Application Guide for the specification of the *Depth of Lowering* using the Cable Burial Risk Assessment (CBRA) methodology

This document is based on the "Cable Burial Risk Assessment Methodology Guidance for the Preparation of Cable Burial Depth of Lowering Specification, CTC 835 February 2015"

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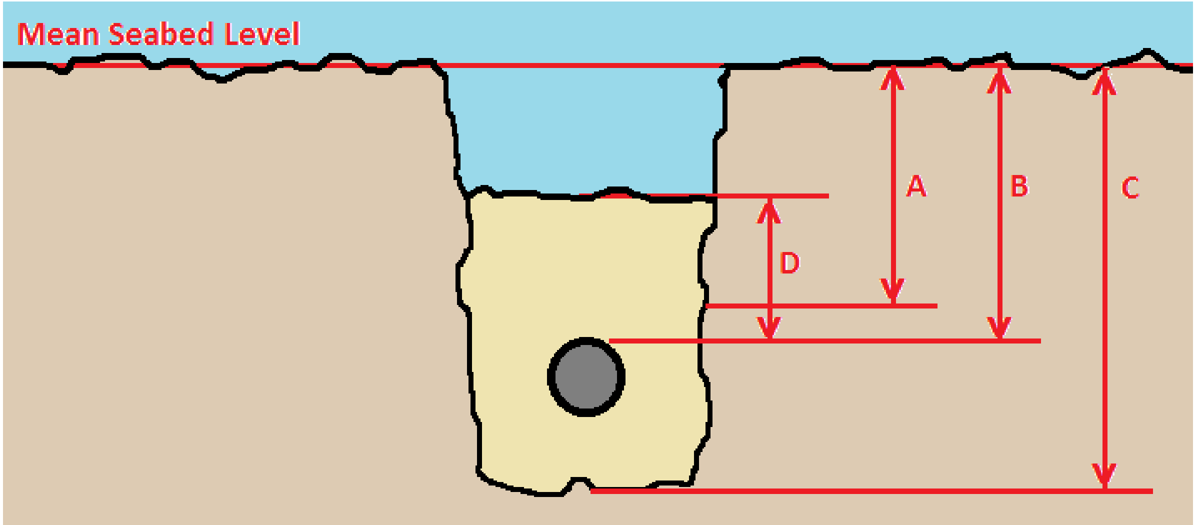
List of Abbreviations & Symbols

AIS	Automatic Identification System
ALARP	As Low As Reasonably Practicable
BPI	Burial Protection Index
BSH	Bundesamt für Seeschifffahrt und Hydrographie, German Federal Maritime and Hydrographic Agency
DECC	Department of Energy and Climate Change
DoL	Depth of Lowering
DNV GL	Det Norske Veritas Germanischer Lloyd, Ship and offshore classification society
DWT	Vessel Deadweight
EN	Equipment Number
FoS	Factor of Safety
HHP	High Holding Power (Anchor)
IACS	International Association of Classification Societies
ICPC	International Cable Protection Committee
IMO number	International Maritime Organization number identifying the vessel
KP	Kilometre Point
MBES	Multi-beam Eco Sounder
MMSI	Maritime Mobile Service Identity
OWA	Offshore Wind Accelerator
OSIG	Offshore Site Investigation and Geo-technics
P	Symbol indicating the probability
PCPT	Piezo Cone Penetration Test
R	Symbol indicating the risk
S_u	Undrained shear strength (kPa)

SUT	Society for Underwater Technology
TWG	Technical Working Group
UXO	Unexploded ordinance
VMS	Vessel Monitoring System

Definitions



A **Depth of Lowering**
B **Target Depth of Lowering**
C **Target Trench Depth**
D **Depth of Cover**

Figure 1 Definition of Trench Parameters

Benthic fish - Fish that lives on or in the seabed

Depth of Cover (D in Figure 1) - The thickness of material on top of the cable after trenching and accounting for potential backfill / seabed mobility. It may not be required for cable protection however could be required for consenting conditions e.g. BSH imposes the 2 K rule in the German Exclusive Economic Zone of the North Sea and the Baltic Sea; the thermal properties of the soil could influence the cable design (e.g. cable overheating).

Depth of Lowering (A in Figure 1) – This is the minimum depth recommended for protection from the external threats. This is the direct output of the risk assessment and should include a Factor of Safety (FoS).

Factor of Safety – Factor used to provide a design margin over the theoretical design capacity to allow for uncertainties in the process. This is generally specified by the developer.

Mean seabed level - The average undisturbed/natural level of the seabed before construction works.

Probability - Measure of the chance of occurrence expressed as a number between 0 and 1, where 0 is impossibility and 1 is absolute certainty.

Return period - Average period of time between occurrences of a given event. The inverse of return period expressed in years is the probability of such an event occurring in any given year.

Risk – Exposure to hazard which could result in damage to the cable or persons/equipment interacting with the cable

Probabilistic Risk Assessment – It is a systematic and comprehensive methodology to evaluate risks associated with a complex engineered technological entity.

Quantitative risk assessment - A process for assigning a numeric value to the probability of loss based on known risks and available, objective data.

Qualitative risk analysis - A collaborative process of assigning relative values to assets, assessing their risk exposure, and estimating the cost of controlling the risk. Differs from quantitative risk analysis in that it utilizes relative measures and approximate costs rather than precise valuation and cost determination.

Residual Risk - Risk remaining after protective measures have been taken.

Semi-quantitative risk assessment – It provides an intermediary level between the textual evaluation of qualitative risk assessment and the numerical evaluation of quantitative risk assessment.

