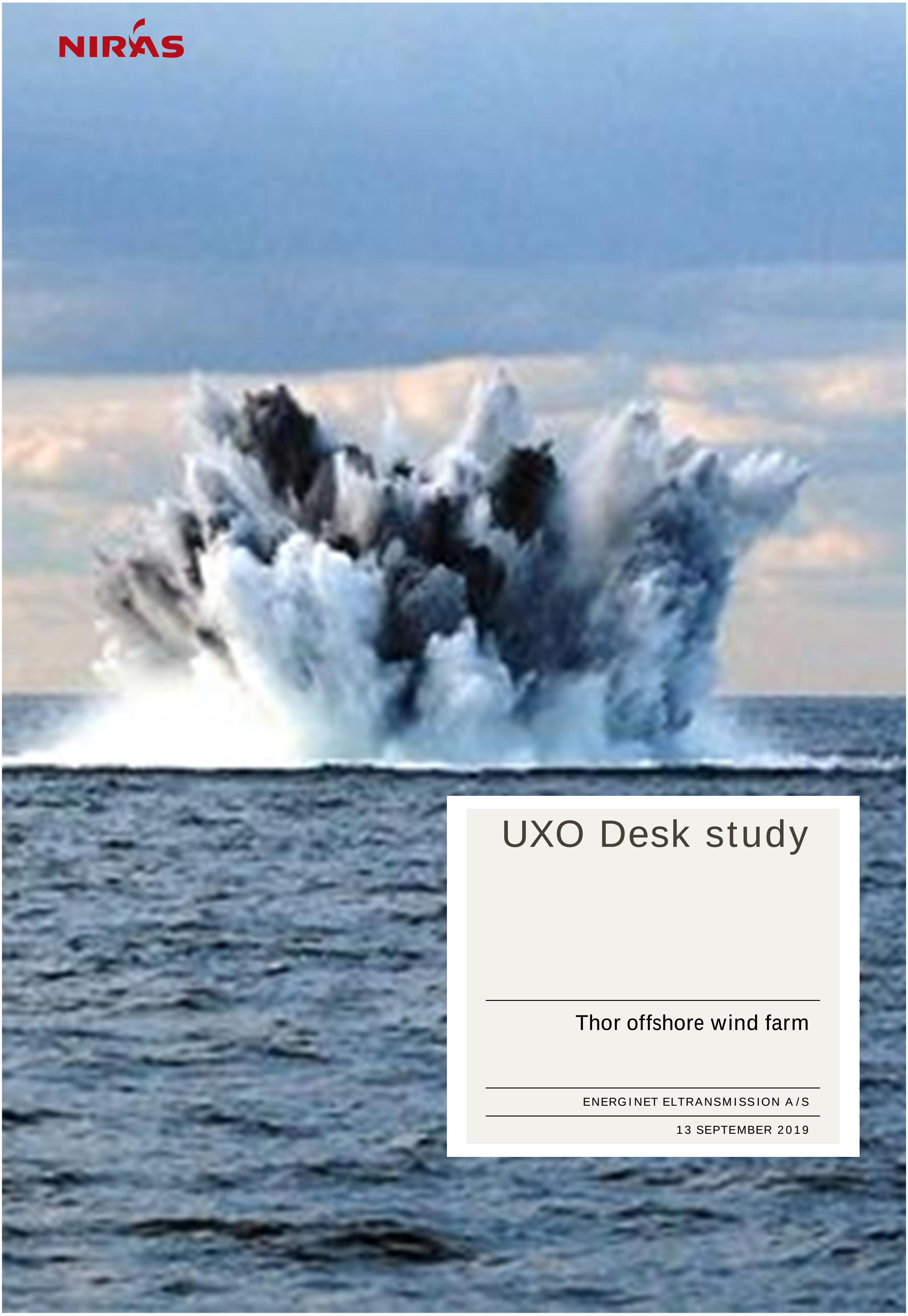

UXO Desk study

Thor offshore wind farm

ENERGINET ELTRANSMISSION A/S

13 SEPTEMBER 2019

Contents

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1 Executive summary

The waters around Denmark were heavily contested by the belligerents during both World War I and World War II. The fighting has left the maritime environment in Denmark littered with explosive remnants of war in the form of unexploded ordnance (UXO), which might still pose a risk in the development of offshore areas.

In relation to the development of the Thor offshore wind farm in the North Sea off Thorsminde, NIRAS has conducted an UXO desk study, in order to:

1. Delimit the geographical areas with potential threat from UXO and characterize the nature of the UXO threat
2. Provide an UXO risk assessment
3. Provide a plan for mitigating the UXO risk.

No known UXO contaminating activities have been found to have taken place within the main part of the Thor OWF project area. The presence of UXO cannot be excluded, though, as UXO from unrecorded events, events where the localization is not accurate or the migration of UXO is still possible.

In a strip along the shore, where the export cable(s) make landfall, the possible presence of UXO from the German fortifications along the western coast of Europe cannot be ruled out. The UXO contamination of the Thor OWF project area is summarised in Figure 1.1.

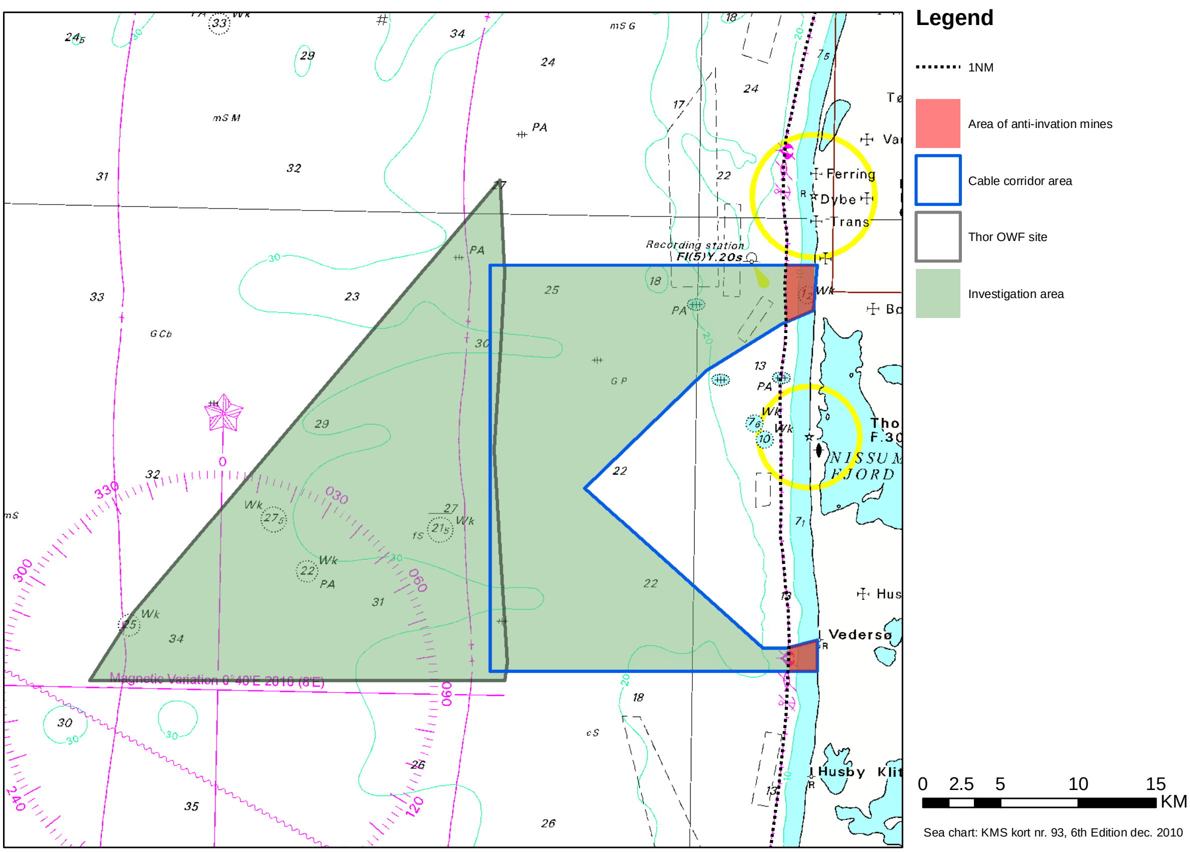


Figure 1.1 Potential UXO contamination of the Thor OWF project area. Green areas correspond to "possible contamination by UXO" and red areas corresponds to "verified contamination by mines".

Besides the degree of contamination, the level of risk associated with a specific location depends on the degree of seabed interaction from construction activities and the consequence, should the asset or unit performing the activity be damaged or lost. The risk level has been assessed for each combination of seabed interaction and possible consequences. This risk assessment is presented in section 5.4. Selected outputs include:

- Activities without seabed interaction can (always) be performed within an acceptable risk level.
- In the entire Thor OWF project area, activities with direct and extensive seabed interaction such as piling or dredging can potentially have disastrous consequences and therefore have an unacceptable risk level.
- Other seabed activities can be performed within the tolerable risk level.

However, this risk assessment is before implementation of any risk mitigation measures, and also without any detailed knowledge about construction activities. Therefore, NIRAS proposes a risk mitigation strategy for the project area that NIRAS assesses will be able to reduce the risk to a reasonable and practical level. The proposed mitigation strategy includes several specific mitigation measures that NIRAS recommends should be implemented on the project, one of these being an UXO survey.

For the UXO survey, two minimum threat items are proposed and corresponding UXO survey parameters have been recommended.

2 Introduction

Based on the Energy Agreement passed by the Danish Parliament in 2018, the Danish Energy Agency has commissioned Energinet to develop the 800-1,000 MW Thor offshore wind farm.

With reference to the contract dated 9th April 2019, Energinet Eltransmission A/S (Energinet) has hired NIRAS A/S to conduct a desk study of the Unexploded Ordnance (UXO) threat in accordance with the Scope of Services dated 14th March 2019.

To consult on UXO survey parameters, NIRAS has hired COWI A/S as a sub-consultant.

2.1 Objective of UXO desk study

Energinet wishes to adopt a proactive approach regarding the potential UXO risks on the Thor project.

The overall objectives of the UXO Desk study are to:

1. Delimit the geographical areas with potential threat from UXO and characterize the nature of the UXO threat
2. Provide an UXO risk assessment
3. Provide a plan for mitigating the UXO risk.

This information will be used by Energinet and subsequent developers and contractors during the entire project lifespan.

2.1.1 Definitions

Some abbreviations and commonly used concepts are defined below.

Abbreviation/concept	Description
ALARP	As low as reasonably practicable; a term used in risk assessment to signify that all possible mitigation measures should be implemented as are economically feasible. This often corresponds to mitigation measures equivalent to industry best practice
Cable corridor area	The final cable routes are yet to be determined, therefore the cable corridors encompass an area containing most of the area between the OWF site and the shore
CPT	Cone penetration test
Investigation area	The area investigated in this UXO desktop study. It comprises the project area plus a buffer zone due to the possible migration of UXO
MBES	Multi-beam echo sounding
OWF	Offshore wind farm
OWF site	The site where the offshore wind turbines will be installed. The site is approximately triangular.
Project area	The area allocated to the Thor offshore wind farm by the Danish Energy Agency, including the OWF site and the area for cable corridors

Abbreviation/concept	Description
SSS	Side Scan Sonar
Inter-tidal zone	The land that is between the extremes of high and low tides, and which is covered by high tide, but exposed at low tide
UXO	Unexploded ordnance, i.e. items containing explo-sives

Table 2.1 Definition of abbreviations and commonly used concepts.

2.2 Area of investigation

The Thor project area includes an OWF site and corridors for export cables. The OWF site is located 20 km west of Thorsminde, as seen in Figure 2.1. The size of the site is approximately 440 km^2, and the water depth varies from approximately 20 to 35 m.

