2024 Paris Session

Paper ID: 10519
B1 INSULATED CABLES
Learning from experiences

A proportional approach of subsea UneXploded Ordnance (UXO)

Marijn HELSLOOT* | **Radboud Universiteit** | **The Netherlands** | **marijn.helsloot@hotmail.com**

Wino SNIP | **TenneT** | **The Netherlands** | **wino.snip@tennet.eu**

Ira HELSLOOT | **Crisislab** | **The Netherlands** | **i.helsloot@crisislab.nl**

Anja DREWS | **TenneT** | **Germany** | **anja.drews@tennet.eu**

SUMMARY

Offshore wind energy will provide a very significant contribution to the energy transition in North-Western Europe. For the transportation of wind energy to the electricity grid on land, high voltage subsea power cables are being installed. To protect them against external threats as dragged fishing gear and dragged anchors, the cables are buried into the seabed and covered by soil, or by rock placements at locations where burial into the seabed is not possible.

The installation of subsea cables exposes those involved to several occupational risks, of which some are potentially fatal. Most of these risks are assessed and mitigated following the approach of risk (hazard) inventories and evaluations, followed by the implementation of risk mitigations. A specific threat when burying cables at sea is the encountering of unexploded ordnance (UXO). UXO are remnants of warfare and of military exercises, for instance sea mines, aerial bombs, artillery shells, depth charges and torpedoes. Typically, these UXO have been laying at or in the seabed for several decades. In the North Sea multiple UXO are fished up each week by fishermen who are using fishing nets dragged over the seabed. The number of fatal incidents with UXO in the North Sea of the last decades, fishermen included, can be counted on one hand.

With regard to the risks associated with UXO however, the common approach used for subsea cable installation over the last decades has been based on worst-case scenarios, where the probabilities of risks involved where assessed to a lesser degree. Following this approach any UXO potentially encountered is for instance considered to be in pristine working order, armed and any thinkable incident involving UXO is required to be mitigated. Often without hardly any limitation to costs or efforts or unintended harmful effects of the mitigating measures, such as the associated occupational hazards.

Given the very extensive plans for the installation and operation of an offshore electricity network on the North Sea and given the extensive efforts which would be required for the associated UXO identification and clearance operations, an investigation has been made with occupational risk experts into the UXO risks. Question was whether the currently followed worst-case scenario approach of UXO risks is proportional to the factual risks mitigated. As a first approach, for this assessment the objective or quantitative risk has been calculated. The UXO risks study concludes that people involved in the mitigation of the UXO related risks at sea are exposed to larger other occupational risks on a fatality, while mitigating UXO related risks, than the mitigated UXO related risk.

As a second approach, a cost-benefit assessment has been made, using the DALY (Disability Adjusted Life Years) methodology to determine if measures taken to mitigate a risk are proportional from a financial point of view. This approach concludes that the financial costs involved in the UXO risk mitigation appear to be very significantly disproportionate to the mitigated risk. The current worst-case scenario approach with regard to the UXO risks lies at the basis of this significant disproportionality.

KEYWORDS DALY (disability adjusted life years) method, Installation cost reduction, Proportional risk assessments, Subsea power cable installation, Unexploded Ordnance (UXO)

1. INTRODUCTION

Offshore wind energy will provide a very significant contribution to the energy transition in North-Western Europe and especially in The Netherlands. In 2022, the Dutch government increased the target for offshore wind energy from 11 to 21 gigawatt (GW) by around 2030 [1]. Currently, five wind energy areas are operational in The Netherlands, one is assigned but still under construction, and four new areas have been allocated.

For all these offshore wind turbine projects, high voltage subsea power cables are needed to connect the wind turbine parks to the grid on land. To protect these cables against external threats as dragged fishing gear and dragged anchors, these cables are buried into the seabed and covered by soil or by rock placements at locations where burial into the seabed is not possible (for instance on crossings with other subsea cables and pipelines). The Transmission System Operator is tasked with the installation of these offshore cables. Installing cables at sea involves various risks, including economic, safety and environmental risks. Many of these risks are assessed *comprehensively* as part of the HAZID (Hazzard Identification) preceding the installation operations. Examples are the fall, trip and slip risks for those working on a ship and the 'line-of-fire' risks, as for instance the risk of being hit by a snapping rope during pulling operations [2].

One of the risks that is not comprehensively assessed is the UXO (Unexploded Ordnance) risk. If even the slightest chance of presence of UXO exists along a cable route, this must be further investigated and detected (and ultimately cleared) using object detection (a method to check for objects with a certain ferro-magnetic mass in the subsurface with a magnetometer or for objects without the required ferro-magnetic mass for detection, but of a certain size, using acoustic methods). This reasoning shows a one-sided focus on the risk: only the (worst-case) likelihood of encountering a UXO is considered, where the possible impact of the UXO as a result of the cable installation operations is examined minimally only. Additionally, we observe that there is no comprehensive consideration of the risk: the amount of societal resources deployed or occupational safety risks to manage the UXO risk is not taken into account in the decision to implement UXO risk mitigating measures.

