1	2	2
	Practice Munitions	1	1	1
Anchor Deployment & Handling (this could be for cable or foundation installation)	WWI Buoyant Mines	1	4	4
	Allied WWII Mines	1	4	4
	Axis WWII Mines	1	5	5
	Depth Charges and Torpedoes	1	4	4
	HE Bombs and Rockets	2	4	8
	Artillery and Naval Projectiles	1	2	2
	Land Service Ammunition/ Small Arms Ammunition	1	2	2
	Practice Munitions	1	1	1
Foundation Installation (Typically piling)	WWI Buoyant Mines	N/A	N/A	N/A
	Allied WWII Mines	N/A	N/A	N/A
	Axis WWII Mines	N/A	N/A	N/A
	Depth Charges and Torpedoes	N/A	N/A	N/A
	HE Bombs and Rockets	N/A	N/A	N/A
	Artillery and Naval Projectiles	N/A	N/A	N/A
	Land Service Ammunition/ Small Arms Ammunition	N/A	N/A	N/A
	Practice Munitions	N/A	N/A	N/A
Jack-up Leg Placement	WWI Buoyant Mines	N/A	N/A	N/A
	Allied WWII Mines	N/A	N/A	N/A
	Axis WWII Mines	N/A	N/A	N/A
	Depth Charges and Torpedoes	N/A	N/A	N/A
	HE Bombs and Rockets	N/A	N/A	N/A
	Artillery and Naval Projectiles	N/A	N/A	N/A
	Land Service Ammunition/ Small Arms Ammunition	N/A	N/A	N/A
	Practice Munitions	N/A	N/A	N/A

Detailed Risk Assessment Results		Norfolk Boreas OWF: Main Array		
Development Stage	**Generic Ordnance Category**	**Likelihood of Occurrence (Encounter *and* Detonation)**	**Severity of Consequence**	**Result**
Unprotected Personnel (considering activities that may potentially recover small items above the water surface – detonation on or very close to the surface; detonation <10m)	**WWI Buoyant Mines**	1	4	4
	Allied WWII Mines	1	4	4
	Axis WWII Mines	1	5	5
	Depth Charges and Torpedoes	1	4	4
	HE Bombs and Rockets	1	4	4
	Artillery and Naval Projectiles	2	2	4
	Land Service Ammunition/ Small Arms Ammunition	1	2	2
	Practice Munitions	1	1	1

Detailed Risk Assessment Results		Norfolk Boreas OWF: Offshore Export Cable		
Development Stage	**Generic Ordnance Category**	**Likelihood of Occurrence (Encounter *and* Detonation)**	**Severity of Consequence**	**Result**
Unprotected Personnel (considering activities that may potentially recover small items above the water surface – detonation on or very close to the surface; detonation <10m)	**WWI Buoyant Mines**	1	4	4
	Allied WWII Mines	1	4	4
	Axis WWII Mines	1	5	5
	Depth Charges and Torpedoes	1	4	4
	HE Bombs and Rockets	1	4	4
	Artillery and Naval Projectiles	2	2	4
	Land Service Ammunition/ Small Arms Ammunition	1	2	2
	Practice Munitions	1	1	1

Detailed Risk Assessment Results		Norfolk Boreas OWF: Nearshore Export Cable		
Development Stage	**Generic Ordnance Category**	**Likelihood of Occurrence (Encounter *and* Detonation)**	**Severity of Consequence**	**Result**
Unprotected Personnel (considering activities that may potentially recover small items above the water surface – detonation on or very close to the surface; detonation <10m)	**WWI Buoyant Mines**	1	4	4
	Allied WWII Mines	1	4	4
	Axis WWII Mines	1	5	5
	Depth Charges and Torpedoes	1	4	4
	HE Bombs and Rockets	1	4	4
	Artillery and Naval Projectiles	2	2	4
	Land Service Ammunition/ Small Arms Ammunition	2	2	4
	Practice Munitions	1	1	1

6 Risk Tolerance and ALARP

6.1 The ALARP Principle

Although European and UK law clearly lays out the obligations on various parties and general preventative principles, the absolute level of risk that is acceptable (if any) is not defined; it is expressed as a relative value.

Certainly in most practical situations in the maritime environment, the level of risk can statistically never be “zero”. The number of hazard items in a typical OWF development area is never known; the limitations of current survey equipment technology mean that the probability of detection can never be “1” and therefore the probability of encounter cannot be zero. Similarly, the sensitivity and stability of any UXO present is not known and, therefore the probability of detonation cannot be zero. Finally, if development activities are to take place, people and equipment will necessarily be put in “harm’s way”. There will always be a residual level of risk. The level will depend on the mitigation measures put in place.

Many European regulatory authorities, including the UK Health & Safety Executive (HSE), require that operational risks should be within acceptable limits and As Low as Reasonably Practicable (ALARP); this is also the case with UXO. Determining that UXO risks have been reduced to ALARP involves an assessment of the UXO risk to be avoided, an assessment of the effort (in terms of money and time) involved in taking control measures to avoid or mitigate that risk and a comparison of the two facets. The graph at *Figure 6.1* demonstrates how ALARP is measured. The principle of ALARP is commonly applied across most of the European offshore renewables industry.

To demonstrate that risks are ALARP, a suitability qualified entity (usually a UXO specialist) must show that enough has been done to reduce risks. In cases where the risks are well-defined, it is sufficient to show that recognised “good practices” have been implemented. In more complex situations, i.e. where the industry or technology is new, to demonstrate risks are ALARP, it is necessary to show that all reasonably practicable risk reduction measures have been implemented and that all other measures that could be implemented are shown to be unjustified. Risk criteria may be defined by national regulations, corporate guidance and well-established industry standards.

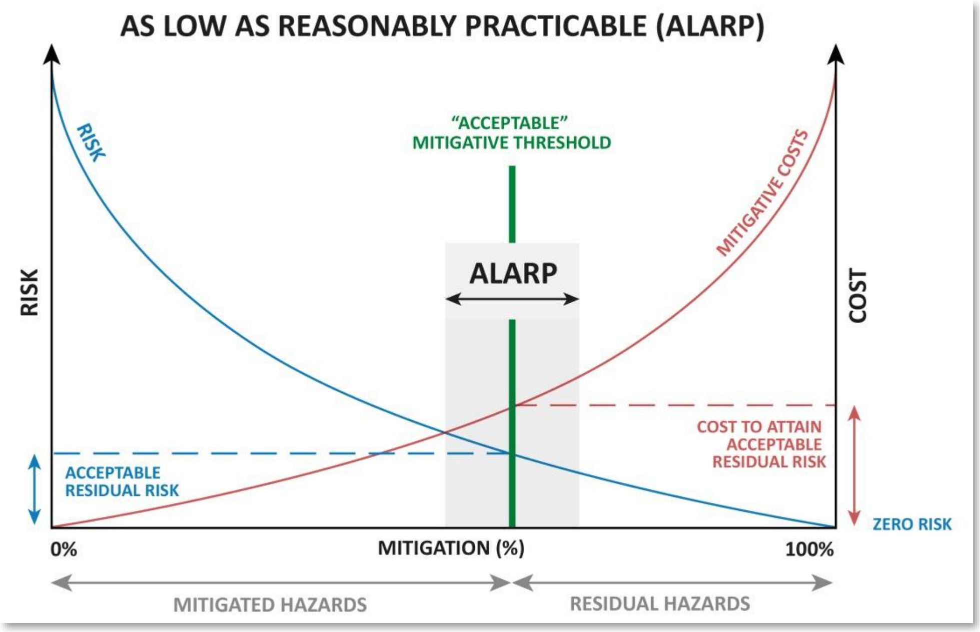


Figure 6.1 - Determining risk are ALARP by measuring Cost versus Effort

6.2 Risk Tolerance and ALARP

The Health and Safety (H&S) risks that UXO poses to the Project personnel and the general public must, by law, be reduced to below a threshold deemed ALARP. On the other hand, the level of Project risk (damage to equipment, delay, reputation etc.) that can be carried is not mandated by legislation. In this case, UXO risk tolerance is a matter for the developer and their insurers.

Our view that the two can be considered separately. As long as the standard of ALARP is achieved for H&S risk, the developer has the option of accepting higher (or, indeed, striving for lower) project risk. In the former (H&S risk), it is necessary to show that all that is reasonably practicable has been done to reduce UXO risk. The key benchmark, therefore, is not the actual *level* of risk but what is seen to be <u>done</u> in its mitigation. If this is judged sufficient, the project can proceed with a *de minimis* risk of a catastrophic UXO event *(De minimis - a residual risk that is deemed to be too trivial or minor to merit consideration, especially in law. In risk assessment, it refers to the level of risk too small to be concerned with or that needs action. There is no legal requirement for further mitigation.)*

On the other hand, when it comes to project risk, managers are concerned with *actual risk levels*; that is, the probability of a detonation occurring for any particular activity and the cost and severity of the likely consequences.

As we noted earlier, the inadvertent detonation of an item of UXO is generally acknowledged as being a very low probability, high consequence event. Therefore the developer, if they judge it acceptable, may forego the potentially high costs of additional survey, contact investigation etc. in favour of risking the costs of the consequences of a detonation, in the knowledge that such a detonation is highly unlikely to occur. Particularly if the project costs incurred may be unreasonable in comparison.

6.3 Risk Assessment Results

It can be seen from a Health & Safety risk assessment perspective that in general the risk to the Project is Low to Moderate-High and very much depends upon the project activities. Based upon this, *Ordtek* then uses the following risk tolerability thresholds to determine the level of mitigation required.

Risk	Category	Action
1 – 3	Tolerable – No mitigation required	Nominal risk. A UXO action plan for contractors would be prudent
4 – 6	Partly Tolerable – Procedural mitigation required	Some risk. Control measures MUST be maintained and monitored. Inexpensive reasonably practical risk mitigation measures should still be implemented. (Use existing survey data if available)
7 – 8	Intolerable – Active mitigation required	Intermediate risk. Any control measures MUST be maintained and monitored and on-going actions completed. UXO specified survey is likely to be required.
9 – 12	Intolerable – Active mitigation required	Risk MUST be reduced. Any control measures MUST be maintained and monitored. Risk mitigation required or Company (management) approval needed.
13 – 25	Intolerable – Active, bespoke mitigation required	Substantial risk. MUST NOT BE ALLOWED. Risk MUST be reduced. Any control measures MUST be maintained and monitored. Bespoke, comprehensive mitigation is likely required.

Table 6.1 - UXO Risk Tolerability

6.4 Risk Tolerance

Given the effort, cost and impracticality of trying to detect and investigate the number of geophysical survey anomalies likely to result from specifying a small UXO item (such as 5 inch projectiles), coupled with the very low risk to personnel above water (which can be satisfactorily mitigated procedurally), ***Ordtek*** **considers that the ALARP standard for H&S risk will be fully met by applying this threshold**, assuming that a suitable risk management strategy is fully adopted.

As shown, *project risk tolerance*, however, also depends on other criteria. A key decision in determining the smallest item that should be specified for sign-off is whether the risk from UXO items *smaller* than the chosen threshold detonating is acceptable; bearing in mind that even though the consequence may be relatively high, the probability of the “event” is likely to be extremely low.

6.5 Smallest UXO Item for ALARP Sign-Off

The choice of the smallest hazard item that needs to be mitigated for ALARP sign-off is determined, *inter alia*, by the prevailing environment (including likely UXO burial) and the ability to detect the item using available geophysical techniques. It is necessary to weigh up the perceived significance of the hazard to specified Project activities against what is “reasonably practicable” in terms of effort to detect it.

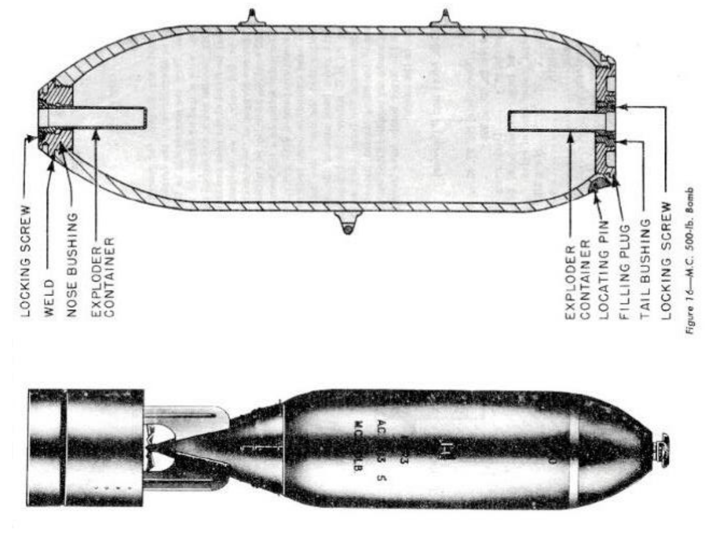
Even though some improvement in detection can be achieved by reducing magnetometer survey line spacing (for example from typically 5m to 3m), generally the detection and identification of all magnetic anomalies that could resemble a small bomb in an area is likely to be impossible, particularly in areas of high ferro-magnetic noise. Investigating the many thousands of resultant anomalies that ensued from data interpretation would be prohibitive in both time and cost. This effort required, in *Ordtek’s* opinion, would not be reasonable and not within our understanding of the ALARP principle.

Smallest Hazard Item for Survey Design

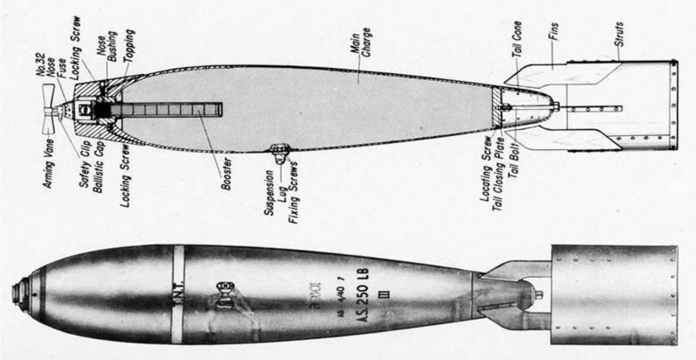
Ordtek recommends that the smallest threat items for geophysical data interpretation is varied based upon the prevailing environment.