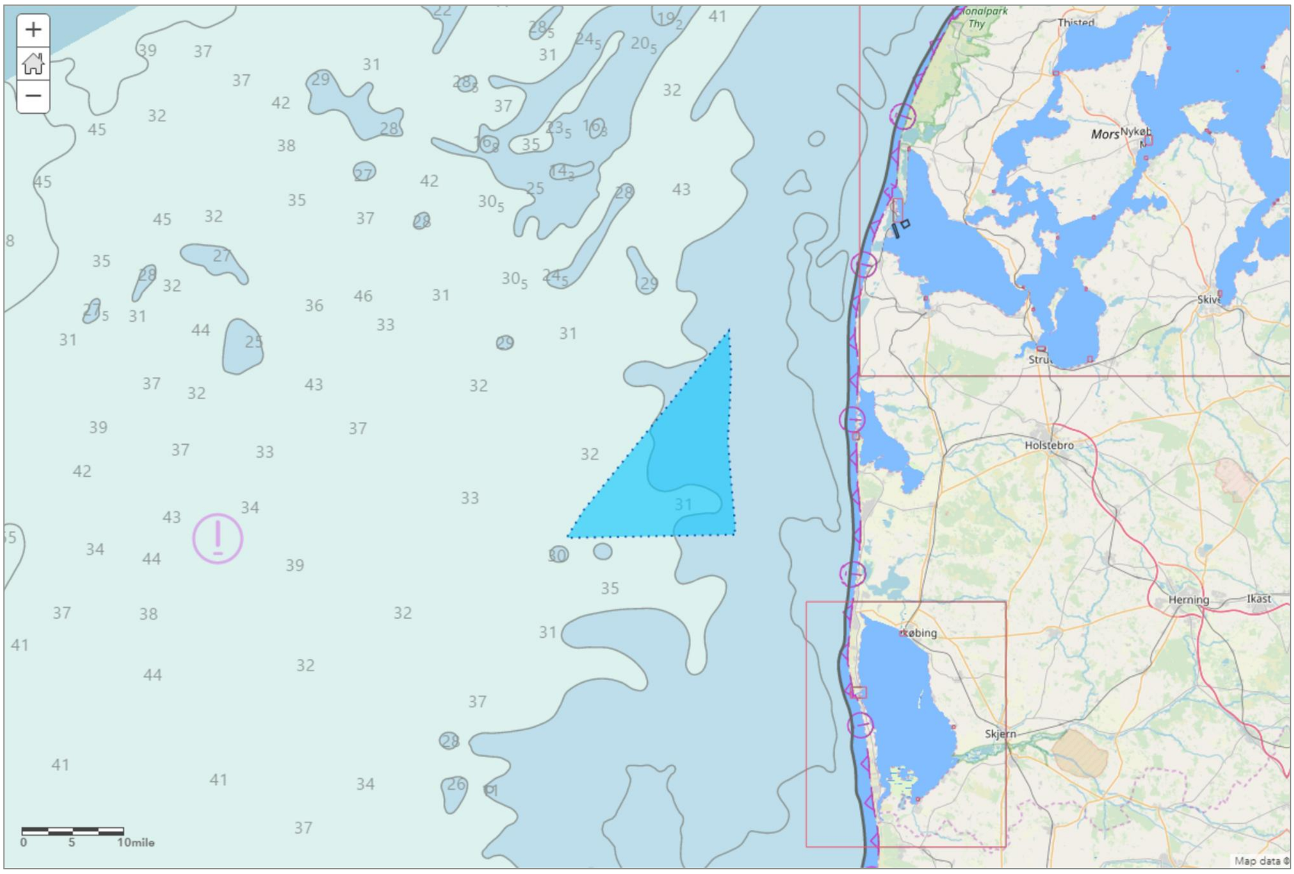


Figure 2.1. Location of the Thor OWF site. Figure from The Danish Energy Agency.

Depending on seabed morphology, currents and activities on the seabed (e.g. fishing), an UXO item might be moved over time. As part of this desk study, the possible migration of an UXO item is assessed. To account for this movement, the area investigated is slightly larger than the project area. The size of the increased 'buffer zone' is determined in section 4.5.

Also, the cable routes are yet to be determined, therefore the investigation area for the cable corridors encom-pass an area containing most of the area between the OWF site and the shore.

The resulting investigation area is shaped as seen in Figure 2.2.

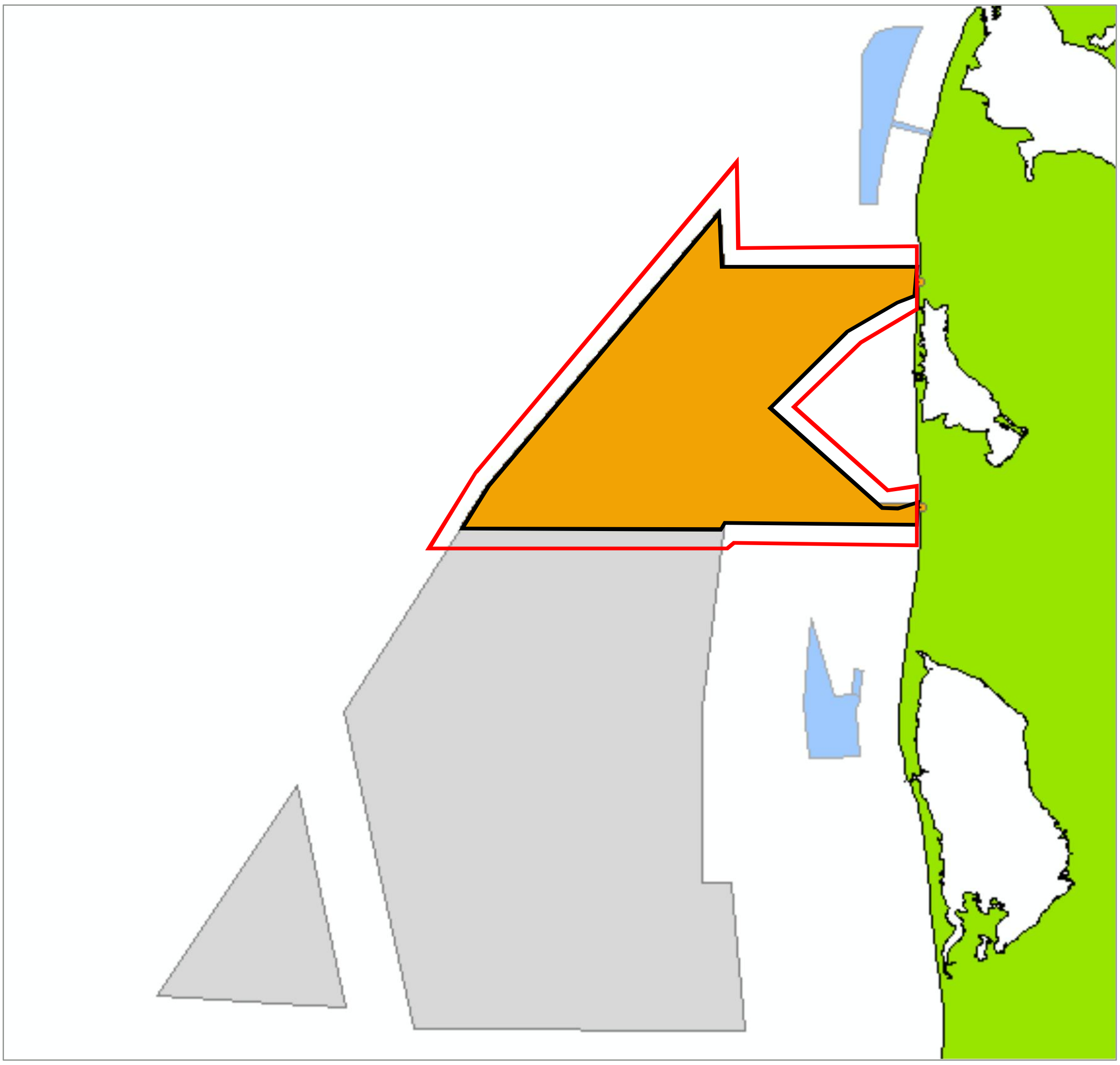


Figure 2.2. Thor OWF project area is marked in orange and the investigation area is indicated with red line. Notice, however that the border of the investigation area in reality is closer to the OWF project area. Background map from Energinet [1].

2.3 Methodology

The study follows the methodology mentioned below

- Collection of data about UXO contaminating activities
- Description of possible UXO types, including the likely condition of the UXO with respect to corrosion
- Assessment of UXO migration and burial
- UXO risk assessment
- UXO mitigation strategy

3 UXO contaminating activities

In the following sections, the identified sources of UXO contamination in the investigation area are presented.

3.1 Sources

The sources used to collect information about possible UXO contaminating activities include:

- Danish military sources
  - Fleet Diving Unit DNK (Søværnets Dykkertjeneste)
  - 2 EOD Battalion of The Danish Army Engineer Regiment (2 EOD-bataljon/Ingeniørregimentet)
- NIRAS' own sources and library, supported by publicly available sources, including:
  - Google Earth
  - www.schleswig-holstein.de
  - www.vragguiden.dk
  - www.ordtek.com
  - www.wikipedia.org

3.2 Hawthorn II

In 1940 the allied forces found that sea mines dropped from the air into Danish waters were a very efficient type of warfare. The UK developed a concept called "gardening" based on the mining of specific zones shown in Figure 3.1. The gardening operations were performed by bombers and special aircraft, e.g. Hampden, Wellington and Lancaster, which carried 1-6 mines called "vegetables".

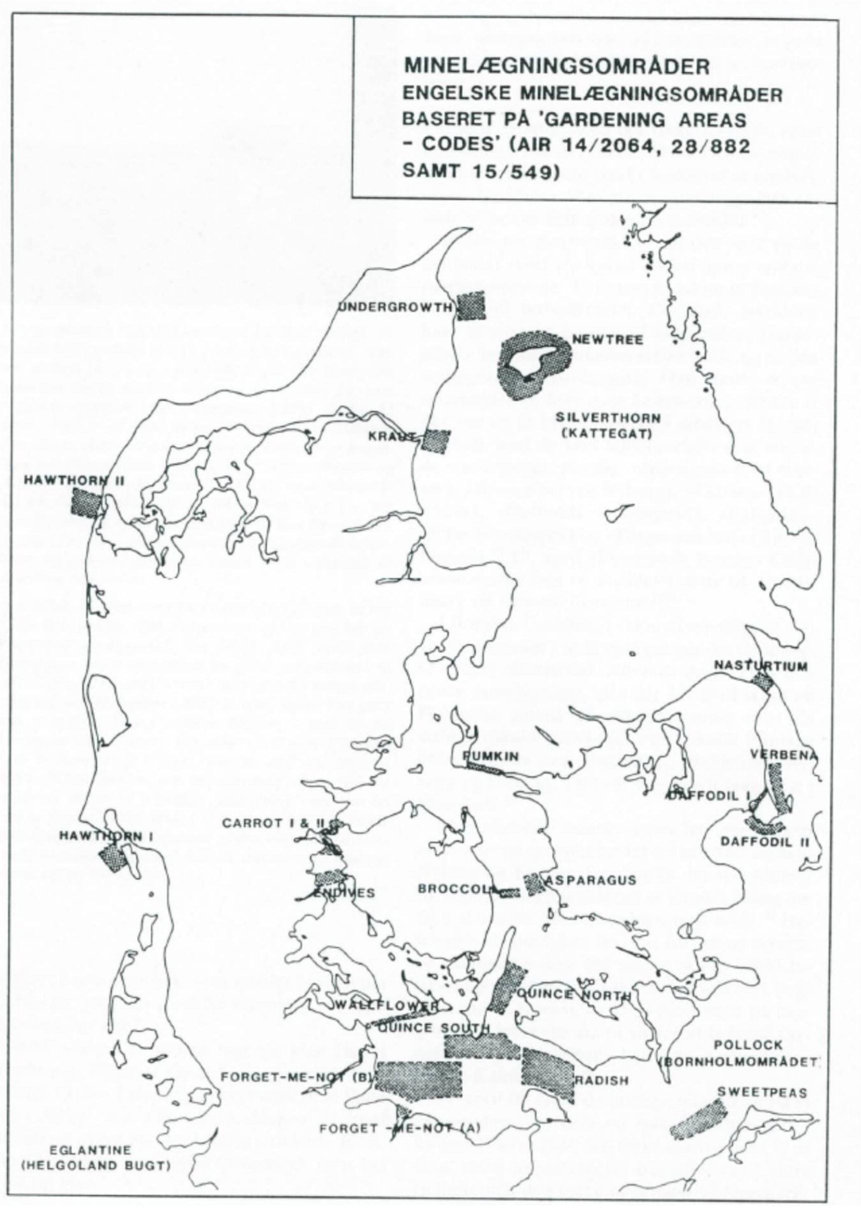


Figure 3.1. Map of British "Mine gardens" in Danish waters. The extent of the individual gardens should not be taken at face value. Figure taken from [2].

The gardening operations commenced in 1940 and continued until the end of the war. The operations were divided into two periods: 1940-41 focusing on the development of methods, and 1942-45 focusing on effective implementation of the mining deployment. The peak of the operations was from 1942 to D-day in 1944.

During WWII the RAF Bomber Command launched a total of 40,307 mines, of which 6,746 were launched into Danish waters. 1,038 were localized and disposed of by German forces. The gardening zone Hawthorn II, seen in Figure 3.1, aimed to block the western entrance to the Limfjord. According to Danish Navy sources the Hawthorn II zone is more extensive than shown in the figure and extends towards the Thor investigation area. According to this information 25 mines were deployed in the Hawthorn II garden, of which 15 have been disposed of. 10 mines still remain.

English mines have a steel casing, which makes them much more liable to corrosion and therefore less likely to remain functional.

3.2.1 Possible UXO types

The air dropped mines were of the type A Mk. I-IV, with the mines in Hawthorn II most likely of the A Mk. IV variety. The four types, Mk. I-IV are very similar – there are only small variations.