The limited focus is partly explained by the widespread application of the precautionary principle [3, 4, 5]. Uncertain risks must be avoided at all costs, especially occupational risks. The infiltration of the precautionary principle has also occurred in The Netherlands, for example, in the Climate Policy of the ministry of Economic Affairs and Climate (See the principles they have formulated e.g., [6]).

Where the degree of risk has not been assessed, it is also unclear what the effect of the mitigating measures is, relative to the mitigated UXO risks. The UXO risk for employees is commonly considered to be reduced, as the effort spend should be considered effective by some means in order to be considered justifiable. It has however not been investigated so far whether these efforts do indeed result in a lower occupational risk for the employees involved. An integral assessment has therefore not been possible so far: as long as the UXO related risks are not quantitatively understood, it is not possible to evaluate whether these efforts are proportional to the effect sorted, or whether societal resources are being spent appropriately.

It is important to take an integral approach to risks, because mitigating measures could also have adverse effects [5]. On the one hand, the current mitigating measures introduce additional risks, due to further extended and prolonged work at the North Sea, where the individual occupational risks in the maritime sector are relatively high compared to occupational risks on land. On the other hand, mitigating measures bear relatively high and significant costs to society, in terms of time, money, and labour. The question must always be asked whether these resources could be spent in a better way.

There are different principles to determine whether a risk is acceptable [7]. The precautionary principle is one of them. This article tests two other principles. In section 3, the principle of absolute risk is tested, and it is examined whether the UXO risk meets the norm. In section 4, the ALARP principle is tested, and it is assessed whether the current investments are reasonable enough to mitigate the risk.

2. CONTEXT

No incidents are known during dredging or cable installation in the Netherlands, at least not since 1970 [8]. In German, there have been several explosions involving UXO during dredging or construction activities at sea (without fatalities since 1950) [9]. Nowadays, a bomb grid is used in the drag head, when dredging in areas where UXO can be encountered, and the pump room is closed watertight during dredging (internal communications[1] and [10]). The size of gaps in the bomb grid is approximately 8-10 cm, based on an analysis of what can explode in the pipes and pump without causing pipe or pump rupture. The pump room is always closed during dredging, but the bomb grid is sometimes removed when working in an area where UXO is not expected. The bomb grid reduces production, where keeping the pump room closed does not.

The Borssele export cables project was the first subsea cable laying project in the Netherlands where an UXO survey was conducted.[2] The costs were approximately € 60 million. At that time, seven UXOs of significant size were found in the cable installation corridors. Subsequently, other subsea cable installation projects also followed.

Formally, this study concerns 'existing explosive remnants of war' (as outlined in the box below). UXO is a more commonly used term. In this study, we use UXO for convenience, but explicitly include 'abandoned explosive ordnance' in this study.

Definition: *Existing explosive remnants of war* means 'unexploded ordnance' and 'abandoned explosive ordnance' that existed prior to the entry into force of this Protocol for the High Contracting Party on whose territory it exists.[3]

Unexploded ordnance means explosive ordnance that has been primed, fused, armed, or otherwise prepared for use and used in an armed conflict. It may have been fired, dropped, launched or projected and should have exploded but failed to do so.

Abandoned explosive ordnance means explosive ordnance that has not been used during an armed conflict, that has been left behind or dumped by a party to an armed conflict, and which is no longer under control of the party that left it behind or dumped it. Abandoned explosive ordnance may or may not have been primed, fused, armed or otherwise prepared for use.

The labour legislation in the Netherlands states that risks must be made transparent, and measures must be taken to mitigate dangers (see Article 5 of the Working conditions act).[4] The first however, making a transparent, comprehensive assessment of all labour related risks, has not been done for the UXO related risks. It is assumed that UXO always poses a significant danger, without considering the specific circumstances (such as work methods, techniques, and instructions) and without considering the likely status of the UXO after more than seventy years at the bottom of the sea since World War II and longer since World War I. As indicated in the Working conditions decree (article 4.10) and the Proportionality Guide [11], it is a shared responsibility between client and contractor to implement mitigation measures for unacceptable risks.

Some limited consideration however is given to the mass of the explosive; for example, on land, Small Caliber Ammunition is generally no longer considered a risk for construction work, and in the North Sea, there is a minimum mass threshold for detection, in many cases dependent on the water depth. [12] has found that there is no risk of injury with aerial bombs of less than 500 lbs at a water depth of at least 20 meters (with an explosion right under the ship) and there is no risk of with aerial bombs of 500 lbs with an explosion 40 meters behind the vessel. The degree of the risk of injury with UXO above 500 lbs is not (quantitatively) determined in this study.