Target Depth of Lowering (B in Figure 1) – This is the depth that cable installation contractors should target. Generally this is specified by the developer. Target Depth of Lowering should be equal to or greater than the recommended minimum Depth of Lowering to allow for any uncertainty and/or anticipated localised depth variations during trenching operations. Where the target Depth of Lowering is not achieved no remedial action would be required as long as the recommended Minimum Depth of Lowering is achieved.

Target Trench Depth (C in Figure 1) – This is the trench depth specified to achieve the target *Depth of Lowering*. The cable installation contractors should determine the target trench depth according to the target DoL, cable properties, preferred trenching tool and taking into account the seabed conditions such as minor bedforms.

Tolerable/Acceptable Risk - Risks considered acceptable by the key project stakeholders.

1. Background and scope

1.1. Introduction

The "Cable Burial Risk Assessment Methodology: Guidance for the Preparation of Cable Burial Depth of Lowering Specification" (Carbon Trust 2015, accessible here) was published by the Carbon Trust to provide a standardised, systematic, quantitative and robust method for assessing the risks affecting offshore wind farm power cables and specify the required protection level, thus the *Depth of Lowering* (*DoL*). The main objective of the method is to optimise the *DoL* of offshore wind farm cables in terms of specifying an economically feasible *DoL* which ensures a satisfactory level of protection and by implication, residual risk.

This Application Guide aims to illustrate how to specify the *DoL* with the CBRA methodology. The structure of the document is as follows. In chapter 1 the background and scope of the CBRA methodology is explained. In chapter 2 all the required inputs that should be available to apply a robust CBRA are briefly presented. In chapter 3 the CBRA methodology is presented in detail illustrating the process that should be followed to specify the *DoL* focusing on the description of what have been historically perceived as the main anthropogenic hazards to subsea cables (shipping and fishing). In appendix A is given more background information on the motivation to develop CBRA. In appendix B the common risks that affect cable burial are described. Finally a worked step by step example is given in appendix C.

1.2. Background

The OWA is a world leading industry-led collaborative programme designed and managed by the Carbon Trust, between DECC, the Scottish Government, Carbon Trust and nine major offshore wind farm developers representing 72% of the licensed capacity in UK waters (DONG Energy, E.ON, Mainstream Renewable Power, RWE Innogy, Scottish Power Renewables/Iberdrola, SSE Renewables, Statkraft, Statoil and Vattenfall). The multi-million pound programme has been running since 2008 with the objective of bringing down the costs of low carbon electricity produced by offshore wind farms. Five Technical Working Groups have been formed on specific areas of offshore wind farm development (Access Systems, Cable Installation, Electrical Systems, Foundations, and Wake Effects).

In late 2013 the OWA Cable Installation Technical Working Group (TWG) contracted UTEC Geomarine, Cathie Associates and Xodus Group to complete a study on site investigations, trenching assessments and burial risk assessments that are completed in the design stage of wind farm projects. The study included consultation with trenching contractors, consultancies and the wind farm developers of the OWA. The development of the Cable Burial Risk Assessment methodology (CBRA) was part of that project.

The main driver to develop CBRA is that the optimisation of the *DoL* specification will result in a reduction of the required *DoL* in many ground conditions and external risk scenarios thus leading to significant reduction of risks and costs associated with cable installation. The motivation to develop CBRA is further described in Appendix 2.

1.3. Scope and limitations

The CBRA methodology considers the risks associated with all common hazards for which cable burial is a mitigating measure. The optimal *DoL* is specified based on probabilistic risk analysis considering the acceptable risk and the cost to achieve the specified *DoL*. The fundamental assumption of the method is that it is impractical to protect a subsea cable from all possible threats, e.g. it is not sensible to specify a *DoL* to protect from a 20 tonne anchor if the vessels equipped with such anchors are only transiting once per year over the asset.

It is anticipated that where stakeholders and consenting bodies require a significant *DoL* due to a perceived threat, CBRA could be used to provide a detailed understanding of the project risk and support the safe reduction of the specified *DoL* based on actual site conditions.

CBRA **does not**:

- Cover the entire cable route design process;
- Consider hazards which are **not** mitigated by means of cable burial, e.g. UXO;
- Consider the requirements of regulatory bodies who might prescribe a minimum *DoL*; however, it might be used as a tool to offer a justified optimisation;
- Specify the methods or extent of survey data that should be acquired. A number of other guidelines and specifications already exist for this. However, is should be clear that the quality of the input dictates the quality of the output and therefore CBRA assumes that high quality survey data is available;
- Explicitly consider the risk to the cable during installation. However, by optimising the *DoL*, the handling of cables by any burial tool is reduced and trenching is potentially completed faster with tools that expose the cable to less risk;
- The selection of an appropriate trenching tool.

CBRA is not intended to be a means of cost reduction although this is anticipated to be possible in many projects, nor it is intended to replace engineering judgement which is always vital.

1.4. When to apply CBRA

CBRA may be applied multiple times during the wind farm development and project phases:

- During the design stages to specify the *DoL*;

- After cable installation to determine the change in risk profile and requirements for post installation mitigation if the *DoL* is not achieved (residual risk); and,
- While the cable is in operation, by updating the input data CBRA can be used to assess the impact of changes in the surrounding conditions to the risk profile of the asset (risk management).

Finally, the CBRA methodology whilst intended to be used in array and export cables in offshore wind farms may equally apply to interconnectors or any other subsea cable.