Within water depths greater than 10m LAT, Ordtek recommends the **British 500lb HE bomb**. The 500lb HE bomb is cylindrical/teardrop in shape and made of cast steel. Depending on the variant, the body length is 1.04m and the diameter is 0.33m. The filling consists of 95-105kg of TNT or RDX.

Within water depths 10m LAT and lower, Ordtek recommends the **British 250lb HE bomb**. The 250lb HE bomb is cylindrical/teardrop in shape and made of cast steel. Depending on the variant, the body length is 0.72m and the diameter is 0.26m. The filling consists of 50kg of TNT or RDX.



British 500lb MC Bomb



British 250lb GP Bomb

Assuming these items can be successfully detected and identified within the geophysical datasets, larger objects will also be detectable. It is also likely that there will be smaller items of UXO present within the Study Area. The relatively small risk that these present can be mitigated by physical and procedural measures.

Table 6.2 – Smallest Hazard Item for Survey Design

7 Mitigation Required to Reduce the Risk ALARP

7.1 Overview

In strategic terms, the UXO risk on this Project can realistically be either:

- Accepted by all parties and no further proactive action is taken.
- Avoided by not undertaking the activities at risk.
- Mitigated with measures to contain, and/or eliminate the UXO risks (by reducing the probability or consequences).
- Carried with the balance of any residual risk transparently exposed to those parties involved with site works.

Although mitigation is generally the most cost effective and efficient option for dealing with UXO risks, a balanced blend of the options is usually required to comply with best practice. This risk profiling study has shown that the risk from UXO to the proposed developments ranges from Low to Moderate-High and that mitigation is required to reduce the risk to ALARP.

Note that the risk from UXO can never be considered "zero” in the offshore environment, due to equipment limitations and the potential for UXO migration.

Mitigation should not focus solely on the Health and Safety risk UXO presents, it is also important to consider other risks to the Project, such as the impact of delay. For example, even if the UXO risk to personnel and equipment was deemed low during offshore work, if a number of suspect UXO items were subsequently found after work had started, the impact to the Project could be major. This has been clearly demonstrated on other offshore Projects around the UK. These other risks therefore need to be taken in to consideration when determining the level of risk mitigation required.

7.2 Geotechnical Campaign

7.2.1 Introduction

The risk of *both* encountering *and* detonating UXO during the geotechnical campaign using a DP vessel and intrusive techniques is *low* but when the severity of the consequences, should a detonation occur, is taken into consideration the calculated UXO risk can be considered to require mitigation.

To reduce the level of UXO risk to ALARP during the geotechnical campaign, Ordtek recommends the following:

7.2.2 Desk-based Planning

- Identify the GI locations to be undertaken and working area required;
- Review existing geophysical data where available: in areas of non-burial existing SSS, magnetometry and MBES survey data may be of sufficient quality to use;
- Identify where new geophysical data is being acquired, ahead of the GI tests: where there is potential for burial, additional UXO specified magnetometry survey may be needed;
- Minimum data requirements for review ahead of GI;
- SSS/MBES with sufficient resolution to identify a 1.0m object within the data set;

- Ensure sample location and working area are within full survey coverage;
- The project should hold a database of all potential UXO targets for avoidance;
- Produce suitable documentation to inform all parties of the potential UXO constrains.

7.2.3 On Mobilisation of Geotechnical Campaign

- Input potential UXO database into vessel navigation software for avoidance;
- Brief all personnel on the potential UXO risk through a series of UXO safety and awareness briefings;
- Ensure the project team are aware of their internal UXO policy including key support numbers.

7.2.4 During Geotechnical Campaign

- Hold a copy of this risk assessment on-board the vessel;
- Avoid contacts within the potential UXO database by 10m radius;
- Where practicable undertake drop down camera survey ahead of geotechnical equipment deployment;
- Hold a UXO specialist on-call in the event of a suspect item being unexpectedly discovered.

7.3 Pre-Installation Survey

7.3.1 Stage 1: Geophysical Survey

Geophysical survey should be undertaken, utilising Side Scan Sonar, Multibeam Echosounder and Magnetometer, for the purposes of locating and identifying items that model as UXO at the wind farm.

The following workflow should be utilised ahead of geophysical survey data collection:

- Establish smallest threat item and develop specification to detect item with required datasets.
- Establish survey areas.
- As part of vessel mobilisation, undertake an equipment verification test on the project site with a deployed known test item, to show all sensors are working as expected and demonstrate data transfer and processing procedures.
- Pass EVT data and report to Client and UXO consultant for review – receive EVT sign off report.
- Acquire geophysical data sets with Client survey representatives onboard providing data QA/QC.
- During larger campaigns or the pre-construction survey it is advised that a preliminary site block is delivered to the Client and UXO consultant to undertake a data audit ensuring data is being processed and collected within expected specifications and methods.

Once the survey data has been collected, the survey contractor should process the navigation and survey data.

The data should then be sent onshore for potential UXO target discrimination. Anomalies will be picked from the processed data that model as UXO and these "potential UXO" will be given an exclusion distance that should not be interfered with.

The output from the data interpretation phase should be presented within a "Potential UXO Target List", containing all anomalies that are potentially UXO with coordinates of their precise locations and a unique designation for each target (usually following the naming convention of the Survey Contractor).

The minimum survey requirement and coverage areas are outlined in the table below.

Project Phase	Activity	Typical Working Area/ Survey Coverage	Minimum Requirement
Pre-Construction Site Investigation	Grab Samples	N/A	None
	Geotechnical Investigations	10m x 10m box	Full working area coverage: • Magnetometer • Multibeam Echosounder • Side Scan Sonar
Monitoring	Wave buoys and LiDAR Station anchoring	N/A	None in isolation, however where geophysical data is available, it should be utilized.
	Met-Mast commissioning / decommissioning	30m radius around foundation	Full working area coverage: • Magnetometer • Multibeam Echosounder • Side Scan Sonar
Construction	Cable lay down	Covering working area	Full working area coverage: • Multibeam Echosounder • Side Scan Sonar
	Pre Lay Grapnel Run (PLGR)	20m corridor	Full working area coverage: • Magnetometer • Multibeam Echosounder • Side Scan Sonar
	Cable plough / trenching / jetting / cutting	20m corridor (inter array cable) 30m corridor (export cable) – offshore, 100m corridor close to shore	
	Foundation Installation	30m radius around foundations	
	Jack-up Operations	200m radius around foundations	
	Scour protection	Covering working area	
	Dredging/pre-sweep		
	Sediment spoil disposal		Multibeam Echosounder/ Side Scan Sonar
	Anchor Handling		Multibeam Echosounder/ Side Scan Sonar

Table 8.1 – Minimum Survey Requirement and Working Areas

7.3.2 Stage 2: UXO Inspection

Should the potential UXO targets remain a constraint to the Project, then they may need to be inspected. This may involve investigation by diver or Remotely Operated Vehicle (ROV).

A UXO Specialist should be embarked onboard the vessel during inspection. When on location, the role of the UXO specialist would be to monitor works, where appropriate advising staff of the need to modify work practices and provide immediate UXO identification and safety advice. If an object was confirmed as UXO, he would help with the vessel/site incident management and provide pertinent specialist advice, which would involve liaison with shore/local authorities and the Client’s UXO consultant.

7.3.3 Stage 3: Potential UXO Avoidance

Any “potential UXO” geophysical anomalies can be avoided by a suitably safe distance for any intrusive seabed interactions. This can be achieved through rerouting or micro-siting of seabed interactions.

In accordance with the ALARP principle, the installation could then proceed with a *de minimis* risk of encountering UXO. However, the safety exclusion zones around the geophysical contacts should be respected. Unless these contacts are investigated and confirmed as not EO related, they should be considered a potential hazard.

7.4 Construction

7.4.1 General

The project should hold a database of all potential UXO targets for avoidance and suitable documentation should be produced to inform all parties of the potential UXO constraints.

Onboard the vessel, the potential UXO constraints to be avoided should be entered into the onboard navigation system and the location of any known wreck sites should be noted. The Project team should be made aware of the internal UXO policy, including key support numbers. In addition, the vessel should hold a copy of this risk assessment.

7.4.2 Obtain UXO ALARP sign-off certificate.

To provide evidence of the risk management process documentation is required to evidence to the project stakeholders and contractors that the UXO risk has been mitigated to a legally acceptable level (ALARP).

The ALARP Sign-off Certificates are a comprehensive document that is unique to any particular location. The certificates should be available for auditing by relevant external bodies including the Health & Safety Executive (HSE) and the developer. The certificates shall be underwritten by external Professional Indemnity Insurance.

7.4.3 UXO Risk Management Plan with Safety Instructions

The contractor’s/vessel emergency response plan (ERP) should identify management responsibilities in respect of reporting potential UXO items, marking of objects, dealing with potential UXO brought onto the vessel inadvertently, securing the area, ensuring the safety of personnel and informing the UXO specialist, whether embarked offshore or on-call ashore.

Management staff and supervisors, for all phases of development, will be required to attend the normal Explosive Ordnance Safety and Awareness Briefing, in addition to a separate expanded briefing detailing actions to be taken in the event that an item of ordnance or suspicious objects encountered. Key staff should be nominated as part of the vessel/site health and safety protocol with specific responsibility for the implementation and maintenance of the Explosive Ordnance Site Safety Instructions.

7.4.4 Protocol in the Event of Encounter with Chemical Warfare Agents

The aim of this document is to define the course of action to take in case of recovering chemical weapons (CW) during offshore working. The document should cover recognition of CW contamination signs, the symptoms of exposure to CW, the procedure to follow in the event of encountering CW and appropriate first aid processes for dealing with exposure to CW.

7.4.5 UXO Safety Awareness Briefings

All involved personnel will be required to attend a safety induction briefing. This formal briefing should include a section on Explosive Ordnance Safety and Awareness and will apply during all work that interacts with the seabed throughout the life of the Project. The briefing will be supported by photographs of the range of ordnance that is considered likely to be encountered. The visual material will depict the ordnance in a ‘typical’ state (e.g. rusting and covered in concretion). A record will be maintained of all personnel who attend the briefing and subsequent update briefings. At the discretion of the principal contractor, all personnel should attend a periodic update briefing, particularly during the seabed engineering phases of the Project.

7.4.6 UXO Specialist On Call

The Project should engage an UXO specialist to be on call in the event of a potential UXO encounter. A procedure can be implemented to ensure the item is viewed and dealt with as quickly as possible.

Annex A

Supplementary Notes on Munitions Types

SUPPLEMENTARY NOTES ON UNEXPLODED ORDNANCE TYPES

High Explosive Bombs and Rockets

The charge weight (commonly referred to as the NEQ - Net Explosive Quantity) of a bomb depends on its purpose. Bombs intended to cause damage principally by blast are relatively thin cased and contain around 75% by weight of HE. Those that are designed to fragment and cause damage to thin-skinned buildings, people and equipment through shrapnel have thicker casings and around 30% HE. "General Purpose" (GP) and "Medium Capacity" (MC) bombs have a charge weight of around 50% of the total weight of the weapon. The German designations for these types of bombs were SB, SD and SC respectively. For example an SC-250 would be a general purpose "Minenbombe" weighing 250kg, with an NEQ of around 125kg of HE. An SD-500 would be a fragmentation "Splitterbombe" weighing 500kg and with a charge weight of around 150kg, depending on the variant.

Allied bombs dropped from medium/heavy bombers could vary from 50lb (~25kg) to 4000lb (~1800kg) or more but, predominantly, the majority were likely to be British General Purpose (GP) or US Medium Capacity (MC) bombs in the order of 100lb-1000lb (~50kg - ~450kg). These are more likely to be present on the inter-tidal zone or the inner Wash.

Bombs employed by the Germans varied from 50kg to 4000kg. However, less than 4% of all bombs dropped on Britain in WWII were of the larger variety; the majority were 500kg or less, with 50kg and 70kg bombs predominating (around 80%). The German HE bombs most likely to be encountered on this project therefore are medium capacity, ranging from the SC 50kg to SC 500kg.

High Capacity Blast Bombs (up to 80% explosives) and "Parachute" mines were also used. When laid by air, these German sea mines were usually fitted with bomb fuses that would function either on impact or with a delay, if they fell on land and did not receive the hydrostatic pressure required to disarm the bomb fuse and activate the mine influence sensors and firing circuits.

German bombs are readily identified by the shape of the tail (if still fitted) and, particularly, by their transverse fusing. Both British and German bombs could be fitted with several kinds of fuses, including singly or in combination: impact, long delay and anti-disturbance. However, any anti-disturbance fuse that relied on a power source is now highly unlikely to function. Moreover, the majority of mechanical fuses or pistols will have been subject to significant corrosion and are also unlikely to function as designed. Nevertheless, some could be in an extremely sensitive state.

A typical rocket was the RP-3. These 3 inch rockets had a 60lb (27 kg) warhead in the HE variant.

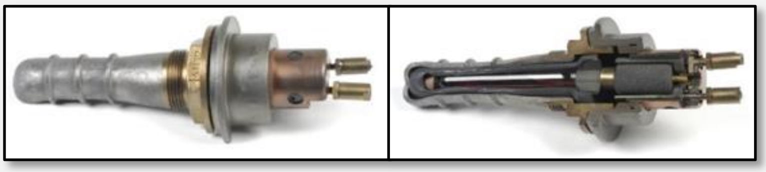
German (R) and British (L) HE bombs as UXO (note typical absence of tail)

Sea Mines

Mines are generally classified by their position in the water and their method of firing (actuation).