3.2.1.1 A Mk. IV British air-dropped bottom mine

The A Mk. IV mine (see Figure 3.2) consists of a 2.92 m steel tube with a diameter of 45 cm filled with approximately 325 kg of explosives.

The mines were dropped by aircraft as part of the gardening operation. At the beginning of the war the mines were deployed from a height of approximately 100 m. Later on in the war the height was 4,000 m. The mine would sink and lie on the seabed, however if deployed on land or in shallow water the mine would detonate.

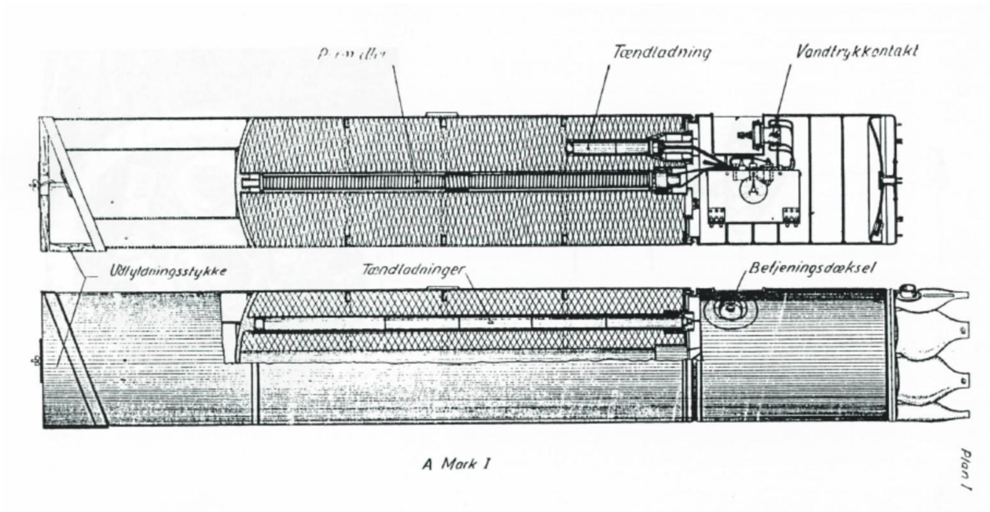


Figure 3.2. Sketch of the English bottom mine A. Mk. I–IV. Sketch from SOKPUB 645-559.

The mines are painted with letters, which provide information on the fuze, sensors, delay mechanism and type of mine.

Technical specifications	
Length	292 cm
Diameter	45 cm
Explosive charge	300-325 kg
Total weight	700 kg
Functionality features	
Delay of initiation	Up to 7 seconds
Clock work, delay of arming	Up to 45 days
Ship passing contact	Up to 14 passings, each 4½ minute
Self-destruct function	
Timing device against mine sweeping	

Table 3.1. Technical specifications of the British bottom mine A Mk. I–IV, taken from SOKPUB 645-559.

In pristine condition, the mine would have contained up to 375-400 kg of ferromagnetic materials, but as the mines are made of steel, they are prone to corrosion.

In June 2019, a fisherman caught an A mine in Kattegat and brought it aboard his fishing vessel. The mine is similar to the possible mines in Hawthorn II and was deployed during the same mining campaign as the mines in Hawthorn II. The mine was disposed of by the Danish Navy.

Figure 3.3. British type A mine caught in Kattegat in June 2019. Notice: An UXO item should never be taken out of the water. Photo by René Dalsø, taken from www.tv2lorry.dk.

3.3 Coastal fortifications

During World War II, the Germans fortified almost all parts of the shorelines of Western Europe, including the part of the investigation area where the cable corridors of the Thor OWF make landfall.

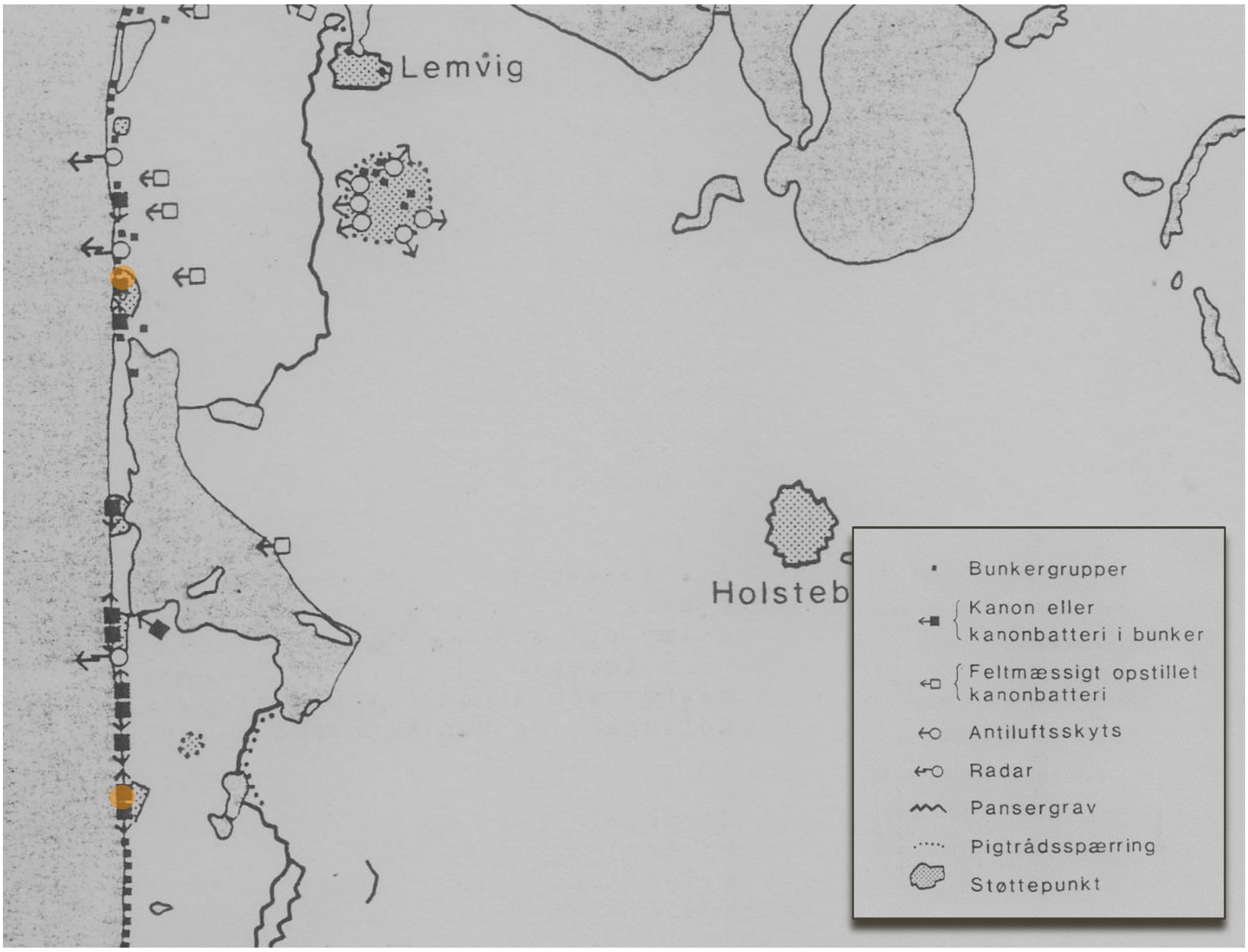


Figure 3.4. Location of German fortifications along the west coast of Jutland. Approximate locations of the Thor cable corridor landfalls are shown in orange. Cut-out of information received from the Danish Army.

At both landfall areas, the coastal area was mined and there were artillery positions covering the area. Known onshore minefields at the landfall areas are shown in Figure 3.5 and Figure 3.6. In the figures, green denotes anti-personnel mines, red denotes anti-tank mines (see section 3.3.1.1) and the combination of red and green denote combined minefields.

Figure 3.5 *Locations of known minefields at the approximate location of the Northern landfall area. Not to scale. The approximate location of the cable corridor area is shown in blue. Cut-out of information received from the Danish Army.*

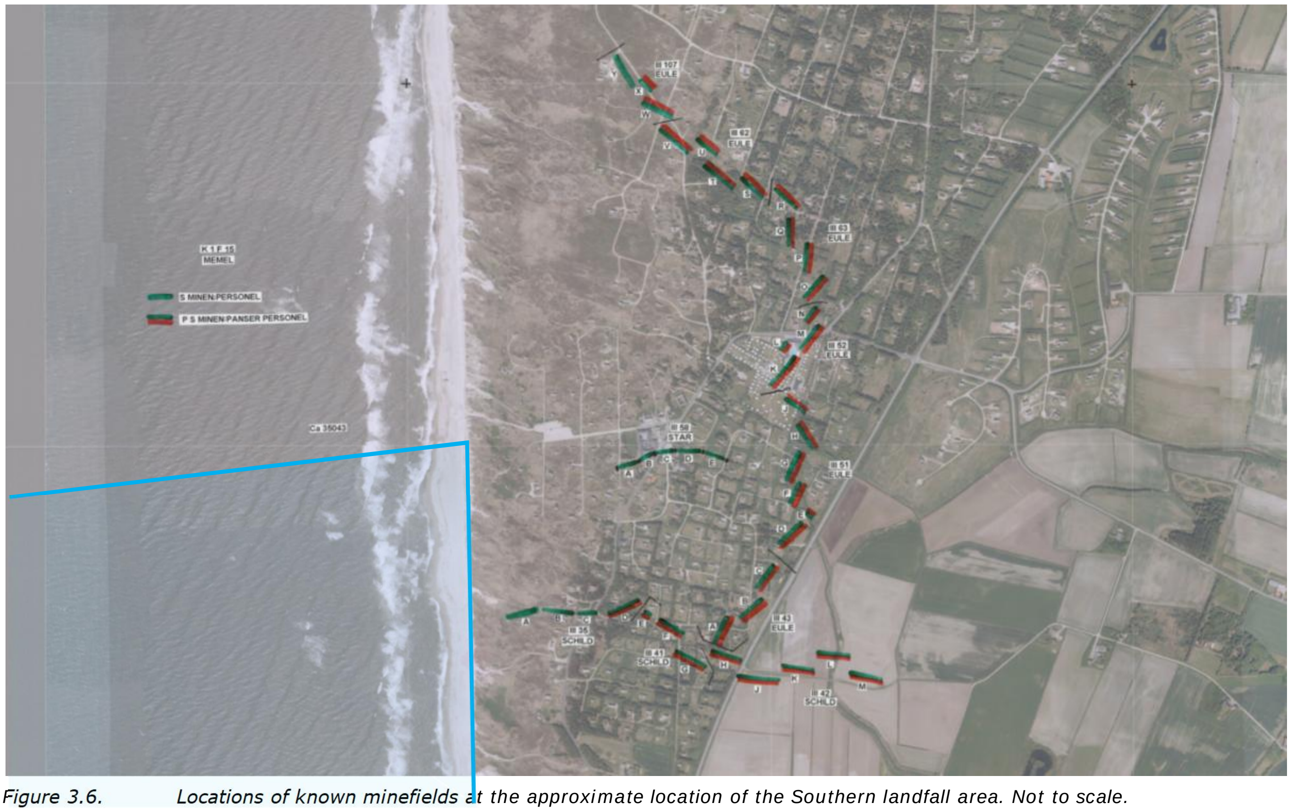


Figure 3.6. *Locations of known minefields at the approximate location of the Southern landfall area. Not to scale. The approximate location of the cable corridor area is shown in blue. Cut-out of information received from the Danish Army.*

All onshore minefields were reported as “cleared” in the period immediately after the war. In spite of this, there are a few activities/mechanisms that might have caused ammunition to end up in the marine environment:

- Exercise or training firing using artillery or mortars, e.g. during World War II
- Surf and coastal morphology may have moved mines offshore (unlikely in this area)
- After clearing the minefields, the mines were disposed of by blasting at designated blasting areas. If part of the mines failed to detonate in the explosion, they might have been thrown into the sea by the blast. The method was presumably also used for excess artillery ammunition. A blasting area in the area of the Southern landfall area is mentioned in information received from the Danish Army.

The nearshore coastal area was also mined with anti-invasion mines, see section 3.3.1.2.

3.3.1 Possible UXO types

UXO types include various types of personnel and anti-tank mines, along with artillery shells and mortar rounds. A typical anti-tank mine used is the Tellermine 43.

3.3.1.1 *Tellermine 43*

The Tellermine 43 is a first-generation anti-tank mine used extensively by the Germans during the latter part of World War II. The name literally means plate mine due to the resemblance to a plate or dish.