2. Input data

2.1. Surveys

The objective of the site survey for offshore cable projects is to obtain sufficiently detailed and reliable site specific seabed information to enable the safe and economic design and installation of assets on or below the seabed level. Detailed data needs to be obtained for the total length of the planned cable route, covering a corridor of sufficient width to provide adequate information for the design of the cable route as well as installation and operation related activities, taking into account possible route adjustments due to subsequent findings. Offshore surveys are required at varying stages of the project as follows:

- Project Planning/feasibility survey;
- Engineering survey for detailed design;
- Installation and commissioning (both pre-installation and post installation); and,
- Operational maintenance survey.

Due to the different requirements of each stage, the survey scope will differ with the engineering survey being typically more detailed than the feasibility survey and including specialist surveys such as Unexploded Ordinance (UXO). It should be highlighted that it is important to specify and use appropriate baseline datum to allow robust and direct comparison between subsequent surveys.

In offshore wind, surveys have a sample frequency similar to trenched pipelines with an average spacing of 0.5 km to 1 km. It is essential to consider that in order for the survey to provide reliable information and fulfil its objective it is recommended that the design is undertaken by a sufficiently experienced and skilled personnel.

2.2. Essential data and information

Whatever methodology is adopted for the specification of the *DoL* it will always rely on the quality of the data/information used as input to the assessment. The following information is considered essential to perform a CBRA along a given cable route:

- Route specific geotechnical survey data targeted at soil and seabed features:
  - Piezo Cone Penetration Test (PCPT) to an appropriate depth below seabed at appropriate intervals along the proposed route and/or where sub-bottom profiling show differences in soil condition and within the array area (subject to array geometry and cable routing);
  - Direct sampling to an appropriate depth below seabed at appropriate intervals along the proposed route and within array area (subject to array geometry and cable routing), might be Vibrocore, Gravity Core, Piston Core, Borehole or similar; and,

  - Geotechnical laboratory testing on selected samples to confirm engineering properties of sediments.

- Geophysical data (as above):

  - High Resolution MBES Survey to establish the bathymetry and identify seabed morphology along and within the route corridor for the export cable and within the array area;

  - Side Scan Sonar to locate and determine the nature and geometry of seabed features;

  - Magnetometer survey to locate metallic obstructions; and,

  - Sub-bottom profiling to retrieve detailed data on the structure of sediments and differentiate between sediment units within the top 5m of the seabed.

- Sediment mobility studies (see B1.1);

- Regional Geological Data (Maps & Memoirs);

- AIS Shipping Data including information on the vessels in transit (age, type, possible failure rate etc.) that will help the designer assess the likelihood of emergency situations requiring the deployment of anchors as well as the behaviour of captains in emergencies;

- Fishing Studies: Although useful, extensive studies are not considered crucial. As explained in section 3.3 a pragmatic approach is possible limiting the required amount of analysis;

- Cable Dimensions;

- Vessel Incident Data;

- Information on other subsea infrastructure (existing and planned).

The AIS shipping data should be processed to yield the following track information:

- Vessel IMO, MMSI, Name, Type, Length, Beam, Deadweight, Draught;

- Vessel Speed and course (across the cable).

This data will be used as inputs to CBRA and to the engineering judgement for the *DoL* specification. Table 1 indicates the required inputs (list may not be exhaustive).

Table 1 Required inputs to perform CBRA

Type	Description
Project information	Cable route
	Cable dimensions and specifications
	Consenting and other authority/stakeholder requirements
Desk study / background data	Desk Studies and/or Regional geological data (maps and memoirs)
	Met ocean studies/data
	Location of existing infrastructure
Survey information	Geophysical survey
	Geotechnical survey
	Sediment mobility studies
Shipping data	AIS shipping data
	Vessel incident data
	Fishing studies

3. CBRA methodology

3.1. Process flow

Figure 2 illustrates the CBRA process flow, thus the steps taken to specify the *DoL*. Once the inputs have been collated as discussed in section 2, the risk assessment is performed. The *DoL* is successively specified based on the outcome of the iterative probabilistic process and the acceptable risk. The CBRA assessment could be revisited several times during the lifecycle of a project as discussed in Section 1.4.

Figure 2 CBRA process flow

3.2. Risks and hazards affecting cable burial

CBRA considers the risks that are mitigated by means of cable burial and the risks that affect the burial of cables e.g. sediment mobility. Table 2 summarises the considered risks. There are two types of hazards namely natural and anthropogenic. In appendix B a short description is given for each hazard, whereas the following subsections focus on the risks related to the main anthropogenic hazards for the mitigation of which the *DoL* has been historically specified (fishing and shipping). The discussion on each risk is not intended to be exhaustive and focuses on describing the impact of each risk to the specification of the *DoL*. It should be highlighted that although the approach is the same in inter-array cables and export cables, the outcome of the risk assessment is different in the two cases due to the different magnitude of the risks and/or consequences. For example in the infield area the risk from shipping is in principle limited compared to export cables since the infield area in principle excludes major shipping lanes.

There are a number of hazards to cables that are not covered by CBRA since they are not normally mitigated by means of cable burial. However, these risks need to be addressed on a project by project basis. A brief description of these hazards is given in appendix B3.

Table 2 Risks Affecting cable burial

Risk Type	Description
Natural	Sediment mobility (e.g. Megaripples, sandwaves)
	Seismic activity
	Submarine landslide
Anthropogenic	Fishing
	Vessel anchoring
	Dredging / Aggregate Extraction / Subsea Mining
	Other existing and/or planned Cables, Umbilicals, Pipelines

3.3. Benthic Fishing

Cable Burial has been historically adopted as an effective means of protecting a cable from benthic fishing activity. In many countries e.g. in the Netherlands, fishing is not allowed within a wind farm. In other areas local restrictions may apply e.g. exclusion zone of 50 m around a turbine but in general fishing is performed within wind farms. It is possible to ascertain the size of the fishing fleet working along a proposed cable route and the adopted methods using:

- AIS data (noting that vessels with gross tonnage of less than 300 t are not presently required to carry AIS transponders);
- Maritime and Coastguard Agency vessel traffic information;
- VMS data (only vessels exceeding 12m length are covered);
- Direct consultation of local and national fisheries organisations.