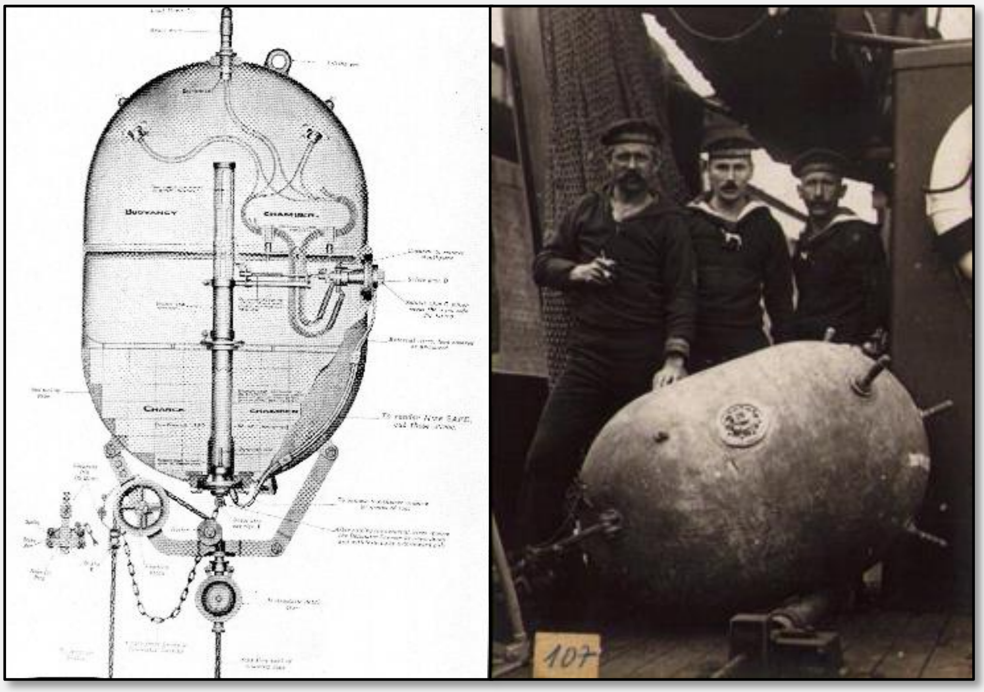
Buoyant Mines

The first and the most commonly employed in WWI, but also extensively deployed in WWII, is the buoyant mine, which is designed either to float just below the surface, tethered to the seabed by a mooring wire and sinker (anchor), or to drift with the ocean currents. Buoyant mines consist of a spherical or ovoid casing with a charge weight of typically 40kg - 250kg of HE, taking up approximately a third of their volume. They are most commonly actuated by contact with the target, using either mechanical switch horns to close a battery-powered firing circuit or “Herz” horns. The latter are also known as “Chemical Horns”. A Herz horn consists of a soft lead or copper sheath enclosing a glass phial of acid at the base of which is a dry battery cell. On contact with a target vessel, the glass phial breaks, releasing the acid to act as the battery cell’s electrolyte, which then provides power to the mine’s detonator. The increased danger a Herz horn presents over a switch horn is that it does not rely on a battery, which will discharge over time, but can provide power to the detonator indefinitely.



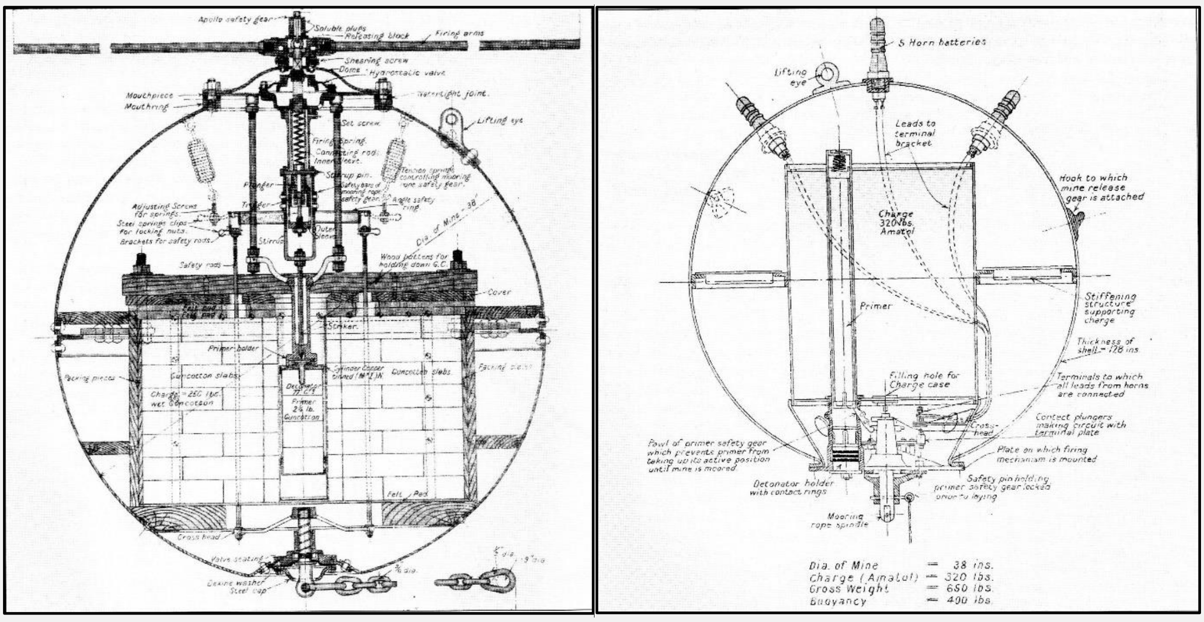
Herz (Chemical) Horn

Other variants of moored mines, but used in much less numbers, were the Antenna Mine, an anti-submarine contact mine that used the current generated by two dissimilar metals rubbing together to fire, and the Magnetic mine, an “influence” mine that was actuated by the small electro-magnetic current generated when a target vessel’s moving magnetic field cut the mine’s internal coiled rod sensor.

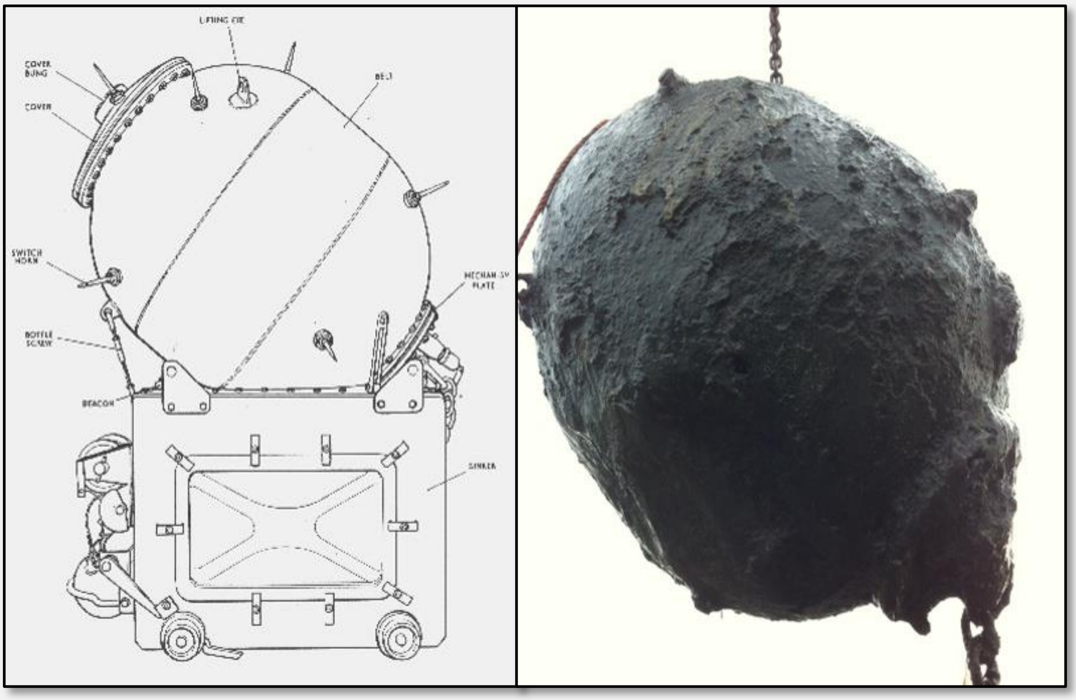


German WWI Type II “Egg” Mine

Mines specifically designed to drift mines are not particularly effective as an anti-ship weapon – their value lays in the fear and disruption they cause – and they were not often employed. However, hundreds of thousands of moored mines were laid during the two world wars. A moored mine frequently became a drifting mine when its cable parted due to the wear and tear of wave motion. In accordance with the Hague Convention of 1907, mines breaking free from their moorings are required to self-neutralise but, in reality, either by design or malfunction, early mines often remained active. They continued to be a danger to shipping and to civilians, if swept ashore. Most eventually sank, often a considerable distance from where they were originally laid. Consequently, estimating the risks posed in any particular area by the mines laid either defensively or offensively during the two world wars is exceptionally difficult. So many were laid that a general assumption is that buoyant mines could be present in any area off the coast of Northern Europe.



British WWI "Naval Spherical" (L) and "H2" (R) buoyant mines



British WWII Buoyant mine in typical condition as found today

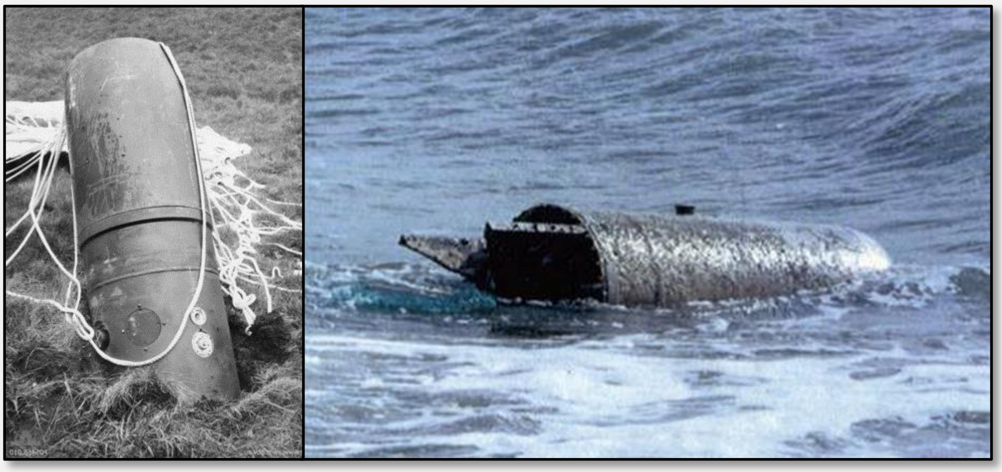
Other variants of moored mines, but used in much less numbers, were the Antenna Mine, an anti-submarine contact mine that used the current generated by two dissimilar metals rubbing together to fire, and the Magnetic mine, an "influence" mine that was actuated by the small electro-magnetic current generated when a target vessel's moving magnetic field cut the mine's internal coiled rod sensor or influenced the dip needle mechanism as, for example, in the German aluminium SMA (GO) buoyant mine shown below.

Ground Mines

Although they were in existence towards the end of WWI, ground mines were neither very effective nor common at that time. However, from 1939 onwards, both British and German influence ground mine technology advanced rapidly.

The influence Ground Mine, as its name suggests, is designed to lay on the seabed. It can be laid by surface vessel, submarine or aircraft and it is most commonly cylindrical in shape. It has a single or a combination of magnetic, acoustic and pressure sensors to detect the influence "signature" of passing target vessels. To be close enough to create sufficient damage to its target, a ground mine must be laid in relatively shallow water; generally not more than 70m but more usually around 30m or less. For the same reason, and because the mine does not have to float, the size of the main charge is considerably bigger than in a buoyant mine, typically 300kg - 750kg. Both Germany and Britain had versions that could be fitted with direct impact bomb fuses in addition to magnetic and acoustic firing circuits. Later in WWII, the German's developed the "Oyster" mine; this had a pressure sensor that was either fitted in combination with an acoustic or magnetic sensor circuit.

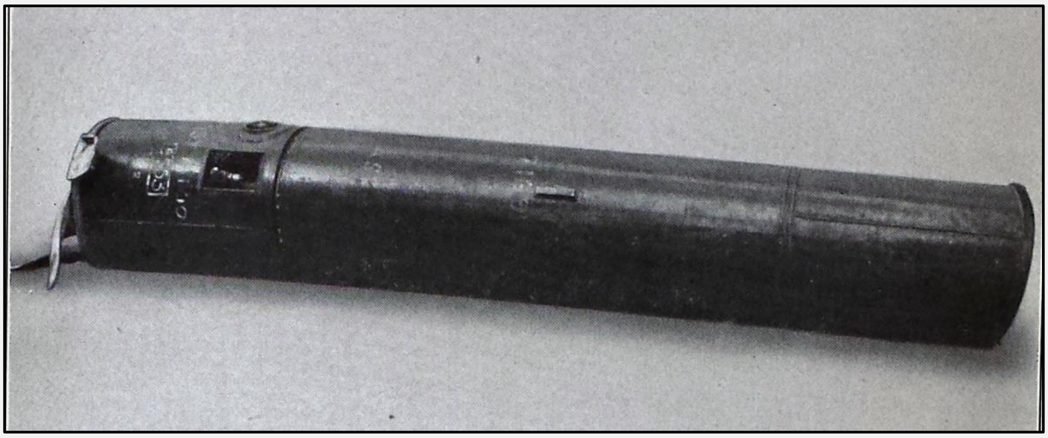
WWII German ground mines were made of aluminium with reliable *Rheinmetal* fuses and superbly engineered and consequently are frequently found in excellent condition after decades in the water. These German air dropped "parachute" mines are likely to be found intact and could probably function as designed if sufficient battery power was available. However, their batteries will now have discharged. Many variants were fitted with booby traps and anti-disturbance devices; some of these relied on battery power, some employed mechanical inertia designed to operate on impact, some had clockwork delay mechanisms and others relied on human intervention; all could be in a very sensitive condition and could function if disturbed.