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[1] Internal communications with two Dutch companies operating in the North Sea. Both organisations were involved in the working group that was involved in the realization of this study (see [13]).
[2] Personal communications with the contractor in the Netherlands that installs export cables on wind farms in the North Sea.
[3] Protocol on Explosive Remnants of War, Genève, 28-11-2003, Article 2.
[4] See Working conditions act article 5 and Working conditions decree article 4.10.

The fact that UXO at sea are not always considered dangerous anymore is demonstrated by the annual recovery of explosives from the bottom of the sea by fishermen, fishing with nets dragged over the seabed. Data from Royal Netherlands Navy show that fishermen registrate most of the encountered UXO in the North Sea. It is estimated that since 1970, at least 30,000 explosives have been retrieved from the North Sea during fishing activities, with two fatal incidents [13]. These two explosions occurred on board the ship and not on the bottom of the North Sea.

Two case studies
Two UXO surveys were recently conducted along the routes of the offshore wind export cables for the Hollandse Kust (zuid) offshore wind farm and for the Borssele offshore wind farm.[5]

Hollandse Kust (zuid) export cables
The survey area of the project Hollandse Kust (zuid) is 7.65 km^2. 1 UXO (above the threshold value) or 0.131 UXO per km^2 was found. A total of 732 objects were examined, and ultimately, only 1 turned out to be an actual UXO above the set threshold mass. This equals 0.137%.

However, it must be noted that not all encountered magnetic anomalies with a modelled ferro magnetic mass above the set threshold value for considered dangerous UXO's were examined. During the survey, 3,680 magnetic anomalies have been encountered. We estimate that (3,680 * 0.137%=) 5 of the magnetic anomalies are UXOs above the set thresholds. This results in an expected number of UXO 0.66 UXO above those set thresholds per km^2.

Borssele export cables
The survey area of the project Borssele is 13.15 km^2. 7 UXO (above the threshold value) or 0.532 UXO per km^2 was found. A total of 1,350 objects were examined, and ultimately, 7 turned out to be an actual UXO above the set threshold mass. This equals 0.519%.

Not all encountered magnetic anomalies were examined. During the survey, 10,681 magnetic anomalies have been encountered.[6] We estimate that (10,681 * 0.519%=) 55 of the magnetic anomalies are UXOs above the thresholds. This results in an expected number of UXO 4.2 UXO per km^2 above the set thresholds.

3. ABSOLUTE RISK

3.1 Risk assessment

There are different ways to assess risks: objectively or subjectively [14]; quantitatively or qualitatively [15]; probabilistic or deterministic [16].

As of now, for the topic of UXO at sea, there is no risk approach that takes into account the *quantitative* probability and impact of an incident with an encountered UXO. We observe three ways in which the issue of the UXO related risks is addressed:

1. Only the 'possible' likelihood of presence (encountering) is considered. This is the approach commonly used with the onshore UXO risk;
2. The focus is on the effect (impact) of an UXO related incident, and then only explosives with a mass above a set threshold are surveyed for. This approach is still very general.
3. Both the effect (impact) and probability of encountering a UXO are qualitatively considered, for example, in a matrix. When both the probability (of encountering) and the consequence (impact) are assessed to be significant, UXO detection is carried out. This is the case, for example, in the UK [17].

The current practice is, therefore, that analyses regarding UXO related risks are primarily subjective or qualitative or deterministic. There is no consensus on the effect of explosion of an UXO [18].

An alternative and new approach is to quantify this risk. The data sets we use for this are:

- Data from Royal Netherlands Navy with regard to encountered UXO at the North Sea[7]
- Data about dredging (quantities) [19]

[5] Data retrieved from internal communication.
[6] Please note that as in the preceding case study we have nearshore area with intense shipping of approx. 35 km long (Rede van Vlissingen, Westerschelde delta, Walvisstaart) with a considerable higher amount of objects and an area further at sea.
[7] Data retrieved from internal communication. In [13] we give an overview of this data.

- Incidents with explosives in the Netherlands (from 1970) (see for incident data [8])
- Previous (technical) studies [e.g., 12, 20]

To quantify the risk, we use the following formula:

$$p_{\text{fat | UXO}} = p_{\text{enc}} \times p_{\text{expl | enc}} \times p_{\text{fat | expl}}$$

$p_{\text{fat | UXO}}$ = Probability of a fatality as the result of an UXO related incident
p_{enc} = Probability of encountering a UXO at sea
$p_{\text{expl | enc}}$ = Probability of an explosion of the UXO as result of the encountering
$p_{\text{fat | expl}}$ = Probability on a fatality as the result of an explosion of the UXO

When studying the statistics, we observe the following notable points:

- In the Dutch North Sea annually, dozens of explosives are still found in nets by fishermen, and explosives are also regularly encountered during dredging (data from Royal Netherlands Navy).
- Until 2015 (when UXO risk mitigating measures began in the North Sea), 1,634.9 million m^3 was dredged at sea in Europe, and 897.9 million m^3 on the Dutch North Sea [19]. This corresponds to approximately 2,610 km^2 and 1,430 km^2 dredged, respectively.
- There are some known incidents where an UXO has exploded on, or around, a fishing vessel. There are no incidents with exploding UXO known of other activities on the (Dutch) North Sea [8].
- The probability of an unexpected explosion due to cable laying and burial into the seabed is smaller than the chance of an unexpected explosion due to dredging, given the very low speed of cable burial, given the water jetting of the seabed during the cable burial which further decreases and physical impact and thus the limited impact energy with obstacles at or in the bottom of the sea as well as given the absence of repetitive contact with a single obstacle as can be the case while dredging in sand borrow areas [20].