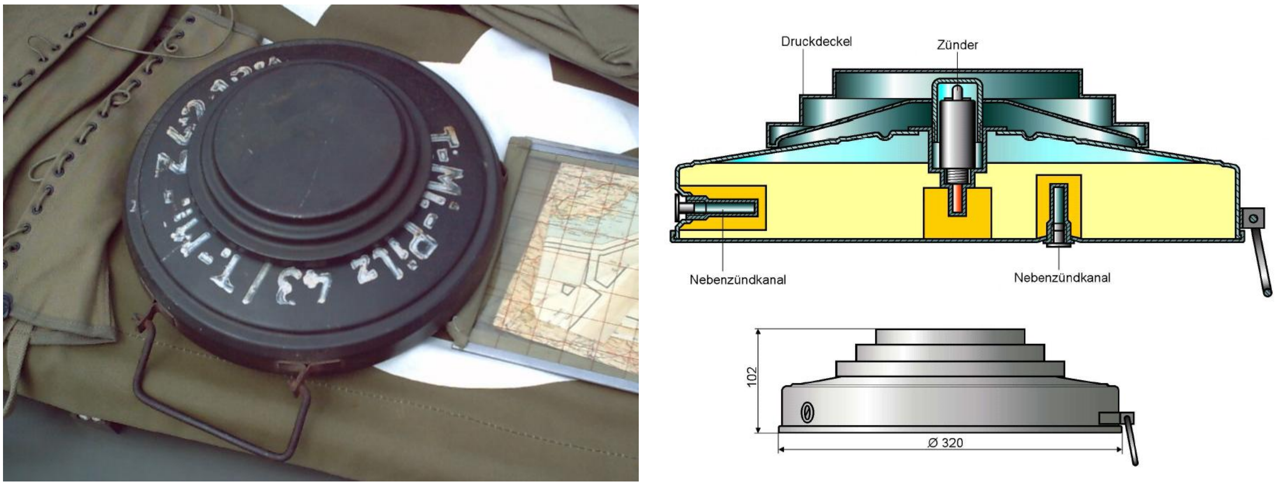


Figure 3.7. Tellermine 43. Photo from Wikimedia Commons (left) and schematics from Danish Coastal Authorities report “Kystdirektoratets kvalitetskontrol ved minerydning på Skallingen, Fase 2” (right).

Various sources differ somewhat on the specifications of the mine. Table 3.2 below summarizes specifications from the Danish Coastal Authority, TM-E 30-451 (1945) which is a US Army manual on German equipment and Wikipedia.org.

Specification	Danish Coastal Authority	TM-E 30-451 (1945)	Wikipedia.org
Diameter	320 mm	12.5 inches (~ 317.5 mm)	318 mm
Height	102 mm	3.5 inches (~ 89 mm)	102 mm
Total weight	9.9 kg	17 lbs, 5 ounces (~ 7.85 kg)	8.1 kg
Charge weight	5.45 kg	Not specified	5.5 kg

Specification	Danish Coastal Authority	TM-E 30-451 (1945)	Wikipedia.org
Trigger weight	Qualitatively specified as "great, e.g. by the weight of a vehicle"	Not specified	100-180 kg
Explosive filling	TNT	Not specified	TNT (sometimes amatol)
Fuze	T.Mi.Z.42	Not specified	T.Mi.Z.42 T.Mi.Z.43
Other mentioned features	Steel casing 1st generation mine Fuze in watertight compartment Secondary fuze wells	Secondary fuze wells	Steel casing PETN booster charge Secondary fuze wells

Table 3.2. Specifications of a Tellermine 43. Various sources.

3.3.1.2 *Küstenmine A*

The predominant mine type in the nearshore coastal minefield is the Küstenmine A (eng: Coastal Mine A), commonly abbreviated as the "KMA mine". Approximately 15,000 KMA mines were deployed along the West coast of Denmark in 1944.

The mine consisted of a concrete base containing the explosives and a tripod with an initiation mechanism, including a snag line, on top. The mines were placed in shallow water with the initiation mechanism or snag line near the surface to prevent allied landing craft from reaching the shore.

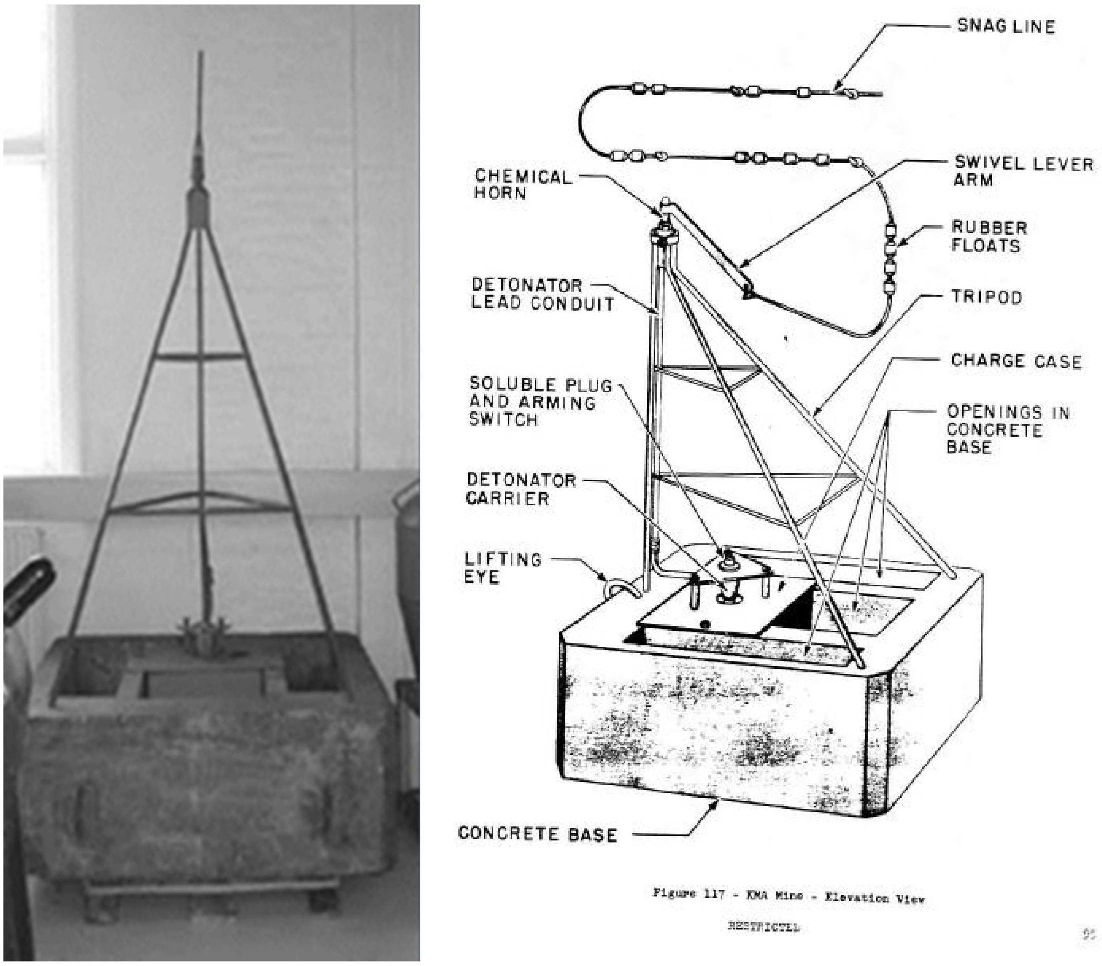


Figure 3.8 *German coastal mine A (Küstenmine A, KMA). From OP 1673A [3] and Sæby NWF UXO desk study, NIRAS, 2013.*

The specifications of the KMA mine are shown in Table 3.3.

Specification	Value
Base size	120 x 120 x 50 cm
Base material	Concrete
Total height	2.25 m
Charge weight	50-75 kg
Total weight	Ca. 1,000 kg
Explosive	Hexanite (approx. 60 % TNT, 40 % hexanitrodiphenylamine (HND))
Maximum effective depth	10 m (30 ft)
Initiation mechanism	Herz horn, initiated by direct impact or by snag line

Table 3.3 *Specifications of the German coastal mine KMA (Küstenmine A). From various sources, including atlantvoldsydvest.dk and OP 1673A [3].*

In March 1945 the German Navy conducted a study of the condition of the mines laid in the autumn of 1944. The mines were found to be in poor condition due to the harsh environment and at the end of the war, the Germans only expected 50 % of the mines to be in working condition.

3.4 Diffuse contamination

Several UXO contaminating activities are known to have taken place, without it being possible to determine the exact location of the contamination in this desk study.

3.4.1 Possible UXO types

UXO might have entered the investigation area due to:

- Ammunition fired at shipping targets of opportunity, e.g. torpedoes, bombs, depth charges or grenades
- Moored mines that have come loose from their moorings, drifted around and finally sunk
- Jettisoned bombs from abandoned bombing runs
- Anti-aircraft artillery grenades fired from ships or onshore batteries
- Downed airplanes
- Sunk ships

A few examples of various types of ammunition are presented in the following sections.

3.4.1.1 Torpedoes

Torpedo design improved gradually during World War II. In World War I and early in World War II, torpedoes like the German G7a (T1), British Mk. VIII and US Mark 14 were not always 100 % reliable and on numerous occasions failed to explode. These will have ended up on, or more likely underneath, the seabed, where they might still pose a risk.

Figure 3.9 British Mk. 12 torpedo (top), German G7e (T2) torpedo (middle) and US Mark 18 torpedo (bottom). Photo: Alexander Buschorn, Wikimedia Commons

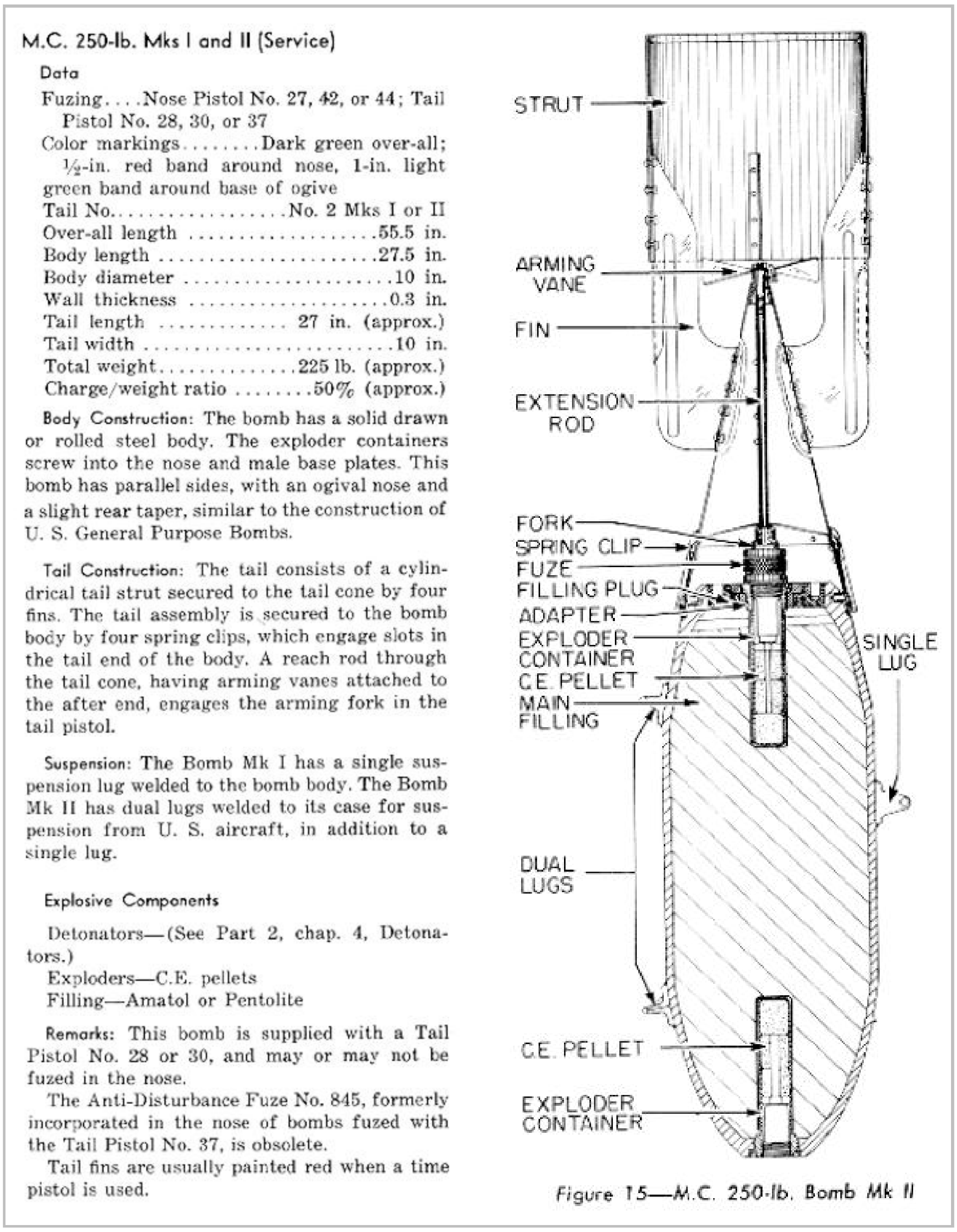
The general design of the various torpedo types is quite similar, as they all have a diameter of 533 mm (21”), a length of 6.5-7.2 m, a total weight of 1,500-1,600 kg and a charge weight of 280-340 kg.