The BPI value of 1 for protection from damage by common fishing gear requires burial depths of between 0.5 m in fine sand and 2.5 m in very soft clay, which is very conservative and therefore deemed excessive and redundant.

Work by Linnane et al. (2000) indicates that fishing gear penetration is limited to a maximum of 0.3 m penetration even in soft sediment. Table 3 reports the fishing gear penetration summary produced by Linnane et al. (2000).

Table 3 Fishing Gear Penetration (Linnane et al. 2000)

Penetration Depth	Reference	Gear type	Substratum
100-150 mm	Arntz and Weber, 1970	Otter boards	muddy fine sand
a thin layer of top substrate	Bridger, 1970	Otter trawl ticklers	sand
80-100 mm	Margetts and Bridger, 1971	Beam trawls	muddy sand
100-200 mm	Houghton et al., 1971	Beam trawls	sand
0-27 mm	Bridger, 1972	Beam trawls	mud
rather limited	de Clerck and Hovart, 1972	Beam trawls	rough ground
few centimetres	Caddy, 1973	Otter boards	sandy sediment
10-30 mm	de Groot, 1984	Beam trawls	mud, sand
200 mm	Khandriche, et al., 1986	Otter board	mud
a few centimetres	Blom, 1990	Beam trawls	sand
= 60 mm	Bergman et al., 1990	Beam trawls	fine to medium hard sand
5-200 mm 20-50 mm	Krost et al, 1990	Otter board rollers on foot rope	mud, sand
200 mm	Laane et al., 1990	Beam trawls	mud, sand
20-300 mm	Rauck, 1988	Beam trawls	mud, sand
5-170 mm	Rumohr (in Krost et al, 1990)	Otter board	mud, sand
40-70 mm	Laban and Lindeboom, 1991	Beam trawls	fine sand
50-60 mm	BEON, 1991	Beam trawls	fine sand
few cm. - 300 mm	Jones, 1992	Otterboards	deepest in soft mud
20-40 mm	Santbrink and Bergman, 1994	Beam trawls	fine to medium sand sediment
15-70 mm	de Groot, 1995	Beam trawls	substratum dependant
~ 140 mm	Lindeboom and de Groot 1998	Otterboards in the Irish Sea	mud

In assessing the threat from fishing gear the following should be taken into account:

1. For fishermen deep penetration of their gear in the seabed is an unfavourable condition due to the increased fuel consumption and wear of the equipment;

2. It is common knowledge in the industry and evidence suggests that the fishing gear currently used for benthic fishing (Pelagic Trawl, Gill Nets, Beam Trawl, Pots & Traps, Demersal Trawl and Seine Nets) does not normally penetrate the seabed beyond 0.3 m (30 cm).

Therefore a pragmatic approach suggests to consider 0.3 m as the effective maximum penetration depth of benthic fishing gear. Site specific fishing activity should be investigated to ensure the applicability of the above statement. In case no other risks are present by applying for example a FoS of 2 the *DoL* results in 0.6 m. However, it should be highlighted that in many real cases there are more factors influencing the *DoL* specification and a FoS of 2 would be unjustifiably conservative.

3.4. Shipping

3.4.1. Factors affecting the risk profile

Grounding of ships in shallow water may present a hazard to subsea cables, however errant or emergency anchoring of vessels is perceived as the most significant threat to subsea cables from shipping. That said, the magnitude of this risk is often exaggerated. CBRA provides a methodology with high potential for standardisation to robustly assess the risk and specify an appropriate mitigating measure. In assessing the risk from shipping the following should be taken into account:

- Future variations of vessel traffic should be considered. This includes:
  - Changes in shipping patterns once the wind farm installation is concluded;
  - The possible vicinity of the wind farm to other planned or under construction offshore projects (any activity e.g. offshore wind, oil and gas or other) should be carefully evaluated, as it can occur that the vessel traffic density could drastically change in time either way (e.g. from 4,000 vessels per year in a certain section of the route after 2 years of operation the number of vessels could drop to 30 vessels per year and vice versa);
  - Other factors locally influencing the vessel traffic should be considered e.g. an expansion of a port in the vicinity of the project etc.
- The vessel traffic should be divided into categories of similar threat levels e.g. the vessels should be categorised according to their type, their deadweight and corresponding anchor they carry;

- All the vessels do not fail with the same rate. It is important to understand that modern vessels with enhanced redundancy in navigation and safety systems will most likely fail less than old tankers (see the following section for a discussion on failure rates);
- The vessel traffic is expected to significantly differ within the offshore wind farm infield area and along the export cable corridor. Between export cables and interconnector cables the vessel traffic is expected to be of similar pattern and magnitude (local variations do exist but the main aspects are similar).

CBRA only considers the deployment of anchors under emergency situations in the probabilistic risk assessment. There could be different situations e.g. accidental deployment of anchors due to equipment failure or a mistake by the crew. These are not considered by CBRA as it is complex to assess the probability of a human error with a standardised approach. However, it should be highlighted that by mitigating against the probability of occurrence of an anchor deployment in emergency situations, the cases that are not considered only affect the level of residual/acceptable risk (thus related to the largest and less frequent anchors) and therefore the impact from the additional risk occurring is marginal. Moreover, in the case of errant or accidental deployment of anchors it is unlikely that the anchors will exert their ultimate holding capacity thus reaching their maximum penetration depth. As a consequence although CBRA does not consider errant deployment of anchors, accounting for the maximum penetration depth and the exertion of the ultimate holding capacity from a given anchor is a conservative approach, thus the additional effective risk from errant anchoring due to equipment failure or crew error is marginal.

