UXO North Sea

An exploratory Risk Assessment for Unexploded Ordnance (UXO) in the North Sea

M. Helsloot
I. Helsloot

Authors
Marijn Helsloot MSc
prof. dr. Ira Helsloot

May 2023

Crisislab foundation is the research group supporting the chair on the governance of safety and security at the Radboud University Nijmegen. The objective of Crisislab is the development and distribution of knowledge in the areas of crisis management and safety governance. The core activity of Crisislab is empirically funded research on safety because these days, facts are often lacking in policy making of and discussing risk and safety management. Based on this research, we advise authorities and businesses to strive for reasonable and proportional safety policy. The exercises and courses we provide are aimed at dealing realistically with crisis mechanisms and with a resilient society.

Crisislab
Dashorsterweg 1
3927 CN Renswoude
www.crisislab.nl

Content

Executive summery

The seabed of the North Sea is extremely important for the future of the Netherlands, as it not only protects the coastal areas through sand extraction, but also plays a vital role in the energy transition by installing cables for wind turbines, which secures the country's sustainable energy supply both now and in the future.

These works are obstructed by the current 'UXO-worst case approach'. One risk associated with activities in the North Sea is the possibility of encountering unexploded ordnance (UXO), which could lead to an explosion resulting in injury or death. However, there is currently no record of this risk materializing during dredging or cable installation activities in the Netherlands (at least since 1970). In this study, we have therefore examined the objective risk of UXO in the North Sea bed during these activities.

In the Netherlands, a risk is considered unacceptable if the probability of death for an individual is greater than once in one hundred thousand years (10^{-5} per year ie 1 in 100,000 years). For cable installation workers, we have demonstrated that the UXO risk is at least smaller than once in one hundred thousand years, which meets the general safety standard in the Netherlands. However, due to a lack of data, we have not yet been able to demonstrate this for dredging workers, making it uncertain whether the UXO risk meets the general safety standard or not.

Despite the fact that we cannot yet conclude that the UXO risk for dredging workers is sufficiently low, there are insights that suggest it is. The UXO risk for fishermen is estimated to be around once in twenty thousand years ($5 * 10^{-5}$ i.e. 1 in 20,000 year). Tens of thousands of explosives have been retrieved from the North Sea by fishermen, with only two fatal incidents since 1970. In all these cases, the explosive was brought on board the ship. Therefore, it is expected that the UXO risk for dredging workers is at least lower than for fishermen.

At the same time, implementing mitigation measures presents a demonstrable and objective risk. People die every year while working at sea, and the general risk of working on *service ships* is once in thirty-five thousand years ($3 * 10^{-5}$ i.e. 1 in 35,000 year). This means that the risk of implementing mitigation measures is higher than the UXO risk for at least cable installation workers, but likely also for dredging workers. This means that the probability of a fatality is higher with UXO mitigation measures than without.

The third aspect that has been considered is the cost-benefit of implementing mitigation measures. It is an objective of governmental and semi-governmental organisations to use societal resources as effectively as possible. Each *safety euro* should be preventing as much damage as possible. Given the small risk, the benefits of the measures are limited. However, the direct and indirect costs of the mitigation measures are enormous. Over a hundred million euros have been spent on controlling the risk, while it has hardly or not at all contributed to increasing safety.

Introduction

1. Introduction

In this chapter we present the rationale for the study, the research question and the main formula used to determine the occupational risk.

1.1 Rationale for the study

The soil and bottom of the North Sea are crucial for the future of the Netherlands, not only for protection of the coast area (sand extraction) but also for the energy transition (e.g., laying and burying cables for wind turbines) securing a sustainable energy supply, now and in the future.

These works (cable burial and dredging) are obstructed by the current ‘UXO-worst case approach’ combined with a ‘zero risk approach for occupational safety’: the starting point of reasoning is that any UXO (UneXploded Ordnance) encountered during the works will certainly detonate with serious consequences for those onboard ships, which is, even if the chances are remote, deemed unacceptable.

The consequence of this approach is always having to implement safety measures (often disproportionate), since zero risk is impossible to reach. Starting with an investigation at sea into the presence of UXO, the so-called UXO survey of the seabed. When an object is encountered which possibly can be an UXO, the ‘right’ measures have to be chosen to identify the object and, in case it appears to be an UXO, to be sure that the UXO is evaded or destroyed.

This attitude (UXO can always be encountered and cause fatalities) does cost organisations, thus the Dutch society indirectly, hundreds of millions of euros. Not only for the additional costs of realizing projects (mainly costs for detection, identification and clearance), but also because of its domino-effects causing delays in energy transition and coast protection.

In comparison with land-based practice, the so-called preliminary research of assessment is less useful. On land, preliminary surveys are used to determine areas where the chance of encountering UXO (a priori) are deemed so low that no additional measures are needed i.e., that the risk is acceptably low. At sea, the concept of using preliminary surveys, however, has its limitations: the knowledge of locations where combat took place or where naval mines still remain is often either unknown, incomplete or imprecise. Aerial photographs, a constituent component of land based historical research, are rarely useful at sea.[1]

[1] See Arlar, L. (2019). Reviewgroep Vooronderzoeken CE op zee.

Therefore at sea, even more than on land, there is a need for a risk-based approach for dealing with potential UXOs on and in the seabed. Our research question therefore is:

> *"What can be said, using generally accepted risk-bases practices and the current state of knowledge on UXO, about proportional safety policies for dealing with the risk of UXO, clearly within the legal boundaries posed by the occupational health and safety act?"*

1.2 Research methods

This research question has been divided in three steps:

1) Based on literature, historic data and incidents, an estimation for the risk of death because of an UXO related incident in the North Sea is calculated. The dataset of the Royal Netherlands Navy is the primary basis for this calculation.

2) The risk, calculated in step 1, is compared to the accepted norm for other risks in The Netherlands. The Dutch national guideline for the acceptance of an individual involuntary risk caused by specific activity is a chance of dying from the risk of 1 per 100.000 years, for those exposed to said risk (abbreviated as 10^{-5}).[2]

3) The Dutch occupational health and safety law allows a cost-benefit analysis. If the risk (step 1) significantly differs from the guidelines, the proportionality of measures will be investigated.

This exploratory research has been done in close corporation with the following professionals from an expert group of TenneT and Rijkswaterstaat: Wino Snip, Robert Koens, Anja Drews, Henk Neggers and Luuk Arlar.

[2] The National Environmental Policy Plan "Dealing with risks" in 1989 mentions this as 'the maximum acceptable level for calamities occurring once every 10^{-5}/year (1 in 100,000 year) for incidents with n=10 or more casualties.

1.3 The core formula

In Dutch safety policies a central measure to determine acceptability of a specific risk is the chance of dying from the risk for those who are exposed to it. To determine this chance of the risk of UXO and the acceptability of it, the following formula is used:

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

Where:

$p_{\text{fat | UXO}}$	=	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

With as acceptance criteria: $p_{\text{fat | UXO}} < 10^{-5}$

In words: the probability on a fatality related to a UXO incident is considered to be acceptable when that probability is less than 10^{-5} (less than 1 in 100,000 year).

The 10^{-5}-norm (1 in 100,000 year) is accepted for other risks resulting in a fatality in the Netherlands (see also annex 4). For example, according to the National Water Plan (2016-2021):

> *The flood risk management policy offers everyone living behind a dike in the Netherlands a tolerable risk level of at least 1 in a 100,000 per year. This means that the probability of dying because of a flood for any individual should be no greater than 0.001% per year.* [3]

The formula is simple but meaningful. If the probability of encountering a risk is low enough, the other factors no longer need to be considered, even if the effects of an explosion would be catastrophic. It actually works the other way around as well: if a prudent work method decreases the probability of people being struck when an UXO explodes, there is no longer a need to consider the probability of encountering or explosion. As presented in chapter 5, smaller projectiles (e.g. grenades) can be excluded from our risk considerations since they have a limited effect for dredging or cable burial vessels.

[3] Ministry of Infrastructure and the Environment (2015) National Water Plan 2016-2021. P. 15.

Semi-quantitative risk analysis in Great Britain
This report has the goal to develop a quantitative approach to deal with the risk of UXO. In other countries sometimes a semi-quantitative approach is used. In Great Britain for example, historical research is used as input for a semi-quantitative risk analysis in which the probability of encountering and explosion and the consequences of explosion are combined.[4] A matrix is used for this. Both the probability of explosion and the consequences are assigned an expert score (1 to 5) and by multiplying the two scores you arrive at a *risk-level* that is translated into *a judgement on the acceptability of the risk*:

- 1 – 5 points: Tolerable
- 6-12 points: Partly tolerable
- 13-25 points: Intolerable

The above is a semi-quantitative approach because of the reliance on expert judgement as a basis for the calculations.

1.4 Preliminary note

In general, very little literature and historical documentation can be found about encountering UXO at sea and (thus) about incidents after encountering UXO. The data about probability of these events is thus sparse. From what has been observed during this investigation, data about encountering UXO has only been recorded systematically since 2005 and only to a certain extent. The number of incidents is also limited: ergo the only recent 21st-century example is an incident in 2005 in which three fishermen died.[5]

Up front acknowledgement is in place that ‘our’ usual statistical approach to calculate risk will have limitations: with limited data the risk can only be ‘maximized’ i.e., a number can be calculated that maximizes the chance of dying but because of the size of the dataset this number probably will be (much) higher than the chance actually is.

To get a deeper insight in the factors that determine the risk, earlier research has been combined on ‘technological’ aspects such as the effect of the explosion of an UXO on a ship. This provides a tentative insight in the outcome of the formulae above while using non-statistical methods. Merely as an example, as indicated earlier, any presence of small calibre ammo can be excluded from the risk consideration because of the robustness of the vessels involved and the very small effect these projectiles cause. This part of the research is presented in a separate part of this report in order to give insight in what kind of future technical research will help further refine risk calculations.

[4] N. Cooper, Royal Haskoning DHV, S. Cooke and Six Alpha Associates, *CIRIA Publication 754: Assessment and management of unexploded ordnance (UXO) risk in the marine environment* (Londen 2015).
[5] For details about the incident, see section 2.3 of this report.

2. The core data brought together

In this chapter we present the data we used for the risk analysis. For the risk analysis we need information about 1) the number of (encountered) UXO in the North Sea, 2) areas where UXO can be encountered, 3) incidents in the past and 4) the individual exposure to the risk.

2.1 Encountered UXO

2.1.1 Registrations

To make the risk assessment, the dataset of the Royal Netherlands Navy has been the primarily basis.

Royal Netherlands Navy dataset

The Royal Netherlands Navy (RNN) dataset is provided to RWS by the NATO Mine Warfare School EGUERMIN, and contains the explosives that have been cleared by the Dutch and Belgian navy within the framework of Operation Beneficial Cooperation. This operation encompasses the clearance of mines that have been encountered by civilian vessels and during military exercises.

Civilian vessels that encounter mines or other explosives (should) report this to the Coast Guard, after which a RNN minehunter is deployed to clear the explosive. Details of encountering these mines are logged from report to clearance by the Coast Guard, forming the RNN dataset. This dataset is the only comprehensive dataset containing UXO encountered in the Dutch North Sea.

Whilst comprehensive, the dataset has several drawbacks:

- Part of the report to the coast guard is an identification of the encountered UXO by the reporting party. A silhouette chart showing the most common types of UXO aids civilian parties in the identification. After the report the coast guard often advises the vessel crew to throw the UXO overboard with a sonar reflector for easy retrieval by the RNN. Clearance by minehunters often takes place with divers or ROVs without detailed examination and identification. Since fishermen are not EOD specialists, the identification may be lacking in detail or false. While it is hard to confuse a contact mine with a torpedo, ground mines and aerial bombs may be hard to tell apart, causing an uncertainty in this dataset.
- The mentioned location of encounter is not the location where the UXO was originally situated. Fishermen only encounter UXO after reeling in the nets after dozens of kilometres of trawling. Dredgers encounter UXO after bringing in the dredge head, which may be after kilometres of dredging the seabed.
- Many reported objects are lost after reporting whilst not cleared by the dispatched navy vessel. This may be caused by burial, adverse weather conditions or the absence or loss of the sonar reflector in the process.

To make the database more accessible for Crisislab, RWS edited the raw data provided by EGUERMIN. The reports were categorized in five categories (fishing, dredging, survey, military and other) based on the reporting type of vessel. The reported UXO are categorized based on the reported silhouette, eliminating detail-level mistakes in identification (i.e., all aerial bomb silhouette reports are grouped as 'aerial bombs'). Finally, the reported coordinates were converted to a GIS-compatible format, enabling geographic analysis of the dataset.

Royal Netherlands Navy's dataset contains the following registrations:

UXO	Registrations
Mine (LMB)	19
Mine (contact)	147
Mine (ground)	48
Unknown	174
Aerial bomb	709
Mine (type unknown)	16
Depth charges	50
Projectiles	273
Other	41
Torpedo	34
Mine clearing charge	6
Scrap	8
Total	**1,525**

Table 2.1: The registrations of the encountered UXO.[6]

In total 94% of the registrations were made after 1-1-2005. The majority of the registrations (65%) were made by fishermen.

Activity[7]	Before 1-1-2005	After 1-1-2005	Year unknown	All
Fishing	82	906	5	993
Dredging	3	389	0	392
Military	2	8	1	11
Survey	0	119	0	119
Other	1	9	0	10
Total	**88**	**1,431**	**6**	**1,525**

Table 2.2: Registrations per activity.

An important reason to start systematically registering UXO appears to be the incident with the fishing vessel 'Maarten Jacob' on 6 April 2005. From 1 January to 6 April 2005, only 4 UXO were registered, while 237 UXO were registered in the period from 7 April 2005 to 31 December 2005. The increased registration of UXO encountered during

[6] Be aware that these registrations are done by the Royal Netherlands Navy. Beached UXO are not included in dataset and are not part of this research.
[7] The distinction is based on the name of the vessel that reported the UXO.

dredging (from 2008) and during surveys (from 2014) also seems to contribute to the number of UXO registrations.

Encountered UXO - fishery

The 'explosion' of registrations (by fishermen) after April 2005 indicates that not all encountered UXO will always be registered. We suppose that the two months after the incident in 2005 (the period April-May) are representative for 'encountered UXO by fishermen'.

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
0	1	2	61	52	29	16	19	18	18	15	8

Table 2.3: Registrations of UXO by fishermen in 2005.

This means that, in a 'normal year', there will be 678 UXO encountered by fishermen:
*Formula: (61 registrations April 2005 + 52 registrations May 2005) / 2 months * 12 months = 678 UXO.*

The fishing fleet in 2005[8] was:

- 15 (large scale fisheries) and 355 (cutter fisheries) = 370 vessels,
- 165 shrimp fisheries (estimation, based on Quirijns et al. (2021)),
- 0 pulse fisheries,
- So: 370 vessels (all) – 165 vessels (shrimp) – 0 vessels (pulse) = 205 vessels that can encounter UXO.

With other words: fishermen encounter (at least[9]) 3 or 4 UXO per year on average.

Furthermore, it must also be noted that it may be possible that some fishermen encounter fewer UXO (after 2006) as a result of a new method of fishing. Quite a few vessels were equipped with a so-called electric pulse. Electric pulse fishing has been used from 2006 till 2021. While pulse fishing only electric pulse conductor wires are dragged over the seabed with some rigging to support the fishing nets and to keep the nets open. This method does not scrape objects from the seabed, as it relies on fish to jump up from the seabed, as a result of the electric pulses, and thus ending up in the nets.

[8] Agrimatie (n.d.).*Visserij in cijfers*. Retrieved November 22, 2021, from https://agrimatie.nl/. For shrimp fisheries: we compared the data from 2005 with the data (p. 17) in the report of Quirijns et al. (2021). *Beschrijving garnalenvisserij: Huidige situatie, knelpunten en kansen*.

[9] In the report after the latest UXO-incident in the North Sea (incident of the OD-1 Maarten Jacob), it is posed that a fisherman catches one or two bombs *per week* at some locations. In an interview held for this report a fisherman told us that he encounters bombs on regular basis, i.e. a few a year.

2.1.2 Categorisation

We differentiate the following objects for the risk assessment:

- Mines,
- Aerial bombs,
- Depth charges and torpedoes,[10]
- Projectiles.

The objects "scrap", "other", and "mine clearing charges[11]" are not included in this research. Moreover, we removed the empty explosives and 'wrong registrations' (e.g., Non-Mine, Mine-Like Bottom Object (NOMBO)) that sometimes has been registered as UXO.

2.1.3 Proportions

In this study we only include 'real' UXO (so we excluded scrap, other, wrong registrations, etc.). Only (1,275 / 1,525 =) 84% of the registered objects is a *real* and identified UXO. At least 5% of the encountered objects is not an explosive.

UXO	Fishing	Dredging	Survey	All
Unknown	46	83	31	167
Wrong registration, scrap, etc.	34	14	33	83
UXO	913	295	55	1,275
All registrations	**993**	**392**	**119**	**1,525**

Table 2.4: Encountered UXO (unknown, wrong registration or UXO).

A distinction can be made between the activities of fishing, dredging, and surveying.[12]

UXO	Fishing	%	Dredging	%	Survey	%	All activities	%
Mine[13]	165	17%	8	3%	40	45%	217	16%
Aerial bomb	660	70%	29	9%	11	13%	706	52%
Depth charge and Torpedo	72	8%	9	3%	1	1%	83	6%
Projectile	16	2%	249	81%	3	3%	269	20%
Other or wrong	34	4%	14	5%	33	38%	83	6%
Total	**947**	-	**309**	-	**88**	-	**1,358**	-

Table 2.5: Encountered UXO (only identified objects).

[10] We combine depth charges and torpedoes because these objects are encountered more or less equally often and in the same area.
[11] We removed mine clearing charges since these explosives are rarely encountered.
[12] We do not include "other" and "military" as a result of the limited number of registered instances.
[13] 67 of the 217 mines are ground mines, 134 are contact mines and 16 are 'type unknown'. Approx. 33% of the mines are ground mines and approx. 67% are contact mines.

Noteworthy is the difference between the type of UXO that different activities have encountered: aerial bombs (mainly by fishermen), projectiles (mainly by dredgers) and mines (relatively often by surveys). An explanation could be the different areas where the activities take place (see part 2.2). Another possible explanation is that not all objects are noticed or called in. For example, dredgers may not notice aerial bombs or mines because the grid blocks larger objects. This example also shows another caveat of this study: some usual and relatively cheap safety measures may be effective enough for the risk to have vaporized already, without a dataset to prove this.

2.2 Risk areas

2.2.1 Research area

In this study, the risk of UXO in the Dutch North Sea area has been considered. All encountered objects (see part 2.1) are encountered in the Dutch Exclusive Economic Zone.

The surface of the Dutch North Sea area is 58,000 km^2 in total.[14]

2.2.2 Risk areas

Imprecise and incomplete registrations

Preliminary research/desk studies for the North Sea are often incomplete and imprecise. Especially for contact mines, little is known about their current whereabouts. Many contact mines came loose of their anchors after minesweeping or storms and went adrift, moving up to hundreds of kilometres from their original positions.[15]

For dropped (aerial) bombs specifically, we assume an equal distribution, this is also prompted by *jettisons*, during which aerial bombs were dumped more or less randomly. According to research by Saricon, 'jettisoned in sea' or 'jettisoned in North Sea' or 'jettisoned in the Channel' was often the only information given by pilots jettisoning their payload.[16] This assumption is supported by the random locations of encountered aerial bombs in the Royal Netherlands Navy dataset.

Coastal region (former minefields and convoy routes)

There are certainly locations with reliable indications for the presence of UXO, such as shooting and exercise areas (with projectiles), minefields with ground mines, or convoy routes/coastal region (with depth charges/torpedoes).

---

[14] Ministry of Infrastructure and the Environment (2015). Beleidsnota Noordzee 2016-2021.
[15] Arlar, L. (2019). Reviewgroep Vooronderzoeken CE op zee.
[16] Saricon (2020) Indicatie en Analyseonderzoek Conventionele Explosieven Kustlijnzorg voor het zandwinvak L12-3 (Vlieland). p. 49-51

Therefore, although UXO can be encountered anywhere, there are areas with an increased probability. GIS can be used to gain insight into where the registered instances originate (see figure 2.1). It must be noted that registered instances are often imprecise: most of these are recorded by fishing, and they can be subject to an inaccuracy of dozens of kilometres as the nets 'trawl the bottom' for an extended period and over a certain distance (so they only encounter the UXO at a later time).

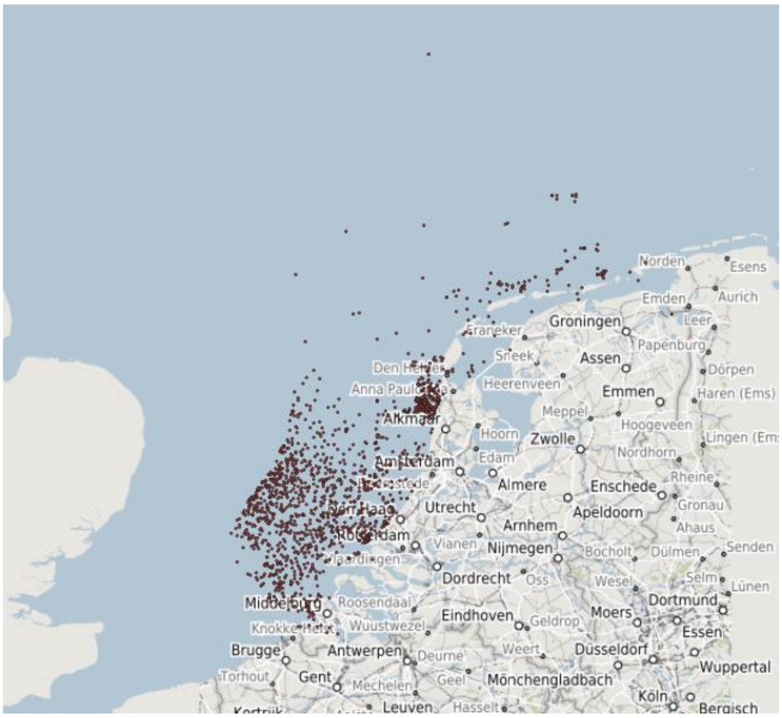

Figure 2.1: Encountered UXO (including scrap) in the Dutch North Sea (Dutch EEZ).