German WWII GC (LMB) mine used both as sea mine and blast bomb

The LMB mine casing is made of aluminium and its ferrous content depends on the sensors fitted but is commonly limited to the dip needle sensor arrangement, which contains magnets, and a few other small ferrous components, mainly within the mechanism section. The BM1000 casing is made of manganese steel and presents a very low magnetic target. The ferrous content of a BM1000 is similar to that of a LMB mine. The

LMB casing is 1.74m long (without any additional fittings) and has a diameter of 0.66m. The overall weight is 988kg (NEQ is 698kg Hexanite). The BM1000 casing is 1.52m long and the diameter 0.66m. The overall weight is 986kg (NEQ is 727kg Hexanite).



British AMIII ground mine

British ground mine casings were generally made of steel and subject to corrosion over time unless they became buried in hypoxic sediment. The mines relied on batteries to power sensors and firing circuit; these will now be discharged and the mine will not function as designed. Charge weights were between 227kg-499kg, except for two specialist mines that had much smaller net explosive quantities (NEQs) of 45kg and 91kg. The British continued to develop ground mines throughout WWII, starting with A Mks I-IV in the early years, finally progressing to the A Mk IX by 1945. The AMks I-IV, which outwardly looked very similar, were the most common mine used by the British for offensive operations.

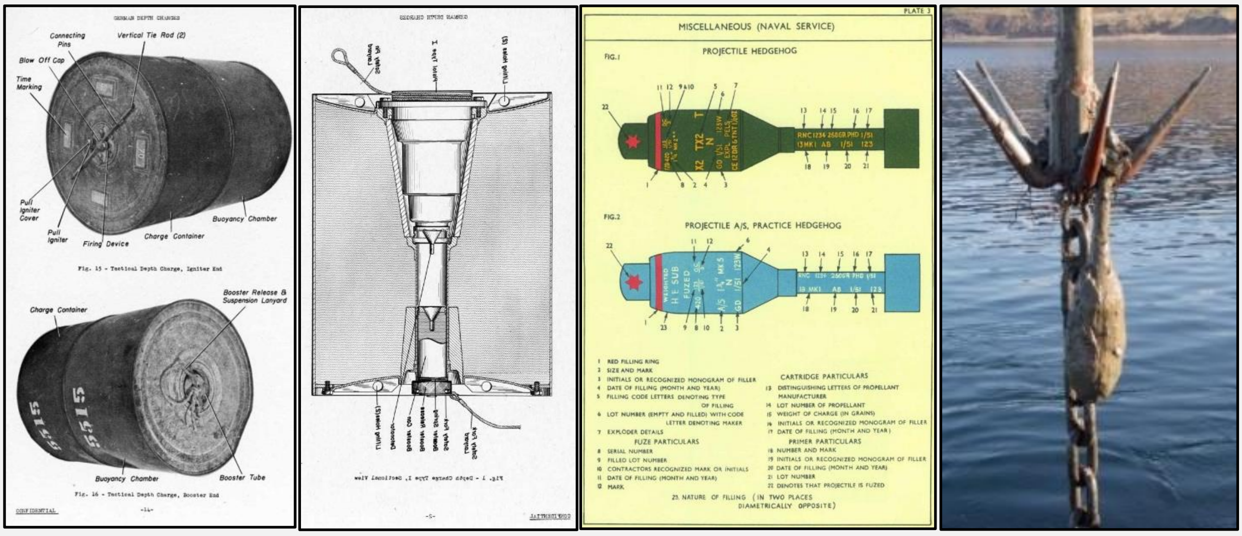
Naval and Artillery Projectiles

Most projectiles encountered in the study area likely to be relatively small calibre shells with an NEQ in the region of 2kg-5kg but larger WWI projectiles could be encountered and these have a slightly larger NEQ – up to 25kg of Picric acid based explosives, such as Shellite. Over time this explosive filling can react with the metal of the shell casing and create sensitive crystals of metal picrates, such as iron picrate. These are extremely sensitive, particularly if they are allowed to dry out and could easily be caused to detonate with sufficient power to initiate the main bursting charge. However, on balance, the risk they pose to Project activities is small. The hazard may reduce when the shells become corroded enough to admit seawater as these materials are water soluble.

An artillery projectile in typical condition on the seabed

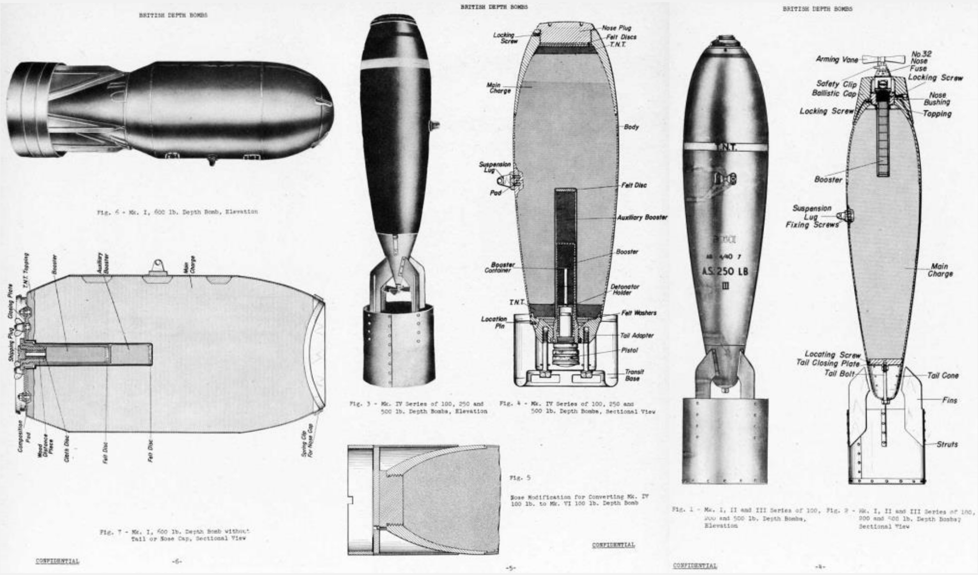
Depth Charges/Depth Bombs

A number of different types of depth charges and depth bombs could have been used to attack submarines, with an NEQ in the range of 50kg-200kg. They would have been caused to detonate by a hydrostatic pistol releasing a cocked striker or perhaps an impact bomb fuse with a delay.



Examples of German Depth Charge (L) and British Anti-Submarine "Hedgehog"

As anti-submarine "blast" weapons, all are thin-cased and consequently subject to severe corrosion in the intervening years, unless deeply buried in hypoxic sediment. Consequently, the firing mechanism is highly unlikely to operate as designed. Nevertheless, the firing train will very probably be complete (i.e. the detonator is in intimate contact with the primer and main charge) and this type of EO could present a significant UXO risk, given the relatively large NEQ. A depth charge could still detonate, for example, if crushed by the leg of a jack-up barge.



British Anti-Submarine Depth Bombs: L-R Mk I 600lb, Mk IV Series, Mk I-III Series

Torpedoes

Any torpedoes present within study area are likely to be of the “wet heater” or “burner cycle” types. During both WWI and WWII, the Germans developed torpedoes of the “wet heater” type; steam driven, with kerosene as fuel and compressed air providing oxygen for combustion. Warheads of around 250kg were detonated by means of a direct impact or magnetic fuse. WWI torpedo fusing was often unreliable and it is quite possible that attacks took place, unrecorded, when the torpedo failed to function and sank to the seabed. German WWII warheads were filled with 280kg of Hexanite and were generally much more reliable. In WWII, the Germans also developed an effective series of battery-driven torpedoes with similar sized warheads.

The standard British airborne torpedo for World War II was the 18-inch, a 450 mm-diameter design that progressed through several Marks through the war. It had an explosive charge of 388 lb (176 kg) of TNT. Later, more powerful versions had a 247kg Torpex warhead. As well as submarines, most ships of any size were fitted with torpedo launchers. The main British 21in heavyweight torpedo in use during WWII was the “improved” Mk VIII. It was used on ships, submarines and motor torpedo boats from 1927 and was the first British burner-cycle design torpedo. Depending on the variant, the warhead consisted of 325kg – 365kg Torpex.

Typical examples of heavyweight (21in/53cm) torpedoes

Annex B

Explosive Ordnance Technical Data

EXPLOSIVE ORDNANCE TECHNICAL DATA

MILITARY DESIGNATION	NATIONALITY	SHAPE	TYPE	FEATURES	NEQ	DIMENSIONS
			MINES			
GD (LMA)	German	Cylindrical	Ground Influence	Air Dropped with parachute/ also Surface Vessel	300kg	Diameter 66cm Length 2.0m (depending on configuration)
GC (LMB)	German	Cylindrical	Ground Influence	Air Dropped with parachute/ also Surface Vessel	700kg	Diameter 66cm Length 3.0m (depending on configuration)
GG (BM1000)	German	Cylindrical	Ground Influence	Air Dropped with parachute/ also Surface Vessel	730kg	Diameter 66cm Length 3.2m (depending on configuration)
TMC (GN)	German	Cylindrical	Ground Influence	Laid by submarine	907kg	Diameter 53.3cm Length 3.36m
EMA and EMB (GU)	German	Ovoid	Moored Contact	Equipped with five Hz Horns. Deployed with base mooring unit. Surface or submarine laid.	163kg or 220kg	Both had similar casing 1.17 m long x 0.863 m in diameter
EMC (GY, GV*)	German	Spherical	Moored Contact	Equipped with seven Hz Horns. Deployed with base mooring unit. Surface laid.	300kg	1.2 m in diameter
EMF (GO)	German	Spherical	Moored Influence	Magnetic influence mine, particularly sensitive in rough sea.	340kg	1.16 m in diameter 1.42m length
UMA (GZ)	German	Spherical	Moored Contact	Five Hz and three switch horns.	30kg	0.81 m in diameter
UMB (GR)	German	Spherical	Moored Contact	Improved moored contact mine with five Hz and three switch horns.	41kg	0.84 m in diameter
A Mk 1 – 4	British	Cylindrical	Ground Influence	Air Dropped with parachute	340-352kg	Diameter 45 cm Length 2.87 m

MILITARY DESIGNATION	NATIONALITY	SHAPE	TYPE	FEATURES	NEQ	DIMENSIONS
A Mk 5	British	Cylindrical	Ground Influence	Air Dropped with parachute	284-306kg	Diameter 40 cm Length 2.057 m
A Mk 6	British	Cylindrical	Ground Influence	Air Dropped with parachute	431kg	Diameter 49.4 cm Length 2.565 m
A Mk 7	British	Cylindrical	Ground Influence	Air Dropped with parachute	281kg	Diameter 42.6 cm Length 2.108 m
A Mk 8	British	Cylindrical	Ground Influence	Air Dropped with parachute	89kg	Diameter 34.3 cm Length 1.448 m
A Mk 9	British	Cylindrical	Ground Influence	Air Dropped with parachute	499kg	Diameter 9.4 cm Length 2.59 m
Naval Spherical Mk III (Service)	British	Spherical	Moored Impact Inertia	Unreliable mine used in the early years of WWI	113kg (wet gun cotton)	~0.8 m diameter
H2	British	Spherical	Moored Contact	5 Herz horns	320lbs (145kg) Amatol	0.97m diameter
Mk XIV	British	Ovoid	Moored Contact	Equipped with 11 mainly Hertz Horns. Used in both WWI and WII.	145kg or 227kg	1.02 m in diameter
Mk XV	British	Ovoid	Moored Contact	Equipped with 11 mainly Hertz Horns. Used in both WWI and WWII.	145kg or 227kg	1.02 m in diameter
Mk XVII	British	Ovoid	Moored Contact	Equipped with 11 switch Horns. Used in WWII.	145kg	1.02 m in diameter
TORPEDOES						
G7a Naval Torpedo (multiple combinations of warhead and fusing)	German	Cylindrical	Impact or Magnetic	Some fitted with Whiskers, Wet Heater propulsion	235kg-295kg	21 inch diameter (533 mm) Length 7.162 m

MILITARY DESIGNATION	NATIONALITY	SHAPE	TYPE	FEATURES	NEQ	DIMENSIONS
G7e	German	Cylindrical	Impact or Magnetic	Electric	280kg	21 inch diameter (533 mm) Length 7.186 m
Luftwaffe Torpedo (F5)	German	Cylindrical	Impact or Magnetic	Wet Heater	200kg	45 cm diameter Length 4.8 m – 5.16 m
Torpedo Mk VIII	British	Cylindrical	Impact or Magnetic	Air/Steam powered	340kg or 365kg	21 inch (533 mm) diameter Length 6.579 m
Torpedo Mk XII	British	Cylindrical	Impact	Air/steam powered	176kg	45 cm diameter Length 4.95 m
DEPTH CHARGES						
DC Type I	German	Cylindrical	Hydrostatic Pistol (cocked striker)	Preset depth set by hand. 5 pistol types	136kg	44.5 cm diameter Length 57.0cm
Mk7 Series	British	Cylindrical	Hydrostatic Pistol (cocked striker)	Preset depth set by hand. 3 versions, depending on depth range	147kg	44.4 cm diameter Length 70.2cm
Mk11	British	Cylindrical	Hydrostatic Pistol (cocked striker)	Dropped by aircraft. Length with tail 1.39m	82kg	27.9 cm diameter Length 94.4cm
BOMBS						
250lb GP Bomb	British	Streamlined sides with ogival nose	Impact/delay	Tail or Nose pistol or fuse	~50kg	Diameter 26 cm Body Length 0.72 m
500lb MC Bomb	British	Parallel sides with ogival nose	Impact/delay	Tail or Nose pistol or fuse	95kg, 100kg, 105kg	Diameter 32.7cm Body Length 1.041 m
1000lb MC Bomb	British	Parallel sides with ogival nose	Impact/delay	Tail or Nose pistol or fuse	215kg, 226kg, 238kg	Diameter 45 cm Body Length 1.33 m