3.4.2. Probabilistic assessment

In order to determine a cost effective and practically achievable *DoL* which provides an appropriate level of protection, it is important to assess the risk of anchoring with a systematic, accurate and quantitative approach. The CBRA method has been conceived in such a way that removes as far as possible the qualitative inputs and clearly identifies all the influential parameters to allow an informed discussion.

CBRA evaluates the exposure of the cable to external threats by considering the amount of time a vessel spends within a critical distance of the cable and the probability that this vessel might have an incident that requires the deployment of an anchor. **The fundamental assumption on this point is that the deployment of an anchor is a risk to the cable and therefore no consideration is made on whether the anchor actually hits the cable or not**. In practice there is always a likelihood that when an anchor is deployed it could bounce along the seabed (anchor tripping) or not penetrate deep enough to hit the cable or even get dragged for a distance inferior to what is expected and therefore not effectively representing a threat. CBRA does not consider the dynamics of the interaction between the anchor, the seabed and the cable to avoid complexity and uncertainty due to the lack of reliable data which would introduce room for interpretations to the analysis. Moreover, by assuming that the anchor is a threat when deployed and not only when it hits the cable, a conservative and safe approach is adopted that avoids the underestimation of the risk.

The probability of anchor deployment in the vicinity of a cable is given by:

$$P_{Strike} = P_{Traffic\ Risk} \sum_{1}^{Number\ of\ vessels\ in\ the\ section} \left(\frac{D_{Ship\ Drag}}{V_{Ship} * 8760\ hrs\ per\ year} * P_{Incident} * P_{WD} \right)$$

Equation 1 Probabilistic formula to assess the risk from anchoring

Where:

$P_{Traffic\ Risk}$	probability modifier based on the tolerable level of risk
P_{WD}	probability modifier for nature and depth of seabed
V_{Ship} (metre/hr)	ship speed when the anchor is deployed
$D_{Ship\ Drag}$ (metres)	distance travelled by the anchor in order to be a threat to the cable
$P_{incident}$	probability of incident requiring the deployment of an anchor for that vessel size and type
8760 hrs	factor to annualise the results

The determination of each factor is discussed in detail in the following subsections. It should be noted that equation 1 only identifies the probability of an anchor deployment in the vicinity of a cable that could result in an anchor strike. As already discussed the deployment of an anchor will not necessarily result into an anchor strike, similarly an anchor strike will not necessarily result in an immediate cable failure. Additional armour provides a certain level of protection from external aggression. It could occur that a cable is struck a number of times without sustaining critical damage. However this could introduce internal weaknesses (especially in the insulation) which will eventually develop in failures. It is therefore considered most conservative to assume that any anchor deployment is a hazard.

3.4.3. $P_{Traffic\ Risk}$ and acceptable risk (acceptable return period)