The map is therefore only an approximation (as it only shows registered objects), but two preliminary conclusions may be drawn:

- UXO are mainly encountered near the coast and in the south.
- Hardly any UXO are found to the north of the traffic separation system "Terschelling – German Bight, which runs in east-westerly direction at approx. 100 km north of the Wadden Islands.

Part of the explanation is (the absence of) activity: no activity (fishing, survey, dredging etc.) means no encounters in that area, see for example the fishing intensity in the North Sea.[17] It is clear that UXO will be mainly found in areas with a lot of activities.

However, as presented later, the fishing intensity does not explain the (significant) difference in the type of UXO in different areas (e.g., 22% of the aerial bombs are found

[17] Compendium voor de Leefomgeving (2021). *Bodemfauna Noordzee en bodemvisserij, 2016 – 2019.* Retrieved November 22, 2021, from https://www.clo.nl/.

in former minefields and convoy routes, while 71% of all mines are found in former minefields and convoy routes).

Distinction is made between the following risk areas:
- Former convoy routes and ground minefields (with torpedoes/depth charges and ground mines) or coastal region;
- Shooting and exercise areas (with projectiles)[18];
- North Sea miscellaneous (equal distribution of all types UXO).

Convoy routes and former minefields

UXO may be encountered everywhere on the North Sea. However, some areas contain a higher density of UXO due to war-related events. A distinct area is a belt between 1 and 40 km offshore off the coast of Holland and between 1 and 80 km off the coast of the Dutch Frisian Islands. The bulk of the relevant World War II combat events in the Dutch EEZ took place in this 'coastal region, mainly due to the presence of German convoy routes, proximity to the shore and the relatively shallow water. Examples of events are:

- >95% of German defensive minefields containing ground mines were positioned here.
- All German convoys sailed and were engaged by allied air forces and patrol boats in this area, leading to a high density of aerial bombs, torpedoes and depth charges.
- All allied offensive minefields against German convoy routes were placed here by aircraft and fast patrol boats, leading to the presence of allied ground mines.
- Allied patrols against German midget submarines took place in this area after June 1944, leading to the presence of aerial bombs and depth charges.

The coastal area therefore contains a higher density of ground mines, torpedoes and depth charges than the rest of the Dutch EEZ. Contact mines were positioned both outside and inside the coastal region but are assumed to be equally distributed because of migration. Aerial bombs were deployed against shipping in the coastal area, but jettisons took place randomly, leading to an assumption of equal distribution as well.

UXO	Coastal region	%
Mine	154	71%
Aerial bomb	157	22%
Depth charge and torpedo	57	69%
Projectile	249	93%
Total	**617**	**48%**

Table 2.6: Encountered UXO in coastal region (former minefields and convoy routes).

Using the distinctions above, the North Sea looks as follows (see figure 2.2):
- The blue-shaded area is the coastal region (i.e. expected higher density for torpedoes, depth charges, and ground mines);
- The green-shaded areas are shooting and exercise areas (i.e. expected higher density for projectiles) (near Petten and Zeeland).

[18] We are aware that these [the projectiles] are unlikely to pose a risk for the work activities that this report is focused on. However, we want to include them for completeness.

Since projectiles have a limited impact (see chapter 5), differentiation is not done for dumping locations in the analyse as different risk area. The coastal region (with former convoy routes and minefields) covers a total of 16,177 km². This is 28% of the total surface area of the North Sea.

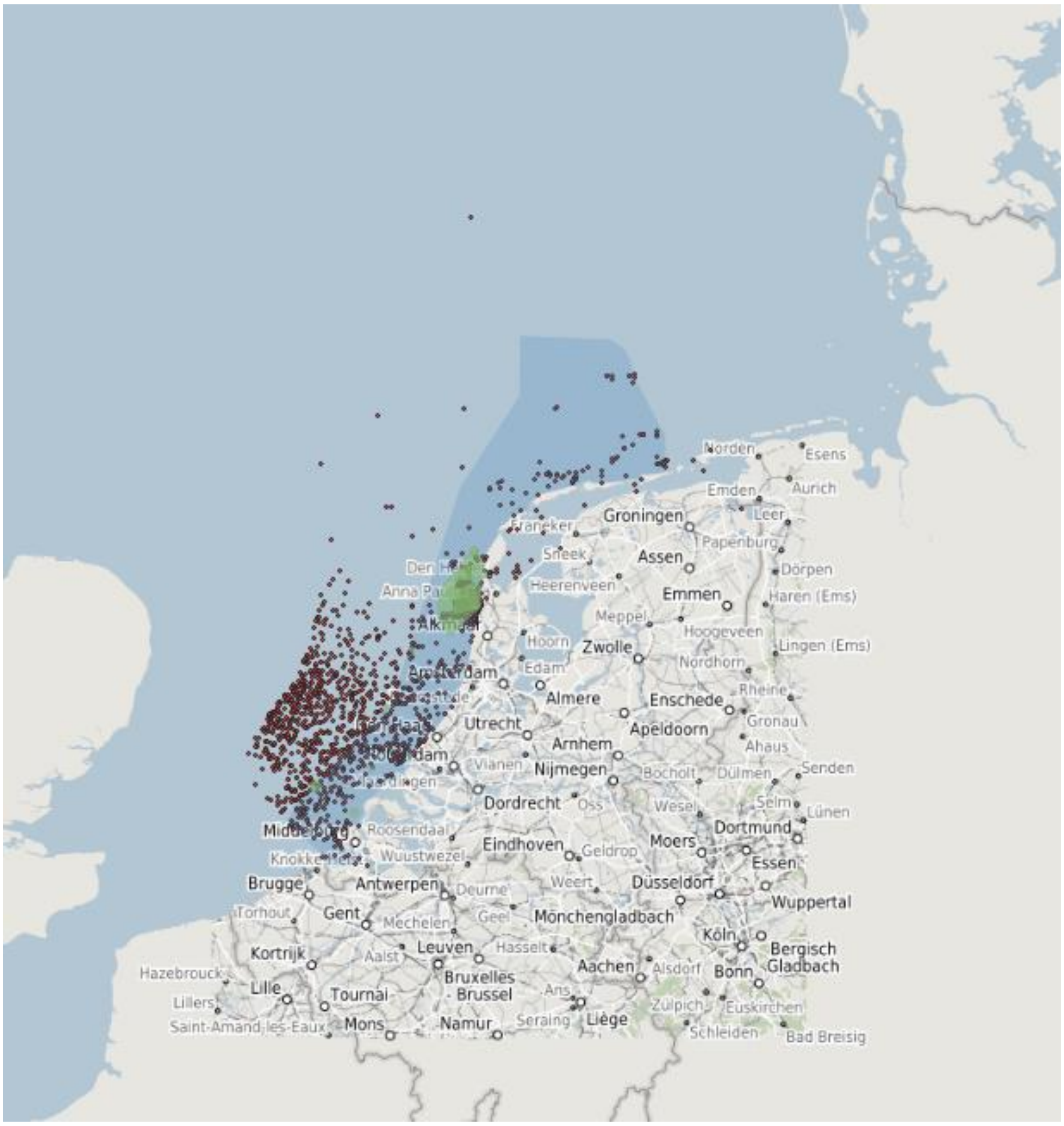

Figure 2.2: Risk areas (green=shooting areas; blue =coastal region).

Separating the different activities indicates that:

- Dredging and surveying mainly occur in the coastal region (former minefields and convoy routes);
- Fishing occurs relatively often in outside the coastal region. This indicates fishermen are active in a wide(r) part of the North Sea.

UXO	Fishing	%	Dredging	%	Survey	%
Mine	107	65%	7	88%	37	93%
Aerial bomb	121	18%	27	93%	9	82%
Depth charge and Torpedo	48	67%	8	89%	1	100%
Projectile	10	63%	236	95%	2	67%
Total	**286**	31%	**278**	94%	**49**	89%

Table 2.7: Encountered UXO in coastal region per activity.

Based on the dataset and historical research, we will assume the following distribution of UXO in the North Sea (table 2.8). 70% of all UXO (excluding aerial bombs) could be encountered in the coastal region**.** A starting point for this report is that aerial bombs are distributed equally, so only 28% of the aerial bombs could be encountered in the coastal region.

	Coastal region	Non-coastal region
Mine[19]	70%	30%
Aerial bomb	28%	72%
Depth charges/torpedoes	70%	30%
Projectiles	70%	30%

Table 2.8: Distribution of UXO in coastal region (former minefields and convoy routes) and non-coastal region.

2.3 Incidents

2.3.1 Netherlands

In the Netherlands, a few instances of unexpected explosion of UXO are known. Over the past 50 years, from 1971:

- 1971 – an **exercise** depth charge was thrown overboard by the Dutch Navy in 1971 and it initiated unexpectedly causing damage to a fishing vessel.[20]
- 1973 – a depth charge was thrown overboard, and the resulting unexpected explosion damaged a fishing vessel.[21]
- 1976 – a projectile fished out of sea explodes on deck and causes the death of a fisherman.[22]

[19] Historical research indicates that contact mines will be distributed more equally than ground mines. Based on the dataset, we cannot draw this conclusion. 66% of the ground mines were encountered in former convoy routes and minefields and 72% of the contact mines were encountered in former convoy routes and minefields.
[20] Het vrije volk (1972). *Dieptebom weigerde; Marine zei niets*. Retrieved November 23, 2021, from https://www.delpher.nl/.
[21] Het vrije volk (1975). Noordzee nog bomvol. Retrieved November 23, 2021, from https://www.delpher.nl/. We did not find any other information about this incident. It could be that it refers to the same incident as in 1971 (the first from our list).
[22] Algemeen Dagblad (1976). *Projectiel ontploft bij teruggooien*. Retrieved November 23, 2021, from https://www.delpher.nl/.

- 2005 – three crew members lost their life after deflagration of an aerial bomb during fishing activities.[23]

Incidents with white phosphorus encountered on the beach are excluded since this ‘effect’ is not a risk for employees during dredging or cable burial activities.

There are no other unexpected initiations of UXO in the Dutch North Sea since 1970 known to us. There are, however, a few other well-known relevant incidents in the North Sea as a whole:

- 1984 – a Dutch North Sea fishing vessel is damaged by a torpedo near the Belgian coast.[24]
- 1985 – a Dutch fisherman dies from a sea mine or projectile exploding on board (German North Sea).[25]
- 1987 – the explosion of a torpedo near the French-Belgian border (on seabed) caused damage to a Dutch fishing vessel.[26]
- 2005 – a Belgian fishing vessel (in Belgian waters) is damaged by a explosion of a bomb in the nets.[27]
- Most recently, in 2020, a British vessel has been damaged by (possible) UXO on the seabed.[28]

2.3.1.1 Methods

Incidents are scrutinized in four ways as such altogether should cover all incidents:

- Data bases with newspaper articles (Digibron, Delpher and LexisNexis). Our assumption being that a serious incident involving UXO is a so-called ‘exotic’ incident which will be covered by media;
- The data base of the Netherlands Coastguard. Our assumption being that the Dutch Coastguard is the principal emergency service responding to an incident;
- Consulted the Human Environment and Transport Inspectorate (Dutch: Inspectie Leefomgeving en Transport, ILT) for known incidents. Our assumption being that occupational health incidents involving vessels have to be called in by the ILT by law;

---

[23] Reformatorisch Dagblad (2005). *Drie doden na explosie op kotter*. Retrieved May 12, 2023, from https://www.digibron.nl/.
[24] Reformatorisch Dagblad (1984). *Eén grote ravage.* Retrieved November 23, 2021, from https://www.digibron.nl/.
[25] Nieuwsblad van het Noorden (1985). *Visser gedood door mijn*. Retrieved November 23, 2021, from https://www.delpher.nl/.
[26] De Telegraaf (1987). *Vissersschip aan ontploffende torpedo ontsnapt*. Retrieved November 23, 2021, from https://www.delpher.nl/.
[27] Reformatorisch Dagblad (2005). *Weer explosief op Noordzee ontploft*. Retrieved November 23, 2021, from https://www.digibron.nl/.
[28] GOV.UK (2022). Subsea explosion resulting in damage to crab potting vessel Galwad-Y-Mor and injuries to crew. Retrieved May 15, 2023, from https://www.gov.uk/.

- The biannual reports of the Dutch Safety Board with (Dutch) incidents at sea. The Dutch Safety Board (Dutch: Onderzoeksraad Voor Veiligheid) has been producing these oversights since 2014.

Remarkable is that in the end, the approach of using databases with newspaper articles, provided insight with what seems to be the most comprehensive list of incidents with UXO in the North Sea.[29]

2.3.1.2 Analysis

As stated above, three national incidents and nine incidents in the entire North Sea are found caused by UXO exploding or detonating unexpectedly after an unwanted initiation. Since 1971, in total five people have died from an exploding UXO in the North Sea.

An important observation is that all these incidents occurred during fishing activities.

For the analysis, we will only include the four incidents in which a ship or the crew members were struck on the Dutch North Sea.

2.3.2 Other countries

In the German part of the North Sea (coast area), 10 unexpected explosions relating to UXO have been registered from 1971 until 2015:[30]

- 4 during dredging activities (0 fatalities)[31],
- 1 during fishing (causing the death of a person; probably a Dutch fisherman, see 2.3.1),
- 4 during a visit to the beach (0 fatalities),
- 1 "self-explosion" (0 fatalities).

The surface of the German North Sea is in size about 70% of the surface of the Dutch North Sea.[32] Only one unexpected explosion is known during fishing (compared with three incidents in the Dutch North Sea).[33] The risk for fishermen thus seems more or less the same in both the Dutch and German North Sea.

---

[29] Furthermore, we consulted the list with incidents that were composed by Expload (see: I. Helsloot e.a. (2016). *Proportionaliteit bij de omgang met conventionele explosieven*) and Haarlemmermeer (Haarlemmermeer (2018). Beleidsplan Conventionele Explosieven (CE)).

[30] Stefan Nehring, S. (2015) Munition – Unfalle – und kein Ende .... *Waterkant, 30* (4), 7-14.

[31] These incidents were in ports or channels. No one was hurt or died during the dredging activities. The UXO consisted of three projectiles and an aerial bomb.

[32] Marineregions.org (n.d.) Marine Gazetteer Placedetails. Retrieved November 19, 2021, from https://marineregions.org/. The surface of the Belgian North Sea and Baltic Sea are also retrieved from this website.

[33] This means that there are (1 incident/ 45 years / 41,334 km^2 =) $5.4*10^{-7}$ incidents with fishermen per year per km^2 in German North Sea area. In the Dutch North Sea area, this is (3 incidents / 50 years / 57,800 km^2 =) $1.0 * 10^{-6}$. And in Belgian North Sea area, this is (at least) (2 incidents / 50 years / 3,495 km^2 =) $1.1 * 10^{-5}$.

Unexpected explosions in the Baltic Sea

In the German Baltic Sea, there were 45 unexpected explosions relating to UXO from 1971 until 2015: [34]

- 17 during fishing (causing the death of one person)
- 26 during a visit to the beach (0 fatalities)
- 1 during munition salvage (0 fatalities)
- 1 self-explosion (0 fatalities)

The surface area of the Baltic Sea is 15,288 km^2. There are relatively often incidents in this part of the German Exclusive Economic Zone.[35]

Any UXO-incidents during dredging in the Dutch part of the North Sea are not observed. There is, however, one incident reported with a Dutch vessel (TSHD Volvox Terranova) in Indonesia in 2014.

Far East[36]

Dutch and Belgian dredging companies have extensively dredged in the areas around Hong Kong — until control was returned to China, Singapore, and Indonesia. In Hong Kong, Singapore, and Indonesia, dredging was performed in areas which were known to contain undetonated explosives. This was especially the case in Singapore, where one of the nearest sand extraction areas in Singapore waters was directly adjacent to a former dumping area of ammunition. During the works, UXO were regularly found in the drag head, and smaller UXO were pumped to the reclamation areas every day.

There are four known incidents from Hong Kong and Singapore in which an UXO exploded during dredging. It caused heavy damage to the drag heads of trailing suction hopper dredgers Geopotes X and PCS van Hattem. After explosion of a UXO in the drag head, TSHD HAM 308 was a total loss as the whole ship was deformed and the impact had blown the main engines off their foundations. Lastly, the explosion of an old (Dutch) sea mine in Indonesia caused severe damage to the hopper dredger Volvox Terranova.

None of the incidents caused the sinking of a trailing suction hopper dredger, nor were there any casualties.

2.4 Exposure to occupational risk of UXO

The core activities to calculate the occupational risk in this report are dredging and cable burial. the following techniques will be used: hopper dredging and cable burial by machines intrusively interacting with the seabed. Inducing the occupation risk for cable burial being lower than that for dredgers (see chapter 4 for an explanation). The risk

---

[34] Stefan Nehring, S. (2015) Munition – Unfalle – und kein Ende …. *Waterkant, 30* (4), 7-14.

[35] An explanation is that about 300.000 tons of conventional munition (estimation) was dumped in the Baltic Sea after WW1 and WW2, see: Freund, A. (2019). WWII munitions: Time bombs at the bottom of the Baltic Sea
From https://www.dw.com/.

[36] The passage was written by one of the UXO-experts who were involved in this study.

for dredgers is only computed because the UXO trigger likelihood by cable burial activities is smaller. Besides, in Dutch waters with mobile seabed (sand waves) almost 50% of the surface the cable is laid has already been dredged. Resulting in a conservative estimation for the risk of UXO for cable burial.

Formula: m^3 dredged in a year / number of employees * employees per vessel

- Only for suppletion, RWS dredged 17.3 * 10^6 m^3 in 2021 (based on internal data). There were 6920 journeys. One journey is approximately 4 hours (dredging time is one hour) and 2,500 m^3. This means that there are (6920 * 4/24=) 1.153 ship days.

- International Council for the Exploration of the Sea (ICES) shows that there have been dredged on average 45.1 * 10^6 m^3 every year between 2006 and 2018. The 'areas over which extraction occurs' was 73,1 km^2 on average.[37] This means that dredgers need about 1.6 km^2 work area to obtain 1 * 10^6 m^3 of sand.

- There are 12 employees on average on a dredging vessel (day/night shift). They work about 180 days a year. This means at least (1153 * 12 /180 =) 77 full time employees would be hired by contractors for coast protection. The individual risk exposure of an employee is (17.3 * 10^6 m^3 /77 employees * 12 employees per vessel =) 2.7 * 10^6 m^3 and (2.7 * 10^6 m^3 * 1.6 m^2=) 4.4 km^2.

2.5 What do we already know?

Country	Before 2015 (10^6 m^3)	2015-2018 (10^6 m^3)
The Netherlands	897.9	85.9
Belgium	67.7	14.0
France	81.6	13.0
Germany North Sea*	38.8	6.6
Germany Baltic Sea*	29.3	4.9
Denmark*	211.5	22.9
United Kingdom*	308.1	49.0
Total	**1634,9**	**196,3**

Table 2.9: N * 10^6 m^3 dredged in North and Baltic Sea. Data from ICES. * = some years are unknown, we have used the average m^3 for these years.

Before we will calculate the objective risk with the formula, we already know the risk is **smaller than** 1 (no incidents with fatalities are known) / (1,634.9 * 10^6 m^3 dredged before 2015 / 2.500 m^3) = **1.6 * 10^{-6} per journey**. This means the individual risk will be smaller than (5 journeys a day, 180 days a year) 1.4 * 10^{-3}.

[37] ICES (2019). WORKING GROUP ON THE EFFECTS OF EXTRACTION OF MARINE SEDIMENTS ON THE MARINE ECOSYSTEM (WGEXT). *ICES Scientific Reports 1*(87); ICES (2016). Effects of extraction of marine sediments on the marine environment 2005-2011. ICES COOPERATIVE RESEARCH REPORT.

Using the statistical approach

3. Probability of encountering

In this chapter we will use different perspectives to calculate the probability of encountering UXO per km². The first approach is using the dataset of the Royal Netherlands Navy because they are called in to destroy encountered UXO. The second approach is using the data of two recent case studies, i.e. surveys of which the data is available to us. The third approach using the registered UXO during dredging. All approaches have their limitations, but the results are more or less the same, i.e., 1 UXO per km² in what we earlier defined as risky areas.[38]

$$p_{\text{fat | UXO}} = \boldsymbol{p}_{\textbf{enc}} \times p_{\text{expl | enc}} \times p_{\text{fat | expl}}$$

Where:

$p_{\text{fat | UXO}}$	=	Probability of a fatality as the result of an UXO related incident
$\boldsymbol{p}_{\textbf{enc}}$	**=**	**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

3.1 Using the dataset of the Royal Netherlands Navy

The dataset with registered UXO of the Royal Netherlands Navy encountered <u>during surveys</u> that are regular practice only since 2014 is used.

Year	Registrations
2010	1
2014	9
2015	13
2016	2
2017	0
2018	1
2019	59
2020	34
Total	**119**

Table 3.1: Encountered objects during survey per year.

After review of the datasets provided, eleven different surveys are found in the Dutch part of the North Sea (from 2014) in which at least two objects were registered. Hereby looking into the vessels and periods in which the surveys were done. In annex 1 the eleven surveys are clustered.

[38] As we will explain later, it turns out that the probability of encountering does not affect much the individual risk because in our statistical calculations a higher probability of encountering UXO will mean a lower historical probability of exploding since more UXO will then be encountered.

The registrations of UXO (for each survey) with each other in chronological order are connected. In this way the minimum distance the survey-vessels have sailed has been identified.