3.4.1.2 *Bombs (armed or unarmed)*

Conventional bombs dropped from aircraft come in various sizes from 4 lbs (1.8 kg) incendiary bombs up to a massive 12,000 lbs (5,400 kg). Other types of western allied bombs for various purposes include bombs of e.g. 40, 100, 250, 500, 1,000 and 2,000 lbs (18, 45, 113, 227, 450 and 900 kg).

A general strategy employed by the RAF during the bombing of German cities, was to each aircraft to be equipped with a single very large bomb and several thousand small incendiary bombs. The idea was that the large bomb would cause all the roof tiles in a street or of a city block to become dislodged, whereafter the incendiary bombs would land in the exposed attics and set the remainder of the building ablaze.

Bombs could have ended up in the investigation area due to either direct attacks on shipping or by being jettisoned (disposed of) by the crew, if they did not want to return to their base with the bomb payload. This could happen for safety reasons, e.g. if the aircraft had failed to find its target or if it was damaged.


M.C. 250-lb. Mks I and II (Service)

Data

Fuzing....Nose Pistol No. 27, 42, or 44; Tail Pistol No. 28, 30, or 37
Color markings........Dark green over-all; ½-in. red band around nose, 1-in. light green band around base of ogive
Tail No..................No. 2 Mks I or II
Over-all length ....55.5 in.
Body length ....27.5 in.
Body diameter ....10 in.
Wall thickness ....0.3 in.
Tail length .... 27 in. (approx.)
Tail width ....10 in.
Total weight..............225 lb. (approx.)
Charge/weight ratio ....50% (approx.)

Body Construction: The bomb has a solid drawn or rolled steel body. The exploder containers screw into the nose and male base plates. This bomb has parallel sides, with an ogival nose and a slight rear taper, similar to the construction of U. S. General Purpose Bombs.

Tail Construction: The tail consists of a cylindrical tail strut secured to the tail cone by four fins. The tail assembly is secured to the bomb body by four spring clips, which engage slots in the tail end of the body. A reach rod through the tail cone, having arming vanes attached to the after end, engages the arming fork in the tail pistol.

Suspension: The Bomb Mk I has a single suspension lug welded to the bomb body. The Bomb Mk II has dual lugs welded to its case for suspension from U. S. aircraft, in addition to a single lug.

Explosive Components

Detonators—(See Part 2, chap. 4, Detonators.)
Exploders—C.E. pellets
Filling—Amatol or Pentolite

Remarks: This bomb is supplied with a Tail Pistol No. 28 or 30, and may or may not be fuzed in the nose.
The Anti-Disturbance Fuze No. 845, formerly incorporated in the nose of bombs fuzed with the Tail Pistol No. 37, is obsolete.
Tail fins are usually painted red when a time pistol is used.

Figure 3.10 Sketch of and specifications for a British Medium Capacity 250 lb. Bomb Mk II. The bomb contains an explosive charge of approximately 50 kg. The 250 lbs MC bomb is suggested as the minimum threat item for the Thor OWF site. Specifications taken from [4].

The specifications of the British 250 lbs MC bomb can be found in Table 3.4.

Specification, 250 lbs MC bomb	Value, Imperial units	Value, SI-units
Colour	Dark green with a red and green band	
Total length	55.5 in	141 cm
Body length	27.5 in	70 cm
Tail length	27 in	69 cm
Diameter	10 in	25.4 cm
Total weight	225 lbs	102 kg
Charge weight	112.5 lbs	51 kg
Weight of case+tail assembly	112.5 lbs	51 kg
Explosive	Amatol or pentolite	

Table 3.4 Selected specifications of a British 250 lbs MC bomb. From [4].

3.5 Other nearby sources

Apart from the already mentioned possible sources of UXO contamination in the investigation area, a few other noteworthy sources near the investigation area exists:

- In 1868 the Russian screw frigate Alexander Nevski ran aground off Thyborøn
- The battle of Jutland in May/June 1916, during World War I, was largest naval engagement of the war, involving 250 combat vessels. The battle resulted in the sinking of several capital ships. The battle took place approximately 100 km west of the Thor OWF project area
- A German submarine, SM U-20, ran aground between Thorsminde and Thyborøn in November 1916. The crew blew up the remaining torpedoes and the Danish authorities removed the deck gun and blew up the remainder of the hull after the war. The wreck can supposedly be found 400 m from the shore off Vrist near Harboøre.

4 UXO migration and burial assessment

4.1 Metocean data

To estimate the seabed and UXO mobility, preliminary waves data has been extracted from public sources [5] and current from an in-house model.

4.1.1 Waves

Statistical values of the wave climate, which are listed in Table 4.1, shows that the average significant wave height is 1.6 m and that the significant waves exceed 6.9 m in 0.1 % of the time. Corresponding near-bed velocities are for the same waves estimated based on linear wave theory. Dominating direction is 210° to 330° with the largest waves from 300° to 330°.

Wave Climate			Depth [m MLWS]					
			5	10	20	25	30	35
Statistics	H_s [m]	T_p [s]	$U_{orbital@seabed}$ [m/s]					
50.0 %	1.4	5.5	0.75	0.38	0.11	0.06	0.03	0.02
Mean	1.6	5.8	0.90	0.48	0.15	0.09	0.05	0.03
90.0 %	3.0	7.0	1.8	1.07	0.49	0.33	0.23	0.15
99.0 %	4.9	8.7	-	2.00	1.10	0.85	0.66	0.52
99.9 %	6.9	10.2	-	2.99	1.79	1.46	1.21	1.01

Table 4.1 Wave climate 1979 to 2018; H_s: Significant wave height, T_p: Wave peak period; $U_{orbital@seabed}$: Orbital velocity at seabed based on linear wave theory. From [5].

4.1.2 Tide & Current

The tidal range is around +/- 0.5 m MSL. Storm surge can decrease or increase the tide with several meters. Under normal conditions, the average depth tidal current range is approximately 0 to 0.4 m/s increasing to around 1 m/s in storm situations. Prevailing current directions are 180° and 350°, i.e. approximately parallel to the shoreline.

NIRAS estimates that the inter-tidal zone at the landfall locations is maximum 50 meters wide.

4.2 Bathymetric data

Water depths within the OWF site varies between 21 and 34 m mean low water spring (MLWS) deepest in the south-westerly corner and in the cable corridor area from 0 m at the shoreline to 30 m MLWS at the OWF site boundary, see Figure 4.1.

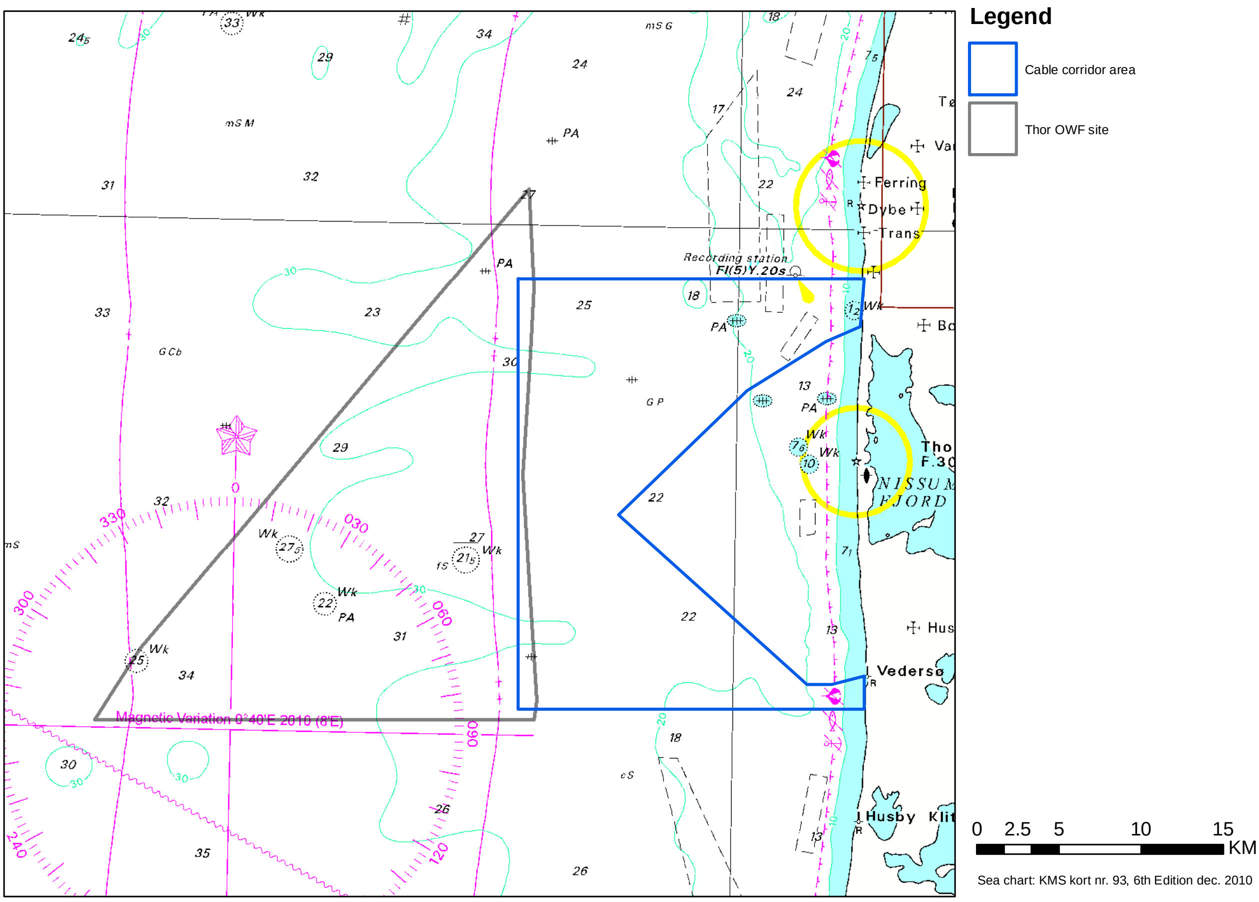


Figure 4.1 Water depths in m (MLWS) in the OWF project area.

4.3 Geology

At both the OWF site and in the cable corridor area most of the superficial sediment is sand with some patches of gravel & coarse sand, till and clay & silt, see Figure 4.2.

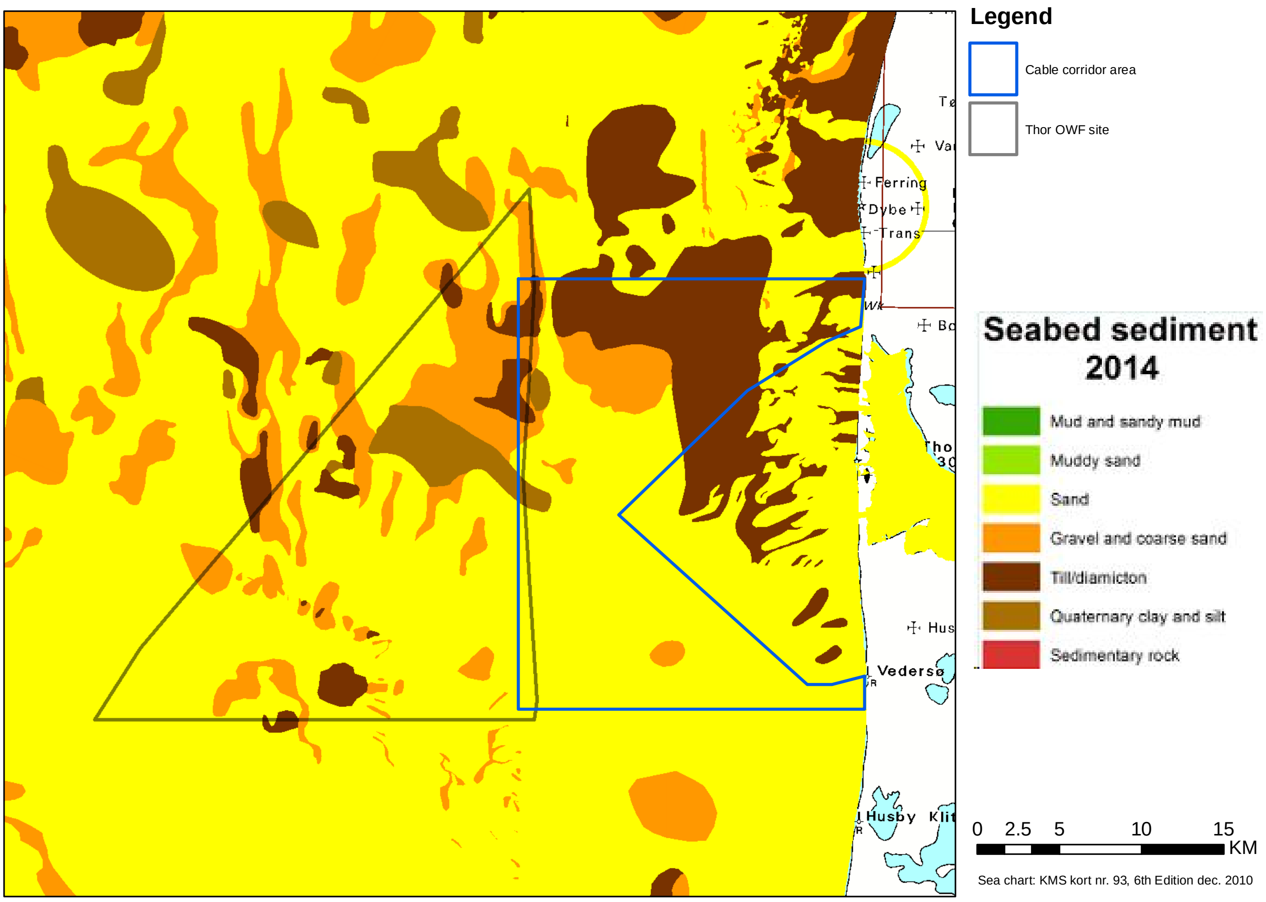


Figure 4.2 Seabed geology [6].