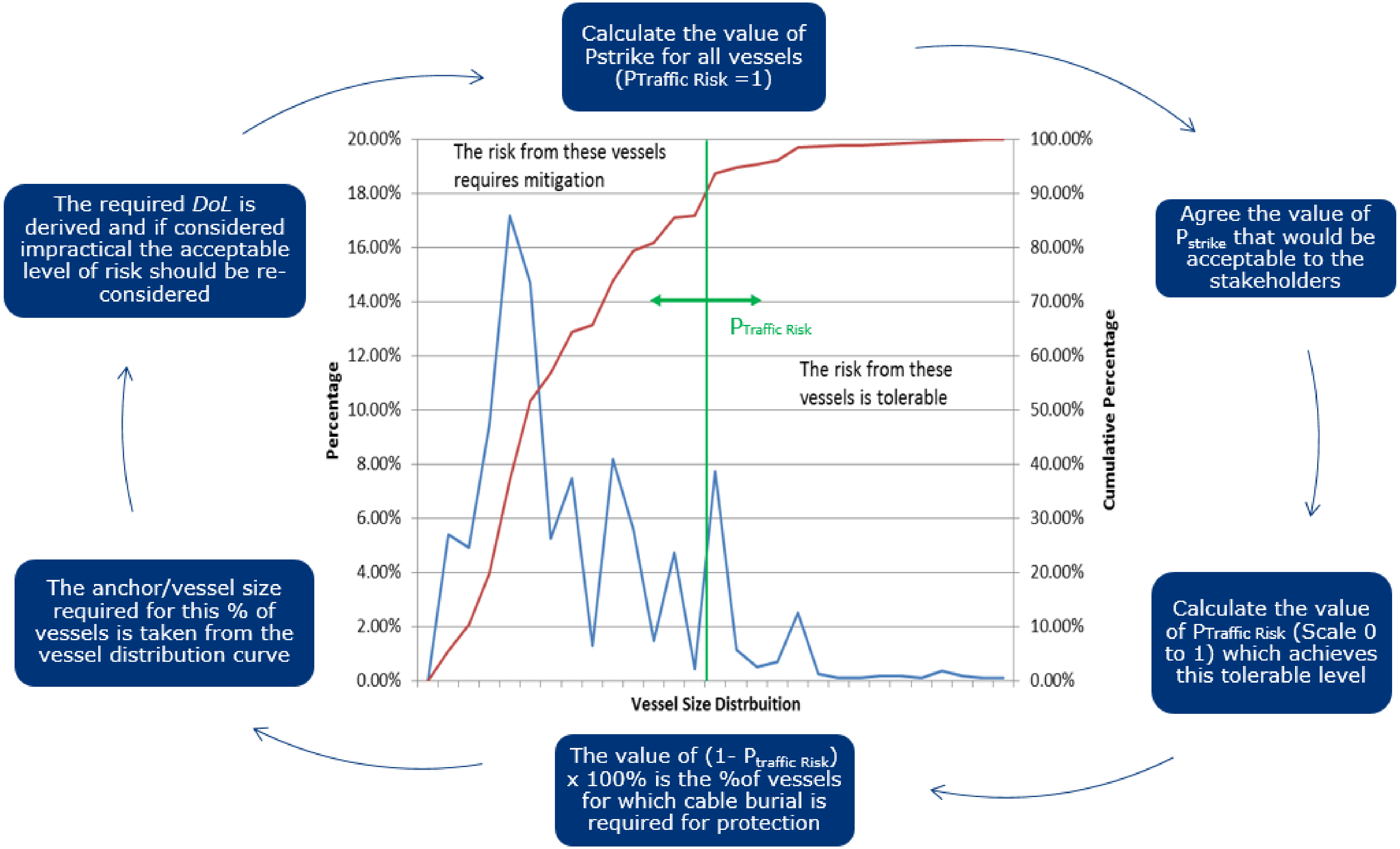


Figure 3 Process to determine the PTraffic Risk probability modifier

The probabilistic approach is intended to be iterative as depicted in Figure 3; in order to specify a *DoL* which results in a tolerable residual risk the value of $P_{Traffic\ Risk}$ is modified as follows:

1. Calculate the value of P_{Strike} for all vessels ($P_{Traffic\ Risk}$ = 1);
2. Calculate the value of the return period corresponding to this value of the P_{Strike} (the inverse of the probability);
3. Agree an acceptable return period with the involved stakeholders;
4. Calculate the value of the P_{Strike} that satisfies the acceptable return period;
5. Calculate the value of $P_{Traffic\ Risk}$ (Scale 0 to 1) which achieves the tolerable level of the P_{Strike};
6. The value of (1- $P_{Traffic\ Risk}$) x 100% is the percentage of vessels for which cable burial is required for protection;
7. The anchor/vessel size required for this percentage of vessels is taken from the appropriate distribution curve;
8. The required *DoL* is derived; and,
9. If the *DoL* is considered impractical the acceptable level of risk should be re-considered.

If the cable burial depth exceeds the expected penetration depth of the largest anchor identified for a vessel in transit in the vicinity of the cable then the probability of a strike is zero ($P_{Traffic\ Risk}$ = 0). Similarly, if no shipping is anticipated in the area the probability of a strike is zero ($P_{Traffic\ Risk}$ = 0). If the cable is not buried the results of the assessment represent the worst case scenario for the cable being subject to risk from any anchoring vessel, i.e. $P_{Traffic\ Risk}$ = 1. If very limited infield shipping traffic is anticipated (i.e. $P_{Traffic\ Risk} \approx 0$) further analysis to assess the risk from anchors may be redundant.

With the availability of accurate shipping information it is possible to estimate the consequences of selecting a recommended minimum *DoL* which will **not** provide protection from some percentage of the largest vessels. It is important at this point that project developers/owners consider if it is realistic to require protection from all vessels that might cross the route. In order to answer this question an iterative probabilistic approach is adopted: by changing the value of $P_{Traffic\ Risk}$ the minimum *DoL* is determined which results in a probability of cable strike (equivalently an acceptable return period) which is acceptable to the project developers/owners, or determines the risk at an economically achievable *DoL*. The selection will be driven by the risk profile which is acceptable to be used to inform the potential for incidents during the life span of the cable and hence estimate the full life costs.

Table 4 Example of categorisation of the frequency of an event based on the wind farm lifetime

Return period	Frequency	Description
<25 years	$>4x10^{-2}$	Greater than 100% likelihood of an event occurring during 25 year lifetime
25 to 100 years	$4x10^{-2}$ to 10^{-2}	100 to 25% likelihood of an event occurring during 25 year lifetime
100 to 250 years	10^{-2} to $4x10^{-3}$	25 to 10% likelihood of an event occurring during 25 year lifetime
250 to 500 years	$4x10^{-3}$ to $2x10^{-3}$	10 to 5% likelihood of an event occurring during 25 year lifetime
500 to 1,000 years	$2x10^{-3}$ to 10^{-3}	5 to 2.5% likelihood of an event occurring during 25 year lifetime
1,000 to 2,500 years	10^{-3} to $4x10^{-4}$	2.5 to 1% likelihood of an event occurring during 25 year lifetime
2,500 to 5,000 years	$4x10^{-4}$ to $2x10^{-4}$	1 to 0.5% likelihood of an event occurring during 25 year lifetime
5,000 to 10,000 years	$2x10^{-4}$ to 10^{-4}	0.5 to 0.25% likelihood of an event occurring during 25 year lifetime
10,000 to 25,000 years	10^{-4} to $4x10^{-5}$	0.25 to 0.1% likelihood of an event occurring during 25 year lifetime
25,000 to 100,000 years	$4x10^{-5}$ to 10^{-5}	0.1 to 0.025% likelihood of an event occurring during 25 year lifetime
>100,000 years	$<10^{-5}$	Less than 0.025% likelihood of an event occurring during 25 year lifetime

The acceptable risk is not a straightforward topic as it depends on the risk appetite of the involved stakeholders and is therefore open to interpretations on what is or is not acceptable. Often the risk categories from the DNV-RP-F107 are adopted to indicate a level of probability with the risk profile. However, as discussed in Appendix A1.2 this failure frequency is derived based on operations and risks/consequences that are not present in offshore wind farms (environmental risks etc.). In addition, the categorisation of the DNV-RP-F107 is deemed not to be entirely appropriate for offshore wind farms. Table 4 indicates an alternative approach which categorises a certain event based on the wind farm lifetime. **It should be highlighted that this table does not give any indication on what is a high, a low or an acceptable risk (the identified categorisation in this document is given as purely a numerical exercise)**. As a consequence due to the lack of fit for purpose industry standards on the acceptable return period the engagement with all the project stakeholders is strongly recommended for the definition of the acceptable level of risk for subsea cables in offshore wind farms.