All objects in this area are assumed to be examined by the surveying company and the results are send to the Royal Netherlands Navy. Furthermore, the dataset is assumed to be in chronological order.

From TenneT is learned that during UXO surveys both sides of the location for the cables is surveyed for 40 m i.e. a corridor of 80 metres wide. However, for the installation of the cables only the middle 50 metres are used, i.e. 25 metre either side of the route, 15 metres either side are being 'cut off', considering the possibility of non-detected targets just outside the 80 meter wide surveyed corridor. TenneT has assessed the encountered objects in the 50 metre wide middle part of the surveyed corridor with regard to the potential nature of the encountered objects. We thus established the examined area by multiplying the distance of the lines by 0.05 km (2 * 25 m).

Survey	**Total distance between encountered objects**	**Surveyed area**
Survey 1	157.0 km	7.9 km^2
Survey 2	85.6 km	4.3 km^2
Survey 3	264.8 km	13.2 km^2
Survey 4	2.2 km	0.1 km^2
Survey 5	561.3 km	28.1 km^2
Survey 6	24.3 km	1.2 km^2
Survey 7	2.6 km	0.1 km^2
Survey 8	2.4 km	0.1 km^2
Survey 9	2.1 km	0.1 km^2
Survey 10	7.2 km	0.4 km^2
Survey 11	1.7 km	0.1 km^2
Total	**1111.2 km**	**55.6 km^2**

Table 3.2: Minimum surveyed area per survey.

Surface of survey projects

The 'clustered surveys' are linked to a few windfarms and/or projects in the North Sea such as:

- Windfarm Hollandse Kust Zuid 236 km^2
- Windfarm Borssele 345 km^2
- Windfarm Ten Noorden van de Waddeneilanden 218 km^2
- Cable for windfarm Borssele 13.1 km^2
- Survey after the container waste from MSC Zoe[39] 3,000 km^2 (both Dutch and German area).

Taken the above into account it can be concluded that at least 55.6 km^2 of the North Sea is surveyed.

In the surveyed area, the following objects were 'encountered', that is the surveying company indicated to the Royal Netherlands Navy that an object that it registered should be categorized as in the table below.

UXO	Encountered UXO	Encountered UXO excluding 'not found'	Encountered UXO with 'unknown-margin'
Mine	35	30	35.5
Aerial bomb	10	10	11.5
Depth charge and torpedo	1	1	1.1
Projectile	3	3	3.4
Unknown UXO	27	12	n/a
Other/wrong	12 + 22	n/a	n/a
Total	**110**	**56**	**51.5**

Table 3.3: Encountered objects in 'clustered' surveys.

In total 12 of the registered objects were registered as 'other', for example 'ammunition box'. In total 22 objects were registered by the surveying company, but the Royal Netherlands Navy encountered a NOMBO (Non-mine, Mine-like Bottom Object) or pipework. Furthermore 20 objects that were registered as UXO were not found by the Royal Netherlands Navy. After all, only 56 of the 110 objects were found by the Royal Netherlands Navy.

In total 12 of the 56 encountered UXO are registered as 'unknown'. These 12 objects could be a mine, bomb, etc. but also scrap. Based on the relative incidence of encountered types of UXO to each other during all surveys (e.g., 45% of the encountered objects during a survey is a mine and 38% is a wrong registration, see chapter 2), we attribute a corresponding 'unknown margin' to all categories.[40]

[39] Please note that for this survey similar methods were used but that the main purpose was not finding UXO.
[40] For example, we calculate the 'unknown-margin' for mines: 12 (unknown objects) * 0,45 (45% of the identified encountered UXO during a survey is a mine, see chapter 2) = 5.5.

Based on this data (encountered UXO and surveyed area), the probability of encountering UXO can be calculated:

UXO	Number of UXO per km^2
Mine	0.638
Aerial bomb	0.207
Depth charge and torpedo	0.020
Projectile	0.061
Total	**0.927**

Table 3.4: Encountered objects in 'clustered' surveys and the number of UXO per km^2.

Using this approach, the probability of encountering UXO is 0.9 per km^2.

Remember that we differentiated between two areas in chapter 2: coastal region (with former convoy routes and minefields) and a non-coastal region area outside those areas. Almost all surveyed areas lay inside a risk-area so the probability found is the probability for a risk-area. As shown in table 3.5, the probability of encountering in a non-risk area will be roughly six times lower than the probability of encountering in the risk area (using the results of chapter 2).

UXO	Probability – general	Probability – risk area	Probability – non-risk area
Mine	0.638	0.638	0.106
Aerial bomb	0.207	0.207	0.207
Depth charge and torpedo	0.020	0.020	0.003
Projectile	0.061	0.061	0.010
Total	**0.927**	**0.927**	**0.326**

Table 3.5: Probability of encountering UXO in different areas.

Remaining UXO according to UXO Intelligence

In a general estimate, the Swedish company UXO Intelligence assumes there are about 36,300 remaining sea mines (26,500 buoyant contact mines, 9,000 ground mines and 800 anti- invasion mines) in 58,000 km^2 (total area of Dutch waters) i.e., 0.623 per km^2.[41] UXO Intelligence used general finding to calculate the remaining number of mines (10% exploded, 25% remaining in minefields, 5% disposed, 30% beached, 30% sunken).

This is more or less the same density we found, but we, however, differentiate two areas. According to our data, there would be (0.638 * 16,177 km^2 + 0.106 * 41,823 km^2 =) 14,700 remaining sea mines in the Dutch North Sea.

[41] Remaining number of mines in northern European waters. Internal communication with UXO Intelligence.

UXO	Objects remaining in North Sea
Mine	14,747
Aerial bomb	12,005
Depth charge and torpedo	473
Projectile	1,5418
Total	**28,643**

Table 3.6: Estimated number of remaining UXO of in the Dutch North Sea.

3.2 Two case studies

3.2.1 Case study cable routes for the Hollandse Kust (zuid) offshore wind farm

TenneT recently conducted a survey along the routes of the offshore wind export cable routes for the Hollandse Kust (zuid) offshore wind farm.

The survey area of the project Hollandse Kust (zuid) is 7.65 km^2. Only 1 UXO (above the threshold value) or 0.131 UXO per km^2 was found. 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: where possible, a "detour option" was taken, and the cable route was "rerouted" around the magnetic anomaly, thus avoiding identification of those anomalies. 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%.

The survey area can be divided into two sub-areas: area's nearshore and in the vicinity of (former) shipping routes, where a lot of debris s encountered, and area's further at sea and not in the vicinity of (former) shipping routes. Our assumption is that the relation between targets and UXO is the same in the entire area.

For the area with many targets (nearshore area where debris from the port and river mouth has ended up and in the vicinity of (former) shipping routes) (and therefore potential UXO), the following applies:

- 1,536 *targets* encountered
- area is 1.6 km^{2},
- this equals 960 targets per km^2
- and thus, an expected number of UXO of 960 * 0.137% = 1.3 UXO per km^2

For the area with few targets (further at sea, away from the debris plum and away from shipping lanes), the following applies:

- 2,144 *targets* encountered
- area is 6.05 km^2
- this equals 354 targets per km^2
- and thus, an expected number of UXO of 354 * 0.137% = 0.5 UXO per km^2

3.2.2 Case study Borssele offshore wind farm export cables

TenneT has also conducted a survey along the route of the Borssele offshore wind farm export cables. The survey area of the project is 13.15 km^2. A total of 1,350 objects were examined, and ultimately, only 6 turned out to be an actual UXO above the set threshold mass. This equals 0.444%.

For the survey area of this project, the following applies:

- 10,681 *targets* encountered
- area is 13.15 $km^{2,}$
- this equals 812 targets per km^2
- and thus, an expected number of UXO of 812 * 0.444% = 3.6 UXO per km^2

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.

3.3 Using the dredging data

As another approach we have a short look into what the dredging data tells us. Please note it is highly likely that a significant portion of UXO encountered by dredging vessels is simply not noticed.

There are dredging activities in the North Sea since 1974. About 1,000 * 10^6 m^3 sand have been dredged in the North Sea since 1974.

The encountered UXO have been reported since 2008: 99% of all registrations are done after 1-1-2008.

The period after 2014 seems less representative since UXO-surveys are more common. We expect that the UXO-surveys are (more or less) mandatory since 2015, 85% of all dredgers are registered between 2008 and 2014.

Data from ICES shows that 448.9 * 10^6 m^3 sand has been dredged in the North Sea from 2008 until 2014. In chapter 2, we calculated dredgers need about 1.6 km^2 work area to obtain 1 * 10^6 m^3 of sand. The extraction was done in (448.9 * 10^6 m^3 * 1.6 km^2 =) 718.2 km^2.

UXO	Dredging	Dredging (incl. unknown margin)[42]	Encountered UXO per km²
Mine	5	6.9	0,010
Aerial bomb	23	29.9	0,041
Depth charge and torpedo	7	9.2	0,013
Projectile	215	274.6	0,377
Other/wrong	8	n/a	n/a
Unknown	74	n/a	n/a
Total	**332**	**320.6**	**0.441**

Table 3.7: Encountered UXO during dredging between 2008-2014.

With these data, we estimated the number of UXO (probability of encountering) is 0.441 per km^2. Please note that a considerable part of the encountered UXO (especially projectiles) is from the exercise area in front of the coastline near Petten.

In total 94% of the dredging activities took place in the coastal region.

3.4 Conclusion

Based on the dataset and case studies explained above, we conclude that the probability of encountering UXO is approximately 0.9 per km^2 in the coastal region and 0.3 per km^2 in other areas of the North Sea.

The much lower probability of encountering UXO when calculated based on dredging data differs considerably from the probability based on survey results. An explanation could be that mines are not noticed by dredging vessels as those are unlikely to get stuck in the drag head of a trailing suction hopper dredger.

From our usual conservative point of view, the survey data in the remainder of this report will be used.

[42] We provide an explanation of the unknown margin in section 3.1.

4. Probability of explosion

The second factor that we must determine regarding the objective risk of UXO in the North Sea is the probability of explosion (being a detonation (supersonic combustion) or a deflagration (subsonic combustion) of a UXO). We first report what previous studies state about this probability. Then we use our statistical perspective to show that the probability must be much lower.

$$p_{\text{fat | UXO}} = p_{\text{enc}} \times \boldsymbol{p}_{\textbf{expl | enc}} \times p_{\text{fat | expl}}$$

Where:

$p_{\text{fat | UXO}}$	=	Probability of a fatality as the result of an UXO related incident
p_{enc}	=	Probability of encountering a UXO at sea
$\boldsymbol{p}_{\textbf{expl |enc}}$	**=**	**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

4.1 The probability of explosion according to the literature

The literature gives findings for two different situations:

- The probability of UXO exploding that are still in war condition (and thus have an equal probability of explosion as when originally dumped). This is the TNO study.
- The effect of deterioration of UXO (and thus a diminishing probability of explosion) because of corrosion. This is the RWS study.

4.1.1 Probability of UXO exploding that are in war condition[43]

TNO has conducted research into the probability of explosion during different work activities at sea. TNO distinguishes between certain work activities and types of UXO (German, American, and British; types of mines, aerial bombs, torpedoes, projectile, and depth charges).

Currently, the focus is only on cable-burial activities and dredging, and the following distinctions in types of UXO are used: ground mines, contact mines, projectiles, aerial bombs, torpedoes and depth charges.

The research only includes explosives with a main explosive charge of 100 kg or more. Ultimately, TNO has distinguished about 40 objects.

Finally, they (TNO) determine the *trigger likelihood* (in %) using both a *conservative* and *realistic* method. The assumption for both approaches is that the objects are in “war condition” and are functioning correctly, which in itself is a conservative approach

[43] From: Kroon, E. & Bouma, R.H.B. (2020). Ammunition trigger study. TNO 2019 R10272.

given that the UXO considered have been laying in (salt) water for more than 70 years. We summarize the so-called realistic approach of TNO.

When we look at the *trigger likelihood* (in %) (with regard to dredging and cable-burial activities), the probability of explosion lies between 1% and 90%, depending on the type of work activities and type of UXO. We have only looked at the most common methods for both types of work activities: hopper dredging and jet trenching.

	Hopper dredging (min-max %)	Jet trenching (min-max %)
Mine (ground)	25 – 53 %	3 - 6 %
Mine (contact)	66 – 90 %	37 - 67 %
Aerial bomb	24 – 53 %	1 - 17 %
Depth charges/torpedoes	36 %	3 - 27 %
Projectiles	24 - 25 %	2 - 4 %

Table 4.1: Probability of explosion for type UXO in war condition according to TNO.

Realising that this is a rather large margin. When we look at the average trigger likelihood for each type of UXO, we arrive at the following "probabilities of explosion" (see following table). Therefor assuming equal distribution and having included all types of explosives with the same relative weight.

Type	Hopper dredging (average)	Jet trenching (average)
Mine (ground)	37.9 %	4.1 %
Mine (contact)	81.1 %	57.4 %
Aerial bomb	32.2 %	11.1 %
Depth charges/torpedoes	36.0 %	14.2 %
Projectiles	24.5 %	3.0 %

Table 4.2: Probability of explosion for type UXO (average) in war condition.

The conclusion based on the above:

- In the event of "interaction during underwater activities", even UXO in war condition (i.e. with still fully functional ignition mechanisms) do not always explode (although the probability for mines is rather high).
- The trigger likelihood of hopper dredging is higher than the trigger likelihood of jet trenching. If dredging is allowed, cable burial must also be allowed.

Jettisons
TNO's study states that the trigger likelihood of aerial bombs is 32.2 for hopper dredgers and 11.1 for cable burial tools (jet trenching) (on average).

Saricon concludes that 69.7% of the dropped aerial bombs are dropped in a safe or unarmed condition. With other words: at least 69.7% of the aerial bombs are not in armed condition.

So, 30.3% of the aerial bombs were dropped in armed condition. Generally spoken, 10% of the 'armed' dropped bombs did not explode in WW2. This means that (at most) 30.3% * 10% = 3% of the dropped bombs are still in armed condition.

4.1.2 Corrosion[44]

A study by Rijkswaterstaat indicates that it is very likely for seawater to penetrate the ignition mechanisms of UXOs laying at or in the bottom of the sea and for the resulting corrosion to render UXO inactive, (possibly with the exception of non-electric ignition mechanisms ground mines since this UXO is designed to withstand water pressure for a longer amount of time. For those mines however any battery to supply electric power is to be considered non-functional after the decades which passed since WW2). Most UXO will be 'not designed to remain underwater for extended periods of time under relatively high water pressure'.

TNO concludes the thickness of the shell will decrease with 0.1-0.3 mm per year (in 250-500 years all projectiles will perish). Most of the investigated objects (from dumping location Oosterschelde) contain leak paths.

The study of RWS concludes:

> *'Due to corrosion, seawater is expected to have intruded in most munition casings. Delicate mechanical and electrical components are likely severely damaged, if not completely dissolved over time. The probability that the fuses on UXO still work as intended, are considered extremely low. Influence mines are the only exception to this conclusion; given their rather robust construction, they are expected to be more resistant to the influence of seawater. Mechanical means of initiating may still function. However, 75 years of salt water will have had its impact.'*

From this perspective, only ground mines can pose a risk with the exception of any battery powered ignition mechanisms, i.e. only with regards to ignitions as a result of non-battery-fed-electric trigger mechanisms.

The decrease of incidents after 1960 implies that the (the quality of) UXO deteriorates (and the risk decreases).

---

[44] From: Arlar, L.J.J. (2021). Impact of corrosion on UXO related risks: Possible effects of corrosion on UXO in the North Sea. RWS Information *and* Den Otter, A. et al. (2021). Monitoring munitiestort Oosterschelde 2020. TNO 2020 R12211.

Incidents after WWII

In Germany (see also table 4.3), there appear to have only been 6 known unexpected initiations of UXO in the North Sea while working (excluding *beach visit*, mostly caused by phosphorus) from 1971 to 2014 (i.e., 0.14 per year), while from June 1945 to 1970 no fewer than 94 incidents are known (i.e., 3.62 per year). In the Baltic Sea, a similar pattern is visible: 0.45 per year on average from 1971, and 5.15 per year on average before 1971. After 1970, two people (both fisherman) died as a result of an unexpected initiation of UXO in the German North Sea and Baltic Sea.

	Dutch North Sea	Dutch fisher involved [45]	German North Sea[46]	German Baltic Sea
1945-1960	Unknown	Unknown	86 (17)	127 (29)
1961-1970	Unknown	Unknown	8 (0)	7 (0)
1971-1980	1 (1)	2 (1)	0	8 (1)
1981-1990	1 (1)	3 (1)	2 (1)	5 (0)
1991-2000	0	0	0	5 (0)
2001-2010	1 (1)	1 (1)	4 (0)	0 (0)
2011-2014	0	0	0	2 (0)

Table 4.3: Number of known incidents ((x)=with fatalities).

4.2 The probability of explosion statistically calculated

In this section the probability of explosion is calculated by using historical data of dredging (that has a higher probability of explosion than cable burial) using two perspectives. The first one is based on noticed and reported encounters. The second one based upon the earlier calculated probability of encountering an UXO.

Since 1974, about 22 * 10^6 m^3 (on average) are dredged every year in de Dutch North Sea. Our assumption is that an UXO-survey is a commonly used mitigating measure since 2015.

4.2.1 Noticed UXO during dredging

Between 2008 and 2014, dredging companies have encountered 321 UXO (see chapter 3) who have dredged 448.9 * 10^6 m^3. Most of the encountered UXO were projectiles.

51 UXO were encountered after 2014 (despite the mitigating measure that are used since 2015).

449.0 * 10^6 m^3 sand has been dredged between 1974 and 2007. Since there are hardly any registrations before 2008, we extrapolated the dataset of the Royal Netherlands Navy (see table 4.4).

[45] We excluded the incident with the exercise bomb and the Belgian vessel.
[46] We excluded 'Strandbesuch' (mostly caused by phosphor): 7 times (North Sea) and 28 times (Baltic Sea).

	Encountered between 2008-2014 (incl. margin)	Encountered between 1974-2014 (extrapolated)	Encountered after 2014[47]	Encountered total
Mine	6.9	13.8	2.2	16.1
Aerial bomb	29.9	59.9	4.8	64.7
Depth charge and torpedo	9.2	18.3	2.3	20.6
Projectile	274.6	549.3	41.3	590.5
Total	**320.6**	**641.3**	**50.6**	**691.9**

Table 4.4: Noticed UXO between 1974 and 2020.

By extrapolating the dataset of the Royal Netherlands Navy, we estimate that at least 692 explosives were encountered while dredging in the North Sea. Since there are no records found concerning any incidents or unexpected explosions during dredging in the North Sea, we consider the probability of explosion to be at least < 1/692 (see table 4.6).

4.2.2 Encountered UXO during dredging based on the probability of encountering

Since 1974, about 692 UXO (see table 4.4) were noticed during dredging based on the registrations. This is, however, less than expected based on the probability of encountering that we calculate in chapter 3. Therefore it is assumed that not all UXO has been noticed during dredging.

With the probability of encountering we calculated in chapter 3, we can estimate the number of encountered UXO (including the 'not-noticed' UXO).
*Formula: probability of encountering * km^2 dredged before 2015.*

- The probability of encountering is 0.927.
- $897.9 * 10^6\ m^3$ has been dredged from 1974 till 2014.[48] This means that (897.9 * 1.6=) 1,453 km^2 have been dredged in this period (see chapter 2).
- Based on the probability we calculate in chapter 3, we estimated that (0.927 * 1,453 =) 1,349 UXO has been encountered during dredging.

[47] 9 encountered UXO after 2015 are registered as unknown.
[48] ICES (2019). WORKING GROUP ON THE EFFECTS OF EXTRACTION OF MARINE SEDIMENTS ON THE MARINE ECOSYSTEM (WGEXT). *ICES Scientific Reports 1*(87); ICES (2016). Effects of extraction of marine sediments on the marine environment 2005-2011. ICES COOPERATIVE RESEARCH REPORT.

	Probability of encountering per km² (from chapter 3) [49]	Encountered between 1974-2014
Mine	0.638	929
Aerial bomb	0.207	301
Depth charge and torpedo	0.020	30
Projectile	0.061	89
Total	**0.927**	**1,349**

Table 4.5: Encountered UXO between 1974 and 2014 (extrapolated, based on probability of encountering, see chapter 3).

Although many objects are encountered during dredging, no incidents are known in Dutch North Sea. Therefore, the probability of explosion as < 0.0007 (7×10^{-4}) is considered.

	Known incidents during dredging in North Sea	Probability of explosion (noticed encounters)	Probability of explosion (based on probability of encountering)
Mine	< 1	< 0.062	< 0.001
Aerial bomb	< 1	< 0.015	< 0.003
Depth charge and torpedo	< 1	< 0.049	< 0.034
Projectile	< 1	< 0.002	< 0.011
Total	**< 1**	**< 1.4E-03**	**< 7.4E-04**

Table 4.6: The number incidents during dredging and the probability of explosion.

Please note that there is a difference between *registered encountered UXO* during dredging (table 4.4) and *expected encountered UXO* during dredging (table 4.5). We assume that a lot of UXO went unnoticed by the dredgers.

[49] We used the 'risk area-probability' (see chapter 3) because dredging activities are mainly in former convoy routes and minefields.

Dredging without incidents
In the Netherlands, Belgium, Germany, Denmark, France and United Kingdom, there is at least 1,634.9 * 10^6 m3 and (1,634.9 * 1.6 =) km^2 dredged before 2015 without incidents (as far as we know since 1970).[50] With an expected sand layer of 0.6 m, at least 2,477.1 km^2 has been dredged and approximately 2,500 objects should be encountered.

	Probability of encountering per km^2	Encountered	P(explosion)
Mine	0.638	1,690	< 5.9E-04
Aerial bomb	0.207	548	< 1.8E-03
Depth charge and torpedo	0.020	54	< 1.8E-02
Projectile	0.061	163	< 6.2E-03
Total	**0.927**	**2,456**	**< 4.0E-04**

Table 4.7: Dredging without incidents in North and Baltic Sea.