4.4 Seabed morphology

The average significant wave height is 1.6 m generating a near seabed velocity high enough to bring sand and finer materials into suspension. Bathymetric survey data has not been available to confirm the presence of seabed features such as ripple, mega ripple and perhaps sand waves but based on the seabed geology and the metocean data these could potentially exist inside the OWF project area thus local seabed changes with up to 2 to 3 meters are possible. Vibrocores [6] from the site indicates that in the areas with sand this is available in the upper 3 to 5 m.

4.5 UXO migration and burial

In a storm situation, even larger and heavier items, like a mine or bomb, could be brought into transport or be buried below as much as 2 to 3 m of sand by migrating seabed features.

The burial of a heavy item, like a mine or bomb, would happen relatively quickly, within a few years. The possible horizontal migration of a mine or bomb depends on the speed of the current near the seabed, the weight of the item relative to the water and the geometry of the seabed and the item. A round item may migrate further by rolling, especially if the seabed is sloping downwards.

The horizontal migration of an unburied 250 lbs MC bomb, lying on a flat seabed at a depth of 20 m, would only move during storms with a return period of 50 years, making substantial horizontal migration unlikely.

As a conservative measure, the investigation area should be equal to the Thor OWF project area plus a buffer zone extending outwards 100 m.

5 Risk of UXO incidents

5.1 Introduction

It is recommended that the management of the risk of UXO incidents should be based on CIRIA report C754 Assessment and Management of Unexploded Ordnance (UXO) Risk in the Marine Environment [7].

The risk of UXO incidents can be expressed in terms of a combination of the consequences of an UXO incident and the likelihood of the occurrence of such an incident (detonation or deflagration of an UXO item).

The evaluation of the UXO risk related to seabed activity in the UXO-contaminated area can be done using semi-quantitative risk assessment (Risk Matrix) in accordance with principles in CIRIA C754 and ISO/IEC 311010 Risk Management – Risk Assessment Techniques [8]. For detailed risk analyses and assessments, tools and examples can be found in the ISO/IEC 311010 Annex A and B.

5.2 Installation activities

The likelihood of an UXO incident is assessed based on a combination of the specific work (see also section 5.3).

At the time of writing the present desk study, the layout of the OWF and the exact location of the cables are not known. Therefore, the methods used during development, construction and operation of the Thor OWF are not known either. However potential/expected methods include:

- Geotechnical operations:
  - Seabed CPT
  - Vibrocore
  - Seabed sampling by independent unit
  - Geotechnical investigation from barge or vessel
- Seabed interaction with:
  - Trenching
  - Ploughing
  - Pre-lay grapnel run
  - Piling
  - Dredging
  - Jetting
- Cable installation
- Jack-up of vessels
- Anchoring
- Placement of scour protection

5.3 Risk assessment methodology

Principles of risk assessment using the risk matrix methodology are presented in the following.

The risk matrix contains the following parameters (classes and levels):

- Consequence Class (I-VI) related to damage and loss caused by an UXO incident
- Likelihood of Occurrence (1-6) of an UXO incident in relation to the Activity Class (A1-A4) and the Contamination Class (B1-B4) of the area
- Risk level (Acceptable, Tolerable, Unacceptable) related to the acceptability of risk of an UXO incident in accordance with the principles of ALARP (As Low As Reasonably Practicable).

The consequence of an UXO incident is divided into six classes as seen in Table 5.1.

Consequence class	Description	Characteristics
I	Negligible	-
II	Insignificant	Minor delays, minor damage to equipment
III	Considerable	Minor personnel injury, delays, damage to equipment
IV	Serious	Severe personnel injury, critical delays, damages to equipment or installations
V	Severe	Fatality, loss of major installations or ships
VI	Disastrous	Several fatalities, loss of major installations or ships

Table 5.1 Severity of consequences of an UXO incident.

There is some degree of correlation between the size and type of an UXO and the obtainable consequence class. Large UXO items generally have greater potential to cause severe consequences. However, as even small UXO can have fatal potential, and a large UXO at a distance might have minor consequences, the UXO size does not determine the consequence class.

If the type and size of UXO, deployed assets and distances etc. are known, the actual consequences can be estimated. Likewise, the processes and activities can be planned and designed in ways that prevent certain consequences.

The likelihood of an UXO incident depends on:

- the seabed interaction
- the presence of an item of UXO, and
- the probability of explosion following the encountering of an item of UXO

The likelihood of an UXO incident is assessed based on a combination of the specific work, expressed in activity classes (see Table 5.2), and the presence of UXO, expressed in UXO contamination classes (see Table 5.3).

Activity Class	Description	Characteristics
A1	No seabed interaction	-
A2	Indirect and limited seabed interaction	Anchoring, Seabed CPT, vibrocore, seabed sampling by independent unit
A3	Direct but limited seabed interaction	Jack-up, geotechnical investigation from barge or vessel
A4	Direct and extensive seabed interaction	Piling, dredging, pre-lay grapnel run, cable installation by ploughing, trenching or jetting, placement of scour protection

Table 5.2 Activity classes with respect to seabed interaction and probability of impacting an item of UXO with sufficient energy to initiate the item.

Contamination Class	Description	Characteristics
B1	Sporadic	No evidence of UXO contamination
B2	Possible contamination	Historic evidence of UXO contamination, diffuse localisation, e.g. loose German anchored mines and British air-delivered mines
B3	Verified contamination of UXO from training fields	Historic evidence and military information on existing and former training fields and target areas.
B4	Verified contamination by sea mines	Historic evidence of contamination by sea mines, types and quantities of UXO estimated, prohibited areas marked on maritime charts

Table 5.3 Contamination classes based on historic references, military sources and other information on the probability of the presence of UXO.

The probability of an unintended explosion also depends on the condition, character and sensitivity of the UXO. For instance, artillery grenades and small calibre ammunition are less sensitive with respect to physical impact. If the contamination in a specific area is known to be of a less sensitive UXO type or in a poor condition, the likelihood of an incident can be reduced accordingly.

The likelihood of an UXO incident is expressed in six UXO incident occurrence classes presented in Table 5.4.

Likelihood of occurrence	B1	B2	B3	B4
A1	Highly unlikely (1)	Highly unlikely (1)	Highly unlikely (1)	Highly unlikely (1)
A2	Highly unlikely (1)	Unlikely (2)	Less likely (3)	Likely (4)
A3	Highly unlikely (1)	Less likely (3)	Likely (4)	More likely (5)
A4	Unlikely (2)	Likely (4)	More likely (5)	Very likely (6)

Table 5.4 Likelihood of occurrence of an UXO incident related to Activity Class (Table 5.2) and Contamination Class (Table 5.3). For less sensitive UXO types or UXO known to be in poor conditions, the likelihood of occurrence can be reduced.

Based on Table 5.1 and Table 5.4 it is possible to establish a Risk Matrix (as shown in Table 5.5), indicating the following levels of risk:

- Acceptable risk (Green)
- Tolerable risk (Orange)
- Unacceptable risk (Red)

Risk Matrix		Consequence Class (Table 5.1)					
		I	II	III	IV	V	VI
Likelihood of Occurrence (Table 5.4)	1						
	2						
	3						
	4						
	5						
	6						

Table 5.5 Risk Matrix, indicating risk levels.

Based on the indicated risk levels (acceptable, tolerable and unacceptable risks) the consequence classes and the occurrence classes need to be examined in detail with respect to the need for mitigation measures.

The risk levels are used to determine the level of risk mitigation. The recommended level of risk mitigation is shown in Table 5.6.

Risk level	Level of risk mitigation
Acceptable risk	Little or no specific risk mitigation required
Tolerable risk	Risk to be mitigated subject to the mitigation being reasonable, practical and affordable. I.e. risk to be reduced to ALARP.
Unacceptable risk	Risk mitigation measures shall be implemented. All risks to be mitigated.

Table 5.6 Risk level and corresponding level of risk mitigation.

5.4 Risk assessment for Thor OWF

The identified possible sources of UXO contamination entail a division of the investigation area into three sub areas. For each of these three sub areas, NIRAS has assessed the risk of an UXO incident before implementation of any risk mitigation measures. The risk assessment for the first sub-area is covered in section 5.4.1, and the risk assessment of the second and third sub-area is covered in section 5.4.2.

5.4.1 Risk assessment for Thor OWF site and part of the cable corridor area

The entire Thor OWF site and most of the cable corridor area is considered to be in Contamination Class B2, in relation to Table 5.3.

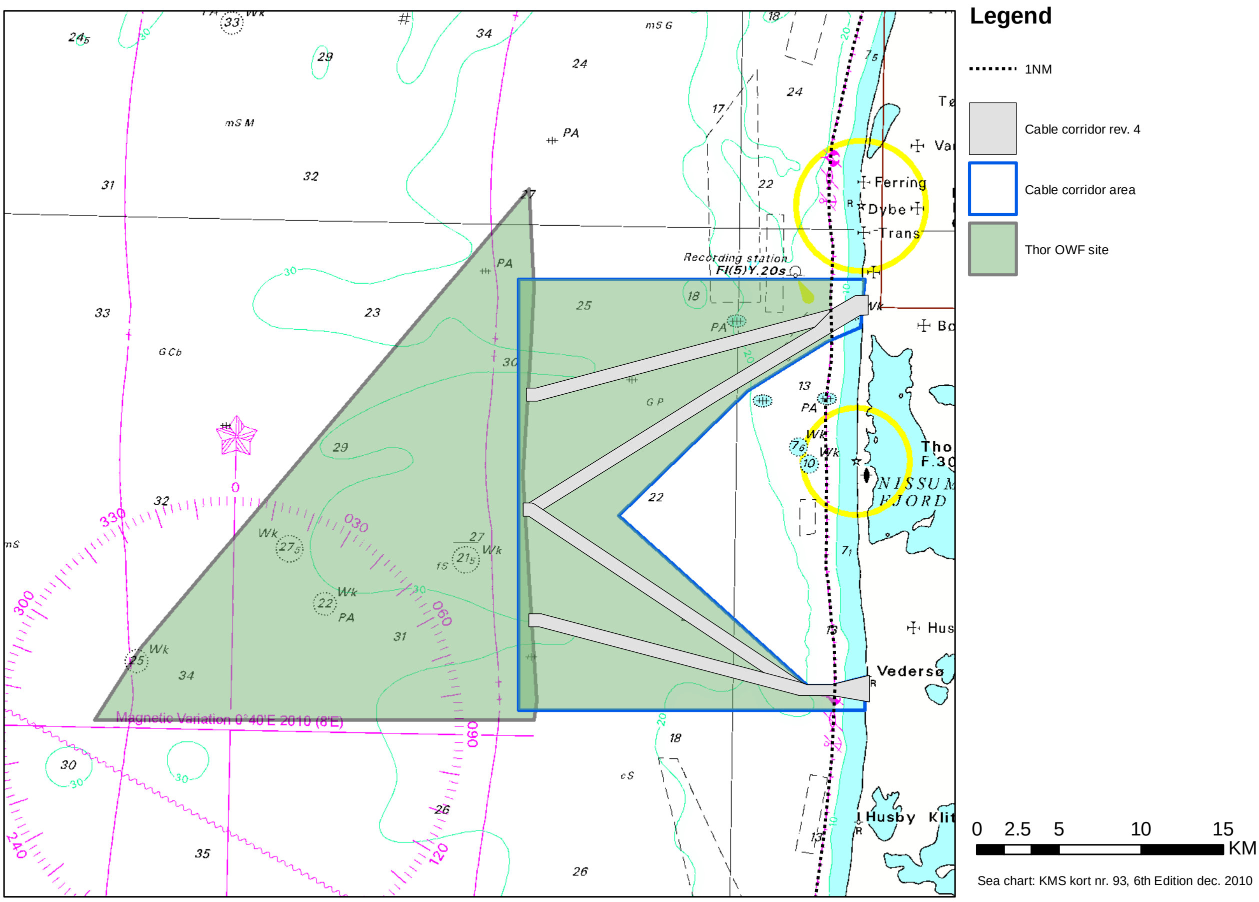


Figure 5.1 Potential UXO contamination of the Thor OWF site and most of the cable corridor area. Green denotes Contamination Class B2, see Table 5.3.