Based on historical data, statistics and scientific studies (see above), we have determined the various probabilities. The results are presented in Table 1. For a complete overview of the quantitative analysis, we refer to the report [13]. Due to the absence of incidents, we could only determine a 'less than' probability. This means that the calculated risk has been conservatively estimated. Moreover, there is no study available (yet) on the effect of seventy years of salt water on the functioning of an UXO. Given the amount of UXO fished up every year however and given the very low number of incidents having occurred over the last decades, it seems justifiable to state that for a very large amount of types of UXO which have submerged in salt water, the likelihood of an explosion as the result of physical contact has reduced significantly with the years. Aerial bombs with a chemical time delay fuse might potentially be an exception to that (however salt water might potentially have a stabilising (corroding) effect on those fuses as well over time).

Type	**P(encounter per km²)**	**P(explosion per object)**	**P(fatality)**	**Individual risk per km²**
Mines	0.638	$< 2{,}7 * 1\ 0^{-4}$	0.039	$< 6.72 * 10^{-6}$
Aerial bombs	0.207	$< 1{,}1 * 10^{-3}$	0.032	$< 7.29 * 10^{-6}$
Depth charges/torpedoes	0.020	$< 1{,}3 * 10^{-2}$	0.047	$< 1.22 * 10^{-5}$
Projectiles	0.061	$< 1{,}4 * 10^{-3}$	0	0
Total	**-**	**-**	**-**	$< 2.62 * 10^{-5}$

Table 1: UXO risk assessment for a fatal incident

Now that we have calculated the risk per km^2, we can also calculate the individual risk for employees on board a ship. The cables are buried at a speed of, in the order of, 200 m/hour as a higher estimation. When the low ground pressure under the tracks or skids of cable burial tools (order 10 – 20 kPa) is considered not to have any significant impact on encountered objects (note: this is a qualitative assumption to us based on results from [20] and which is supported by the absence of explosions of UXO at the seabed over the last decades as the result of the impact of dragged otter boards over the seabed, during fishing with dragged nets), the width of soil disturbed by cable burial is in the order of 0.6 m. So, every hour (0.6 m * 200 m =) 1.2 * 10^{-4} km^2 seabed is affected.

If we assume 24-hour 'on-and-off' shifts, with 150 working days per year, an employee affects 0.432 km^2 seabed per year, and the individual risk is at least smaller than 1.1 * 10^{-5} per year (less than 1 in 91,000 year).

Case Doordewind Wind Farm Zone

In the study, the probability of detection of a UXO per km^2 is determined based on statistics and historical finds. It is a general analysis of the probability of detection in the North Sea. However, a project specific probability on encountering a UXO map can also be created for projects using historical data from former mine fields and jettisons (aerial bombs dropped at sea).

For the Doordewind Wind Farm Zone (DDWWFZ) project, a map has been created showing the probability of encountering a UXO [21]. In the area where the Doordewind Wind Farm Zone is located, the probability of encountering mines and aerial bombs is indicated. The majority of the area consists of a probability of less than 0.1 per km^2 (47% of the area), 0.1-0.5 per km^2 (33%), or 0.5-1.0 per km^2 (12%). In the southwest and southeast of the area, the density is higher: 1.0-1.5 per km^2 (5%), 1.5-2.0 per km^2 (2%), or 2.0 – 2.5 per km^2 (1%). The probability of encountering aerial bombs is minimal (less than 0.05 per km^2) in the area, and the probability of encountering torpedoes and depth charges has not been determined. In this illustrative case, we only consider the probability on a fatality due to sea mines.

Density mines	**P(encounter per km²)**	**P(explosion per object)**	**P(fatality)**	**Individual risk per km²**	**Area in %**	**Individual risk**
< 0,1 per km^2	0.05	< 2.7 *10^{-4}	0.039	< 5.27 * 10^{-7}	47%	< 2.47 * 10^{-7}
0,1 – 0,5 per km^2	0.3	…	…	< 3.16 * 10^{-6}	33%	< 1.04 * 10^{-6}
0,5 – 1,0 per km^2	0.75	…	…	< 7.90 * 10^{-6}	12%	< 9.48 * 10^{-7}
1,0 – 1,5 per km^2	1,25	…	…	< 1.32 * 10^{-5}	5%	< 6.58 * 10^{-7}
1,5 – 2,0 per km^2	1,75	…	…	< 1.84 * 10^{-5}	2%	< 3.69 *10^{-7}
2,0 – 2,5 per km^2	2,5	…	…	< 2.37 *10^{-5}	1%	< 2.63 * 10^{-7}
Total	**-**	**-**	**-**	**-**	100%	< 3.53 *10^{-6}

Table 2: UXO risk assessment for case Doordewind Wind Farm Zone

If we take into account the working hours and seabed disturbance per employee, the risk is < 1.5 * 10^{-6} per employee per year.