4.3 Conclusion

The dataset used for this research presents that at least 1,300 UXO must have been encountered during dredging in Dutch North Sea waters without resulting in any reported incidents. Not all encountered UXO would have been noticed by the dredging company.

Since more than 1,000 objects were encountered during dredging (based on the probability of encountering we calculated in chapter 3) and there are no incidents known to us, we conclude that the probability of explosion is less than 4 * 10^{-4} per encountered object.

Probability of explosion during cable burial
Based on the study of TNO (see part 4.1.1) the probability of explosion (or trigger likelihood) is probably smaller for cable burial by (jet) trenching than for dredging. Since we do not have data about the encountered objects during cable burial, we cannot calculate the risk of explosion for cable burial activities. We, however, know that there are 4,500 km pipes and 3,300 km cables in the Dutch part of the North Sea.[51] The majority of these cables is probably installed without UXO-survey and we have not found any incidents. We can roughly say that the probability of encountering *and* explosion is less than (< 1 incident / 7,800 km^2=) 0.0001 per km^2.

Please note that this is a rough estimation since we do not know which part of these cables and pipes were buried before WWII or with UXO-survey. Besides, we do not know how many cables and pipes were already removed, replaced or maintained.

[50] There are however four incidents known to us in Germany during dredging in ports or channels, all without fatalities or injured employees.
[51] Ministerie I&M en EZK (2015). Beleidsnota Noordzee 2016-2021.

5. Probability of fatality

The third factor that we must determine to calculate the individual risk posed by UXO in the North Sea is the probability of fatality. During dredging or cable-laying work activities, crew members are not "directly" in the affected area of the UXO (as they are on a vessel). Because of the absence of fatalities in reality, we distil from the literature two possible sub-risks that together give the individual risk: the vessel sinks (so drowning) and the effects of the explosive shock after initiation.

$$p_{\text{fat | UXO}} = p_{\text{enc}} \times p_{\text{expl | enc}} \times \boldsymbol{p}_{\textbf{fat | expl}}$$

Where:

$p_{\text{fat | UXO}}$	=	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
$\boldsymbol{p}_{\textbf{fat | expl}}$	**=**	**Probability on a fatality as the result of an explosion of the UXO**

5.1 The probability of fatality according to the literature

In this section we describe what the literature tells us about the probability of fatality for all types of UXO found in the North Sea.

5.1.1 Risk of (immediate) sinking

Two studies show that the probability of sinking depends on the depth of the water/distance and weight of the UXO.

A first study uses *Cole's formula* to demonstrate that 16 metres is the safe minimum distance for a sea mine with a TNT mass of 150 kilograms (most aerial bombs have a TNT mass of 150 kilograms or less, at least the commonly found in German waters).[52] The TNT mass of the commonly found mines in German waters varies from 45 kilograms till 725 kilograms.

Within 16 metres, there is a *likelihood of sinking*. For sea mines with a TNT mass of 1200 kilograms, this safe distance is 30 metres.

[52] Szturomski, B. (2015). The effect of an underwater explosion on a ship. *Zeszyty Naukowe Akademii Marynarki Wojennej*, *56*(2 (201)), 57-73.

Mine mass (TNT)	Likelihood of sinking (>16 MPa)
150 kg	< 16 m
300 kg	< 19 m
500 kg	< 23 m
800 kg	< 27 m
1.200 kg	< 30 m

Table 5.1: Likelihood of sinking according to Szturomski (2015).

Please note: this study shows the (theoretical) likelihood of sinking but this do not mean that the vessel will immediately sink (figure 5.1). Only from 250 MPa there is a risk of immediate sinking.

Pressure [MPa]	Effects of action of shockwave on a ship
12–16	Considerable deformation and cracking of the hull and bulkheads, flooding of compartments. Destruction of mechanisms and appliances. Numerous cases of death among crew members. Total loss of maneuver and combat capabilities. Many months docking and shipyard repairs necessary
16–27	Likelihood for the ship to sink. Cracking of bulkheads and widespread destruction of mechanisms and appliances. High number of death cases among crew members. If the ship does not sink she can be considered for repairs
250–350	Possible immediate sinking of the ship. If the ship does not sink, the destruction is so serious that she will be beyond repair
350–500	Possible breaking of the ship, her capsizing and sinking. If the ship does not sink, the destruction is so serious that she will be beyond repair
above 500	Immediate sinking

Figure 5.1: Likelihood of (immediate) sinking according to Szturomski (2015).

TenneT has conducted a similar study and examined scenarios in which there was a risk of sinking.[53] It showed that a risk of sinking can be prevented by maintaining a sufficient distance: for a 500 lb bomb, this is a water depth of 20 metres or more, or a water depth of 10 metres where the bomb is located 20 metres or more behind the ship.

[53] DNV GL (2020) *Full-ship and local structure UXO response simulation.*

TNT mass (kg)	UXO mass (lb)	Risk of sinking[54]
15	100	< 7,5 m (water depth)
31	250	< 10 m (water depth)
66	500	< 20 m (water depth) or < 10 m (water depth) with bomb 20 m behind vessel
218	1,000	< 40 m (water depth) with bomb 80 m behind vessel

Table 5.2: Risk of (immediate) sinking according to DNV GL (2020). The explosive weight (TNT mass) is from the report.

DNV GL found a safe distance but not *the minimum* safe distance to prevent (immediately) sinking. A risk of *global hull girder failure* can be excluded for all investigated scenarios (excluding the scenario with the 100 lb bomb detonating within 5 metres).

Finally, TNO also shows that there only is a risk of hull rupture during nearshore dredging (water depth up to 10 metres and depending on the weight [TNT kg] and draft of the ship) and that there is no risk of sinking with a water depth of over 20 metres (including for a full hopper (draught 6,81 m)). TNO includes UXO up to 200 *kg TNT*.[55]

TNO used a 'real' hopper dredger (that is often used by RWS) in their scenarios.
The three studies show that it is very unlikely (or impossible) a vessel will break into two by exploding UXO during dredging or cable burial (with a minimum distance of 10 m). Furthermore, Szturomski shows (compare figure 5.1 and 5.2) the risk of immediately sinking is only probable near the *epicenter*.

[54] Global hull girder failure (“breaking in two”).
[55] TNO (2017). *Effects of an explosion on a trailing suction head dredger*.

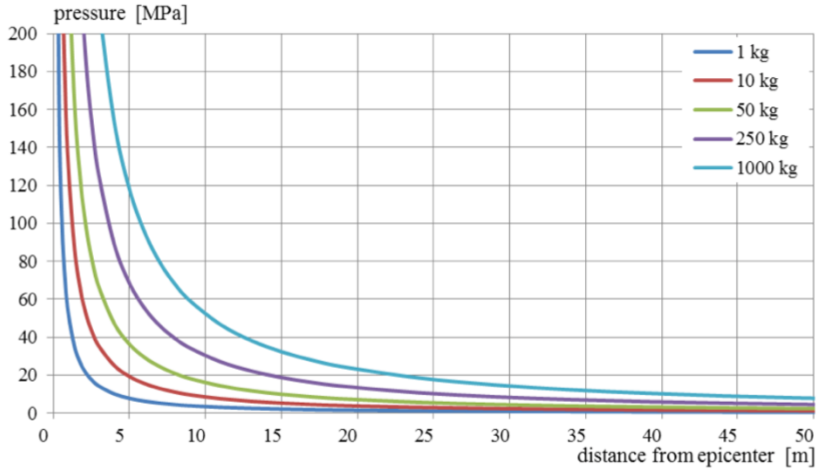

Fig. 4. The pressure values on the shockwave front in the function of distance and TNT mass of 1, 10, 50, 250, 1000 kg following T. L. Geers, K. S. Hunter [9]

Figure 5.2: Pressure values according to Szturomski (2015).

The decrease of pressure (figure 5.2) provides us an explanation for the fatalities with fishermen (after all explosions onboard) and the lack of fatalities with dredgers.

Comparison between fishing UXO-incidents and dredging working procedure

When the nets are opened on deck, the fishermen are standing nearby. They open the nets and guide the fish caught into the hull of the ship for sorting. If a UXO has been fished up from the seabed, the UXO will drop on deck or in the hull. If the UXO would detonate or deflagrate, it is thus in the direct vicinity of the fishermen.

When a drag head of a TSHD is brought above water and put in its cradles on deck, the able seamen of the dredging vessel are at a safe distance. In all area where UXO's are likely to be encountered, shrapnel curtains guard off the wooden plating on the deck underneath the drag head when it is in its cradles. If a UXO would fall on deck and explode or deflagrate, any shrapnel flying around would be caught in the shrapnel curtains. A camera is mounted on deck to remotely inspect the drag head on UXO's. Only if no UXO's are visible in the drag head, the able seaman will approach the drag head for further inspection and clearance of debris and stones from the UXO grid in the drag head. This method of working mitigates the risk of able seamen being hit by shrapnel from an UXO falling to deck from the drag head and detonating or deflagrating.

5.1.2 Risk of injury because of a shock wave

The same studies can also be used to examine the affected area in relation to injury or risk of death as a result of a shock wave.

First of all, Szturomski (2015) states that the shockwaves from 8 MPa could result in 'numerous injuries and cases of death'. Safe distances will be:

Mine mass (TNT)	Safe distance
150 kg	< 28 m
300 kg	< 35 m
500 kg	< 42 m
800 kg	< 49 m
1.200 kg	< 56 m

Table 5.3: Likelihood of sinking according to Szturomski (2015).

For UXO above 150 kg TNT, the safe distance is between 28-50 metres (see table 5.3). For UXO under 50 kg TNT, the safe distance is 15 metres or less (see figure 5.2).

Secondly, DNV GL (2020) differentiates the risk of injury for personnel onboard at the nearest location and personnel onboard at distance (half breath of ship).

TNT mass (kg)	UXO mass (lb)	Distance with no injury risk (at nearest distance)	Scenarios with risk of injury
15	100	Unknown	5 m (water depth) = 3/3 -> 100%
31	250	< 17,5 m (water depth) or > 10 m (water depth) with bomb 20 m behind vessel	10 m (water depth) = 2/4 -> 50%
66	500	< 25 m (water depth) or > 10 m (water depth) with bomb 20 m behind vessel	20 m (water depth) = 2/4 -> 50%
218	1,000	< 40 m (water depth) with bomb 80 m behind vessel	35 m (water depth with 70 m behind vessel) = 1/1 -> 100%

Table 5.4: Risk of injury at nearest distance according to DNV GL (2020).

TNT mass (kg)	UXO mass (lb)	Distance with no injury risk (at Distance; half breadth of ship)	Scenarios with risk of injury
15	100	Unknown	5 m (water depth) = 1/3 -> 33%
31	250	< 10 m (water depth) or > 10 m (water depth) with bomb 20 m behind vessel	10 m (water depth) = 0/4 = 0%
66	500	< 25 m (water depth) of > 10 m (water depth) with bomb 20 m behind vessel	20 m (water depth) = ¼ = 25%
218	1,000	< 40 m (water depth) with bomb 80 m behind vessel	35 m (water depth with 70 m behind vessel) = 1/1 -> 100%

Table 5.5: Risk of injury at distance (half breadth of ship) according to DNV GL (2020).

The risk of injury is controlled even at the nearest location with a water depth equal or greater than 25 m or a water depth equal or greater than 20 m with bomb exploding 20 m behind the ship (excluding 1,000 lb bombs). The risk of injury for 1,000 lb bombs can only be excluded with a water depth equal or greater than 40 m with bomb exploding 80 m behind the ship.

The safe water depth is lowered when we assume that a “safe” location is selected for work activities and that crew members are not “at nearest distance” but “at distance (half breadth of ship)”: for 250 lb bombs, there is no risk of injury at a water depth of 10 metres, and for 500 lb bombs, this value is still at 25 metres, but the risk of injury at a water depth of 20 metres is 25%. With a water depth equal or greater than 20 metres, only 500 lb bombs (probability of injury is 0,25) and 1,000 lb bombs (probability of injury is 1,0) could be considered as a risk.

Finally, according to TNO (2017), there is a probability of injury for crew members during dredging works in case of bombs heavier than 50 kg TNT mass and a depth of up to 20 metres (only for a full vessel[56]). At a water depth of 30 metres, this only applies from a weight of 200 kg TNT mass.

With the explosive weight, we can define which UXO are not a risk, pose a risk depending on their weight and pose a serious risk of injury. Based on the commonly found UXO in German Bight, we conclude that projectiles do not pose a risk.[57]

Mitigating measures

Mitigating measures against UXO risks are considered standard dredging industry practice. Low impact measures with little effect on the dredging process are almost always implemented during dredging. The primary (and arguably most effective) measure is the so called ‘bomb grid’. This grid is attached to the dredge head and blocks larger objects from entering the ship, preventing a possible explosion inside the vessel. These grids were originally used to prevent rocks from being thrown on the beach during beach suppletion works. The grid size is based on the smallest type of UXO that can cause substantial damage when exploding inside the vessel.

The second measure is a series of working protocols. For example, some TSHD crews are not allowed to work under the waterline when the pumps are active. Others TSHD crews preventively close the bulkheads when pumping. These protocols reduce the chance of serious consequences after an explosion.

When the dredge head is brought back up, it is often brought over a matrass or another soft surface. This ensures a soft landing of any UXO that may fall from the bomb grid in which they were stuck. The dredge head is subsequently inspected remotely by camera or physically by an employee. Any UXO contained in the dredge head are reported to the coast guard and cleared by the Royal Navy.

These simple and no-regret measures prevent incidents or injuries and death when an incident occurs, reducing risks caused by UXO during dredging works.

---

[56] Please note that this is in accordance with the study of TenneT (2020) that states that in 25% of the scenarios (at distance) an explosion of a 500 lb (about 68 kg) bomb will cause (potential) injuries.
[57] Data received from one of the experts who supported this study.

5.1.2 Conclusions based on literature

Starting with the assumption that dredging and cable burial activities are done with a minimum water depth of 20 metres (this can be replaced by creating a distance of 20 metres) and that hopper dredgers will have a grid to prevent the ingress of objects above the size of the grid spacing.[58] We explicitly say *water depth* because the studies considered both depth and draught.

Based on the three studies, the conclusion is drawn that there is no risk of (immediate) sinking during dredging or cable burial since the 'safe distance or water depth' is at least 10 metres. Hence, UXO will only cause damage or fatalities by a secondary cause.

The risk of injury depends on the distance or water depth and charge weight (kg TNT). With a water depth equal or greater than 20 metres, we assume the following risk of injury:

- < 50 kg TNT mass: 0.0
- 50 kg TNT mass - 66 kg TNT mass (=500 lb bomb according to DNV GL, 2020)): 0.25
- > 66 kg TNT mass (= 1,000 lb bomb according to DNV GL, 2020): 1.0

Keep in mind that this is the risk of injury and not the risk of fatality.

Based on the encountered UXO in German Bight (with the assumption that the encountered UXO is more or less the same as in Dutch North Sea), we conclude that:

- All ground mines and torpedoes are a serious risk of injury;
- Contact mines, aerial bombs and depth charges pose a risk of injury depending on their weigh;
- Projectiles are not a risk during dredging or cable burial.

5.2 The resulting probability that an encountered UXO will lead to a fatality

In this section we combine the literature on the probability of a fatality per subtype of UXO (such a different types of bombs that together form the UXO-category of bombs) with the earlier results on the composition of all types of UXO encountered to calculate a probability of a fatality per UXO-type encountered.

[58] For cable burial: a minimum water depth of 20 metres could be replaced by a towed system of at least 20 metres (see section 5.1.1).

Incidents
The number of incidents from the past shows us that UXO lead to fatalities when the UXO is or was on board. In spite of fishermen regularly "catching" mines, an initiation of UXO under the water does not lead to fatalities in those cases. The incidents in the Far East (see previous section), where dredging led to unexpected explosion of UXO, did not result in fatalities.

According to the previous studies (see previous section), there is no probability of death as a result of the ship sinking during cable-burial and dredging activities (we assume the water depth is at least 20 metres normally). This is also clear from the past: underwater UXO explosions have not yet to lead to fatalities and incidents in the Dutch North Sea. It means that people are only at risk of dying as a result of a secondary cause, such as a fall, collision, constriction, etc.

Literature states that only 500 lbs bombs (and UXO with more than 50 kg TNT) cause a risk of injury during dredging.

In the Dutch dataset, the weight of 13 contact mines (table 5.6), 156 aerial bombs (table 5.7) and 0 depth charges/torpedoes are given. We consider 13 mines as not representative.

UXO mass (lb)	TNT mass (kg)	Encountered mines	%
<100	<14	2	15%
<250	<31	1	8%
<500	<66	7	54%
>500	>66	3	23%
Total		**13**	**100%**

Table 5.6: Encountered contact mines with (estimated and/or given) weight.

The weight of 156 aerial bombs is given in the set. We consider this as representative.

UXO mass (lb)	TNT mass (kg)	Encountered aerial bombs	%
<100	<14	1	1%
<250	<31	35	22%
<500	<66	78	50%
>500	>66	42	27%
Total		**156**	**100%**

Table 5.7: Encountered aerial bombs with (estimated and/or given) weight.

We assume that only 50% (probability of injury is 0.25[59]) and 27% (probability of injury is 1.0) of the aerial bombs are a risk of injury for during dredging and cable burial activities.

[59] We use 25% since it is unlikely that the detonation is direct under the vessel and the employee will be on nearest location.

Since data about the mines and depth charges and torpedoes are insufficient, we consider the risk of injury as 1.0. This is a conservative point of view.

So, the next step is to calculate the risk of fatality from the risk of injury. Here we use a factor of 0.17 i.e., that 11.7% of all injuries lead to death. This factor is based on the incident proportion of all occupational health incidents in maritime sector resulting in a fatality as reported by the Dutch Safety Board (Dutch: Onderzoeksraad voor Veiligheid, OvV). We consider this a quite conservative approach because only the ‘relatively major incidents’ will probably be noted and researched. Indeed, as we calculate in annex 3 recent incidents show us that approximately 0.05 - 0.1 of the (Dutch) maritime incidents will result in fatalities.

5.3 General risk of fatality after injury

Risk of (potential) injury does not mean that there is a fatality: only a part of the people who were injured will ultimately lose their life due to these injuries.

Due to a lack of incidents with UXO (we only know 6 incidents with exploded UXO during dredging in Far East and in Germany, with no fatalities), we cannot directly compute a probability of fatality. However, since we only consider the risk of fatality of ‘secondary cause’ such as falling or constriction, we will explore the 'general’ risk of dying after an incident.

In Dutch waters and/or with Dutch employees, (at least) 320 incidents with hospitalisation in the maritime sector (we will describe this in annex 4) in the period 2013-2021 (April) are noted.

Maritime sector	Incidents with hospitalisation or fatality	Incidents with fatality	Fatalities (total)	Risk of fatality
Dutch waters	77	11	11	0.143
Dutch vessel	205	24	26	0.117

Table 5.8: Occupational health incidents and fatalities in Dutch maritime sector (shipping).[60]

Based on the incidents reported by the Dutch Safety Board (Dutch: Onderzoeksraad voor Veiligheid), 0.117 of the occupational health incidents in maritime sector results in fatality. We consider this as quite conservative because only the ‘relatively major incidents’ will probably be noted and researched.

[60] Retrieved from the biannually reports of the Dutch Safety Board.

5.4 Conclusion

Based on the literature on the fatality risk of subtypes of UXO and our calculation of the fractions per type of UXO encountered, we conclude that:

- there is no risk of sinking,
- Because a lack of data, we consider mines, depth charges and torpedoes all to pose a serious risk of injury,
- Aerial bombs pose a risk of injury depending on their weight,
- Projectiles cause no risk of injury.

Recent incidents show us that approximately 0.05 - 0.1 of the (Dutch) maritime incidents will result in fatalities (see annex 3), we however use the fraction given by the Dutch Safety Board of 0.117.

UXO	Risk of injury	Risk of fatality	Probability of fatality
Mine	1.0	0.117	0.117
Aerial bomb	0.13 + 0.27 = 0.4	0.117	0.046
Depth charge and torpedo	1.0	0.117	0.117
Projectile	0.0	0.117	0.0

Table 5.9: Probability of fatality for different kinds of UXO.

6. The UXO individual risk for dredging

In this chapter we present the individual risk assessment for North Sea Works. We present three probabilities that together describe this risk and calculate the resulting conservative individual risk level for dredging employees and thus also a very conservative assessment for cable burial.

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

Where:

$p_{\text{fat | UXO}}$	=	**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 a UXO

6.1 Risk assessment for dredging and cable burial operations

Probability of encountering

The probability of encountering UXO during dredging and cable burial is presented in chapter 3. This probability of encountering is based on the UXO-surveys. We will use 'risk area probability' since this probability considered the working area (mainly in the coastal region).

Note that dredging and/or cable burial activities outside the coastal region (or former convoy routes and minefields) will have a smaller probability of encountering.

UXO	Probability – Coastal region	Probability – non-coastal region
Mine	0.638	0.106
Aerial bomb	0.207	0.207
Depth charge and torpedo	0.020	0.003
Projectile	0.061	0.010

Table 6.1: Probability of encountering per km^2.

Probability of explosion as result of encountering a UXO

The probability of explosion as result of encountering a UXO during dredging has been presented in chapter 4. It was concluded the probability of explosion is smaller than 0.001 – 0.034 (depending on the type of UXO). The probability of explosion due to cable burial cannot be calculated (with the dataset), however based on the literature it can be concluded that this will be smaller than for dredging.

	Probability of explosion
Mine	< 0.001
Aerial bomb	< 0.003
Depth charge and torpedo	< 0.034
Projectile	< 0.011

Table 6.2: Probability of explosion per encountered UXO.