For areas in Contamination Class B2, the possible Likelihoods of Occurrence in Table 5.4 can range from 1-4. Depending on the activities performed and which assets/personnel are near a potential UXO item, and thereby which Consequence Classes that might be obtainable, different risk levels are obtained. In Table 5.7 the risk assessment without risk mitigation measures is summarised.

Because the potential consequences cannot be fully estimated at the present stage, consequence examples are given in Table 5.7. The examples describe the activity in general terms and the obtainable consequences.

Activities	Likelihood of occurrence			Consequence		Risk	
	Activity class	Contamination Class	Likelihood of occurrence class	Consequence Class	Consequence Example	Risk Class	Need for risk mitigation
- Piling - Dredging - Pre-lay grapnel run - Cable installation by ploughing - Trenching or jetting - Placement of scour protection	A4 - Direct and extensive seabed interaction	B2 - Possible contamination	Likely (4)	Class V to VI	A pile is rammed into the seabed and strikes an UXO. The UXO detonates and a person on top of the piling-vessel is killed (i.e. Consequence class V).		Risk mitigation measures shall be implemented. All risks to be mitigated.
				Class II to IV	A pile is rammed into the seabed and strikes an UXO. The UXO detonates and small damages to the installation vessel is sustained causing a two-day delay (i.e. Consequence class III).		Risk to be mitigated to ALARP
				Class I	A pile is rammed into the seabed and strikes a minor UXO. The UXO detonates, however there is no equipment damage, personnel injury or delays (i.e. Consequence class I).		Little or no specific risk mitigation required
- Jack-up - Geotechnical investigation from barge or vessel	A3 - Direct but limited seabed interaction	B2 - Possible contamination	Less likely (3)	Class III to VI	A jack-up barge places its first leg and applies load to an UXO item. The UXO detonates and causes damage to the leg. The barge can be replaced however delays are unavoidable (i.e. Consequence class III).		Risk to be mitigated to ALARP
				Class I to II	A jack-up barge places its first leg and applies load to a minor UXO item. The UXO detonates, however there is no equipment damage, personnel injury or delays (i.e. Consequence class I).		Little or no specific risk mitigation required

Activities	Likelihood of occurrence			Consequence		Risk	
	Activity class	Contamination Class	Likelihood of occurrence class	Consequence Class	Consequence Example	Risk Class	Need for risk mitigation
- Anchoring - Seabed CPT - Vibrocore - Seabed sampling by independent unit	A2 - Indirect and limited seabed interaction	B2 - Possible contamination	Unlikely (2)	Class IV to VI	During retrievement of a core sample the vibrocore unit strikes a highly sensitive UXO. The UXO detonates and a person on top of the vessel used for vibracoring is killed (i.e. Consequence class V).		Risk to be mitigated to ALARP
				Class I to III	During retrievement of a core sample the vibrocore unit strikes a highly sensitive but small UXO. The UXO detonates however only the sampling unit is destroyed (i.e. Consequence class II).		Little or no specific risk mitigation required
- Sailing	A1 - No seabed interaction	B2 - Possible contamination	Highly unlikely (1)	Class I to VI	-		Little or no specific risk mitigation required

Table 5.7 Risk assessment without risk mitigation measures for Thor OWF site and part of the cable corridor area.

5.4.2 Risk assessment for the nearshore cable corridor area

The area near the shore, i.e. within 1 nm (1.852 km) of the shore, has a verified presence of KMA mines corresponding to Contamination Class B4. Furthermore, in the inter-tidal zone (the wet beach i.e. the land that is between the extremes of the high and low tides, and which is covered by high tide, but exposed at low tide) there is a possible contamination from tellermines corresponding to Contamination Class B2.

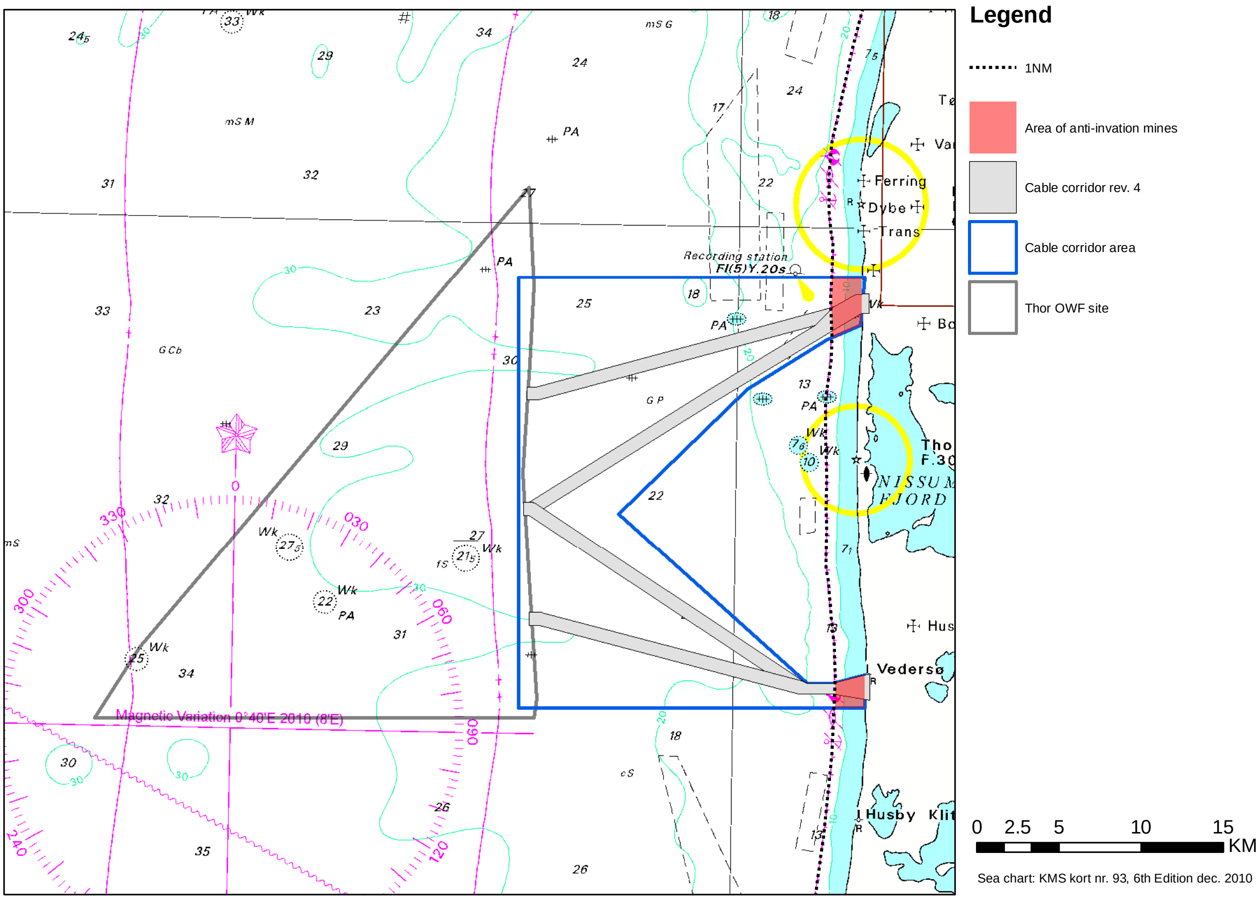


Figure 5.2 *Potential UXO contamination of the Thor cable corridor area near the shore. Red denotes Contamination Class B4, see Table 5.3.*

For areas in Contamination Class B4, i.e. within 1 nm (1.852 km) of the shore, the Likelihoods of Occurrence can be 1, 4, 5 and 6. However, because any remaining KMA mines are considered non-functioning because of many years in a highly degradable environment, the likelihood of occurrence class is reduced to maximum "Unlikely (2)".

For the inter-tidal zone, the likelihood of occurrence of an incident involving a tellermine can range from 1-4. However, because the tellermine condition is likely to be poor due to of many years in a marine environment the likelihood of occurrence class is reduced to maximum "Less likely (3)". In Figure 5.3 the inter-tidal zone is indicated.

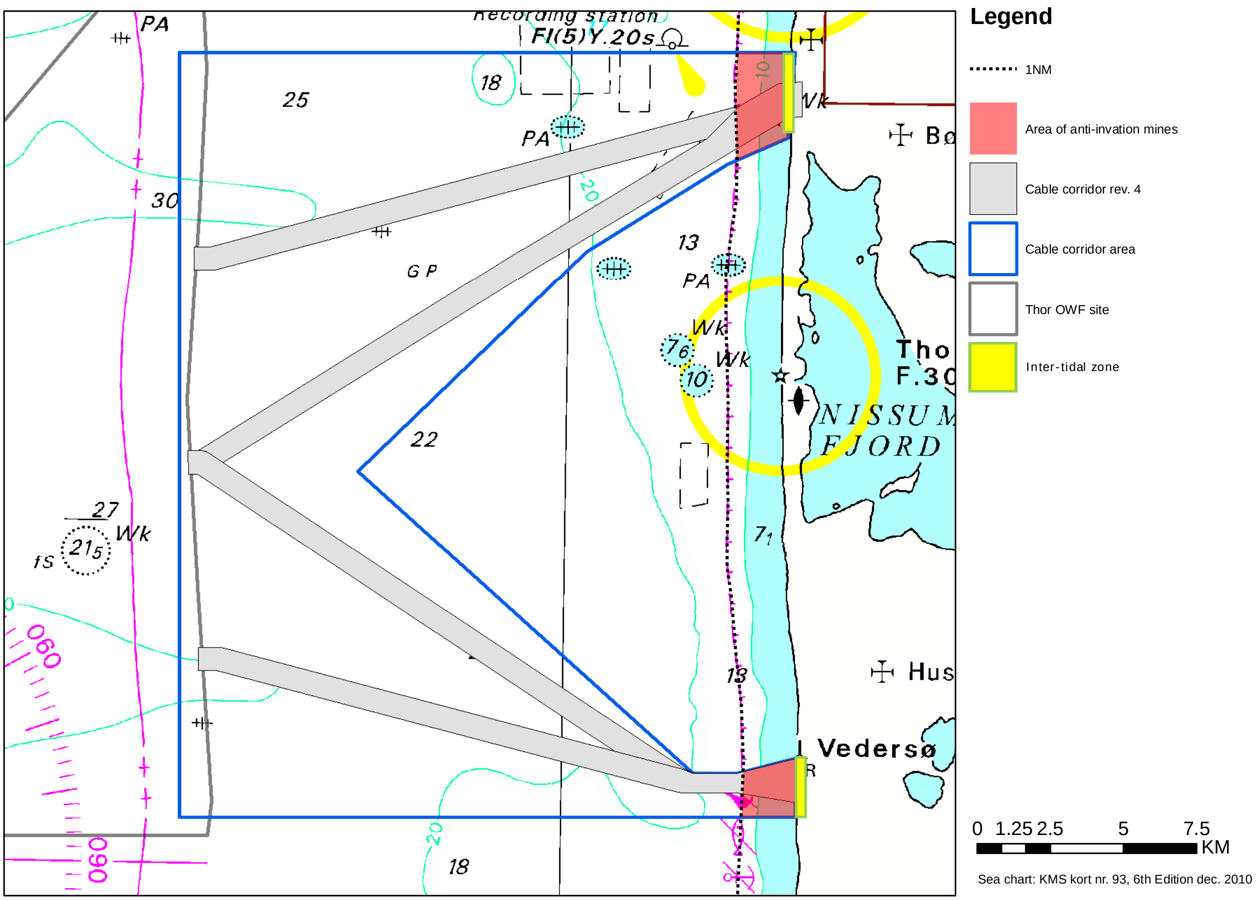


Figure 5.3 Approximate location of inter-tidal zone with potential tellermines.

In Table 5.8 and Table 5.9 the risk is assessed without risk mitigation measures for “KMA mines within 1 nm of the shore” and “Tellermine 43 in inter-tidal zone” respectively.

However, notice that these two risk assessments are UXO type specific and does not include other UXO such as the British 250 lbs MC bomb. For an UXO incident, within 1 nm of the shore, involving another type of UXO than the KMA or tellermine the risk assessment in Table 5.7 is applicable. This means that when risk mitigation is planned it shall be on the basis of the highest risk level when comparing Table 5.8 and Table 5.9 with Table 5.7.