Finally, the probabilistic risk assessment may be repeated after cable installation and burial, or later in the life time of the cable when vessel traffic and/or seabed levels may have changed. The *DoL* should be used to inform the percentage of vessels which carry anchors large enough to be a threat to the cable. This defines the value of $P_{Traffic\ Risk}$ which represents the actual residual risk to the cable. This will define the requirement for eventual remedial operations on the cable.

3.4.4. P_{WD}

Table 5 Example of Probability Modifiers for Water Depth

Vessel deadweight, DWT (t)	2,000	5,000	20,000
Vessel draft	4.0	6.0	10.0
Water Depth/Profile	Probability Modifier		
Water Depth Greater than e.g. 50m	0	0	0.1
Water Depth between e.g. 30m and 50m	0.0	0.1	0.3
Water Depth between e.g. 10m and 30m	0.3	0.5	0.9
Wide Shipping Channel with shallow water at margins	0.2	0.5	0.6
Narrow Shipping Channel with shallow water at margins	0.3	0.7	0.9
Proximity of a designated anchorage	0.9	0.9	0.9

The effect of the water depth (and of the bathymetric profile) is considered important and is included as a qualitative factor. Although qualitative, if the model is developed logically the results will be repeatable. The water depth and the bathymetric profile influence the navigation of vessels and their behaviour in emergency situations, thus the likelihood of anchor deployment. In addition water depth also affects the selection of the trenching tool (e.g. ROV jet trenchers are affected by the water depth).

During emergencies involving loss of control of a vessel (uncontrollable drifting) prior to deploying an anchor, Captains typically consider:

- The risk of the vessel hitting an obstacle;
- The risk of the vessel going into very shallow water, thus the risk of grounding.

These two aspects will guide the decision of the Captain whether to deploy the anchors. For example assuming a vessel with 10 m draft drifting in 50 m water depth and heading towards a windfarm is clearly a situation where the vessel will deploy the anchor as quickly as possible. If however, no obstacle is around and the vessel is drifting towards areas with no significant change in water depth, it is more likely that the Captain will not deploy the anchor and will focus on recovering control of the vessel. It is therefore of utmost importance to understand the probable behaviour of the different vessel types in emergency situations and how these are affected by the water depth. It is strongly recommended that the probability modifiers should be project specific and should be developed based on:

- The seabed profile (water depth);
- Potential obstacles; and,
- The vessel traffic.

For example, at some locations along the cable route, the water depth may be great enough to prevent the use of an anchor, reducing the probability of damage to a cable to 0; however, at the other extreme, close to an anchorage a modifier of 1 might be used. In any case local conditions should be thoroughly assessed to develop the modifiers.

Table 5 gives an illustration of the assignment of P_{WD} in various situations for three vessel sizes; however, this is **only intended to be an example and therefore these values are not expected to be appropriate in the vast majority of practical scenarios**. The assessment can be made conservative by setting the value to 1.0 for all water depths. However this will introduce the paradox that the calculation is the same in 10 m water depth and in 1000 m water depth, thereby implying that the vessel behaviour is the same during emergencies regardless of the water depth.

3.4.1. V_{Ship} and $D_{Ship\ Drag}$

V_{Ship} and $D_{Ship\ Drag}$ determine the exposure of the cable in terms of the number of hours per year that a vessel is close enough to the cable to become a threat if it deploys its anchor. V_{Ship} and $D_{Ship\ Drag}$ vary for each vessel type/size. The sum of the exposure time of each vessel along the route (or section) gives the total exposure time of the cable per year.

V_{Ship} is the velocity with which the vessel drifts while it is deploying an anchor. The deployment of anchors at high vessel drift speed is undesirable due to personnel and equipment safety requirements. V_{Ship} is typically less than 1 knot while for smaller vessels its maximum could even be 2 knots. For the largest vessels V_{Ship} is considerably less than 1 knot as they should almost stationary to safely deploy an anchor. However, it should be highlighted that there could be situations where the deployment of the anchor will occur at a higher vessel velocity e.g. in close proximity of an obstacle.