Note this is a conservative approach since the probability of explosion for fishery (see annex 2) is (much) smaller, especially for mines, bombs and torpedoes.

Probability of fatality as a result of an explosion of a UXO

The probability of fatality as a result of an explosion of a UXO during dredging has been presented in chapter 5. It was concluded the probability of fatality is 0.0 to 0.117 (depending on the type of UXO) for both dredging and cable burial activities.

We assumed in this study that dredging and cable burial activities are done with at least 20 metres water depth (or distance between the vessel and object) and (for dredgers) there is a grid that blocks UXO.

UXO	Probability of fatality
Mine	0.117
Aerial bomb	0.046
Depth charge and torpedo	0.117
Projectile	0.0

Table 6.3: Probability of fatality per encountered UXO.

Note that we consider the 'risk of injury' in terms of 'yes or no'. A conservative approach has been adopted since it is proven to be impossible to calculate the exact/objective risk of injury. Therefore, the probability of fatality (after encountering, explosion and injury) would be probably smaller.

Probability of death per year due to risk

The probability of death per year due to risk for an individual employee by is calculated by:

- Using the formula
- Multiplying the output from the formula with the average working area (in km2) for an individual employee

The probability of death per year due to risk is < 1,9 * 10^{-4} per km^2 in coastal region and < 5,8 * 10^{-5} in non-coastal region. Note a conservative approach has been adopted in our calculations.

UXO	Probability – Coastal region	Probability – non-coastal region
Mine	< 8.0E-05	< 1.3E-05
Aerial bomb	< 3.2E-05	< 3.2E-05
Depth charge and torpedo	< 8.0E-05	< 1.3E-05
Projectile	0.0	0.0
Total	**1.9E-04**	**5.8E-05**

Table 6.4: Probability of encountering, explosion and fatality per km^2.

94% of the dredging activities take place in the coastal region. We assumed that (individual) dredger-employees dredge 4.4 km^2 per year on average (full time employment, see chapter 2). The individual risk is **smaller than 8.1 * 10^{-4}** (1 in 1,200 years).

The small dataset is problematic (see chapter 8). Therefore, we cannot conclude that the individual risk is lower (or higher for that matter) than the accepted risk level using our statistical method.

7. Cost-benefit analysis of UXO-measures

Based on the individual risk assessment in the previous chapter, we can make a cost-benefit analyses. We will present the maximum allowed investments to proportionally mitigate the UXO-risk.

7.1 Proportional measures: maximum investment per DALY

A measuring unit used to quantify the severity of a risk, is the number of 'healthy life years' that are lost because of the risk, called *Disability Adjusted Life Years* or DALYs. DALYs are recommended by the WHO and other international bodies to compare risks and to determine if the measures taken to mitigate a risk are proportional.[61] The central perspective being that money can best be spent on the greater risk(s) in terms of DALYs lost.

This perspective is also implemented in the Netherlands, the use of DALY is accepted to determine whether safety and health measures are proportional.[62] In the Dutch health care system, the maximum allowed investment to gain a DALY is set as €80,000 for chirurgical treatment, €40.000 for medicines and €20.000 for vaccination (excluding Covid).[63]

It is an objective of governmental and semi-governmental organisations to use societal resources as effectively as possible.[64] Each *safety euro* should be preventing as much damage as possible. Given the small risk, the benefits of the measures are limited. However, the direct and indirect costs of the mitigation measures are enormous. Over a hundred million euros have been spent on controlling the risk.

In this chapter the approach as presented above is used to determine when UXO-measures are proportional.

7.2 The benefits of UXO-measures

In previous chapters the individual risk per employee per km^2 is computed.

[61] Homedes, N. (1996). *The disability-adjusted life year (DALY) definition, measurement and potential use (No. 16128, p. 1).* The World Bank.
[62] De Hollander, A.E.M., & Hanemaaijer, A.H. (2003). De Hollander, A. E. M., & Hanemaaijer, A. H. (2003). *Nuchter omgaan met risico's. RIVM rapport 251701047.*
[63] Raad voor Volkgezondheid en Zorg (2006). *Zinnige en duurzame zorg*.
[64] De Algemene Rekenkamer states that there should be an understanding that public funds are spent sensibly, efficiently, and with care (see: report *Inzicht in publiek geld* from 2016). This was also one of the principles in the vision of the Rutte II cabinet regarding security policy (Kamerbrief Tweede Kamer der Staten-Generaal, Bestuurlijk balanceren met risico's en verantwoordelijkheden, 9 november 2015, kenmerk 2015-0000650903).

Type of risk	Individual risk [65]
Risk of injury or fatality per km^2	$< 1.6 * 10^{-3}$
Risk of fatality per km^2	$< 1.8 * 10^{-4}$

Table 7.1: individual risk for employees per km^2.

With the individual risk for employees and the 'permissible investment' per DALY, we're able to calculate the maximum investment to mitigate the risk proportionally.

Starting point is that fatal cases *cost* 40 DALYs on average. Based on data from RIVM, it is computed that an occupational health incident in the Netherlands (without fatality) *costs* 0.16 DALYs per incident.[66]

The maximum allowed investment to gain a DALY is set as €80,000.

Since there are multiple employees on a vessel whom are all exposed to the risk, we need to know how many are onboard. Based on the knowledge of our expert group, we assume that there are on average 12 employees on a vessel.

The maximum amount of money to invest in mitigating the risk proportionally then can then be computed as *(((1.6 * 10^{-3} – 1.8 * 10^{-4}) * 0.16 * €80,000) + (1.8 * 10^{-4} * 40 *€80,000))) * 12 employees* equals €7,300 per km^2.

This allows us to calculate the maximum allowable additional[67] investments in specific projects:

- The maximum investment for RWS coastal protection per year to mitigate the UXO-risk is *€7,300 * 17,3 * 10^6 m^3 * 1,6 (fraction between m^3 and m^2 dredged) equals* €200,000.
- The maximum investment for TenneT's Borssele-cable-project is *€7,300 * 2,63 km^2 (*using a cable corridor of 10 metres) *equals* €20,000.

---

[65] We assumed that 94% of the activities are in coastal region and 6% of the activities are in non-coastal region.

[66] VZinfo.nl (n.d.). *Ziektelast van letsels door ongevallen in 2011*. Retrieved from: https://www.vzinfo.nl/. There were 81,000 occupational health incidents with hospitalisation in the Netherlands in 2011: 76,500 First Aid hospitalisations with a disability weight of 0.02 for the first year and 4,500 'regular' hospitalisations with a disability weight of 0.195 for the first year. 1.7% of the hospitalisations has permanent injury with a disability weight of 0.192. Formula: (76,500/81,000 * 0.02) + (4,500/81,000 * 0.195) + (1.7% * 0.192 * 40) = 0.16.

[67] Keep in mind that measures are already being taken: a grid, no employees in the engine room during dredging, etc. These measures are not visible in our historical / statistical approach and will reduce the risk even further than we have calculated. So, also the costs of these measures should be included in the calculation of the proportionality of UXO safety measures.

	Maximum investment
Maximum investment per km²	< €7,300
Maximum investment RWS coastal protection per year	< €204,716
Maximum investment Borssele-cable-project (cable route is 260 km)	< €19,200 <€74 / km

Table 7.2: Maximal investment per year or project.

7.3 Conclusion

Using the regular norms for proportional safety investments only a limited amount of money may be spent. A central norm for proportional UXO safety investments is €7,300 per km² (or € 19.200 for a cable installation project comparable to the Net op zee Borssele project (approx. 260 km of sea cable route length) thus < € 74 / km).

UXO surveys for the Net op zee projects

TenneT informed that the identification of a single object at the seabed did cost approx. € 10,000 to € 20,000 on the recent Net op zee projects. The UXO surveys for the Net op zee projects did cost in the order of magnitude of € 150,000 - € 250,000 per kilometre route length in the Dutch North Sea (Borssele and HKZ). It can thus be concluded that the actual casts made for the UXO surveys on the TenneT Net op zee projects are significantly disproportional to the mitigated risk related to fatalities as a result of UXO incidents: 2,000 to 3,300 time higher than the common Dutch maximum investment per DALY.

Cable installation

8. The risk during cable installation

In this chapter, we calculate the UXO risk for cable installation. We do this in the same way as we did for dredging activities: we look at the probability of encounter, the probability of explosion, and the probability of fatality.

8.1 Introduction

In the previous chapters, we specifically discussed the risk for dredging activities. The risk for burying cables is likely lower, as shown in the aforementioned study by TNO.[68] The trigger likelihood of UXOs for these activities is much lower than for dredging activities, mainly because the mechanical impact of the cable burial operations on encountered obstacles in the seabed is significantly lower than the impact of dredging tools, because the velocity and mass of the cable burial tools is significantly lower than of those dredging tools. Please note that this TNO study considers the explosives in pristine wartime conditions, which is no longer the case after more than 75 years in seawater. From the TNO report, p2: *"The assessments [...] assume that the: [...] mechanical components and energetic materials of initiation systems function correctly and according to design."*

In this chapter, we will examine how much smaller the risk on a fatality, as the result of an UXO is, for installing cables, compared to dredging. We will do this in the same way as in the previous chapters:

- We will investigate the chance of encountering explosives per km^2;
- We will investigate the chance of explosion per explosive;
- We will investigate the chance of fatality after the effect of an object;
- This will result in a risk per km^2. In this way, we can calculate the individual risk per employee.

8.2 Probability of encountering

The probability of encountering UXOs when installing cables will be more or less the same as when dredging. We deliberately say "more or less" because, in addition to the two-dimensional factor, it is partly dependent on the three-dimensional factor (how deep do you dig or dredge?). We do not address this point in this report since it is not a significant factor, as shown in the Deltares study: explosives will be located on or in the upper (sand) layer and in areas with mobile seabed reasonably not below the modelled lowest seabed since 1945.[69]

---

[68] TNO (2020). Ammunition trigger study | v2. TNO 2019 R10272.
[69] Deltares (2020). Memo: Review Hindcast Methodology TenneT. Reference number: 11205931-002-HYE-0001.

The probability of encountering explosives is estimated to be about 1 object per km^2 in the areas where cables will mainly be installed (see table 8.1). If work takes place outside the "risk zone" (the zone where mines, torpedoes, and depth bombs could reasonably be found, such as former minefields and convoy routes), a new analysis could be made for that area, with a lower density of UXO's. Air-dropped munitions can be found anywhere, so the probability of encountering them will remain more or less the same. If more detailed studies will be executed into the density of mines and bombs int the North Sea, than the probability of a fatality as the result of an UXO related accident can be detailed out further per route section. That does however not influence the overall conclusion derived in this chapter.

What differs from dredging, is the number of square kilometres seabed that one employee on a ship affects per year. The seabed influenced during cable burial operations to such an extent, that the deformation could theoretically inflict explosion or deflagration of a UXO, is conservatively assessed to be only 0.6 metre wide. A cable route of TenneT is taken to be about 200 km long. That is to be considered a conservative approach, as the current cable routes are less than 200 km long. At the end of this chapter, we will discount the total chance per km^2 with the number of km^2 that an individual employee affects.

UXO	Probability – general	Probability – risk area	Probability – non-risk area
Mine	0.638	0.638	0.106
Aerial bomb	0.207	0.207	0.207
Depth charge and torpedo	0.020	0.020	0.003
Projectile	0.061	0.061	0.010
Total	**0.927**	**0.927**	**0.326**

Table 8.1: Probability of encountering UXO in different areas.

In the meantime, four UXO surveys have been fully completed by TenneT in the North Sea, covering a total of 54.1 km^2. During these surveys:
- 27,831 contacts were found above the considered threshold;
- 2,932 objects were approached;
- 27 UXOs were found.

A quick calculation shows that the probability of encountering explosive objects is thus about (27 UXO / 54.1 km^2 =) 0.5 to (27 UXO / 2,932 objects * 27,831 contacts / 54.1 km^2 =) 4.7 per km^2. It should be emphasized that only those objects within the surveyed corridors, which could not be avoided by route engineering to a distance more than the considered safe stand-off distance (of approx. 15 metre) have been investigated on and in the seabed, in order to be identified. For the selection of the obstacles to be avoided only the modelled mass is used, as there is no way to establish whether an object with a certain modelled mass is an UXO or not without visually investigating the object in or on the seabed. The relation between the modelled mass and the encountered mass of the investigated obstacles however has appeared to be very poor to non-existent.[70] Thus, without actual relation between modelled mass and encountered mass, the effectiveness of avoiding UXO's by the route engineering efforts is considered to be doubtful at least. Thus, the density of the UXO's is to be considered more in the order of 0.5 per km^2 and not in the order of 4.7 per km^2. At the same time there is already a filtering process in place for approaching or not approaching objective considered to be potential explosives, where the less objects considered to be less likely a UXO are not investigated. This means that the figure of about 5 per km^2 is not realistic as in significantly higher than can be expected to be realistic.

Given this and previous data, we still consider the likelihood of encountering about 1 explosive object per km^2 to be a reasonable estimate. Further studies into the distribution of mines and bombs in the North Sea can nuance and lower this number, when those studies become available.

And please note: if the probability of encountering explosives were to be higher than estimated, this would also mean that more explosives have been found during past activities where no measures were taken (see Chapter 4 and 8.3). In that case, the probability of explosion (see 8.3) would be lower than what we have assumed.

8.3 Probability of explosion

In previous chapters, it has been shown that UXOs in the North Sea are clearly no longer in "war condition": often explosives are found, but there are hardly any known incidents where an encountered UXO did detonate or deflagrate.

This is logical, since the objects have been lying in the North Sea for 75 years now (and have possibly been touched by fishermen many times).

[70] This is evidenced by the fact that many targets that were investigated ultimately turn out not to be UXOs. Conversely, TenneT's practice shows that (small) objects and UXOs are not always noticed and recognized as such (insight gained through internal communication). The repeatability is very limited. It should be noted that really large objects are always detected.

Other research into aging

Research shows that after 2.5 years (140 weeks), none of the tested AT-26 mine detonators function anymore after being in salt seawater.[71]

However, it cannot be entirely ruled out that explosives in the (sand) soil can still detonate. German landmine detonators based on lead azide/lead styphnate can still function after being buried for 70 years: 1 out of 16 tested detonators resulted in a full explosion.[72] A study into the corrosion and deterioration of ignition systems of UXOs, which have been laying at the bottom of the sea for decades, focussing on the ignition systems used for mines and bombs which are encountered at sea, could bring a further nuance into this matter. Such a study is expected to further reduce the probability of an explosion as the result of a mechanical impact during cable installation.

For dredging, we have now been able to determine a maximum probability. We know that more than 1,300 objects must have been found during dredging without this leading to an incident. The probability of an incident is therefore at least smaller than $7 * 10^{-4}$ per object during dredging.[73]

At the same time, we also know that the likelihood of an effect of an explosive during jet trenching is about 3 but smaller than during hopper dredging. These are the most commonly used methods for cable installation and dredging. If an explosive does not go off during suction hopper dredging, it probably won't go off during jet trenching either, as the mechanical impact energy of jet trenching is significantly lower than of dredging.

TNO has conducted research into the probability of explosion during different work activities at sea.[74] When we look at the trigger likelihood (in %) (with regard to dredging and cable-burial activities), the probability of explosion lies between 1% and 90%, depending on the type of work activities and type of UXO. We have only looked at the most common methods for both types of work activities: hopper dredging and jet trenching.

---

[71] Ham, N.H.A. & Duvalois, W. (2003). Onderzoek AT26 ontstekers, TNO rapport PML 2003-A60. Via Kroon et al. (2015). Inventarisatie van WOII vliegtuigbom ontstekers in NL bodem. TNO 2015 R10074.

[72] Duvalois, W. & van Ham, N.H.A. & Kroon, E.J. (2011). Risk Assessment of Old German Detonators, TNO-rapport TNO- DV 2011 C233. Via Kroon et al. (2015). Inventarisatie van WOII vliegtuigbom ontstekers in NL bodem. TNO 2015 R10074.

[73] Experts acknowledge that the number of 1,300 encountered objects during dredging may be too low. We obtained this number through the probability of encountering (see paragraph 2 of this chapter) and the amount of dredged seabed. If the number of 1,300 objects is too low, then the probability of encountering them in reality will be slightly higher. Therefore, this does not make a difference for the risk analysis.

[74] TNO (2020). Ammunition trigger study | v2. TNO 2019 R10272.

	Hopper dredging (min-max %)	Jet trenching (min-max %)
Mine (ground)	25 – 53 %	3 – 6 %
Mine (contact)	66 – 90 %	37 – 67 %
Aerial bomb	24 – 53 %	1 – 17 %
Depth charges/torpedoes	36 %	3 – 27 %
Projectiles	24 – 25 %	2 – 4 %

Table 8.2: Probability of explosion for type UXO in war condition according to TNO.

When we look at the average trigger likelihood for each type of UXO, we arrive at the following "probabilities of explosion" (see following table). Therefor assuming equal distribution and having included all types of explosives with the same relative weight.

Type	Hopper dredging (average)	Jet trenching (average)	Difference in trigger likelihood (factor)
Mine (ground)	37.9 %	4.1 %	9,2
Mine (contact)	81.1 %	57.4 %	1,4
Aerial bomb	32.2 %	11.1 %	2,9
Depth charges/torpedoes	36.0 %	14.2 %	2,5
Projectiles	24.5 %	3.0 %	8,2

Table 8.3: Probability of explosion for type UXO (average) in war condition.

The probability that an explosive explodes through jet trenching is 1.4 to 9.2 times lower (depending on the explosive) than through hopper dredging.

Reasonably, we can assume that the chance of explosion when installing cables is about three times lower (excluding projectiles) than when dredging. The chance is then at least smaller than ($7 * 10^{-4} / 3 =$) $2 * 10^{-4}$.

Type	P(explosion) dredging (see chapter 4)	Difference in trigger likelihood (factor)	P(explosion) trenching
Mine[75]	< 1,1E-03	4,0	< 2,7E-04
Aerial bomb	< 3,3E-03	2,9	< 1,1E-03
Depth charges/ torpedoes	< 3,3E-02	2,5	< 1,3E-02
Projectiles	< 1,1E-02	8,2	< 1,4E-03
Total	**< 7.4E-04**	**≈ 3**	**< 2,4E-04**

Table 8.4: Probability of explosion for trenching.

[75] Approx. 33% of all the encountered mines in the North Sea are ground mines and approx. 67% are contact mines.

Significantly less chance of explosion than in wartime conditions
It is often assumed that explosives become more dangerous because the charge becomes unstable. However, the dataset shows that explosives actually have a significantly lower chance of exploding. There have been no known explosions during dredging in the North Sea. Therefore, this number falls outside the 99% confidence interval in any situation based on a normal distribution (based on 3 times the standard deviation).

Type	Trigger Likelihood Hopper dredging	Encountered UXO (see chapter 4)	Estimated number of explosions based on the trigger likelihood	Confidence interval [99%]
Mine (ground)	37.9 %	310 explosives	117 explosions	92 - 143 explosions
Mine (contact)	81.1 %	619 explosives	502 explosions	473 - 532 explosions
Aerial bomb	32.2 %	301 explosives	97 explosions	73 -121 explosions
Depth charges/torpedoes	36.0 %	30 explosives	11 explosions	3 - 19 explosions
Projectiles	24.5 %	89 explosives	22 explosions	10 – 34 explosions

Table 8.5: Confidence interval explosions during dredging.

The explosives in the seabed are clearly becoming significantly less dangerous over time.

8.4 Probability of fatality

Based on the water depth and distance between the ship and the explosive, the risk of fatality varies. For cable installation in relatively shallow waters as the North Sea, it is usually done at least 2.0 times the water depth behind the ship.[76] Assuming that employees are usually halfway on the ship and not at the nearest location, the distance from the ship to the bomb can be calculated based on the water depth.

This means that the distance from the stern of the ship to the explosive is:
- At a water depth of 10 metres: $\sqrt{10^2 + 20^2} = \sqrt{500} = 22$ m
- At a water depth of 15 metres: 34 m

[76] Please note that we are very conservative with only 2.0 times the water depth behind the ship. A distance behind the stern of 3.5 to 4.0 is mentioned by other experts (internal communication) as a more common approach for sandy soils, for harder soils 4.5 times the water depth has been used.

- At a water depth of 20 metres: 45 m
- At a water depth of 25 metres: 56 m

From previous studies, it has been shown that there is no risk of injury beyond a certain depth/distance. However, damage to equipment can still occur.

Using the previous studies, the "safe," "uncertain," and "certainly unsafe" explosive masses can be determined based on the risk of injury (not necessarily death and not potential damage).

Water depth/distance	Certainly safe			Certainly unsafe		
	DNVGL	TNO[77]	Szturomski	DNVGL	TNO	Szturomski
10 m /22 m	500 lb	50 kg TNT	50 kg TNT	1000 lb	75 kg TNT	150 kg TNT
15 m / 34 m	500 lb	150 kg TNT	250 kg TNT	1000 lb	200 kg TNT	300 kg TNT
20 m / 45 m	500 lb	200 kg TNT	500 kg TNT	1000 lb	? kg TNT	800 kg TNT
25 m / 56 m	500 lb	200 kg TNT	1000 kg TNT	1000 lb	? kg TNT	1200 kg TNT

Table 8.6: Results of the DNVGL[78]-, TNO[79]- en Szturomski[80] -study.

Therefore, at a water depth of 15 metres, only aircraft bombs of 1000 lb (pound) or more, (ground and contact) mines, and depth bombs with a TNT mass of 150-300 kg or more, pose a risk of injury to cable installers.

At a water depth of 20 metres, only aircraft bombs of 1000 lb or more, mines, and depth bombs with a TNT mass of 200-800 kg or more pose a risk of injury to cable installers. In most situations, the water depth will be 20 metres or more.