3.2 Risk acceptance through testing against a guidance

E. Vanem in "Ethics and fundamental principles of risk acceptance criteria" [7] provides different perspectives on risk acceptance. The absolute risk is one of them. By testing against a standard, it can be objectively determined whether something can be considered safe enough. A distinction is often made between unacceptable, acceptable, and negligible risks.

Central assumption: Given the central position of the risk of a fatal incident in the Dutch safety policy, the central risk assessed for a proportional approach of UXO, is the risk of a fatal labour related incident. An explosion of a UXO subsea bears other risks as well, for instance the risk of an environmental impact (killing and harming of mammals and fish, spreading of polluting chemicals from the explosive material in the UXO), the risk of time delays and additional costs on the project and the risk of a negative exposure in media. Those risks have been assessed as well (see for instance 4.3), but these are not the primary focus of this publication.

In the Netherlands, there is no guidance for occupational safety for acute danger. The generally accepted individual risk in the Netherlands since 1989 is 10^{-5} per year (1 in 100,000 year) [22]. The accepted risk per risk component, such as exposure to a hazardous substance, is 10^{-6} per year (1 in 1,000,000 year). The generally negligible risk for both aspects is one hundred times lower (i.e., 10^{-7} (1 in 10,000,000 year) as the risk of death from an activity/risk compartment and 10^{-8} (1 in 100,000,000 year) for a specific substance/risk component). These standards apply to various areas, including Water Safety (Delta Plan), Seismic Risks, and External Safety of Installations but also to hazardous substances.

Note that in the international maritime sector, a lower standard applies: probabilities less than 10^{-6} (1 in 1,000,000 year) are deemed negligible, and probabilities less than 10^{-4} (for the crew) (1 in 10,000 year) are deemed acceptable [7, 23].

Considering all this, the conclusion must be that for this assessment, the best option is to fall in line with the current developments of legislation on risk policy, which specifies into the use of an individual risk as leading figure for the assessment, with a validation criterion set on a probability of a fatal involvement of 10^{-5} (1 in 100,000 years).

If we test the risk against this guidance, the risk of a fatality, due to an explosion of a UXO as the result of subsea cable installation operations, could be considered to be acceptable. The risk that a full-time employee dies due to UXO in the North Sea is *less* than $1.1 * 10^{-5}$ (less than once in 90,909 year), allowing us to conclude that the risk of a fatality due to an explosion of a UXO as the result of cable installation operations for the North Sea *on the average* is acceptable according to regular Dutch safety policy. For the risk of a fatality due to a UXO for specific areas of the North Sea, the density of UXO for that specific area needs to be assessed and applied in the area specific risk estimation.

An employee will not be installing cables full-time and year-round. In the Netherlands, a maximum 200 km of subsea export cable will be installed in the North Sea per year.[8] Given the low ground pressure below cable installation tools (in the order of 10 – 20 kPa) and given the absence of explosions in the North Sea as the result of the impact of bottom trawling fishing gear with UXO, only physical contact between the ground penetrating part of the cable burial tools and an UXO is considered to potentially pose a risk of any significance to cause an explosion of that UXO. Assuming a disturbed seabed width of 0.6 meters during cable burial, approximately a maximum of 0.12 km^2 of the North Sea floor is disturbed per year on the current projects in the Netherlands. A cable burial ship covers an average of 200 meters per hour, requiring 42 days of cable burial operations per year. As mentioned, we assume 24-hour ‘on-and-off’ shifts. Employees work 21 days at sea for cable installing, disturbing approximately 0.06 km^2 of the North Sea seabed per employee per year. In that case, the individual risk is less than $1.6 * 10^{-6}$ (less than once in 625,000 year) and as such meets the standards for a risk component on a labour related fatal incident.

3.3 Principle of equivalency

Another principle for determining whether an assessed risk is acceptable, is by comparing it with a similar or more familiar risk [7]. First of all, note that until a few years ago, the risk of a fatality due to an explosion of a UXO as the result of installing a subsea cable, without a dedicated UXO survey and without the identification and clearance of any potential UXO’s, was considered an acceptable risk. That approach did not result in any known fatalities during subsea (telecom- or power-) cable installation as the result of an accident with an UXO. The factual risk of such a fatal incident has not increased since then. Instead, aging and corrosion of UXO at the bottom of the sea appears to reduce the likelihood of the most commonly encountered UXO at sea to explode upon mechanical impact [24, 25]. What has changed over the last decades, is the perception of the risk of UXO related incidents and the acceptance of the perceived risk. It seems that the fewer UXO related incidents occur (see [8]), the lower the acceptance of the perceived risk gets.