MILITARY DESIGNATION	NATIONALITY	SHAPE	TYPE	FEATURES	NEQ	DIMENSIONS
12000lb HC bomb	British	Parallel sides with convex nose	Impact/ Delay	3 nose pistols, sectional construction (each section ~1.23m	5425 kg	Diameter 0.97m Body Length 3.7m
500lb MC	US	Parallel sides with ogival nose	Impact/delay	Tail or Nose pistol or fuse	126kg	Diameter 0.36 m Body length 1.2 m
1000lb MC	US	Parallel sides with ogival nose	Impact/delay	Tail or Nose pistol or fuse	260kg	Diameter 0.48 m Body length 1.37 m
2000lb MC	US	Parallel sides with ogival nose	Impact/delay	Tail or Nose pistol or fuse	525kg	Diameter 59.2 cm Body Length 1.824 m
50kg SC	German	Parallel sides with ogival nose	Impact/delay	Transverse fusing	25kg	Diameter 0.20m Body length ~0.67 m
250kg SC	German	Parallel sides with ogival nose	Impact/delay	Transverse fusing	130kg/145kg	Diameter 0.368 m Body length 1.2 m
500kg SC	German	Parallel sides with ogival nose	Impact/delay	Transverse fusing	220kg	Diameter 0.46 m Body length 1.45 m

Annex C

Explosive Ordnance Detonation Mechanisms and Effects

EXPLOSIVE ORDNANCE DETONATION MECHANISMS AND EFFECTS

Potential Detonation Mechanisms

Air Dropped Bombs

Statistics compiled after the war showed that approximately 8.5% of the bombs dropped failed to explode. Subsequent Home Office analysis came up with figure of between 9%-11%. The reasons for failure were several, the main ones were:

Not armed correctly on release from the aircraft

- Deliberately dropped “safe” (if being jettisoned)
- Failure/jamming of a clockwork delay mechanism
- Impact fuse malfunction on striking the ground
- Failure of the detonator or gaine (booster)

Today, in the marine environment, pistols and fuses are likely to be corroded and unlikely to function as intended, although they may be in a sensitive state through the exudation of sensitive salts (this is much less likely underwater than on land). However, a blow with sufficient kinetic energy directly onto a fuse or fuse pocket could be enough to detonate the EO. Small bombs could be lifted inadvertently in the flukes of an anchor; this is unlikely in itself to cause the UXO to detonate but if allowed to dry out, it may become much more sensitive to knocks and friction. Most bombs are relatively thick-cased and therefore not easy to crush; they are more likely to be pushed further into the sediment or moved aside.

Incendiary bombs containing phosphorous pose a particular danger in certain scenarios. If exposed to the air, phosphorous will spontaneously ignite and, while not detonating, will burn fiercely, thereby presenting a threat to exposed personnel and inflammable equipment.

Buoyant Mines

Today, if encountered both WWI and WWII buoyant mines will be found situated on the seabed, often partially buried in the sediment. The mine casings will be heavily corroded. Chemical (Hertz) horns may still be capable of functioning but internal wiring and firing mechanisms are unlikely to be effective. Switch horn mines require power from an internal battery and these will no longer function. The explosive filling is likely to be stable if undisturbed but the mine may still detonate if appropriate criteria are met. If wiring is intact on Hertz horn variants, crushing or deforming the horn could trigger the mine. Charge weights are between 145 - 227kg.

British Ground Mines

WWII British ground mines were made of steel. If encountered, they could be partially or completely buried. Significant corrosion to the casing may have taken place, depending on the depth of burial. Internal batteries, required to power internal influence sensors and the firing mechanism, will have discharged. These mines will not function as intended but have a large charge weight (300kg - 450kg) that could still detonate if the right conditions are met. The detonator is placed in line with the booster by hydrostatic pressure. Once the correct depth of water is reached the detonator is locked into place and cannot easily be withdrawn. It is not possible to see on a cursory external visual inspection (e.g. by diver or ROV) whether the mine is armed or not. It must be assumed that the mine is fully armed and the firing train is complete.

German Ground Mines

WWII German ground mines were very well engineered, with casings of corrosion-resistant aluminium or manganese steel and fuses made by Rheinmetal. They are very liable to be found intact and in excellent condition. The mines could still function as designed if sufficient battery power was available. However, the batteries will have discharged. Many variants were fitted with booby traps and anti-disturbance devices. Charge weights are likely to be in the region of 700kg of HE. Common German ground mine variants, GC & GD, are relatively thin-cased and therefore susceptible to crushing.

Projectiles

HE Naval and artillery projectiles typically will be around 5kg NEQ, but less than 50kg, and consequently present minimal threat to vessels and equipment. Any fusing will be corroded and unlikely to function as designed. However, as relatively small items, they could become wedged in the flukes of an anchor and be brought to the surface, presenting a blast and fragmentation hazard to exposed deck-hands. WWI projectiles were filled with Picric Acid, and derivatives that could be in an extremely sensitive state, particularly if allowed to dry out.

Torpedoes and Depth Charges

As with most UXO, torpedo warheads are liable to be stable if undisturbed but remain a potential hazard, particularly if after launch from the torpedo tube, safety détentes have been removed and the firing train is complete; that is, the detonator is married to the booster and main charge within the warhead. Any depth charges encountered, unless they have been completely buried in hypoxic sediment, are likely to be severely corroded and decomposed to the point of presenting minimal hazard. The firing mechanism is highly unlikely to operate as designed. Nevertheless, the firing train will very probably be complete (i.e. the detonator is in intimate contact with the primer and main charge) and this type of EO could present a significant UXO risk, given the relatively large NEQ. A depth charge could still detonate, for example, if crushed by the leg of a jack-up barge or a vessel grounding.

Land Service Ammunition

A mortar relies on a striker hitting a detonator for detonation to occur. If a mortar failed to function as designed, it is possible that the striker may already be in contact with the detonator and that only a slight increase in pressure would be required for initiation. Similarly, a grenade striker may either be in contact with the detonator or still be retained by a spring under tension and therefore shock may cause it to function. In addition to HE, these items of LSA may be filled with "pyrotechnics" which come in a variety of flares and smoke generating compounds and can include magnesium, thermite and phosphorus.

Small Arms Ammunition

Small arms ammunition (SAA), even if it functioned, is not contained within a barrel and consequently detonation would only result in local overpressure and very minor fragmentation from the cartridge case. SAA cartridges are frequently discovered in military practice areas. These are likely to have been dropped inadvertently during training or deliberately discarded by soldiers. Although technically explosive ordnance, they pose little risk unless they are caused to function by a deliberate act. Moreover it is illegal for an unlicensed person to be in possession of SAA, therefore all finds no matter how minor should be reported in accordance to the appropriate procedure.

Practice Munitions

Most modern practice munitions are painted light blue and/or have fluorescent orange markings. Older practice weapons were often painted white. Generally these are inert but may have small smoke and flash components, which could present a small hazard to personnel close by if these have not been expended. Many practice bombs are readily distinguished as "practice" by their shape and size. However, most practice ordnance items use the same casings, filled with inert material, as the HE versions. Older practice ordnance that has been immersed in sea water for some time will not easily be distinguished from the live, HE-filled, version, even by an EOD expert. If encountered, usually these items will have to be treated as if live.

Potential Detonation Effects

General

It is important to consider the baseline UXO hazards to the OWF site prior to any works and before any mitigative measures being implemented. Generic information about the potential causes of inadvertent detonation and typical mechanisms and causes of damage and injury are provided. This is then tailored to the specific activities associated with the Project to permit a detailed risk assessment and recommendations for mitigation to be formulated.

The risk that UXO poses to a Project activity is the product of three key elements:

- The likelihood of encountering an item of ordnance.
- *If* that encounter happens, the likelihood of the UXO detonating.
- *If* the UXO detonates, the severity of the consequence to vulnerable receptors (people and equipment).

Likelihood of Encounter

Likelihood of encounter, the first element, is a function of the density of UXO items and the total area of intrusive engineering interaction of as a proportion of the total area of the site (to be accurate: by volume to the maximum intrusive depth). It is rarely possible to know precisely how many items of UXO are potentially present within the site boundary (if any) but we make a judgement call based on the results of our historical search, our experience and our knowledge of the types of project activities to be undertaken.

The factors to consider for the study area in relation to each other are:

- Likelihood of UXO burial
- Likely density of UXO by type
- Areas covered
- Project activities
    - Intrusive (deep)

    - Intrusive (shallow)
    - Non-intrusive

Ordtek has assumed that cables will typically be installed to ~1.0m-1.5m below bed level and that dredging may take place to reduce the height of sand waves and to level out the cable path.

Given the military history of the region, the potential for UXO contamination of the study area is judged to be low overall.

The Likelihood of Encounter is only one factor of the risk calculation and a relatively high Likelihood of encounter of a particular UXO type does not necessarily mean that the overall risk to all Project activities will necessarily also to be high.

Types of Encounter

How a piece of equipment interacts with an item of UXO will determine whether a detonation is initiated and the main types of encounter and detonation mechanisms are discussed below. However, it is also important to consider what might be considered "primary" and "secondary" encounters.

When calculating the risk and potential consequences of an inadvertent detonation of an item of UXO to equipment, a vessel or a crew within a vessel, the primary (or initial) interaction is usually the one considered – i.e. the crushing effect of a jack-up barge leg; the kinetic blow of a dredger bucket; the disturbance caused by a cable plough; the whiplash to a vessel caused by the "bubble pulse" from an underwater detonation etc.

When considering potential consequences to people or soft-skinned equipment working on the deck of a vessel, or similar situation, "secondary" encounters are also important. For example, it is common during pre-lay jetting during cable burial to fit a "debris hook" to the vertical injector head. There is the potential for small items of UXO – projectiles, small bombs, rocket heads etc. – to be snagged by the flukes of the hook and brought to the surface. A similar situation can occur during a pre-lay grapnel run (PLGR) operation. The "primary" encounter of debris hook and UXO item is unlikely to cause a detonation and, if it did, the consequence to the equipment would probably be minimal. However, a "secondary" encounter incident, where the UXO dropped from the debris hook onto the deck of a vessel and then detonated could have devastating consequences for unprotected personnel.

The possibility for secondary encounters must be allowed for when developing procedural mitigation measures.

Likelihood of UXO Detonation

Factors Affecting Likelihood of Detonation

The second element, *Likelihood of the UXO detonation*, we cannot know with any accuracy: most UXO that has been in the ground for a long time is relatively stable, even if subjected to unintended vigorous stimuli but, if the explosive ordnance is for any number of reasons particularly sensitive, or it is hit hard or crushed, it could detonate. However, the risk of detonation can be reduced by the adoption of certain mitigation measures, considered later in this report.

The factors, among others, that will affect the UXO's susceptibility to inadvertent detonation are:

- Condition and type of UXO
    - Sensitivity to impact (kinetic energy)
    - Sensitivity to crushing
    - Sensitivity to friction, heat, static electricity
    - Sensitivity to movement and vibration

        - Cocked strikers
        - Clockwork fuzes re-starting
        - Highly sensitive metallic salts within fuze pockets etc.
    - Sensitivity to sympathetic detonation
        - Burial depth
        - Orientation
        - Proximity to donor charge / energy source (e.g. plough)
- Type of Interaction
    - Kinetic blow, crushing, vibration etc. as above

Before a weapon can detonate, a sequence of events must happen, called the Explosive Train (also known as the Firing Train), which starts with the removal of any safety measures and culminates in the detonation of the main charge of high explosive.

The accidental detonation of an item of UXO that has lain undisturbed on the seabed for several decades is a rare event, even when subjected to quite a heavy shock such as being struck by heavy equipment or dragged by a ship’s anchor.

Most HE weapons have four principal components: a fuze (the part of the weapon that initiates function), a safety and arming mechanism/unit (often contained within the fuze), a detonator and a main charge. Additionally, most EO has a booster charge (also variously known as the primer or gaine) between the detonator and the main filling, to give the detonation shock wave from the initiating detonator sufficient energy to ensure the weapon’s complete detonation.

The detonator is filled with a Primary Explosive, such as Lead Azide, which is extremely sensitive to stimuli such as impact, friction, heat or static electricity and a relatively small amount of energy is required for its initiation. The detonator’s purpose is to trigger the primer and, subsequently, the larger main charge. This is made of much less sensitive Secondary Explosive and requires substantially more energy to be initiated but is relatively safe to store and transport. The safety and arming system ensures that the detonator and main charge remain separated and the firing chain broken until the weapon is clear of its carrier/launcher and is in a position to function as designed.

Although it may not actually be the case, when UXO is encountered, it must always be assumed that the explosive train is intact: that is, all safety measures have been removed and the detonator is in contact with the main charge.

Nevertheless, the main filling is inherently stable and such a detonation is a rare event, even when UXO has been subjected to robust handling, for example when a bomb is caught up in a dredger head or ship’s anchor. Most UXO – particularly EO that has lain on the seabed for several decades – will have been the subject of significant corrosion to its casing and to any mechanical moving parts. It is extremely rare for UXO found on the seabed to function as intended; detonation will almost always be the result of unusual and vigorous kinetic stimuli.

Detonation Mechanisms

From the previous paragraphs it can be seen that for a detonation to occur, the UXO must be in a sensitive state and a certain set of conditions satisfied. It is evident from the many items of UXO that are recovered from building sites, farmers' fields, anchor flukes, fishing nets and dredger suction heads every year that these conditions are hardly ever met and an accidental detonation is unusual.