It has been shown in previous chapters that only 27% of aircraft bombs weigh 1,000 lb or more. In addition, contact mines and depth bombs generally have less explosive mass than 250 kg TNT. Torpedoes and influence mines often have a larger explosive mass than 250 kg TNT. See the overview of ammunition that may be encountered in the German Bight.[81]

Therefore, the following assumptions are made:
- 27% of aircraft bombs pose a risk of injury.
- Only influence (ground) mines, which is 33% of the mines, pose a risk of injury.
- Only torpedoes, which is 40% of the depth bombs/torpedoes, pose a risk of injury.[82]

[77] TNO's study only considers water depth, which is interpreted as the distance between the explosive and the ship in this study.
[78] DNV GL Maritime (2021). Full-ship and local structure UXO response simulation. MRGDE719 2017.107_rev3.
[79] Van Aanhold, J.E. (2017). Effects of an explosion on a trailing suction head dredger. TNO 2017 R11126.
[80] Szturomski, B. (2015). The effect of an underwater explosion on a ship. *Zeszyty Naukowe Akademii Marynarki Wojennej*, *56*(2 (201), 57-73.
[81] German Bight Munitions Register_R01. Received from TenneT by internal communication.
[82] There were encountered 34 torpedoes and 50 depth charges according to our data set.

- Projectiles pose no risk of injury.

This overview only shows the risk of injury in the event of an explosion and does not yet take into account the risk of death. In the previous chapters, we assumed that 11.7% of employees would die from injuries, which we will continue to use.

Type	P(injury)	P(fatality)	P(fatality total)
Mine	0,33	0.117	0.039
Aerial bomb	0,27	0.117	0.032
Depth charges/torpedoes	0,40	0.117	0.047
Projectiles	0	0.117	0

Table 8.7: Probability of fatality after explosion UXO.

8.5 Risk assessment

The risk per square kilometre is calculated by multiplying the three probabilities. We arrive at a risk that is at least smaller than $2.6 * 10^{-5}$ per km^2.

Type	P(encounter per km^2)	P(explosion per object)	P(fatality)	Individual risk per km^2
Mine	0.638	< 2,7E-04	0.039	< 6,72E-06
Aerial bomb	0.207	< 1,1E-03	0.032	< 7,29E-06
Depth charges/torpedoes	0.020	< 1,3E-02	0.047	< 1,22E-05
Projectiles	0.061	< 1,4E-03	0	0,00E+00
Total	-	-	-	< 2,62E-05

Table 8.8: Risk assessment per km^2.

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. So, every hour (60 cm * 200 m =) $1.2 * 10^{-4}$ km^2 seabed is affected.

It is unknown to us how many hours employees are on board the ship. Assuming a full-time job (1,720 hours per year), an employee affects 0.206 km^2 seabed per year, and the individual risk is at least smaller than $5.4 * 10^{-6}$ per year.

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.

With this, the 'at least smaller than' risk practically with its conservatism meets the safety standard in the Netherlands of $1 * 10^{-5}$ per year.

9. Cost-benefit analysis

Based on the individual risk assessment in the previous chapter, we can make a cost-benefit analyses We use the data from four TenneT-projects to conduct a social cost-benefit analysis.

9.1 Introduction

In the past seven years, TenneT has completed UXO surveys on four Net op zee projects. We use the data from these four projects to conduct a social cost-benefit analysis.

We have received an overview from TenneT with statistics from these projects. The most important data are:

- A total of 777 km of cables has been laid on these four projects. This means that, with 0.6m width of disturbed soil, 0.467 km^2 of the seabed has been disturbed.
- During these projects, there were 27,813 contacts. 2,932 (11%) of these contacts were investigated by ID&C. Of these targets, 27 were ultimately found to be UXOs.
- The total costs of these four projects were €114.5 million.

9.2 Potential benefits

It would be clear what the primary benefit is of mitigating the risk of death or injury 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 detect all UXO within reach of cable burial operations above the considered UXO threshold. 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 and larger) will be detected due to their relatively large ferro-magnetic mass.

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 on damage to the equipment.

To determine the benefits, we use the following assumptions:

- To determine the benefits of mitigating the risk of injury and death, we use the DALY methodology: we look at the number of healthy life years lost. The assumptions we use in this report are as follows (see also chapter 7):
    - 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 "costs" a maximum of € 80,000.[83]

- On a TenneT 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 exposed to the risk.
- A secondary benefit is the prevention of damage to equipment. We have no insights into the costs of any damage. 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).

Using these figures, we can determine the expected benefits:

- By preventing fatalities: 2.62 * 10^{-5} (risk per km^2) * 0.467 km^2 * 70 (employees on the ship) * 40 (remaining life expectancy) * €80,000 (cost of lost healthy life year) = €2,739.
- By preventing injuries: 2.22 * 10^{-4} (risk per km^2) * 0.467 km^2 * 70 (employees on the ship) * 0.16 (lost healthy life years) * €80,000 (cost of lost healthy life year) = €93.
- Primary benefits: **€3,832**.
- By preventing damage (a secondary benefit): 7.45 * 10^{-4} (risk per km^2) * 0.467 km^2 * €10,000,000 = €3,479.
- Total benefits (both primary and secondary): **€6,311**.

9.3 Potential costs

We see two social costs that arise from conducting a survey at sea and approaching explosives during the ID&C (Identification and clearance) phase of the UXO survey. Firstly, the financial expenses for these activities. Secondly, and more importantly to us, the costs incurred due to the occupational health and safety risks at sea.

To mitigate the risk, two activities are performed: first, a magnetometer survey is conducted, and then objects assessed to be above the set threshold are either identified and cleared or avoided by route engineering in the available surveyed corridor. It is already noted that the magnetometer survey must be performed in any case to avoid obstruction to cable burial by obstacles and to avoid damage to the cables (both now and in the future).

In this analysis, we again look at the four projects that TenneT has carried out.

The costs incurred in mitigating the risk are clear. The UXO survey efforts of the four projects together did cost € 114.5 million. About half of these costs are for the magnetometer survey, which must be performed regardless of the UXO risk. The other

[83] the Dutch health care system, the maximum allowed investment to gain a DALY is set as €80,000 for chirurgical treatment, €40.000 for medicines and €20.000 for vaccination (Raad voor Volkgezondheid en Zorg (2006). *Fair and sustainable care*).

half of the costs, € 57.25 million, is for identifying and clearing objects (ID&C). These are the extra costs in this case.

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.

Identifying and clearing objects takes place at a rate of 4 to 6 locations per day. An important factor here is the weather: one-third of the time, the weather is unworkable, and the employees wait for better weather. Therefore, we assume that an average of 5 locations per day is done. In TenneT's projects, 2,932 objects were identified. This means that employees worked at sea for at least (2,932 / 5=) 586 days to identify these objects.[84]

Based on this information, we can estimate the occupational health and safety costs involved as follows:

- The risk of death when working at sea is approximately $3 * 10^{-5}$ to $5 * 10^{-5}$ (see Annex 4 of the report). In this analysis, we conservatively assume a risk of $3 * 10^{-5}$ per employee per year.
- The risk of death after injury at sea is 0.117 (see section A.5 and chapter 5 of the report). This means that the risk of injury is 8.5 times higher than the risk of death. Therefore, we estimate this risk at $2.5 * 10^{-4}$.
- We assume that there are approximately (24 to 40, on average) 32 people on board an ID&C ship. An employee works approximately 150 days, 24 hours a day. This means that a total of 417 fulltime employees (working years) are needed to identify and clear objects.
- The rest of the parameters are described in section 9.2.
- The occupational health and safety-risk ‘costs’ **€12,401** in this case (by lost life years).

We did not include diving related risks on a fatal incident in this analysis. The diver's risk on a fatal incident is significant.[85] Therefore, TenneT tries to avoid diving on its projects as much as possible. If divers are still employed, it will result in a considerably greater risk on a fatal incident as caused by the UXO risk mitigation measures.

---

[84] In reality the amount of targets per day on the Net op zee projects was significantly lower, due to the specific conditions of near shore operations of the Net op zee projects so far. So, 5 objects per day is very conservative. We have received the overviews of the ID&C activities for the Hollandse Kust (west) Beta project from TenneT. On average, only 1.1 to 1.5 targets were identified each day. This means that employees worked at sea for at least (2,932 / 1,5=) 1,955 days to identify these objects.

[85] See for example: NTvG (2012). Decompressieziekte. Retrieved May 12, 2023, from https://www.ntvg.nl/.

9.4 Analysis

Approximately € 55 million has been spent on identifying and clearing objects in the four TenneT's projects assessed. In addition, employees have been exposed to risky conditions (because working at sea is a risk!), with safety costs of around € 12,000 (by lost life years). The safety benefit (excluding damage) is about € 3,000 (by lost life years). It is clear from a cost-benefit perspective that these investments are unjustifiable: the safety benefit is nil while the costs are enormous.

Of course, there is also the risk of damage, although this risk is also small. It should be noted that in practice, it is difficult to insure against this damage (caused by UXOs). One possibility is for TenneT to take on this "insurance" itself. This study shows that it is only a very small risk.

An important consideration, according to us, is also that mitigating the risk in this way with the UXO survey including an extensive ID&C effort costs more lives than it saves. If only the risk of death is considered, then it appears that these measures have resulted in the loss of 0.155 healthy life years, while only 0.034 have been "saved" by implementing these measures. The chance of an employee dying is thus at least four times higher when identifying and removing objects, or bypassing/avoiding them, is done, than when it is not done.

Conclusions

10. Putting it all together

We summarize our findings and present the overall conclusions in this chapter. We also reflect upon the meaning of our results.

10.1 Risk assessment of exposure to UXO

A central measure in Dutch safety policies to determine the acceptability of a specific risk is the chance of dying, because of the risk for those who can be exposed to it. Since the eighties, the central norm for this is that an individual risk of dying of once in the hundred thousand (100,000) years (short: IR 10^{-5}) is considered acceptable for the risks that together form a so-called risk compartment. We consider the exposure of people working at sea to the risk on a fatality due to a UXO related incident as such, a risk compartment.[86]

To determine this individual risk for those exposed to UXO, while working on the North Sea, and the acceptability of this individual risk, the following formula is used:

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

Where:

$p_{\text{fat | UXO}}$	=	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

The formula is simple but meaningful. If the probability of encountering is low enough, the other factors no longer need to be considered even if the effects of an explosion would be catastrophic. It actually works the other way around as well: if a prudent work method decreases the probability of people being struck if an UXO explodes, then there is no longer a need to consider the probability of encountering an UXO or of the probability of an explosion of it.

Once an individual risk has been calculated, another standard norm can be used to calculate what the so-called proportional safety investment is. In the Netherlands across risk domains, it is accepted that a maximum investment of €80.000 per healthy life year (denoted as DALY) gained is the norm.

[86] Should one wish to consider the risk of UXO as a sub risk compartment within the risk compartment of all occupational risk, which is a political choice, then according to standard policy a norm of IR 10^{-6} should be used. Please note that, for example, the risk of exposure to dangerous substances during work is considered as a risk compartment on its own.

The individual risk because of UXO for dredging and cable burial never has been calculated before. Up to 15 years ago nobody considered this a risk that had to be taken seriously in the sense that UXO would have to be surveyed for in advance of operations at sea. The measures taken in the past were related to dealing with encountered UXO once those were in plain sight, for instance caught in a drag head of a dredger or found on a cable burial tool when it was recovered to deck.

TenneT and Rijkswaterstaat have asked Crisislab to try to calculate the individual risk and the resulting proportional safety investments. We have tried to use a so-called historical statistical approach, meaning we have used historical data such as that dataset of the Netherlands Coastguard (Kustwacht) of all UXO findings registered in order to arrive at an estimation of the individual risk.

10.2 Findings on the individual risk

Using the formula, the following conclusions are seen on the individual risk and the sub risks composing it.

Probability of encountering

Based on the dataset and two case studies, it can be concluded that the probability of encountering UXO is approximately 0.9 per km^2 in the coastal region (with former minefields and convoy routes) and 0.3 per km^2 in other areas of the North Sea. This is in line with several 'guesstimates' of consulting companies.

Probability of explosion as a result of encountering

Our calculations using the above method of probability show that at least 1,300 UXO in the Dutch North Sea must have been encountered during dredging, without any incidents occurring. Therefore, it can be concluded that the probability of explosion is **less** than $7.4 * 10^{-4}$ per encountered object.

Reasonably, we can assume that the probability of explosion when installing cables is about three times lower (excluding projectiles, which given their size and given that those remain underwater, are not considered to pose a threat to people involved) than when dredging. The probability of explosion during cable installation is then at least smaller than $2 * 10^{-4}$.

Probability of fatality as a result of an explosion

Based on the literature on the fatality risk of subtypes of UXO and our calculation of the fractions per type of UXO encountered, it can be concluded that:

- there is no risk of sinking,

- because a lack of data, we consider mines, depth charges and torpedoes all to pose a serious risk of injury (probability of injury given an explosion is 1.0) during dredging. During cable installation, only ground mines and torpedoes pose a serious risk of injury,
- aerial bombs pose a risk of injury depending on their weight (probability of injury is 0.0, 0.25 or 1.0),
- projectiles cause no risk of injury.

Recent incidents shows that approximately 0.05 – 0.1 of the (Dutch) maritime incidents will result in fatalities (see annex 3), however the conservative fraction given by the Dutch Safety Board of 0.117 is used.

Individual risk assessment

Using above formula, the risk of a fatality per km^2 while dredging and during cable burial operations is smaller than $1.9 * 10^{-4}$ in the coastal region (with former minefields and convoy routes) and smaller than $5.8 * 10^{-5}$ in non-risk areas.

To calculate the individual risk two assumed facts are needed:
- Almost all dredging activities (94%) takes place in the coastal region.
- A(individual) crewmember on a dredger- dredges 4.4 km^2 per year on average.

With these assumptions, the conclusion must be that the individual risk **for dredging** is **smaller than $8.1 * 10^{-4}$** per year.

For cable installation, we assume 24-hour 'on-and-off' shifts, with 150 working days per year. The individual risk is at least **smaller than $1.1 * 10^{-5}$** per year.

10.3 Limitations to the historical statistical approach

Pointing out to the fact that we use a historical statistical method. This means that the strength of the conclusion corresponds directly to the strength of the dataset used. So, the strength of our method is that real life data is used instead of modelling. The weakness is however that when in possession of little data, the accuracy might be less than desired.

To be a bit more specific:
- We calculate the risk of an action essentially as the ratio between the number of accidents when performing the action versus the number of times the action has been performed in total.
- Without accidents, we can only provide an upper limit for a chance of a risk, i.e. 1 / (the number of times the action has been performed in total).

Let us present some simple examples:

- Assume an action has been performed twice and there has been one accident, then clearly the risk is ½. (This dataset is so small that the reliability of this calculation could be questioned, however that is another matter.)
- Assume an action has been performed twice and there has been no accident, then we can only say that the risk is less than ½. So, suppose we are asked to calculate the risk that when opening a kitchen closet you will be bitten by a tiger, then after opening the closet 10 times we can only say that this risk is lower than 1/10. We need another way of reasoning to assure us that the risk is acceptable low.

Now applying these insights to this research:

There have been no accidents on the North Sea involving our type of work and UXO's. However, the number of people exposed to the risk is rather low, at least far below the 100.000 working years, so we have no dataset that allows us to directly conclude that the risk is lower than $1 * 10^{-5}$ for those working a year and being exposed to UXO's

That is why we have tried to use the formula p(encountering an UXO) * p(letting the UXO explode) * p(fatality caused by the exploding UXO)
- We have a serious dataset that shows that the chance of finding a UXO is 0,9 per km^2. This seems a hard number.
- We have however a small dataset of exploding UXO and of exploding UXO causing harm. This means that both chances must be limited by another way of semi-quantitative reasoning. We have mainly relied on other reports to exclude parts of the collection of UXO that can be found. As can be seen, because of the conservatism in all these reports our calculated risk is still rather high.

In table 10.1 we summarize all the conservative assumptions in this study.

Chapter	Conservatism	Suggestion for further research
2	We assumed that contact mines are mainly in former minefields and coastal region. There are indications that (formally) floating contact mines are distributed more equally in the North Sea as a result of drifting away from the former mine fields (e.g., contact mines were encountered near the Afsluitdijk).	Data about the exact locations of former contact-minefields and the coordinates of the encountered UXO (during survey of dredging) could provide information about the drifting of contact mines.
2	In the risk analysis we assumed that only 77 employees are 'responsible' for the dredging activities for the coastal protection. With other words: we assumed an 'optimal production-process'.	Information about number of employees that are hired to perform the dredging activities for coastal protection could provide us the average number of m^3 and/or m^2 that an employee dredges per year. The number of m^3 and/or m^2 affects the individual risk.

2	Despite day/night shifts we assumed an 'full exposure to the UXO-risk' during the time that the crew is on the vessel. Crew members however could be in safe places when considering the risk of a fatality due to an explosion without the ship sinking (e.g., sleeping cabin).	The exposure to the risk affects the risk assessment. Further research has to be performed to conclude what time the crew members are exposed to the risk (working time) and not exposed to the risk (sleeping time).
2	We consider the risk for cable burial as the same as dredging. The trigger likelihood (according to TNO's study) is however much lower for cable installation than for dredging.	Data about the number of buried cables (and/or pipes) between 1945 to 2014 could give more insight in the risk of cable burial. Then we could perform a risk analysis such as we did for dredging activities.
3	To determine the 'surveyed area' we take the minimum distance between to registrations. This is, probably, not the whole surveyed area. Our estimation is in line with Saricon and the survey of TenneT.	To determine the 'exact probability of encountering', more surveys like TenneT's survey could be done, more data about the performed surveys could be exchanged or more advanced data sets could be used as for instance the data gathered by the Swedish Navy on mine fields in the North Sea.
4	We calculate the probability of explosion by dividing the known incidents by the encountered objects for each type of UXO. We, however, do not know any incident with UXO and therefore the probability of explosion is quite high for each type of UXO, despite the are indications that most UXO do not pose a risk anymore.	Further technical research should be performed to determine the probability of explosion and the influence of (salt) water on the functioning of the explosive ie into the effect of corrosion and aging on the functioning of the UXO.
5	We differentiate the probability of injury or fatality into 0.0, 0.25 and 1.0. The literature and the dataset do not provide an 'exact' probability of injury or fatality (only yes or no).	We do not have suggestions for further research or data collection.
5	We assumed that the probability of fatality after an injury is 0.117. Other calculations (see annex 3) show that the probability of dying after hospitalization is much lower.	We used the highest probability in the risk assessment. Another calculation is possible (see annex 3).
8	We assumed that jet trenching is done at least 2.0 times the water depth behind the ship. A distance behind the stern of 3.5 to 4.0 is mentioned by other experts (internal communication) as a more common approach.	We do not have suggestions for further research or data collection. It could vary from project to project.

9	'Mitigation risk': we did not include the diver's risk and assumed that 5 targets were identified per day (probably high).	A more systematic review about the risk of mitigation measures could lead to a more complete social cost benefit analysis.

Table 10.1: Conservative assumptions in this study.

To gain a better insight in the individual risk for dredging and cable burial we therefore have to apply other semi-quantitative insights.

10.4 Conclusions and recommendations

Our first conclusion is that using our historical statistical method we cannot conclude that the risk is smaller than $1 * 10^{-5}$, the accepted norm in other safety domains. Due to a lack of data, the historical statistical approach does not offer an answer to whether the risk is acceptable or not (for dredging activities).

Despite the fact we cannot conclude the individual risk to be below generally accepted norms, three remarks have to be made:

- It is an objective of governmental and semi-governmental organisations to use societal resources as effectively as possible. Each *safety euro* should be preventing as much damage as possible. Using our upper limit on the individual risk we can compute that a maximum investment of 7,300 euros per km^2 is allowed to mitigate the risk proportionally (or € 74 per km route length for cable installation). This limit could be used as a guidance to implement the 'reasonable'-part when applying the ALARP-Principe (as low as reasonable possible) to UXO. This quickly results in the conclusion that the presently spend € 150,000 to € 250,000 per km route length is to be considerably significantly disproportional, when applying the maximum investment per DALY approach.

- A semi-quantitative risk comparison to the UXO risk for fishermen seems to indicate that this risk for fishermen is substantially higher than for dredgers. In annex 2 we calculate the UXO-risk for fishermen. The individual risk of UXO for fishermen can be better computed because of the larger data base and turns out to be $5 * 10^{-5}$ per year. We may subsequently conclude that the individual risk for dredgers and cable burial tools will be smaller than $5 * 10^{-5}$ per year also.

- A quick calculation shows that the general individual risk for maritime workers is about $5 * 10^{-5}$ per year (1 in 20,000 year) (annex 4). This, on the one hand shows that the UXO risk for fishermen and probably for dredging employees is not higher than the general risk (that thus is higher than the generally accepted $1 * 10^{-5}$ norm. 1 in 100,000 year). On the other hand, when using a ship to survey and identify and clear objects in the North Sea bed as a mitigating measure for the UXO risk, employees on this ship are exposed to a risk that probably is higher than the UXO risk for dredging and cable burial.

These remarks must be considered in any decision whether to take mitigating measures for the UXO-risk.

For cable installation, but likely also for dredging workers, we conclude, based on this risk analysis, that it practically meets the general safety norm in the Netherlands and that the risk is at least lower than the general risk of working at sea. This means that the probability of a fatality is higher with the currently used UXO mitigation measures than without those mitigation measures.

The current approach of the UXO risk for cable installation (and probably for dredging), in particular the investigation in and on the seabed of objects which are considered to be above a UXO threshold, is therefore to be considered disproportionate and counterproductive with regard to the objective to reduce the risk on fatal incidents as a result of working at sea.

Based on the insights of this study, we have the following (practical) recommendations:

1. Following the assessments made in this study, it is recommended for any future UXO related assessments and surveys to assess only the probability on a fatality and not to assess probabilities on damage to equipment, as the related probabilities of damage to equipment and as the costs involved for the mitigating measures to avoid damage to equipment are assessed to be significantly disproportionate to the risk of potential damage caused to equipment.