An equivalent with which the UXO risk can be compared, are regular activities in the construction industry (Dutch sector) or work at sea. The risk of a labour related fatal incident in the construction industry in the Netherlands is $4.8 * 10^{-5}$, i.e., 1 in 20,000 years [26]. Major risks there include falling from heights and working with machinery. These risks also apply to working at sea. This means that the UXO risk in the North Sea is at least 4 to 5 times smaller than the regular occupational risk of a fatality. Moreover, 29% of all incidents involve falling from heights. Insight into the number of fatal incidents due to falling from heights is lacking, but if we consider the 29% as representative, the risk of death from falling from heights in construction is $1.4 * 10^{-5}$ per employee per year (1 in 71,000 years). The UXO risk is thus smaller than the risk of death due to falling while working at heights in construction.

[8] Personal communications with the contractor in the Netherlands that installs export cables on wind farms in the North Sea.

Working at sea also has risks, in particular fall, slip and trip risks and line of fire risks (for instance being hit by a snapping wire). The fact that people at sea are working on a constantly moving surface (roll, pitch, heave etc of the vessel), in a relative confined space (a ship) and are often exposed to harsh conditions (swell, storm etc.), does increase the risks on labour related accidents. Every year people die while working at sea. The general risk of working on service ships is once in thirty-five thousand years ($3.0 * 10^{-5}$, i.e., 1 in 35,000 years) [27]. This means that the UXO risk in the North Sea is at least three times smaller than the regular occupational risk of working at sea.

An observation following the above comparison is that the UXO risk is smaller than the risk of regular activities at sea. The employees conducting the investigation, detection and clearance of obstacles encountered at and in the bottom of the sea, which could potentially be a UXO, are therefore exposed to a higher risk than the (additional) risk that employees face due to the presence of UXO on and in the soil. Moreover, the UXO survey work and UXO related route clearance work take significantly longer than installing (lay and burial) of the cables into the North Sea bed.

3.4 Sub-conclusion

The UXO risk to which people working at the North Sea are exposed on average, during the installation of cables at sea, without taking mitigating measures, meets the guidance for safety in the Netherlands. The labour risks following from implementing mitigation measures to reduce the perceived UXO risk, are higher than the UXO risk itself, for at least cable installation workers for the North Sea on average. This means that the probability of a fatality during all cable installation associated operations for the North Sea on average is actually higher with the current UXO mitigation measures than without those UXO mitigating measures. The current approach of the UXO risks at sea thus results in an increased probability on a fatality, rather than in a reduced risk of a fatality. The current approach of the UXO risk at sea thus is counterproductive with regard to labour safety. It is due to a currently common lack of quantitative assessment of the statistics of labour related fatalities at sea, including the UXO risks, and due to the fact that for the UXO related risks at sea a *worst-case scenario* approach is used, that people working at sea, under the current approach for the North Sea on average, are exposed to a larger risk of a fatality, instead of to an intended reduced risk of a labour related fatality.

4. ALARP

4.1 As low as reasonably practicable

Another principle for assessing whether risks are acceptable is the ALARP principle [7]. Unlike the (meeting the) absolute risk (section 3), this principle looks at what is 'reasonably practicable', both concerning the risk and the measures taken. This approach prevents too much focus on meeting standards [23].

Considering what is reasonably practicable contributes to assessing risks in their context. According to [5], risks must be seen in the right perspective. Societal resources can only be spent once and therefore it should be allocated in a way that maximizes the most benefits.

There are at least two ways to democratically assess what is reasonably practicable. The first way is to determine the Value of Statistical Life (VOSL). A value can be assigned to determining the value of a statistical human life. The VOSL may vary by risk source. [28] conclude that the VOSL for prime aged workers in the USA is $ 6,7 million. This has not been determined for the UXO risk or the risk for employees in Dutch context.

A second way is a cost-benefit analysis [5]. In this study, we see two benefits and two costs. The benefits are preventing accidents and preventing damage to equipment. The costs include the direct costs of mitigation measures and the additional risk caused by the mitigation measures. In contrast to the absolute risk, accidents causing injury will now also be considered, as this contributes to a loss of quality of life.

4.2 Costs of mitigation measures

4.2.1 Direct costs

The current costs incurred in mitigating the UXO risk are clear. On average, the mitigation measures cost € 0.15 million per km cable route on the average (internal data from four recent projects in the

Netherlands[9]). Conservatively approached about half of these costs are for the magnetometer survey. The other half of the costs, € 0.075 million per km, is for identifying and clearing objects (ID&C). These are the costs for approaching the encountered magnetic anomalies at the bottom of the sea with a remotely controlled vehicle, uncovering these objects and visually identifying the nature of the objects. These ID&C costs are the extra costs in this case, as the magnetometer survey is required as well to survey the route for (other) obstacles to effective cable protection by burial into the seabed.