The potential for UXO to be initiated if encountered during project operations will depend on its condition and the energy with which it is struck or moved, or if it is subjected to crushing, friction, static electricity or excessive heat. The movement of vessels and implementation of non-intrusive surveys will not result in the initiation of ordnance through influence alone.

The UXO could be caused to detonate several ways: if the detonator is struck accidentally with sufficient force or is subjected to heat, static charge, friction or crushing; if a fuze containing a temporarily jammed cocked striker is jarred and the striker is released; similarly if a seized clockwork mechanism restarts; or if the sensitive iron picrates associated with a picric acid filled munitions are subjected to friction, heat or are knocked, particularly if they have been allowed to dry out. In addition to the danger of iron picrates, some other HE can exude metallic azides and salts that, once they dry out, are extremely sensitive. These salts are often hidden within fuze pockets and not readily seen.

The main mechanisms that have the potential to cause unintended detonation of an item of UXO are:

- Crushing of the casing, imparting energy to the EO's detonator leading to its detonation (the main filling is unlikely to be initiated independently).
- A blow with sufficient energy by heavy equipment or, perhaps, a rock against a sensitive fuze pocket or exposed detonator.
- Sympathetic detonation caused by another item of UXO sufficiently close by or by a shock wave with sufficient energy imparted by an activity such as percussive piling.
- Vibration, blow or friction sufficient to initiate sensitive metallic salts, leading to detonation of the main filling.

Small items of UXO, such as AA, naval and artillery projectiles and small air-dropped bombs are relatively thick-cased and are considerably more likely to be pushed into the soft sediment of the seabed than crushed (this is obviously not true for outcrops of rock where the sediment is very thin and the underlying surface is hard). Other than in unusual circumstances on hard rock, the probability of a detonation via this mechanism for these types of EO is low.

Larger naval weapons, such as depth charges, sunken buoyant mines and ground mines have thinner cases and are therefore more likely to be susceptible to crushing.

In all but the most unusual circumstances, for a high order detonation initiated by the detonator to occur, the EO needs to have been armed; i.e. the detonator is in intimate contact with the primer and main charge.

The following are typical activities that may cause inadvertent UXO detonation during offshore developments.

- Jack-Up barge leg deployment – crushing.
- Percussive piling (monopile installation) – sympathetic detonation, vibration, kinetic blow.
- Rock dumping/Concrete mattress installation – crushing, high kinetic energy blow.
- Borehole/Horizontal drilling – high kinetic energy blow, vibration (in contact with sensitive UXO).
- Anchor deployment – crushing, blow.
- PLGR – dragging (with UXO striking hard object on seabed, e.g. boulder).

- Cable Plough – crushing (unlikely but possible).
- Cable jetting – disturbance of a sensitive item of UXO.
- Cable surface lay-down – disturbance of sensitive item of UXO.

Friction and heat are much less likely to cause a detonation underwater than impact or movement. However, it is possible for a small item to become wedged in the flukes of an anchor, or other equipment, and be raised to the surface. In such an event, if the UXO was then subsequently allowed to dry out, sensitive salts (picrates and metallic azides) that had exuded through fuze pockets or corroded shell casing could be very sensitive to heat and friction.

In all cases, encounter and interaction with the UXO must occur first.

Effects and Consequences of UXO Detonation

Overview

Severity of consequence of detonation, the third element of the risk calculation, is a multifaceted issue depending on a wide range of variables – sensitivity of receptor (e.g. robustness of the vessel/equipment) and protection (are deck crew below the water line, on deck, under hard cover etc.), range from UXO, type of weapon (casing, filling type, charge weight, orientation), depth of water, depth of burial, sediment/ground consistency etc. Quantifying the precise damage that may occur to a vessel or equipment from a specific item of UXO will depend on how its construction reacts to the shock and impulse generated. *Ordtek* can therefore only offer generic advice. The equipment manufacturer and naval architects are best placed to make this calculation.

Effects of Detonation Underwater

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. 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 structures and vessels is shock transmitted through the seabed and water column.

Shock

The principal effect that causes damage to vessels and structures in the far field is shock transmitted through the water column and the seabed (ground). 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 structure, 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 it 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.

There is very little literature that covers the seismic damage to buried structures from a detonation of explosive ordnance underwater, situated on the seabed. 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 (P_{max}) and Impulse (I) (momentum) experienced by a receptor (vulnerable structure) at distance R from a charge W can calculated using Coles' equations, which for TNT are:

$$P_{max} = 52.4\ (W^{1/3}/R)^{1.13} \quad \text{MPa}$$

$$I = 5.75.\ W^{1/3}(W^{1/3}/R)^{0.89} \quad \text{MPa-ms}$$

Examples of calculated Peak Pressure values for various typical UXO at representative ranges are shown at in Section 8.4.5

Seismic Shock

The peak pressure experienced by a buried structure (e.g. a cable) will depend principally on the range from the UXO, the sediment type, whether the UXO is on the surface of the seabed, partially or wholly buried and the charge weight.

Quantifying the shock experienced by a buried receptor is difficult: there are a great many variables. Seismic shock propagation in earth media is a complex function of the dynamic constituent properties of the sediment, the explosive products and the geometry of the explosion. No single sediment index or combination of indices can adequately describe the process in a simple way for all cases. In particular, whether the sediment is unconsolidated or consolidated makes a significant difference to both the speed of propagation and attenuation rate of the seismic wave. The attenuation rate has been found to be greater in the latter (we have assumed that the cable is buried in unconsolidated sediment, in this case sand).

The optimum depth of water for maximum efficiency of energy transfer from the medium of water into the sediment is calculated as:

$$d=38.41*W^{2/11}$$

Some of the energy of detonation will also be expended in the formation of a crater and the ejection of seabed material from it and on detonation. Energy is lost across the boundary of the two mediums, water and sediment. Taking all these losses into consideration, energy transfer into the sediment from a detonation of a UXO item on the seabed is usually, at most, around 50%-60% of the initial energy generated by the detonation and therefore it is the distance of the receptor from the UXO through the water column that is the dominant consideration.

Shock Factor

The most widely used parameter for describing shock severity is the shock factor value. Normally applied to vessels, this value is a shock input severity parameter that is a function of charge weight and charge distance (stand-off from a receptor). A small explosive charge close to a receptor can give the same SF as a larger one further away, although the pressure characteristic and damage mechanism may be different. Shock damage to the hull area of a vessel can vary quite appreciably, depending on the charge size, orientation and proximity to the hull. If the charge is located directly or almost directly underneath and/or close to a vessel, the bubble collapse onto the ship's hull and the whipping caused by the bubble pulse will contribute to the damage.

In simple terms, the larger the UXO charge weight and the closer it is to any given structure, vessel, equipment or person, the more damage it may cause. A deep draft vessel is at more risk of damage than a shallow draft one operating in the same depth of water. A vessel is more at risk at Low Water than at High Water. The formula used to calculate the HSF is based on simple spherical spreading of the shock wave and is:

$$\text{HSF} = \frac{\sqrt{C}}{R}$$

where C is the charge weight equivalent in Kg of TNT and R is the distance to the nearest point of the receptor. When the charge is on the seabed and measured relative to the keel of a ship on the water's surface, the angle of incidence of the shock wave with respect to the vessel is also taken into account, the calculated value is referred to as the Keel Shock Factor (KSF) or sometimes "Q" or just the Shock Factor (SF).

In this case,

$$\text{KSF} = \frac{\sqrt{C}}{R} \cdot \frac{(\text{Sin}\ \Theta + 1)}{2}$$

In the hypothetical case that a receptor on the seabed (such as a cable or pipeline), rather than a vessel, is subject to the effects of a HE detonation, Sin ϴ will tend to zero and, in theory, the SF received by the cable will be =

$$\frac{\sqrt{C}}{2R}$$

However, we have found no experimental or wartime empirical data to support this assumption and it should be applied with great caution.

Table 8.1, below, shows typical vessel damage symptoms for SF values, taken from the US Navy Salvage Engineer's handbook. The representative damage shown can only be indicative and must be treated with a great deal of caution: the construction of civilian vessels varies considerably and, in deeper water, the bubble pulse must also be taken into account. The SF values, which were originally calculated in imperial values, have been converted by *Ordtek* to metric.

SF (√kg/m)	Typical Damage
<0.22	Minor damage (defects to fuzes, destruction of light bulbs/luminescent tubes and the like.
0.22 to 0.33	Damage to piping with leaks, possibly individual pipe ruptures, damage to fuzes, lamps, electronic failures and the like.
0.33 to 0.44	Increase in the above described damage symptoms, piping ruptures and misalignment of machinery on its base likely.
>0.44	Serious damage to ship, general machinery damage
>1.1	Typically total loss of ship.

Shock factors with typical damage symptoms (taken from US Navy Salvage Engineers' Handbook, converted by Ordtek for kg/m)

Representative Hull Shock Factor at Varying Water Depths

Table 8.2 shows typical representative calculations for various UXO for Hull Shock Factor and possible damage for a vessel at varying water depths from the detonation where the UXO is situated on the surface of the seabed.

UXO Type	~NEQ	Water Depth					
		15m	30m	50m	70m	100m	130m
LMB (GC)	700kg	0.84	0.42	0.25	0.18	0.13	0.10
Torpedo	300kg	0.52	0.26	0.16	0.11	0.08	0.06
1000kg Bomb	500kg	0.67	0.34	0.20	0.14	0.10	0.08
250kg Bomb	120kg	0.33	0.17	0.10	0.07	0.05	0.04
250lb Bomb	55kg	0.22	0.11	0.07	0.05	0.03	0.03
100lb Bomb	25kg	0.15	0.08	0.05	0.03	0.02	0.02
5in Shell	5Kg	0.07	0.03	0.02	0.01	0.01	0.01

Table 8.2 – Representative calculations for Hull Shock Factor at varying depths of water

Table 8.3 shows typical representative calculations for various UXO for Peak Pressure, Keel Shock Factor and Minimum Safe Distance for a vessel at 50m and 200m range from the detonation and where the UXO is situated on the surface of the seabed in 15m depth of water.

Representative Peak Pressure and Shock Factor Values for typical UXO at 50m and 200m range, 15m depth								
UXO Type	~NEQ	Peak Pressure (MPa)		Keel Shock Factor (“Q”)		Possible Damage	Possible Damage	Minimum Safety Distance (m)
		50m	200m	50m	200m	50m	200m	12√C
LMB (GC)	700kg	6.82	1.33	0.33	0.07	Moderate	Negligible	320
Torpedo	300kg	4.88	0.95	0.21	0.05	Minor	Negligible	210
1000kg Bomb	500kg	5.97	1.16	0.28	0.06	Moderate	Negligible	270
250kg Bomb	120kg	3.40	0.66	0.14	0.03	Minor	No damage	130
250lb Bomb	55kg	2.50	0.49	0.09	0.02	Negligible	No damage	90
100lb Bomb	25kg	1.83	0.35	0.06	0.01	Negligible	No damage	60
5in Shell	5Kg	0.97	0.19	0.02	0.01	No damage	No damage	25

Table 8.2 – Representative calculations for Peak Pressure, Shock Factor and Minimum Safe Distance at 50m and 200m in 15m depth of water

The calculations above have shown what the effects might be to vessels should UXO detonate. However, while this is based upon a quantifiable approach, there are some assumptions and variables that have been made (and does not consider effects on equipment on the seabed). Therefore, while the calculation suggests “minor damage” would occur in some scenarios, in accordance with the ALARP principle it is not considered tolerable to accept a potential hazardous scenario if it could be reasonably avoided.

Effects above Water

Above water, the blast effect is relatively short range and decays rapidly. 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 receptor will not be affected by the pressure wave if it is out of line of sight. This is also true for the shrapnel that will be simultaneously ejected outwards with very high kinetic energy from heavier cased items.

In air, fragmentation (shrapnel), together with secondary products such as gravel etc., can be thrown considerable distances. Typically this is 1-2 km or more for medium sized bombs and projectiles. Isolated heavy fragments such as fusing components, lugs and baseplates etc. of large bombs and mines have the potential to travel in excess of 3km. For UXO underwater, the kinetic energy the fragmenting case receives from the HE charge is attenuated by the water and the distance it will be thrown once it reaches the surface is proportional to the depth underwater. As described earlier, fragmentation can generally be ignored for all but the largest UXO in water depths > 10 m.

Both blast and shrapnel will be mitigated substantially if the UXO is buried (for the purpose of entering safety tables, “buried” means covered by >2.5 x the EO length. However, the seismic shock created can cause significant damage to unprotected and vulnerable subsurface infrastructure such as pipelines. As a rule, cables are much less vulnerable. On land, a 1000lb bomb, detonating fully buried (i.e. deeper than 2.5 times its length) will cause a crater of approximately 13.7m (45ft) x 3.7m (12ft). Underwater, the dynamic forces are more complicated but the land figures can be used to give a reasonable approximation of likely crater size (while factoring in the optimum depth calculation for maximum energy transfer).

It follows that exposed soft-skin equipment and personnel are likely to suffer injury or damage from items of UXO that detonate close to or on the surface. The larger the NEQ of the UXO, the greater the severity of the consequence. Personnel under solid cover will also be less likely to be injured than those caught in the open.