2. It is recommended to further fact based assess the probability on an explosion as the result of contact between a ground penetrating operation and a UXO, taking into account the aging and deterioration of the UXO. The currently used assumption that all UXO encountered are in pristine working order is in sheer contradiction with the observed facts with regard to the amount of UXO touched by fishing and dredging activities and the absence of weekly or monthly explosions. This as well should result in a more proportionate stand-off distance to the larger magnetic obstacles.

3. Following the assessments made in this study, it is recommended to thoroughly and objectively consider the added value of UXO risk mitigating measures before implementing them in offshore projects. UXO survey, identification and removal is counterproductive in most cases in terms of overall safety. Survey may however be unavoidable for other aspects of project preparation, such as geological and archaeological research and obstruction removal. Using data from these surveys for additional UXO risk reduction may pose a no-regret measure. In that case however, where obstacle survey data is used for UXO risk reduction, the thresholds used should be in line with the risk which is intended to be mitigated i.e. the risk of a fatal incident and not of equipment damage, taking into account the water depth and the method of working.

4. This study is based upon a set of *conservative* assumptions that either could be found directly in the literature or were deduced because of the absence of direct available knowledge. We therefore recommend bringing together all literature and ongoing research in mechanisms that lead to deterioration of the UXO in order to come to a further narrowing down of a *realistic* estimation of the risk on a fatality by an incident with an UXO.

10.5 Closing remark from the steering group

No fatal UXO related incidents after 1970 are known, relating to dredging and cable installation operations in the North Sea. Although no fatalities have been reported during these activities, the risk perspective with regard to UXO encountered during these operations has changed over time since 2000, for reasons only partially understood.

One of the reasons could be that the acceptance of UXO risks in offshore projects has reduced, because of the increased focus on safety and risk analysis on the offshore projects during the last decades. Another reason could be that over the last years new survey techniques have been developed, which significantly increased the capabilities to detect ever smaller obstacles on and in the seabed. The fact that some UXO have been found during many surveys with the increasingly more sophisticated techniques, contributed to the idea that UXO must be surveyed for, as they for a fact were encountered.

The lack of scientifically quantified substantiations of the factual risk on a fatality, as the result of a UXO related incident, made it difficult to proportionate the approach of the UXO risk. The majority of the UXO desk top studies performed over the last years have been assessing worst case scenario's, which did flag a risk of encountering UXO practically everywhere in the North Sea and a risk on significant damage as a result of encountering UXO. This does however not reflect reality as witnessed on the projects or on other ground touching activities at sea. It is not in line with the fact that fishing and dredging activities did thoroughly disturb significant parts of the seabed in the North Sea and did move around many encountered obstacles, without any significant number of UXO incidents. Every week though, fishermen brought, and are still bringing, UXO on deck without a long list of UXO exploding.

This Crisislab North Sea UXO study adds risk management based on data analysis to the considerations with regard to UXO in the North Sea. This study contributes to a proportionate approach of the UXO risks in relation to other risks as well as in the relation to the financial costs made to mitigate the risks. This report adds existing industry guidance, such as the CIRIA guidance. The approach by Crisislab is considered to be a first step towards looking at the UXO risk in the same manner as at any other risk faced while working at sea by, making it possible to compare the risks and to gain insight in the total risks to which people working at sea are exposed.

The decision on how to proportionate the UXO survey related efforts should stem from a better quantified assessment of all risks involved when working at sea. That decision should be made in combination with a decision on which mitigation measures are to be considered proportionate (what is still practicable and what is not anymore?). Here, first of all, the framework of the legal occupational health and safety requirements applies. Transparency of the assessments and traceability of the data sources used would better meet such legal requirements.

The past 15 years the changing approach of UXO risks at sea has led to a series of, sometimes very expensive, safety measures without an evaluation of their necessity and effect and without a check on the proportionality of the approach. The complexity of dealing with a combination of probabilities, which individually might be considered justifying the current UXO efforts, is considered to have hampered previous attempts to proportionate the approach of UXO. An overarching, better substantiated scientific assessment of the combination of risks was needed to come to a better understanding of what can be considered proportionate and what not. This UXO North Sea study is considered a first useful result on that road to improve safety for those working at sea by reducing measures which, based on data driven risk analysis, are to be considered counterproductive and disproportionate, and as such unnecessary.

Annex

Annex 1. Clustered surveys

1	ID	STAT_DATUM	CODE2	Activiteit	STATUS	Details	POINT_X	POINT_Y	#	
980	1874	2020-08-20	MV GEOHOLM	Survey	0	Vliegtuigbom	57112,00925	478300,1463	1	
1218	1875	2020-08-21	MV GEOHOLM	Survey	Recovered	Onbekend	63271,1679	485677,3767	1	
1226	1876	2020-08-22	MV GEOHOLM	Survey	0	Vliegtuigbom	63913,36187	484163,086	1	
1240	1877	2020-08-23	MV GEOHOLM	Survey	Recovered	Onbekend	63247,42573	485622,1732	1	
1271	1878	2020-08-24	MV GEOHOLM	Survey	0	Overig	63391,25505	484191,2914	1	
1272	1879	2020-08-25	MV GEOHOLM	Survey	VERKEERD	Onbekend	63829,34738	484535,5989	1	
1273	1880	2020-08-26	MV GEOHOLM	Survey	0	Onbekend	67084,81818	489354,6747	1	
1274	1881	2020-08-27	MV GEOHOLM	Survey	VERKEERD	Overig	66744,117	489342,2118	1	
1275	1882	2020-08-28	MV GEOHOLM	Survey	VERKEERD	Vliegtuigbom	63953,58823	484496,2104	1	
1281	1883	2020-08-29	MV GEOHOLM	Survey	0	Onbekend	60044,76088	485052,0875	1	
1287	1884	2020-08-30	MV GEOHOLM	Survey	0	Overig	56616,75713	488606,3964	1	
1289	1885	2020-08-31	MV GEOHOLM	Survey	0	Onbekend	56187,50793	486444,7483	1	
1290	1886	2020-09-01	MV GEOHOLM	Survey	0	Overig	58654,28678	480738,6619	1	
1291	1887	2020-09-02	MV GEOHOLM	Survey	Recovered	Overig	56422,30118	481135,0956	1	
1292	1888	2020-09-03	MV GEOHOLM	Survey	0	Mijn(type onbekend)	58307,95068	476980,0887	1	
1294	1889	2020-09-04	MV GEOHOLM	Survey	0	Overig	56369,93349	488184,6991	1	
1295	1890	2020-09-05	MV GEOHOLM	Survey	VERKEERD	Overig	49289,23629	486773,1734	1	
1297	1891	2020-09-06	MV GEOHOLM	Survey	0	Vliegtuigbom	60056,47306	485070,4107	1	
1298	1892	2020-09-07	MV GEOHOLM	Survey	VERKEERD	Overig	59030,32369	481191,3485	1	
1299	1893	2020-09-08	MV GEOHOLM	Survey	0	Mijn(contact)	71218,66781	487045,8734	1	
1306	1894	2020-09-09	MV GEOHOLM	Survey	0	Mijn(contact)	62596,47533	479112,7763	1	
1307	1895	2020-09-10	MV GEOHOLM	Survey	0	Vliegtuigbom	63127,90637	478455,5494	1	
1308	1896	2020-09-11	MV GEOHOLM	Survey	0	Mijn(contact)	63096,61961	478424,599	1	
1316	1897	2020-09-12	MV GEOHOLM	Survey	0	Vliegtuigbom	60951,9115	476001,7211	1	
1320	1898	2020-09-13	MV GEOHOLM	Survey	0	Vliegtuigbom	60951,9115	476001,7211	1	
1356	1904	2020-09-19	MV GEOHOLM	Survey	0	Overig	58558,63893	475597,0543	1	
1363	1905	2020-09-20	MV GEOHOLM	Survey	0	Overig	58550,27733	475576,8141	1	
1364	1906	2020-09-21	MV GEOHOLM	Survey	0	Overig	58511,14146	475495,9642	1	
1366	1907	2020-09-22	MV GEOHOLM	Survey	0	Overig	57386,6351	475440,1089	1	
1367	1908	2020-09-23	MV GEOHOLM	Survey	0	Geschutmunitie	55947,39753	477631,4672	1	
1368	1910	2020-09-25	MV GEOHOLM	Survey	0	Overig	56234,08502	480421,0178	1	
1369	1911	2020-09-26	MV GEOHOLM	Survey	0	Overig	56212,60369	476383,4086	1	
1370	1912	2020-09-27	MV GEOHOLM	Survey	0	Mijn(contact)	64866,75702	490822,9278	1	
1371	1913	2020-09-28	MV GEOHOLM	Survey	0	Schroot	56428,2054	481146,1071	1	157,0 km
1372	1830	2019-10-22	KAMARA	Survey	0	Vliegtuigbom	-7451,130519	402960,3503	2	
1373	1818	2019-08-16	KAMARA	Survey	VERNIETIGD	Mijn(invloed)	-2184,381763	409415,3908	2	
1374	1817	2019-08-15	KAMARA	Survey	WAS AL VERNIETIGD	Vliegtuigbom	-6054,266414	422266,1815	2	
1375	1816	2019-08-09	KAMARA	Survey	vernietigd	Mijn(invloed)	-4475,852068	411769,6135	2	
1376	1815	2019-08-08	KAMARA	Survey	vernietigd	Mijn(invloed)	-2313,076269	412313,8357	2	
1377	1814	2019-07-19	KAMARA	Survey	vernietigd	Mijn(contact)	-7291,40956	418539,3649	2	
1378	1812	2019-07-06	KAMARA	Survey	Vernietigd	Mijn(contact)	-4396,255937	402972,3737	2	
1379	1798	2019-04-30	MV KAMARA	Survey	Stalen pijp	Vliegtuigbom	-6167,292742	422295,7861	2	
1380	1787	2019-04-18	KAMARA	Survey	Vernietigd	Mijn(invloed)	-1606,405524	416484,9966	2	85,6 km
1381	1807	2019-05-25	MV FRIENDSHIP	Survey	vernietigd	Mijn(contact)	126825,7906	589990,8755	3	
1382	1806	2019-05-24	MV FRIENDSHIP	Survey	vernietigd	Mijn(contact)	130962,0651	592639,4744	3	
1383	1805	2019-05-20	MV FRIENDSHIP	Survey	Overgedragen GE	Geschutmunitie	246173,1848	629181,7424	3	
1384	1801	2019-05-03	MV FRIENDSHIP	Survey	NOMBO	Mijn(contact)	217852,6166	620559,2563	3	
1385	1800	2019-05-02	MV FRIENDSHIP	Survey	NOMBO: STEEN	Mijn(contact)	218207,5214	622276,3781	3	
1386	1799	2019-05-01	MV FRIENDSHIP	Survey	stalen drum	Mijn(contact)	219790,9879	623390,4469	3	
1387	1797	2019-04-29	MV FRIENDSHIP	Survey	vernietigd MK1	Mijn(invloed)	218695,1593	622796,7959	3	
1388	1796	2019-04-28	MV FRIENDSHIP	Survey	niets gevonden	Mijn(contact)	218203,8571	623216,9603	3	
1390	1793	2019-04-25	MV FRIENDSHIP	Survey	niets gevonden	Mijn(contact)	214359,4823	620904,0209	3	
1393	1792	2019-04-24	MV FRIENDSHIP	Survey	vernietigd MK17	Mijn(contact)	214177,0931	620829,3951	3	
1394	1791	2019-04-23	MV FRIENDSHIP	Survey	vernietigd	Mijn(contact)	213701,7819	620955,2324	3	
1395	1790	2019-04-22	MV FRIENDSHIP	Survey	NOMBO	Mijn(contact)	216441,5094	621474,0331	3	
1396	1789	2019-04-20	MV FRIENDSHIP	Survey	NOMBO	Mijn(contact)	216207,032	621246,5246	3	
1397	1788	2019-04-19	MV FRIENDSHIP	Survey	nombo	Mijn(contact)	218121,3603	618614,782	3	
1401	1783	2019-04-14	MV FRIENDSHIP	Survey	vernietigd emd	Mijn(contact)	217287,6376	619846,8297	3	
1402	1778	2019-04-07	MV FRIENDSHIP	Survey	niets gevonden	Mijn(contact)	213729,6189	624603,0163	3	
1404	1777	2019-04-05	MV FRIENDSHIP	Survey	vernietigd EMC	Onbekend	156240,5195	612199,3179	3	
1405	1776	2019-03-29	MV FRIENDSHIP	Survey	VERNIETIGD	Mijn(contact)	164473,5501	613865,1152	3	
1406	1775	2019-03-28	MV FRIENDSHIP	Survey	NOMBO met SFXI	Mijn(contact)	160491,0075	615435,6342	3	
1407	1774	2019-03-27	MV FRIENDSHIP	Survey	vernietigd EMC	Mijn(contact)	156910,2262	613726,2206	3	
1408	1763	2019-03-07	SALVAGE VESSEL FRIENDSHIP	Survey	vernietigd MK15	Mijn(contact)	147279,9689	607591,99	3	264,8 km
1409	1795	2019-04-27	MV SIEM N-SEA	Survey	vernietigd	Vliegtuigbom	-15615,1915	414324,5234	4	
1410	1782	2019-04-13	SIEM N-SEA	Survey	vernietigd	Onbekend	-16271,9383	416035,4663	4	2,2 km
1412	1769	2019-03-13	OFFSHORE VESSEL GEOSUND	Survey	NOG NIET	Mijn(contact)	95462,11985	618475,6004	5	
1413	1768	2019-03-12	OFFSHORE VESSEL GEOSUND	Survey	vernietigd MK14	Onbekend	152714,091	614414,5903	5	
1414	1767	2019-03-11	OFFSHORE VESSEL GEOSUND	Survey	NIET GEVONDEN	Onbekend	213614,3881	637314,1999	5	
1415	1766	2019-03-10	OFFSHORE VESSEL GEOSUND	Survey	NOG NIET	Mijn(contact)	213382,8904	638239,0211	5	
1416	1764	2019-03-08	OFFSHORE VESSEL GEOSUND	Survey	Lege minecase	Mijn(contact)	139607,0606	611060,8455	5	
1417	1762	2019-03-06	OFFSHORE VESSEL GEOSUND	Survey	NIET GEVONDEN	Onbekend	146428,9622	614623,9282	5	
1418	1761	2019-03-05	OFFSHORE VESSEL GEOSUND	Survey	niets gevonden	Mijn(contact)	194268,7577	613238,2802	5	
1422	1760	2019-03-04	OFFSHORE VESSEL GEOSUND	Survey	NIET GEVONDEN	Mijn(contact)	142088,0681	621833,1825	5	
1423	1759	2019-03-03	OFFSHORE VESSEL GEOSUND	Survey	VERNIETIGD	Mijn(contact)	141043,233	614859,2412	5	
1424	1758	2019-03-02	OFFSHORE VESSEL GEOSUND	Survey	pipework	Mijn(contact)	151675,4663	654763,068	5	
1426	1757	2019-03-01	OFFSHORE VESSEL GEOSUND	Survey	NIET GEVONDEN	Onbekend	146423,4376	614625,7931	5	
1427	1756	2019-02-28	OFFSHORE VESSEL GEOSUND	Survey	MK17 VERNIETIGD	Onbekend	213785,6237	641249,7066	5	
1428	1755	2019-02-27	OFFSHORE VESSEL GEOSUND	Survey	BETONNEN BUIS	Onbekend	198392,6053	632040,9939	5	
1429	1754	2019-02-26	OFFSHORE VESSEL GEOSUND	Survey	NIET GEVONDEN	Onbekend	205155,6681	639016,7782	5	
1430	1753	2019-02-25	OFFSHORE VESSEL GEOSUND	Survey	NIET GEVONDEN	Onbekend	205166,471	639035,4458	5	
1431	1752	2019-02-24	OFFSHORE VESSEL GEOSUND	Survey	NIET GEVONDEN	Onbekend	205199,8622	638998,6932	5	
1433	1751	2019-02-23	OFFSHORE VESSEL GEOSUND	Survey	NIET GEVONDEN	Onbekend	205211,0583	638980,2587	5	
1434	1750	2019-02-22	OFFSHORE VESSEL GEOSUND	Survey	NIET GEVONDEN	Onbekend	205233,254	638961,9408	5	
1440	1749	2019-02-21	OFFSHORE VESSEL GEOSUND	Survey	VERNIETIGD	Onbekend	205233,6475	638924,8386	5	
1481	1748	2019-02-20	OFFSHORE VESSEL GEOSUND	Survey	METALEN OBJECT	Onbekend	202918,1714	638362,8096	5	
1482	1747	2019-02-19	OFFSHORE VESSEL GEOSUND	Survey	VERLOREN CARGO	Onbekend	193135,3694	630151,7527	5	
1483	1746	2019-02-18	OFFSHORE VESSEL GEOSUND	Survey	VERLOREN CARGO	Mijn(contact)	193845,0189	630161,2165	5	
1484	1744	2019-02-07	OFFSHORE VESSEL GEOSUND	Survey	GEEN UXO	Torpedo	149192,8901	614601,2177	5	561,3 km
1485	1633	2015-06-25	Deep Helder	Survey	VERNIETIGD	Mijn(invloed)	183375,4255	674158,4335	6	
1486	1631	2015-06-07	Deep Helder	Survey	VERNIETIGD	Onbekend	183375,4255	674158,4335	6	
1487	1628	2015-05-26	Deep Helder	Survey	VERNIETIGD	Mijn(invloed)	198452,6474	670362,416	6	
1488	1625	2015-05-23	Deep Helder	Survey	VERNIETIGD	Mijn(contact)	196631,5458	674370,5391	6	
1489	1624	2015-05-22	Deep Helder	Survey	VERNIETIGD	Mijn(contact)	196620,0473	674312,9155	6	
1490	1623	2015-05-13	Deep Helder	Survey	VERNIETIGD	Mijn(invloed)	199404,2796	674880,2646	6	
1491	1622	2015-05-11	Deep Helder	Survey	VERNIETIGD	Mijn(invloed)	199733,7565	673528,8459	6	24,3 km
1492	1632	2015-06-08	Vos Sympathy	Survey	VERNIETIGD	Dieptebom	186160,8321	671823,3578	7	
1493	1627	2015-05-25	Vos Sympathy	Survey	VERNIETIGD	Mijn(contact)	186408,5751	673977,3697	7	2,6 km
1494	1597	2014-10-05	EPHYRA	Survey	N/A	Onbekend	91884,95851	537905,9562	8	
1495	1596	2014-10-04	EPHYRA	Survey	N/A	Onbekend	91661,62149	537665,8755	8	
1496	1595	2014-10-03	EPHYRA	Survey	N/A	Onbekend	91769,08173	536596,107	8	
1497	1594	2014-10-02	EPHYRA	Survey	N/A	Onbekend	92115,29412	536949,6028	8	
1498	1593	2014-10-01	Ephyra	Survey	VERNIETIGD	Onbekend	92016,65961	536969,4255	8	2,4 km
1499	1529	2014-05-06	VOS SATISFACTION	Survey	VERNIETIGD	Geschutmunitie	73095,87379	492534,1068	9	
1500	1520	2014-04-27	FOS SATISFACTION	Survey	VERNIETIGD	Vliegtuigbom	70901,06591	492055,4469	9	2,1 km
1510	1666	2016-10-23	ZEEBEEST	Survey	N/A	Onbekend	18225,27261	393557,9238	10	
1511	1662	2016-08-15	ZEEBEEST	Survey	VERNIETIGD	Vliegtuigbom	22568,69579	387877,2471	10	7,2 km
1512	1649	2015-10-22	Blue Marlin IV	Survey	Geen Explosief	Onbekend	91764,745	535396,1032	11	
1513	1648	2015-10-21	Blue Marlin IV	Survey	N / A	Onbekend	91901,92087	536353,2592	11	
1514	1647	2015-10-20	Blue Marlin IV	Survey	N/A	Onbekend	92274,38758	536912,3098	11	1,7 km

Annex 2. A tentative comparison to fishery risk

A2.1 Probability of encountering

On average, we found 163 trawlers in the period 2005 – 2020 (see table A2.1). Some of these trawlers use the pulse techniques, and it isunlikely (or less likely) that these trawlers encounter UXO.[87]

Year	Big scale trawlers	Cutter Trawlers	Shrimp fisheries	Cutter trawlers (excluding shrimp fisheries)	% Pulse (excludin g shrimp)	'Normal' beam trawlers and big scale trawlers[88]
2005	15	355	-*	190	0	205
2006	13	344	-*	179	0	192
2007	14	348	-*	183	0	197
2008	14	329	165	164	0	178
2009	14	308	160	148	3%	158
2010	13	295	155	140	7%	143
2011	14	291	145	146	29%	118
2012	14	279	155	124	50%	76
2013	12	278	170	108	55%	61
2014	10	279	170	109	66%	47
2015	8	280	165	115	68%	45
2016	7	280	170	110	68%	42
2017	8	283	180	103	67%	42
2018	8	287	175	112	60%	53
2019	7	289	150	139	43%	86
2020	6	292	-*	142	15%	127
2020	6	292	-*	142	15%	127
Average	**11**	**301**	**163**	**138**	**33%**	**111**

Table A2.1: Fisheries since 2005. *= unknown, we used the previous year (e.g., 2005 = 165 and 2020 = 150).[89]

We suppose that April and May 2005 are representative (see part 2.1). A cutter vessel will encounter at least three UXO per year.

[87] We are aware that shrimp fisheries and pulse fisheries also can encounter UXO. From conservative point of view, we excluded these trawlers in the calculations.
[88] This is including SumWing, Flyshoot and miscellaneous.
[89] Agrimatie (n.d.). *Visserij in Cijfers*. Retrieved November 22, 2021, from: https://agrimatie.nl/ and Quirijns et al. (2021). *Beschrijving garnalenvisserij*. Wageningen Marine Research rapport C049/21a.