4.2.2 Indirect costs

The other cost is the number of occupational health and safety accidents that occur while working at sea. These additional occupational risk costs arise from identifying and clearing objects. On average, 3.8 objects are identified and cleared per km cable route. (In nearshore areas, near the approached to harbours and in the vicinity of shipping routes however this number can be very significantly higher.) Less than 1% of the identified objects, as encountered on the most recent subsea power cable installation projects in Dutch water, did appear to be UXOs which needed to be cleared. Identifying and clearing objects takes place at (conservatively approached) a rate of 5 anomaly locations per day, so 1 km cable route results in 0,76 working days at sea on the average. (In coastal sections, near the beach, this number however can be as low as 1 anomaly location per day).

To determine the *safety costs* of mitigating the risk of injury and death, we use the DALY (Disability Adjusted Life Years) methodology: we look at the number of healthy (disability adjusted) life years lost. The assumptions we use in this study are as follows:

- When an employee dies, an average of 40 healthy life years is lost. When an employee is injured, an average of 0.16 healthy life years is lost.
- A lost healthy life year is considered to *cost* a maximum of € 80,000. This is the maximum allowed investment to gain a DALY is set as € 80,000 for chirurgical treatment in the Dutch health care system [29].
- We assume that there are approximately (24 to 40, on average) 32 people on board a ship involved in ID&C operations.
- The individual risk of fatality when working at sea at a service vessel is $3 * 10^{-5}$ per employee per year. The individual risk of injury when working at sea at a service vessel is $2.5 * 10^{-4}$ per employee per year [13]. An employee works approximately 150 days, whiles being 24 hours a day on board of the vessel during those days. The risk of a fatality is $3 * 10^{-5} / 150$ per employee per day and the risk of an injury $2.5 * 10^{-4} / 150$ per employee per day.

The safety costs according to the DALY methodology is € 16.08 per km.

4.3 Benefits of mitigation measures

4.3.1 Primary benefits

It would be clear what the primary benefit is of mitigating the UXO related risks by conducting a survey and approaching objects for their identification: the UXO risk is reduced to (almost) 0, if the survey would be able to indeed detect all UXO within the area affected by the cable burial operations, above the considered UXO threshold values. We note that not all objects are detected even with a survey, but we expect that the larger UXOs, that pose a potential risk to employees (i.e., the 1,000 lb aerial bombs and larger and the ground mines) will be detected due to their relatively large ferro-magnetic mass or to the specific survey methods, deployed in areas with a higher risk of encountering non-ferro-magnetic ground mines, as the LMB mines.

To determine the benefits of mitigating the UXO related risk of injury and death, we use the DALY methodology (see above). The new assumptions we use in this study are:

- On a cable burial ship, there are an average of approximately 70 people present at the same time. All these people (both those who work and those who rest) are in a conservative approach exposed to the UXO related risk.

[9] Personal communications with the contractor in the Netherlands that installs export cables on wind farms in the North Sea. We received data from the projects Borssele & Hollandse Kust North & West & South.

- The individual UXO risk of fatality when working at sea at a service vessel is $2.6 * 10^{-5}$ per employee per km^2. The individual UXO risk of injury when working at sea at a service vessel is $2.2 * 10^{-4}$ per employee per km^2 [13]. With 0.6 m width of disturbed soil during cable burial, 0.0006 km^2 of the seabed has been disturbed per km route length.

The safety benefits according to the DALY methodology are € 3.61 per km of cable route.

4.3.2 Secondary benefits

A secondary benefit is the prevention of damage to equipment. It is however to be appreciated that the costs associated with the UXO survey efforts will have to be balanced against the costs of the risk of damage to the equipment.

For convenience, we assume € 10,000,000 in case of UXO explosion (regardless of type). The damage will mainly occur to the jet trencher (€ 2,000,000) and the resulting delay (€ 8,000,000). The risk of explosion is $< 7.5 * 10^{-4}$ per km^2 (depending on de type of UXO, see table 1). With 0.6 m width of disturbed soil, 0.0006 km^2 of the seabed has been disturbed per km of cable route.

The secondary benefits are € 4.47 per km of cable route.

4.4 Sub-conclusion

Approximately € 0,075 million (= € 75,000) per km has been spent on identifying and clearing objects from cable routes, which are suspected to be UXO. In addition, employees have been exposed to risky conditions (because working at sea is a labour risk), with safety costs of around € 16.- (by lost life years) per km cable route. The safety benefit (excluding damage) is about € 4.- (by lost life years) per km cable route. The secondary benefits are €4.50 per km cable route. It is clear from a cost-benefit perspective that these investments are unjustifiable: the safety benefit is nil while the costs are enormous.

We note that insurance companies also assess the risk in a similar manner. Currently, the risk of damage due to a UXO incident is covered by the CAR (Contractors' All Risks) insurance. The premium paid for this coverage is very low because insurance companies perceive the UXO risk as a very small risk based on their statistics.