Annex D

Supplementary Notes on UXO Burial

SUPPLEMENTARY NOTES ON UNEXPLODED ORDNANCE BURIAL

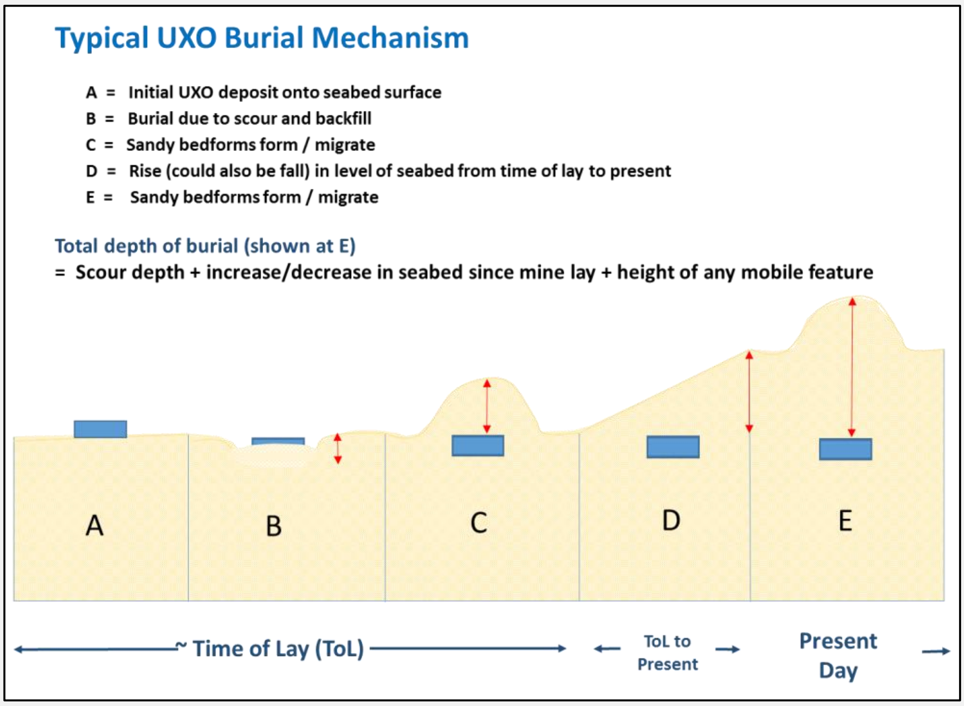
Overview

Over a period of several decades, the seabed level within an area can change due to the process of sediment accretion (also sometimes referred to as “deposition”) or erosion. It is an important factor that must be taken into consideration when determining the potential for munitions burial. The movement of sandy bedforms (ripples, mega-ripples, sand waves, etc.) also has the potential to bury (or expose) items of UXO over time and therefore the seabed sediment composition, morphology and mobility must also be considered. Bedforms in shallow water migrate and change shape due to forcing by tides and currents. Most active bedforms are those formed of sand, although where currents are strong, particularly in the nearshore, gravel can also be mobilised; this is particularly prevalent during high-energy storm events.

Within dynamic sediment conditions, items of ordnance are likely to become buried; the depth of burial at any one location is dependent on a number of variables that will be explored below. It should also be noted however that where seabed conditions are relatively stable (limited or no accretion or bedform movement) or where there is limited or no sand/gravel cover, burial of ordnance is less likely and in some environments does not happen.

- **Initial impact –** within water depth <5m
- **Liquefaction –** within shallow and nearshore sands/silts
- **Self-burial by scour, sinking and backfill –** within sands and silts
- **Bedform migration –** within areas of sandwaves and mega ripples

The figure below shows an example of how the combination of self-burial, sediment accretion and sand wave migration might lead to deeply buried ordnance.



Typical UXO Burial Mechanism

A = Initial UXO deposit onto seabed surface
B = Burial due to scour and backfill
C = Sandy bedforms form / migrate
D = Rise (could also be fall) in level of seabed from time of lay to present
E = Sandy bedforms form / migrate

Total depth of burial (shown at E)
= Scour depth + increase/decrease in seabed since mine lay + height of any mobile feature

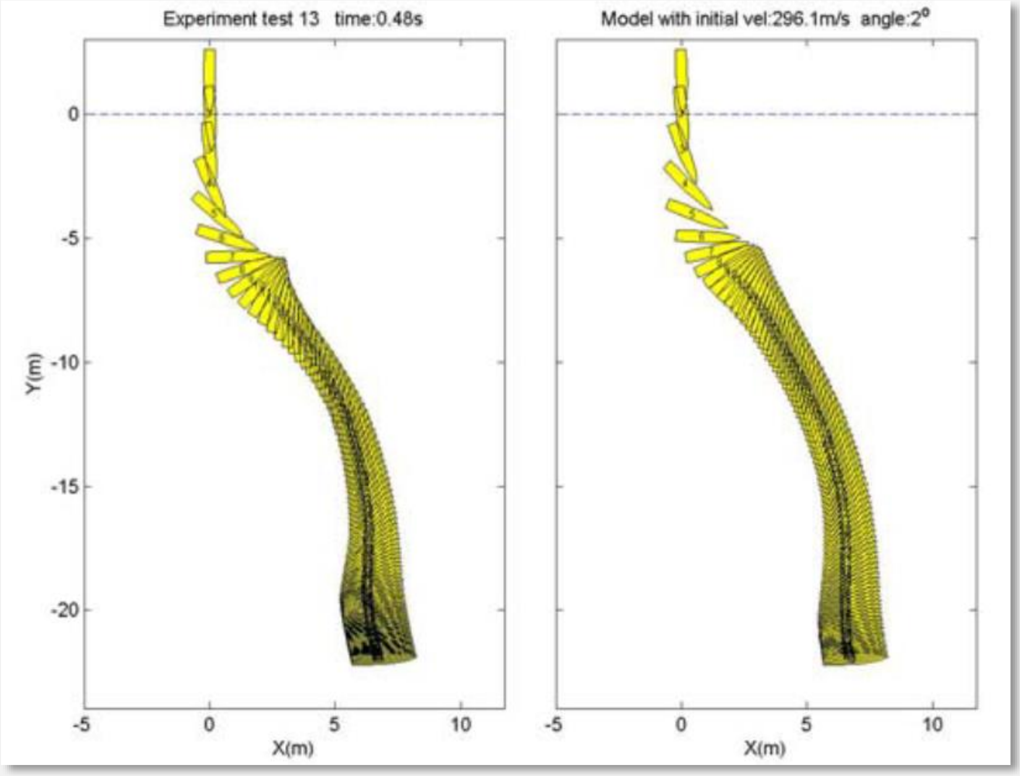
Typical UXO burial mechanisms

Initial Impact Penetration

The first mechanism for UXO burial to consider is that due to initial impact, however this method is only applicable within water depths less then 5m LAT.

The depth an air-delivered bomb will penetrate to on land is well understood; there is ample empirical data from WWII on which to base a reasonably accurate estimate. However, determining how far an unexploded bomb will penetrate into the seabed is more problematic. As on land, it depends among other factors upon its speed of entry, which is a function of the height from which it is dropped, its weight and construction, its shape, the angle of entry, and the properties and underlying geology of the sediment. However, in the maritime environment, the bomb's kinetic energy is rapidly attenuated by the water it passes through and its trajectory underwater is altered from near perpendicular in the air to a much shallower angle of entry into the sediment.

To our knowledge, there is no comprehensive and proven data on which to base a reliable calculation regarding how far a bomb will penetrate into the seabed in various depths of water and in differing sediment conditions. However, experiments on Mk84 bombs in the USA show that the trajectory of a bomb falling into water at an angle of entry of ~90° is rapidly altered by the new medium, reaching near parallel to the seabed by a depth of around 5m (*Chu et al.*, 2010). For a period subsequently, the bomb orientates to fall tail first, but by now it can be assumed that most of the kinetic energy gained through its fall through the air has bled off and at whatever angle the bomb finally strikes the seabed, its burial due to impact will be minimal.



Comparison between modelled and observed Mk84 bomb trajectories (Chu et al., 2010).

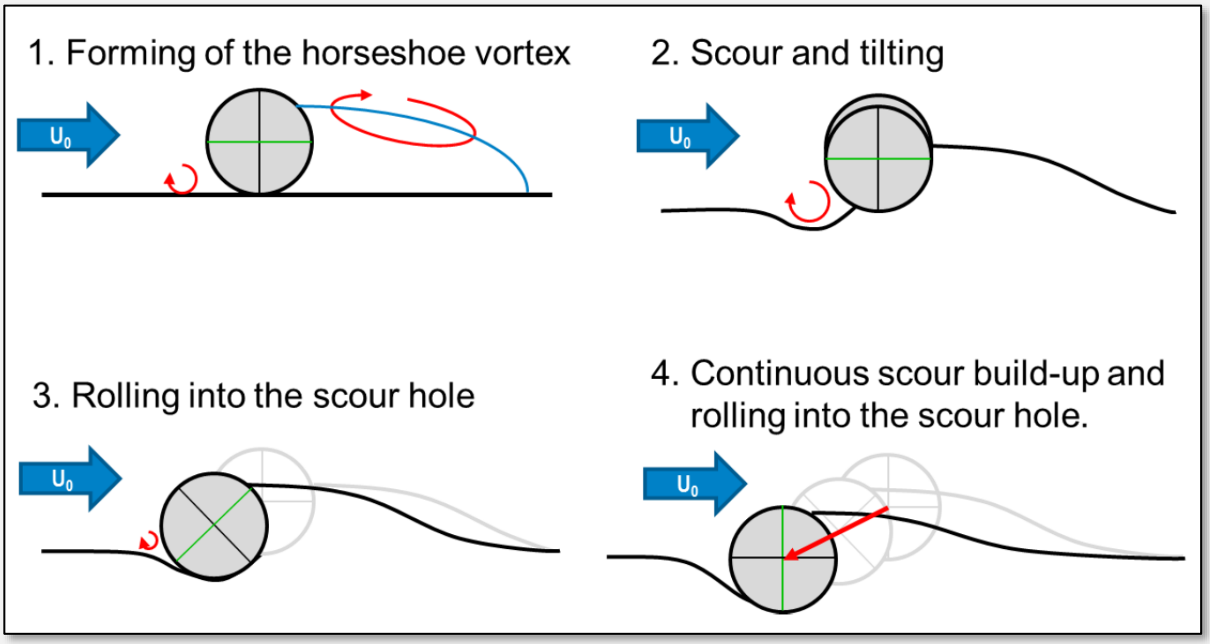
Thin-cased blast bombs and sea mines (when laid by air) were usually retarded by parachute and, unless they fell on particularly soft material, are very unlikely to penetrate into the seabed on initial impact.

Liquefaction

Ordnance burial due to liquefaction can occur on initial impact or in relatively shallow water due to wave motion. The phenomenon of liquefaction is most often observed in saturated, loose uncompacted silty sands and sandy soils. Loose sand has a tendency to compress when a load is applied; dense sands by contrast tend to expand in volume (i.e. dilate). If the sand is saturated, then water fills the gaps between sand grains ('pore spaces'). In response to the sand compressing, this water increases in pressure and attempts to flow out to zones of low pressure (usually upward towards the surface).

Self-Burial by Scour, Sinking and Backfill

The self-burial process by scour, sinking and backfill depends upon sediment grain size; as this becomes coarser, and approaches gravel size, seabed burial will reduce and instead a settling effect will occur working the ordnance partially into the seabed. Self-burial of ordnance on hard consolidated surfaces such as clay or chalk will not occur. Where the required conditions, sediment grain size and tidal flow, are met ordnance burial by scour, sinking and backfill will occur.



Model of burial for a cylindrical object in constant incident flow (Menzel and Leder, 2015)

When an item of ordnance is situated on an unconsolidated sediment bed in the tidal flow, wave motion and currents of a marine environment, scour will develop in its immediate vicinity. The local change in the flow will generally cause an increase in the bed shear stress and in the turbulence level, resulting in an increased sediment transport close to the structure and thus leading to scour. After the onset of scour, the scour occurs in the form of tunnel erosion, which is followed by lee wake erosion. The scour depth approaches a steady state through a transitional period.

The type and transitional phase of the self-burial, before equilibrium is reached, will depend among other factors on the shape and weight of the item of ordnance and sediment grain size. However, the mechanism is essentially the same in all cases. There are three stages in this ordnance/seabed interaction process: scour, sinking, and backfilling. As the process continues, the underlying bearing area reduces, placing an increasing load on the sediment. Eventually, the bearing capacity of the sediment is exceeded and it fails. The failure occurs by sliding in an outward direction. As the scour continues, this process is repeated, leading to the permanent sinking of the item of ordnance. The process will stop only when the ordnance sinks to such depths that it will be protected against scour. When the scour stops, the repeated failure of the bed will stop, and consequently the sinking of the sphere will come to an end (Truelson et al., 2005). In the final stage, the space between the ordnance and the scour hole is gradually filled with sand, this is known as backfilling.

Within test conditions self-burial of a sphere in sand (0.18mm) has been seen to reach equilibrium at 0.5 x the diameter (Truelson et al., 2005). For a bomb shaped cylinder, it will vary on precise shape and circumstances but will be similar to the sphere, and around 0.6 x the diameter.

In finer sediment (silts and sands), self-burial is likely to be greater becoming closer to complete burial of the item (0.6<1 x ordnance diameter), however where the sediment is coarser, or consists of gravel or pebbles, the maximum scour depth will be less; varying with the granularity from 0<0.6 x ordnance diameter.

Bedforms and Accretion

Ordnance burial (and exposure) is also caused by the formation and migration of bedforms such as sand banks, sandwaves, ripples and mega ripples. The presence and size of these features are a function of grain size and seabed current plus orbital velocity. It is also dependent on the turbulence, the velocity profile and the grain density.

The characteristics of the sediments and distribution of grain sizes, coupled with the wind, wave and current conditions dictate the characteristics that can cause sandwaves to occur. Sandwaves form within non-cohesive sediments because the sand grains have a roughness which creates turbulence as water flows over the surface and are an expression of a minimum energy loss system. When the drag on a particle gives it an uplift force which exceeds its weight, it is transported along the seabed. Relatively slow flow speeds can achieve this effect for sand particles. Gravel, however, because it is heavier than the uplift force that is generated over its surface, tends to be more stable.