According to *Compendium voor de Leefomgeving*,[90] a beam trawler will disturb the bottom circa 0.26 km^2 per hour (two cm into the ground). We assume that a vessel will be at least 200 days active (24 hours). The annual 'work area' will be 1,248 km^2 per vessel.

The probability of encountering, based on data of the registered data by fishermen, is 0.003 per km^2. This is lower than the results based on dredging and surveying activities.

*Formula: 109 objects /2 months * 12 months / 205 vessels / 1,248 km^2 work area*

UXO	April and May 2005	Extrapolated to 2005	On average per vessel	On average per km^2
Mine	18	108	0.527	4E-04
Aerial bomb	82	492	2.400	2E-03
Depth charge and torpedo	8	48	0.234	2E-04
Projectile	1	6	0.029	2E-05
Unknown	0	n/a	n/a	n/a
Total	**109**	**654**	**3.190**	**3E-03**

Table A2.2: Encountered UXO in 2005 by fisheries, including unknown-margin and extrapolated to other years. (*divided into ground and contact mines).

A fishermen will encounter at least 0.003 * 1,248 km^2 = 3.2 UXO per year.

Conclusion

The probability of encountering UXO per km^2 for fisheries is much smaller than the probability presented in chapter 3. Not all UXO on or in the bottom of the North Sea will be *found*. Notwithstanding this, fishermen will encounter more UXO (on a regular basis) than dredgers.

A2.2 Probability of explosion

Fishermen encounter UXO at least 3 or 4 times a year. We assume that the probability of explosion is more or less the same for dredgers and cable burial tools because the UXO is moved about the bottom of the sea for up to 20 km.

Therefore, we consider the probability of explosion after encountering by fishermen. We know four incidents in the past 50 years (see chapter 2) with vessels in Dutch North Sea:

- 1 incident with aerial bomb (but deflagration) on board;

[90] Compendium voor de Leefomgeving (2021) *Bodemfauna Noordzee en bodemvisserij, 2016 – 2019.* Retrieved November 22, 2021, from https://www.clo.nl/.

- 1 incident with a depth charge after throw it back into sea;
- 1 incident with a projectile on board;
- 1 incident with an exercise depth charge.

We have (implicitly) assumed that every explosion would be notice and reported.

We assume that:
- there were 111 (on average) (beam cutter) trawlers in the 2005-2020 period;
- there were 205 (beam cutter) trawlers in 2005. We assume that the fishing-fleet has (at least) the same size before 2005 (the period 1971-2004).

By extrapolating the encountered UXO in 2005 to 1971-2020, we expect that there are (at least) 27,902 UXO will be encountered. Given the fact that most UXO 'are thrown overboard', the number of encountered UXO will slowly decrease. Hence, it is possible to catch the same UXO multiple times.

Based on the data related to fishing, we can state that the probability of an unexpected initiation after encountering UXO is $1.1*10^{-4}$ per object (see table A2.3).

	Encountered in April and May 2005	UXO per vessel per year	Extrapolated to 1971-2020 (total)	Incidents	Probability of explosion
Mine	18	0.527	4,608	< 1	< 2,2E-04
Aerial bomb	82	2.400	20,990	1	4,8E-05
Depth charge and torpedo	8	0.234	2,048	1[91]	4,9E-04
Projectile	1	0.029	256	1	3,9E-03
Total	**109**	**3.190**	**27,902**	**3**	**1,1E-04**

Table A2.3: Encountered UXO between 1971 and 2020 (extrapolated), the number incidents and the probability of explosion.

Conclusion

The probability of unexpected initiation of the explosive for fisheries is smaller than the probability of explosion presented in chapter 4. Only three incidents are known while almost 30,000 UXO are *found* by fishermen since 1970.

We assume that the probability of explosion is more or less the same as for dredgers and cable burial tools.

[91] We excluded the exercise depth charge since this UXO was not a WW1 or WW2 remnant and therefore not representative. The depth charge was at the bottom of the North Sea for only 20 days.

A2.3 Probability of fatality

The risk of fatality should be greater for fishermen since the UXO could explode on- or near board. All known incidents (see part 2.3) with fatalities show that the UXO is exploded on- or near board.

Therefore, we consider the probability of fatality for fishermen: 5 (known fatalities after explosions in North Sea (including other relevant incidents, see part 2.3)) / 9 (known explosions in North Sea (including other relevant incidents, see part 2.3) total) / 4 crew members[92] = **0.139**.

Furthermore, the risk of fatality is greater for fishery than for dredging. Hence, dredging vessels will probably 'safer' than trawlers.

A2.4 Risk assessment

The *individual UXO-risk* for fishermen is approx. 5 * 10^{-5}. This is 5 times higher than accepted norm in other domains (but equal to the general risk for agriculture, forestry and fishing, see annex 4).

UXO	Probability of encountering	Probability of explosion	Probability of fatality	Individual risk
UXO	3.2 (UXO per year)	1.12E-04	0.139	4.8E-05

Table A2.4: Risk assessment for fishermen per year.

The UXO risk during fishery must be considered in perspective. After all, the individual risk for crew members of trawlers is relatively high (roughly 10^{-3} to 10^{-4}).

[92] There are about 1,120 crew members and 293 cutters in 2020. From: Agrimatie (n.d.). *Visserij in Cijfers*. https://www.agrimatie.nl/.

Sector	Injuries	Fatalities	Employees
Dutch occupational health incidents – Agriculture, forestry and fishing [93]	88 (average, 2016-20)	5 (average, 2016-20)	103,100
Dutch maritime sector – Fishery [94]	57 (accidents between 2013-2021 (April))	9 (fatalities between 2013-2021 (April))	1,120
EU maritime sector – Fishery[95]	1,385 (injuries between 2011-2018)	142 (fatalities between 2011-2018)	163 000

Table A2.5: Occupational health incidents and fatalities for fishery.

[93] From: Ministerie van Sociale Zaken en Werkgelegenheid (2021). Monitor Arbeidsongevallen 2020.
[94] Data from Dutch Safety Board (biannual reports) and Agrimatie (n.d.). *Visserij in Cijfers*. https://www.agrimatie.nl/.
[95] Data from EMSA (2019). Annual Overview of Marine Casualties and Incidents 2019 and Eurostat (2020). *Agriculture, forestry and fishery statistics*. European Union.

Annex 3. The risk of fatality after an occupational health and safety accident

In this annex we calculate the risk of fatality after an occupational health and safety accident.

A3.1 Occupational health incidents

In the Netherlands, we found 2,250 occupational health incidents and 62 fatalities each year. Theoretically the risk of fatality will be 0.028 for a person who is involved in an accident. The probability is higher in the sectors Agriculture, forestry and fishing, mineral extraction, energy supply, water pipe- and waste management and construction industry.

Sector	Incidents	Fatalities	Risk of fatality
A. Agriculture, forestry and fishing	87.6	5	0.057
B. Mineral extraction	1.8	0.2	0.111
C. Industry	603.2	9.2	0.015
D. Energy supply	7	0.4	0.057
E. Water pipe- and waste management	52	1.8	0.035
F. Construction industry	441	16	0.036
Total	2,249.8	62	0.028

Table A3.1: Occupational health incidents and fatalities.[96]

For mineral extraction, the risk of a fatality after an incident is 0.111.

A3.2 Risk of fatality during dredging and cable burial operations

The IMCA (International Marine Contractors Association) reported a FAR (Fatal Accident Rate)[97] of 2.24 in 2019 and 0.31 in 2020. Besides IMCA reported a TRIR (Total recordable injury Rate)[98] of respectively 1.11 and 1.09. This means that the probability after 'the risk of injury' is between (2.24/100/1.11=) 0.020 and (0.31/100/1.09=) 0.003.[99]

---

[96] From: Ministerie van Sociale Zaken en Werkgelegenheid (2021). Monitor Arbeidsongevallen 2020.
[97] FAR = Fatalities * 100,000,000 / Total man-hours.
[98] Fatalities + LTIs (Lost Time Injury) + Restricted Work Cases + Medical Treatment cases) x 1,000,000 / Total man-hours.
[99] IMCA (2021). 2020 Safety statistics.

Furthermore, the EMSA (European Maritime Safety Agency) states that there were 566 marine fatalities and 6,063 marine injuries on between 2011-2018 (only European Union). This means that the probability of fatality after 'the risk of injury' is: 566/(566+6,063)= 0.085.[100] For service ships and (more precise) dredging vessels, the risk will be respectively **0.045** and **0.038** (4.5E-02 and 3.8E-02).

Maritime sector	Fatalities	Injuries	Risk of fatality
All categories	566	6,063	0.143
Service ship	44	980*	0.045
Dredger	6	150*	0.038

Table A3.2: Fatalities and injuries in the maritime sector.[101] * = Because only graphs were given (and not numbers), we had to estimate the figures.

Fatalities vs. hospitalisations

Figures from Statistics Netherlands (CBS) show that on average, 3,658 people die as a result of an 'accidental fall' (period 2013-2018). The majority of those are not in the working population (we used the 20-65 age group for this): only 6% of the people who died as a result of an accidental fall were between the ages of 20 and 65 years old. [102]

Incidentally, 'caught, crushed, jammed, or pinched in or between objects' relates to this working population more often: 60% of people with this cause of death are in the 20-65 age group.

In the Netherlands, an average of 4,784 people per year die as a result of an "external cause of mortality". Accidental falls form the largest proportion of this: in 76% of the cases with an external cause of mortality, an accidental fall is the cause of death.

The working population (we used the 20-65 age group for this) die less by an external cause: an average of 582.3 people per year die as a result of an "external cause of mortality" (excluding drowning and poisoning).

Cause of death	Total (all ages) – average 2013-18	Total (20-65) – average 2013-18
Accidental fall	3657.5	201,2
Traffic accident	628.2	288.8
Drowning	87.8	42.5
Poisoning	174	144.2
Other accidents	236.2	92.3
Total	**4783.7**	**769**

Table A3.3: Fatalities between 2013-2018 (on average) by accidents.

[100] EMSA (2019). Annual Overview of Marine Casualties and Incidents 2019.
[101] From: EMSA (2019). Annual Overview of Marine Casualties and Incidents 2019.
[102] Statistics Netherlands (CBS) (n.d.). Overledenen; doodsoorzaak (uitgebreide lijst), leeftijd, geslacht Retrieved from https://opendata.cbs.nl/.

Cause of death	Total (all ages) – average 2013-18	Total (20-65) – average 2013-18
caught, crushed, jammed, or pinched in or between objects	16.2	9.7

Table A3.4: Fatalities between 2013-2018 (on average) by caught, crushed, jammed, or pinched in or between objects.

In the same period, an average of 236,805 are hospitalised for with injuries as a result of an accident. [103]100,129 of these are of the working population (we excluded poisoning and drowning). With other words: annually at least 100,129.2 + 582.3 = 100,711.5 people of the working population were involved with an injury related accident.

Hospital admissions due to injury or poisoning	Total (all ages) – average 2013-18	Age 20-65 - average 2013-18
Total	236,805	104,543.5
Total without poisoning and drowning	230,040	100,129.2
Drowning	145	39.2

Table A3.5: Hospitalisations between 2013-2018 (on average) by accidents.

Ultimately, we can use this to estimate the "risk of fatality" as a result of a secondary cause. We calculate a **0.006** probability of death as a result of accidental injury, this is 582.3 divided by 100,711.5.

[103] From: Statistics Netherlands (CBS). (n.d.) Ziekenhuisopnamen en -patiënten; diagnose-indeling VTV. Retrieved from https://opendata.cbs.nl/.

Annex 4. The UXO-risk in perspective, a comparison with other risks

In this annex we put the UXO-risk in perspective of the Dutch norms for individual risk.

A4.1 Individual risk

From a more philosophical point of view, there is an ongoing debate on what the point of risk policies is: to what degree is the 'societal norm' of what is considered acceptable or uncontrollable, or is this something that is mainly depending on the sentiments in the society in relation to recent events? This touches the subject of predictability of this sentiment, and the discussion whether policymaking should be sensitive to that.

Fact is that until the mid '80's, the Dutch government didn't concern itself much with developing policies on risk assessment. Several events in the '70's however, urged several policymakers to put some things on paper about this, resulting in the 'IMP (indicative multi-year program) Environmental management 1986-1990', which led to the subsequent National Environmental Policy Plan "Dealing with risks" in 1989. This created a policy framework, but still not a judicial framework. Concepts like 'individual risk' and 'group risk' were first mentioned here. In these concepts, the definition of risk was explained as 'undesirable consequences of a certain activity, related to the probability of occurrence'. The difference between individual risk and group risk was defined as that individual risk only concerns itself with the probability of undesirable effects for a person when exposed to certain 'agents' (sources of danger), expressed in probability per annum (or concentration per annum); group risk is the probability per annum that a group of a certain size is victimized by an accident.

The IMP EM '86-'90 is the first program that uses the concept of a 'risked based approach'. It distinguishes 'unacceptable risks', 'risk reduction desirable' and 'negligible risks'. The idea of this policy was 'to address a variety of environmental risks with a similar approach as much as possible'.

In the mentioned policy plan, this is translated to an identification method with a maximum acceptable level of 10^{-6}/year (a probability of fatality in a year is once in a million) and a neglectable risk of 10^{-8}/year (the probability is once in a hundred million). Noteworthy is that in a figure in the document, which visualizes the area between these two levels, no longer is stated that 'risk reduction is desirable' but 'risk reduction is needed'.

The approach of this policy plan wasn't translated into any legislation, until the early 2000's. The firework disaster of Enschede caused an urge to review the subject of external safety in the regulations. The level for negligible risks isn't to be found in there, but the level for the maximum acceptable risk is mentioned as the boundary value for the 'site-specific risk'.

Another concept that was legislated, is the group risk. The policy plan from '89 mentions this as 'the maximum acceptable level for calamities occurring once every 10^{-5}/year (1 in 100,000 year) for incidents with n=10 or more casualties, once every 10-7/year (1 in 10,000,000 year) for incidents with n=100 or more casualties, and so on. For each of these risks, it is also mentioned that the neglectable risk is a hundred times under the maximum acceptable risk.

In related regulations (BEVI=Decision External Safety on Industrial plants) group risk is described as something that needs to be justified by the authorities, when motivating a decision to granting a business license.

The complexity of this approach is that these probabilities are difficult to substantiate, for both businesses as for the authorities, because the historical data needed to validate these figures is non- existent. An incident with 1,000 casualties or more is extremely rare, even more so if this needs to be differentiated to multiple sources of risk.

Thus, the group risk couldn't be applied as a strict norm. Troublesome in the formulated acceptance values the policy plan came up with (and later added to the regulations), is that the boundary value is increased by a factor of 100, when the number of victims is increased by a factor of 10. This is problematic for the large numbers (with a huge uncertainty about these numbers, due to the absence of historical data), the non-linear expansion is increasingly unexplainable, both for the impact on development possibilities, as the questionability of an evidence-based approach (for larger incidents with numerous victims, likelihood is in the range of once in a million years, thus a lack of evidence emerges due to missing historical data).

Nonetheless, use of group-risk wasn't abandoned right away, inclusion in policies showed that the notion of this norm as a 'value for orientation' has been lost, ignoring the opportunities for reconsideration that the authorities initially have.

Notably, this 'Dutch' approach is rather unique. Internationally, for instance in the UK, the 'ALARP'-principle is frequently used: As Low As Reasonably Practicable (or Achievable: ALARA). This terminology suggests that risks should be considered in a 'reasonable' way, taking both costs and benefits in increased risks into account. This approach bears comparison with the 'maximum investment per DALY' approach as described in chapter 8.

Another method that is frequently used internationally, is the 'risk-matrix'. This method is troubled with the same shortcoming as group risk, namely a shortage of evidence to substantiate made assumptions. To avoid this problem, a more qualitative descriptive approach is quite common, but this doesn't pose a real solution, because for the interpretation of the qualitative descriptions, the shortcoming still emerges.

Sometimes, a group of experts is asked to come up with an estimation, in order to put some figures into the matrix. A downside of this is that the evidence is still very thin but the figures themselves create an appearance of certainty, with the risk of these becoming their own 'truth', leading to false accuracy.

Considering all this, the conclusion must be that for the 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 once every hundred thousand years (10^{-5}).

In this research, notable issues concerning the wellbeing of large groups will be addressed. The main point is that the results of the overall analysis give a fair and honest insight in the actual risks, taking into consideration how these risks compare to all other risks a dredger or cable burial operation is exposed to.

A4.2 Other (North) Sea risks

Dutch maritime sector (shipping)

According to the Dutch Safety Board (Dutch: Onderzoeksraad voor Veiligheid at least 303 (occupational health and safety) accidents occurred between 2013 and 2020 in the Dutch maritime sector (only shipping):

- Dutch vessel/Dutch waters (excl. fishery): 22 accidents, 3 with fatalities (total 3 fatalities);
- Only Dutch waters (excl. fishery): 51 accidents, 8 with fatalities (total 8 fatalities);
- Only Dutch vessel (excl. fishery): 170 accidents, 21 with fatalities (total 23 fatalities);
- Dutch fishery: 52 accidents, 7 with fatalities (total 11 fatalities);
- Other: 1 accident, 1 with fatalities (total 1 fatality)[104].

Furthermore, at least 49 (occupational health and safety) accidents occurred between 2013 and 2020 at the (entire) North Sea, including fishery. 10 of these accidents resulted in a fatality (total 15 fatalities).[105]

Note of these accidents were caused by UXO.

[104] Vessel from Luxembourg, Port of Zeebrugge, but a Dutch employee was involved.
[105] Excluding fishery: 18 accidents, 6 with fatalities (total 8 fatalities). Only Dutch North Sea: 7 fatalities between 2013-2020 (see: Ongevalscijfers scheepvaart, 2020).

At least 26 employees (excl. fishermen) died in the past eight years (between 2013-2020) on a Dutch vessel, so on average 3.25 employees died each year. There were 57,682 (direct) employees on average.[106] We calculate that the Dutch individual risk in maritime sector will be at least 3.25 / 57,682 = **$5.6 * 10^{-5}$** (1 in 18,000 year).

International maritime sector

IMCA calculates the annually 'Fatal Accident Rate'(FAR): the number of fatalities per 100 million hours worked. On average, the FAR is 1.13 per year (between 2010-2020). With 200 working days of 12 hours[107], the objective risk (for these contractors) is **$2.7 * 10^{-5}$** (1 in 37,000 year).

For offshore activities only, the FAR is 1.549 per year and the individual risk is **$3.7 * 10^{-5}$** (1 in 27,000 year).

Furthermore, the EMSA (European Maritime Safety Agency) states that there were 566 maritime fatalities (only crew) between 2011-2018 (only European Union), about 63 per year. Roughly estimated, the individual risk is **$5.4 * 10^{-5}$** (1 in 19,000 year) for offshore activities.

Maritime sector	Fatalities (between 2011-2018)	Fatalities per year	Employees	Individual risk
All categories	566	62.89	1,172,279[108]	$5.4 * 10^{-5}$
Service ship	44	4.89	164,474[109]	$3.0 * 10^{-5}$
Dredger	6	0,667	25,000[110]	$2.7 * 10^{-5}$

Table A4.1: individual risk for offshore activities according to EMSA.

[106] Maritieme haven en binnenhavenmonitor. Retrieved November 27, 2021, from https://maritiemehavenenbinnenhavenmonitor.nl/. We included the categories maritime shipping, inland shipping, offshore and 'construction on water'.
[107] IMCA has assumed a 12-hours day.
[108] Roughly estimated: There are about 4,500,5000 employees, including port activities, shipbuilding, etc. In the Netherlands, 26% of the maritime sector is 'offshore industry' (Visserij, Offshore, Waterbouw. or Zeevaart) and 80% of the maritime sector is 'onshore industry (Maritieme toeleveranciers, Jachtbouw/Watersportindustrie, Maritieme dienstverlening, Marine, Havens, Binnenvaart, or Scheepsbouw). For offshore activities only, there would be (26% * 4,500,0000 =) 1,172,279 employees. Retrieved November 29, 2021, from https://op.europa.eu/ and https://maritiemehavenenbinnenhavenmonitor.nl/.
[109] Roughly estimated: 15.2% of the service ships involved in a marine casually or incident were dredgers. If we assume that the proportions of (service ships involved in a marine) casually or incidents are representative for the total number of vessels/employees, then there will be (25,000 / 0.152=) 164,474 employees.
[110] Retrieved November 29, 2021, from https://european-dredging.eu/.

A4.3 Other sectors

The general 'occupational risk' in the Netherlands is $7.6 * 10^{-6}$ (1 in 130,000 year) (see table A4.2). For relevant sectors, the risk is much higher (about $2.0 - 5.0 * 10^{-5}$) (1 in 50,000 year to 1 in 20,000 year).

Sector	Fatalities (average, 2016-20)	Employees	Individual risk
A. Agriculture, forestry and fishing	5	103,100	$4.8 * 10^{-5}$
B. Mineral extraction	0.2	8,400	$2.4 * 10^{-5}$
C. Industry	9.2	775,000	$1.2 * 10^{-5}$
D. Energy supply	0.4	28,000	$1.4 * 10^{-5}$
E. Waterworks and waste management	1.8	35,600	$5.1* 10^{-5}$
F. Construction industry	16	332,800	$4.8 * 10^{-5}$
Total	**62**	**8,126,900**	**$7.6* 10^{-6}$**

Table A4.2: individual risk for economic activities in the Netherlands.

Fishery

11 fishermen died between 2013 and 2020. There were about 1,587 fishermen in the Netherlands (on average between 2013-2019).[111] We consider the risk as (11 fatalities / 9 years / 1,587 fishermen =) **$7.7 * 10^{-4}$** (1 in 1,300 year).

[111] Maritieme haven en binnenhavenmonitor. Retrieved November 27, 2021, from https://maritiemehavenenbinnenhavenmonitor.nl/.