Case Borssele offshore wind farm export cables

The density of UXO for the Borssele export cable routes has appeared to be 3.6 per km^2. This results in an individual risk of $1.1 * 10^{-4}$ per km^2 (see table 3). The project was 270 km in total (for 4 cable routes) with an average of 70 employees on board. By mitigating the risk, approximately 0,05 healthy life years were saved at most. This equals € 4,000.-. Secondary benefits, by avoiding potential equipment damage, were € 30,000.-.

A total of 1,350 objects were examined. The direct cost of the project was (little over) € 60 million in total. The indirect costs according to the DALY methodology was € 6,000.-.

Type	**Density[10] per km^2**	**P(explosion per object)**	**P(fatality)**	**P(injury)**	**Individual risk per km^2**
Mines	2.66	$< 2.7 * 10^{-4}$	0.039	0,33	$< 2.80 * 10^{-5}$
Aerial bombs	0.862	$< 1.1 * 10^{-3}$	0.032	0,27	$< 3.03 * 10^{-5}$
Depth charges/torpedoes	0.083	$< 1.3 * 10^{-2}$	0.047	0,40	$< 5.09 * 10^{-5}$
Total	**3.6**	**-**	**-**	**-**	$< 1.09 * 10^{-4}$

Table 3: UXO risk assessment for case Borssele offshore wind farm export cables

The benefits are approximately € 35,000.-. The costs are more than € 60 million. It is clear from a cost-benefit perspective that these investments are disproportional.

[10] Based on the distribution in paragraph 3.

5. CONCLUSION AND DISCUSSION

In this study, we have examined the objective risk of UXO in the North Sea on average to facilitate a risk comparison. We have placed the risk into perspective in two ways: by comparing it to the safety norm and the risk of fatality from working at sea, and by conducting a societal cost-benefit analysis.

In comparison with the accepted risk level, the UXO risk generally complies with the regular safety standards in the Netherlands. The individual risk of death from UXO during activities in the North Sea is equal to or less than $1 * 10^{-5}$ (1 in 100,000) per employee per year. Additionally, it is demonstrated that the risk of fatality from working at sea is greater than the overall UXO risk itself. The current UXO risk mitigating measures taken for the installation of subsea power cable in the North Sea thus do increase the risk of a fatal labour related incident rather than reducing the risk of a fatal labour related incident.

A societal cost-benefit analysis does reveal as well that the current expenditures on mitigating measures are grossly disproportional to the factual risk by all means. To manage the safety risk, the costs are a thousand times higher than the benefits when applying the standards used in healthcare in the Netherlands. From a comprehensive safety perspective, the costs could be better allocated elsewhere where the safety risk is higher, for instance to reduce fall, trip and slip and line-of-fire incidents at sea.

[15] suggests that even in situations with a high degree of uncertainty, a quantitative risk analysis can be helpful:

> *By attempting to quantify the uncertainties and to identify the dominant contributors, QRA analysts contribute to the common understanding of the issues and, in addition, may provide useful input to the allocation of research resources.*

This study also demonstrates that this applies to UXO in the North Sea: despite the uncertainties involved, it is clear that a careful consideration must be made regarding the resources deployed.

To assess the specific UXO risks for a specific cable route instead of for the North Sea on average, the uncertainty with regard to the UXO risk can be reduced in particular by explicitly examine the probability of encountering UXO during the project, for instance by assessing the historical databased on the presence of sea mines and on jettisons (aerial bombs dropped at sea). The case of Doordewind Wind Farm illustrates that this is possible, and a similar approach has been chosen for the IJmuiden Ver and the Nederwiek export cable routes in the Dutch North Sea. This method can be further developed to be applicable for other projects at sea.

Additionally, a more in-depth analysis can be conducted on the probability of an unexpected explosion of a UXO which has been laying on or in the seabed for over 70 years. A study by TNO shows for instance that the initiators of landmines deteriorate due to the influence of (salt)water, and the likelihood of functioning diminishes [24, 25]. To address this uncertainty, statistics were utilized in this study. A technical study could contribute differently to reducing this uncertainty.

This study only considered the risk of death from UXO during the installation of cables in the North Sea seabed on average. Due to a lack of data, we were unable to demonstrate that the risk for dredging operations in the North Sea is lower than the generic norm of 10^{-5} per year (1 in 100,000 year) [13]. There are indications that the UXO risk is also lower in such operations. For example, fishermen still discover tens to hundreds of UXO annually, with only two known fatal incidents after 1970. It should be noted that these explosives surfaced above the waterline during the fishing operations. The impact of dragging an explosive over the seabed in fishing gear and bringing the UXO to deck seems greater than that of certain other activities in the North Sea, in particular greater than the impact of cable burial operations. For other activities in the North Sea, such as dredging, as well as the installation of pipelines or other cable projects, an activity specific UXO safety assessment could be made.

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