As a sediment bedform moves across the seabed, any ordnance in its path will be alternatively buried and exposed. For very large formations, such as migrating dunes, the resulting motion and burial depth of the ordnance has the potential to be quite complex, depending on where the ordnance originally falls; whether, for instance, it lands on the forward slope, crest or back slope of the feature. The ordnance will tend to gravitate towards the base of a slope but not necessarily reach equilibrium at the deepest point. However, taking the worst case, it follows that the burial depth of the ordnance will vary with the depth of any bedform that covers it.

When added to self-burial by scour, the resultant maximum depth of the ordnance in the sediment will be the height of the feature plus the self-burial.

Annex E

Supplementary Notes on UXO Migration

SUPPLEMENTARY NOTES ON UNEXPLODED ORDNANCE MIGRATION

General Principles

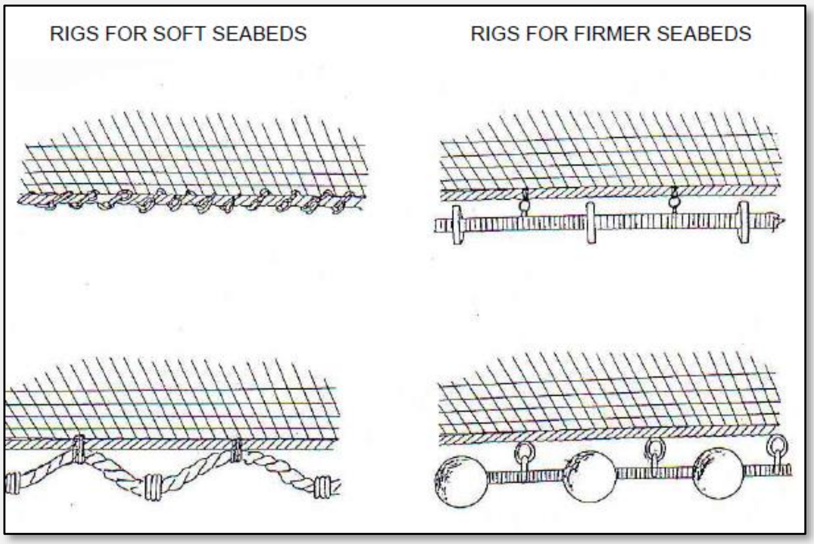
It is often a misconception that the movement of ordnance in the marine environment is equal or similar to sediment migration, i.e. is caused by it. The likelihood of an item of ordnance migrating along the seabed due to water flow (tidal stream/current) is a function, among others, of seabed composition, firmness and morphology (slopes, ripples, troughs, boulders etc.); the current strength, duration and persistence of direction; and the weight, shape (particularly of protrusions, such as lifting lugs) and orientation of the ordnance.

Some smooth, cylindrical types of ordnance, such as ground mines and torpedo warheads, have been known to roll along the seabed when conditions are favourable; i.e. if the seabed is flat and without obstruction, if it is firm and if the current is strong enough and predominantly uni-directional. If the ordnance is laid in shallow water, storm surges etc. can also produce the conditions necessary to move the item from its original position.

It is very common for fishing trawlers to encounter explosive ordnance; either knowingly by bringing it into the vessel in their nets or inadvertently by dragging an item for a distance along the seabed before it eventually falls free. In fact, 50% of finds reported to the OSPAR commission have been due to fishing. Anecdotally, fishermen that have recovered explosive ordnance in their nets have also been known to occasionally dump it back into the sea rather than report the incident. However, modern trawls do not penetrate the seabed to any great degree; they are designed to ride over boulders and other debris.

On soft sand and mud, light chain is used as ‘ground gear’ to ride over seabed obstructions, but when fishing stony, rougher bottoms various heavier ground gears are attached below this fishing line. The heaviest ground gears are made up of rubber discs and wheels threaded onto chains and wires all chosen to be tough and hard wearing to ease the relatively fragile advancing net over any stones and boulders that may be in its track.

Ordnance already buried is unlikely to be moved by this process and it is very unlikely that even modern EO deposited as the result of relatively recent ad hoc naval and air exercises in the area will be caused to move.



Examples of Trawl Ground Gear Rigs, designed to ride over seabed obstacles

Despite this, *Ordtek* considers that this is the most likely vector for migration of UXO into a project area, post pre-installation mitigation and across the life of the Project. Although the likelihood of this is significantly diminished where the object is partially buried.

Of note, in reality it is very difficult to quantify this migration mechanism; mainly because finds are rarely recorded. Those that are, are not usually done so collectively as a coherent archive. The number of encounters and post-find disposal areas cannot therefore be measured with any accuracy. Moreover, unseen, inadvertent movement of UXO, i.e. dragged by a trawl for a distance and then released is, by its nature, unquantifiable. Nonetheless, it is important to consider this migration factor as part of the baseline residual risk.

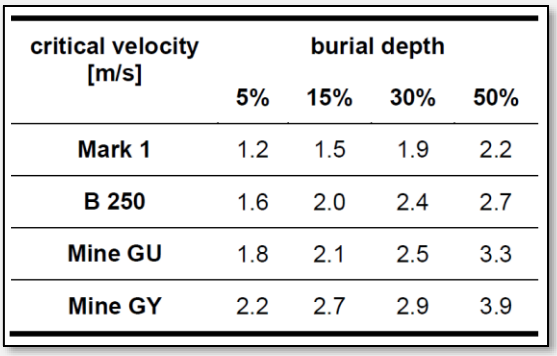
Recent Migration Research Findings

A study has been undertaken by the *University of Rostock* to gain a better understanding of the migration of objects on the sea floor. The aim of the study is to investigate the requirements of initial movement of objects representative of ordnance in the German Bight – the British Depth Bomb Mark 1, the British 250lb General Purpose Bomb, the German Mine Types GU and GY – on the sea floor.

To determine if an object will migrate, the critical force that is needed to move it from its stable position on the sediment bed must be calculated. The stable position is provided when the object is partially buried. The force on the object is solely induced by hydrodynamics. The analysis of the migration of objects on the sea floor was completed using the conditions of a wind tunnel and a water channel. A series of numerical simulations were created to allow comparisons, combinations and generalisation of experimental results.

The results display scenarios with conservative assumptions: the seabed is sandy and non-cohesive, the objects are partially buried, an accumulation area is formed in the wake of the objects, flow through the sediment is neglected, the influence of surface waves is neglected, ripples, dunes and the overall shape of the seabed is constant, the influence of the water column above the object is neglected, and the value of the incident velocity is defined 20 cm above the sea floor in realistic scale.

The target of this study was to describe the initial movement of four representative items on the sea floor due to an incident velocity. The figures in the research report and the critical velocities can be extracted as a basis for further risk assessments.



critical velocity [m/s]	burial depth			
	5%	15%	30%	50%
Mark 1	1.2	1.5	1.9	2.2
B 250	1.6	2.0	2.4	2.7
Mine GU	1.8	2.1	2.5	3.3
Mine GY	2.2	2.7	2.9	3.9

Critical velocities (in m/s) for the individual objects at different burial depths.

The results display scenarios with conservative estimates. The following assumptions have been made:

- A sandy non-cohesive seabed is required
- The objects have to be at least partially buried
- An accumulation area is formed in the wake of the objects
- Flow through the sediment is neglected
- The influence of surface waves is neglected
- Ripples, dunes and the overall shape of seabed are constant
- The influence of the water column above the object is neglected
- The value of the incident velocity is defined 20 cm above the sea floor in realistic scale

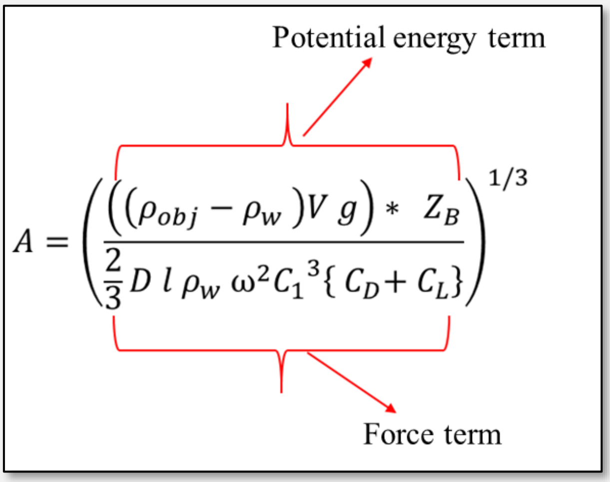
Wave-Induced Migration Calculations

Preliminary equations have been formulated for the initial movement of objects due to wave action. The equation gives the wave-amplitude (= half of the wave height).

The approach was as follows:

- Work that has to be done to lift the objects out of their position.
- Work is the integral of forces for a half wave-cycle
- Forces are given by the Morrison-Equation in dependency of the velocity and acceleration
- Velocity and acceleration are derived from the linear wave theory

Using the formula at Figure 3.5, the graph at Figure 3.6 shows the critical wave height required to move an item of ordnance at different levels of burial:

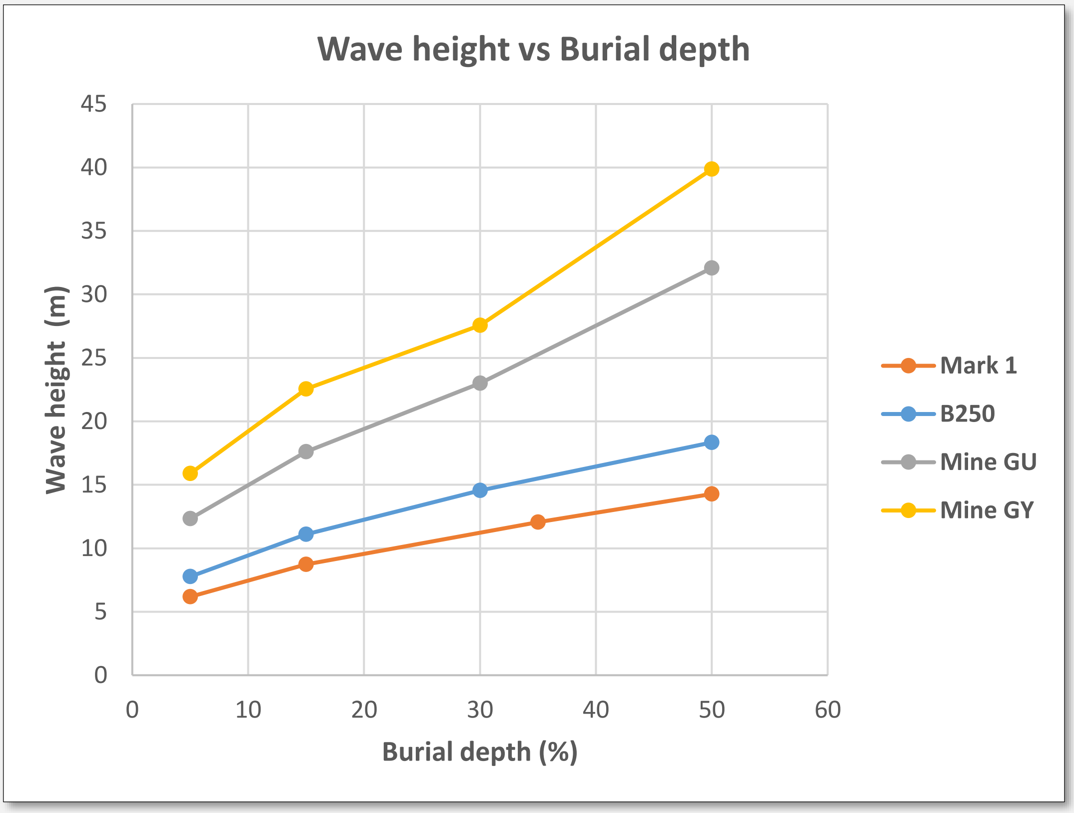


$$A = \left(\frac{\overbrace{\left(\left(\rho_{obj} - \rho_W \right) V\, g \right) * \; Z_B}^{\text{Potential energy term}}}{\underbrace{\frac{2}{3} D\, l\, \rho_W\, \omega^2 C_1{}^3 \{ C_D + C_L \}}_{\text{Force term}}} \right)^{1/3}$$

A - Wave Amplitude (m)
ρ_{obj} - Density of object $({}^{kg}/_{m^3})$
ρ_w - Density of water $({}^{kg}/_{m^3})$
V - Volume of object (m^3)
g - Acceleration due to gravity $({}^{m}/_{s^2})$
Z_B - Burial depth (m)

D - Diameter of object (m)
l - Length of object (m)
ω - Wave frequency $({}^{1}/_{s})$
C_D - Drag coefficient
C_L - Lift coefficient
C_1 - $\frac{\cosh\ k(z+d)}{\sinh kd}$

Wave-Induced Migration Formula



Wave Height Required to Move an Item of Ordnance at Varying Burial Depths

Annex F

Seabed Effects During Explosive Ordnance Disposal (EOD)

TECHNICAL NOTE 01

Title	Strategic Unexploded Ordnance (UXO) Risk Management – Seabed Effects During Explosive Ordnance Disposal (EOD)
Client	Vattenfall
Project and Number	JM5503 – Norfolk Boreas - TN01 – V1.0
Author	Tim Curd/Henry McPartland
Reviewer	Lee Gooderham
Date	14 August 2018
Reference	A. 6Alpha- East Anglia One UXO Threat and Risk Assessment with Risk Mitigation Strategy, Report Number: P2825, May 2012. B. Fugro – Norfolk Boreas Offshore Windfarm Geophysical Site Investigation, GE059/R1/2/Rev.02, 2018. 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

Vattenfall have commissioned *Ordtek* to provide guidance on blast calculations from detonations of the various types of UXO identified as potentially present within the Site; *Vattenfall* 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 Boreas 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 Boreas OWF

3. Seabed Conditions

The seabed conditions for the at Norfolk Boreas 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 20m and 43m LAT. Minimum water depth was found at the crest of sand bank 4. Maximum water depth was found between sand bank 3 and sand bank 4.

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 Boreas, 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 Boreas 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 Boreas 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. 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 Boreas 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.