Activities	Likelihood of occurrence			Consequence		Risk	
	Activity class	Contamination Class	Likelihood of occurrence class	Consequence Class	Consequence Example	Risk Class	Need for risk mitigation
- Piling - Dredging - Pre-lay grapnel run - Cable installation by ploughing - Trenching or jetting - Placement of scour protection	A4 - Direct and extensive seabed interaction	B4	Unlikely (2)*	Class IV to VI	During cable-ploughing operations the plough strikes a functional KMA mine. The KMA mine detonates and a person on top of the vessel dragging the plough is killed (i.e. Consequence class V).		Risk to be mitigated to ALARP
				Class I to III	During cable-ploughing operations (where a plough is dragged after a vessel) the plough strikes a functional KMA mine. The KMA mine detonates and damages only the plough. A new plough shall be retrieved causing project delays (i.e. Consequence class III).		Little or no specific risk mitigation required
- Jack-up - Geotechnical investigation from barge or vessel	A3 - Direct but limited seabed interaction	B4	Unlikely (2)*	Class IV to VI	A jack-up barge places its first leg and applies load to a KMA mine. The KMA mine detonates and a person on top of the jack-up barge is killed (i.e. Consequence class V).		Risk to be mitigated to ALARP
				Class I to III	A jack-up barge places its first leg and applies load to a KMA mine. The KMA mine detonates and causes damage to the leg. The barge can be replaced however delays are unavoidable (i.e. Consequence class III).		Little or no specific risk mitigation required

Activities	Likelihood of occurrence			Consequence		Risk	
	Activity class	Contamination Class	Likelihood of occurrence class	Consequence Class	Consequence Example	Risk Class	Need for risk mitigation
- Anchoring - Seabed CPT - Vibrocore - Seabed sampling by independent unit	A2 - Indirect and limited seabed interaction	B4	Unlikely (2)*	Class IV to VI	During retrievement of a core sample the vibrocore unit strikes a KMA mine. The KMA mine detonates and a person on top of the vessel used for vibracoring is killed (i.e. Consequence class V).		Risk to be mitigated to ALARP
				Class I to III	During retrievement of a core sample the vibrocore unit strikes a partly destroyed KMA mine. The KMA mine detonates however only the sampling unit is destroyed (i.e. Consequence class II).		Little or no specific risk mitigation required
- Sailing	A1 - No seabed interaction	B4	Highly unlikely (1)	Class I to VI	-		Little or no specific risk mitigation required

Table 5.8 *Assessment of risk from KMA mines within 1 nm (1.852 km) of the shore. The risk class is without implementation of any risk mitigation.*
**The likelihood of occurrence class is actually above "Unlikely (2)", however because any remaining KMA mines are considered non-functioning the likelihood of occurrence class is reduced to "Unlikely (2)".*

Activities	Likelihood of occurrence			Consequence		Risk	
	Activity class	Contamination Class	Likelihood of occurrence class	Consequence Class	Consequence Example	Risk Class	Need for risk mitigation
- Piling - Dredging - Pre-lay grapnel run - Cable installation by ploughing - Trenching or jetting - Placement of scour protection	A4 - Direct and extensive seabed interaction	B2 - Possible contamination	Less likely (3)**	Class III to VI	During cable-ploughing operations (where a plough is dragged after a vessel) the plough strikes a functional tellermine. The tellermine detonates and a person on top of the vessel dragging the plough is killed (i.e. Consequence class V).		Risk to be mitigated to ALARP
				Class I to II	During cable-ploughing operations (where a plough is dragged after a vessel) the plough strikes a functional tellermine. The tellermine detonates and causes only minor damages to the plough. Operations are up and running the same days (i.e. Consequence class II).		Little or no specific risk mitigation required
- Jack-up - Geotechnical investigation from barge or vessel	A3 - Direct but limited seabed interaction	B2 - Possible contamination	Unlikely (2)**	Class IV to VI	During geotechnical investigations load is applied to a tellermine. The tellermine detonates and a person nearby is killed (i.e. Consequence class V).		Risk to be mitigated to ALARP
				Class I to III	During geotechnical investigations load is applied to a tellermine. The tellermine detonates and causes damage to the drilling rig. The rig can be replaced however delays are unavoidable (i.e. Consequence class III).		Little or no specific risk mitigation required

Activities	Likelihood of occurrence			Consequence		Risk	
	Activity class	Contamination Class	Likelihood of occurrence class	Consequence Class	Consequence Example	Risk Class	Need for risk mitigation
- Anchoring - Seabed CPT - Vibrocore - Seabed sampling by independent unit	A2 - Indirect and limited seabed interaction	B2 - Possible contamination	Unlikely (2)	Class IV to VI	During retrievement of a core sample the vibrocore unit strikes a tellermine. The tellermine detonates and a person on top of the vessel used for vibracoring is killed (i.e. Consequence class V).		Risk to be mitigated to ALARP
				Class I to III	During retrievement of a core sample the vibrocore unit strikes a partly destroyed tellermine. The tellermine detonates however only the sampling unit is destroyed (i.e. Consequence class II).		Little or no specific risk mitigation required
- Sailing	A1 - No seabed interaction	B2 - Possible contamination	Highly unlikely (1)	Class I to VI	-		Little or no specific risk mitigation required

Table 5.9 Assessment of risk from Tellermine 43 in the inter-tidal zone. The risk class is without implementation of any risk mitigation.
***The likelihood of occurrence class is actually one class higher, however because any remaining tellermines are considered in poor condition the likelihood of occurrence class is reduced by one class.*

6 Risk mitigation strategy

6.1 Introduction

The successful completion of the project requires the management of all identified risks, including the risks associated with UXO as identified in this study. The management of UXO related risks should be done within the project's overall risk framework, adhering to the special considerations that the UXO issue calls for.

Management of UXO related risks is a continuous process that runs throughout all phases of the project, and it is important to stress, that no matter how many mitigation measures are implemented, the risk can never be reduced to zero.

The risk mitigation strategy must as minimum include an UXO survey, before site investigation requiring seabed interaction and any installation activities begin, and the subsequent analysis of the gathered survey data. In order to specify the parameters of this UXO survey, minimum threat items for different parts of the investigation area are defined. The extent of the UXO survey in the cable corridor area and the OWF site can be reduced to cover an area surrounding the locations where seabed activities are expected to be performed.

Further mitigation measures should also be implemented depending on the activities undertaken, where the risk assessments in section 5.4 call for it. A mitigation strategy is proposed in section 6.4.

6.2 Minimum threat items

In the part of the Thor cable corridor area within 1 nm (1.852 km) of the shore as marked on navigation charts and denoted in red in Figure 5.2, the possible presence of anti-invasion mines (KMA mines) exists. These are however considered to be non-functional and are therefore not recommended as a minimum threat item. In the inter-tidal zone, the presence of the Tellermine 43 is possible and even though they are probably also in poor condition some are potentially still functioning. Therefore, a Tellermine 43, as described in section 3.3.1.1 is considered the minimum threat item in the inter-tidal zone.

For the rest of the Thor cable corridor area and the entire Thor OWF area, a British 250 lbs MC bomb as described in section 3.4.1.2 is considered the minimum threat item. The MC version is selected because it has a higher mass ratio of explosives to case materials for the same overall mass, than the GP version, making the MC version both more potent and harder to detect.

6.3 UXO survey parameters

The recommended survey configuration for UXO detection of the identified minimum threat items should include a Multibeam Echosounder (MBES), a Side Scan Sonar (SSS) and Magnetometer sensors. All utilized sensors must be able to map items corresponding to the dimensions of the identified minimum threat items. The magnetometer should be configured to map items down to a depth below seabed corresponding to the maximum burial depth.

The Tellermine 43 only poses a threat in the inter-tidal zone and the survey recommendations for MBES and SSS is only valid for the offshore portion targeting the 250 lbs MC Bomb threat item. The MBES Survey parameter recommendation is minimum three hits per 0.25 x 0.25 m cell. Furthermore, it is recommended that the utilized Side Scan Sonar is configured to hit the target minimum three times per pass. Full coverage including nadir for both systems is recommended.

The magnetometer configurations are based on forward modelling of the identified minimum threat items. The calculations take into account the object dimensions, maximum burial depth and sensor height above seabed. Any deterioration or alterations to the item form or shape has not been accounted for. Recommended survey parameters for magnetometer sensors are found in Table 6.1 below.

Item	Magnetometer configuration	Survey line spacing	Sensor height above seabed
250 lbs MC Bomb	TVG	Maximum 5 meters	Maximum 2.5 meters
Tellermine 43	1 m sensor separation	Maximum 1 meter	Maximum 1 meter

Table 6.1 Recommended survey parameters.

The strength of the magnetic field varies in relation to the angle between the item and the tow direction. The weakest signal is achieved when an item is positioned perpendicular to the sensor direction. Both items are relatively small in size and at the maximum burial depth may prove a challenge to detect. The response from each individual magnetometer and the TVG result should be recorded and analysed. The utilized sensors must be of a cecium vapour type and operate at a high recording frequency. It is recommended that underwater positioning is achieved using Ultra Short Baseline System (USBL).

Survey for tellermines in the inter-tidal zone can most-likely be performed with standard onshore methods.

6.4 Proposed mitigation strategy

The risk assessment for Thor OWF (see section 5.4) identifies that the risk from UXO varies, depending upon the location within the project area and the activities conducted. The UXO risk varies from acceptable, over tolerable to unacceptable risk. Specifically, for activities involving direct and extensive seabed interaction, such as piling or dredging, NIRAS has evaluated that the risk can become unacceptable. Notice, however that this risk level is evaluated based on high-level assumptions of the seabed activities involved, the potential disturbance an activity has on an UXO item and the consequences an UXO incident can cause. Detailed information about an activity (such as a work description or method statement) can refine these assumptions and most-likely reduce the risk to a tolerable level.

A proposal for a risk mitigation strategy with a reasonable and practical level of mitigation is as follows:

- Conduct UXO survey in project area and take appropriate measures to mitigate any potential UXO items
  - Should an UXO item be found, the Danish Navy must be contacted immediately according to the standard terms of Danish Maritime Agency and the contractor must not touch it
- Obtain the ALARP sign-off certificate before initiating seabed activities
- Ensure UXO awareness for involved personnel
- Ensure adequate first aid readiness
- Engage an UXO consultant to the project, one that can be on-hold if a potential UXO is discovered
- Manage any risk from wrecks.

With this level of risk mitigation, and with specific attention to the planning of activities with an unacceptable risk level, NIRAS' immediate assessment is that the risk will be mitigated to ALARP.

However, before commencing new offshore activities, the need for further mitigation measures should be evaluated. In section 6.5 examples of UXO risk mitigation measures are given for further inspiration.

6.5 Examples of mitigation measures

Table 6.2 gives general examples of measures that can be taken to reduce the risk of an UXO incident relevant for the UXO types found in the Thor OWF project and cable corridor areas.

Measure	Description	Comments
Localisation of UXO	UXO Survey using MBES, SSS, Magnetometer. Visual inspection using ROV/diver	Search in areas of planned seabed interaction in accordance with the activity classes. Check for anomalies on the seabed. Larger anomalies should be considered as such until they are confirmed not to be UXO
	Operational procedures during seabed interaction.	Check seabed close to impact area.
Planning of seabed interactions	Suitable choice of work methods and tools with respect to the actual UXO risk.	Use of remote-controlled machines. Extension of the arms of the machines in order to maximise the distance between a possible UXO detonation site and the driver of the machine.
	Time planning including slack time for handling UXO.	
Handling of identified UXO	Avoiding	Avoiding the risk by moving the planned activity to a different location, e.g. by changing the cable route. Care should be taken to avoid activities near confirmed UXO
	Operational procedures for Explosive Ordnance Disposal (EOD)	Procedures for EOD assistance from the Danish Navy.
	Permanent assistance from EOD specialist.	The specialist could either be present offshore or on call onshore
	Disposal in situ (BIP) by low order detonation	
	Moving of mines for disposal elsewhere	Careful lifting of mine using air filled bladders before towing
Protection of personnel and assets	Safety procedures in case of identification and disposal of UXO.	Safety distances to non-involved ships, structures and personnel. Divers out of water
	Dredging or excavation	Material passes through two sieves. Catch examined by EOD trained personnel
	Physical protection	Protection of ships, machines and installations against explosion, e.g. armouring drivers' cabins, using air bubble curtain, blast and shock protection of directly involved personnel and assets.

Measure	Description	Comments
	First aid	Carrying of adequate first aid equipment and supplies. Trained personnel.
Education and training	UXO awareness training	All personnel.
	UXO identification courses	Designated personnel.
	MEDIC courses	Designated personnel.
Contingency planning	Proactive measures to encounter UXO incidents and consequences.	Resilience and redundancy, dou-bling of critical assets etc. Detailed plans for action to be taken in case of an unintended UXO explosion or other incidents must be integrated into the con-tractor's HSE plan.
UXO communication	Disseminate UXO information	Keep UXO risk assessments (e.g. this report) available to all rele-vant personnel during all relevant phases

Table 6.2 Example of general measures that can be taken to reduce the risk of an UXO incident.

7 References

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