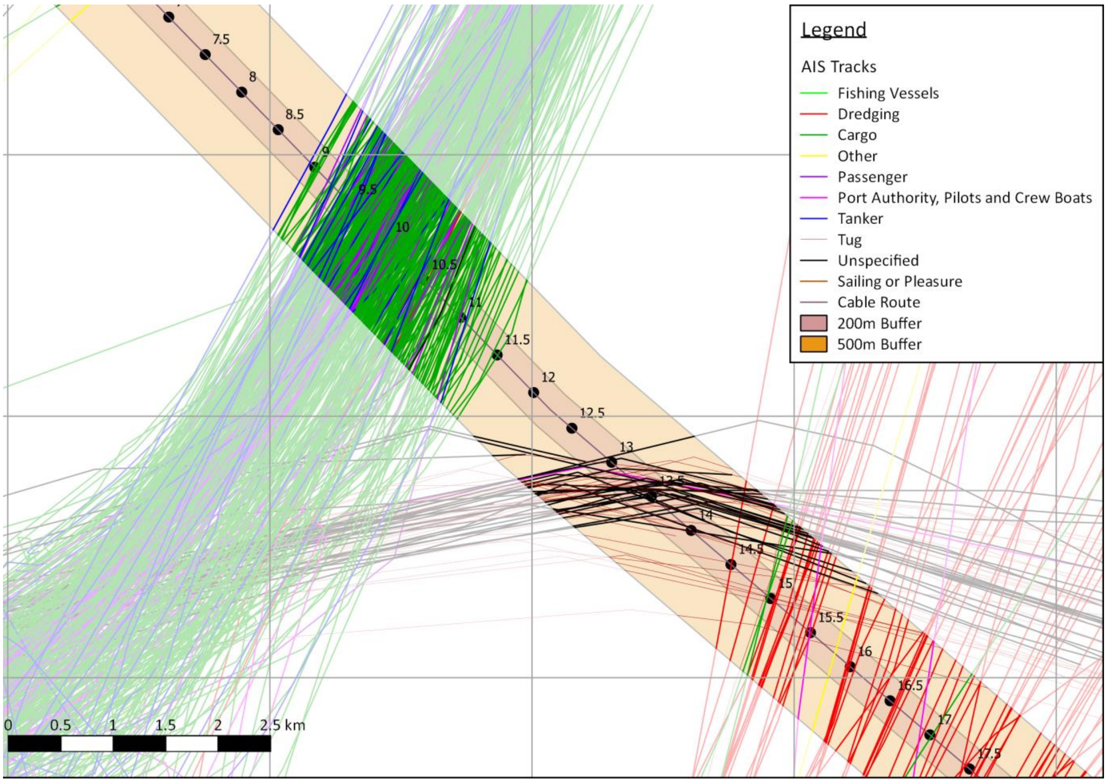


Figure 4 Illustration of the buffer zone for anchor risk analysis (DShip Drag)

Table 6 Indicative values of Vship

Scenario	V_{ship}
Small vessel anchoring	<2knots
Large vessel anchoring	<1knots
Local current speed	Depends on local conditions but could potentially be e.g. ~4knots

In the event of losing the propulsion system, the vessel will be influenced by the met ocean conditions e.g. currents. There are locations where currents could have a higher velocity e.g. 4 knots and this means that the anchor could be deployed at higher velocity, thus potentially increasing the exposure time of the cable. Table 6 summarises indicative speeds for controlled anchoring. It is strongly recommended to carefully consider the local conditions and specify V_{Ship} in accordance with the specific behaviour during emergencies of each vessel type in transit.

$D_{Ship\ Drag}$ is the distance travelled by the anchor when deployed in order to exert its holding capacity and (theoretically) immobilise the vessel. A vessel transiting beyond a distance equal to $D_{Ship\ Drag}$ from the cable is not a hazard. $D_{Ship\ Drag}$ can be estimated using the kinetic energy theorem based on the vessel's weight, speed and anchor holding capacity in the anticipated conditions (equation 2).

Equation 2 Formula for a rough estimation of DShip Drag ignoring hydronamics

$$D_{Ship\ Drag} = \frac{m * V_{Ship}^2}{4 * UHC}$$

Where:

$D_{Ship\ Drag}$ (m)	distance travelled by the anchor in order to be a threat to the cable
m	Vessel mass (deadweight + ship light weight), usually taken as displacement (tons)
V_{Ship} (m/s)	ship speed when the anchor is deployed
UHC	Ultimate Holding Capacity of the anchor

However, this equation ignores the hydrodynamics of the anchor movement on the seabed and has uncertainty with regards to the estimation of the UHC as it depends on the anchor type, size, weight and the soil characteristics. The UHC can be estimated upon consultation with anchor manuals (e.g. an anchor manual from an anchor supplier (Vryhof) can be found here) where normally is defined as anchor weight multiplied by an efficiency factor. The efficiency factor can vary significantly with the soil conditions and therefore this estimation is highly approximate.

A more pragmatic approach suggests the use (where possible) of empirical data from anchor trials where the drag distance of various anchor types may be measured in various soil conditions. The anchor penetration trials of BSH and TenneT performed in the German Bight have given experimental results on the drag distance of anchors in various types of sand. By expanding the trials in other soil types and anchor sizes/types, $D_{Ship\ Drag}$ could be obtained from experimental data and not from theoretical formulas.

$D_{Ship\ Drag}$ may be determined for the probabilistic analysis as follows:

- Breakdown the vessels into different size/type categories e.g. <2000te, 2000-4000t, etc. This should provide a level of refinement without the need to assess each vessel individually;
- Determine the anchor size for each vessel type and estimate the $D_{Ship\ Drag}$ for each type. Therefore, the time that the cable is exposed to each vessel is different for each vessel size/type;
- To simplify a buffer zone around the cable could be determined based on the largest vessel against which you mitigate. For example if the 90th percentile size vessel (thus anchor) is considered the risk against which you mitigate, the drag distance for the 90th percentile vessel could be calculated and set as the buffer distance either side of the cable as shown in figure 4. This approach is conservative.

The choice of the area under observation affects the outcome of the probabilistic assessment. The selection of a very larger buffer increases the exposure time for the cable and may result in a very conservative assessment. It is strongly recommended to carefully consider the site specific vessel information and soil conditions when specifying the $D_{Ship\ Drag}$.

3.4.2. $P_{incident}$

Table 7 Example of Failure rates and return periods from the literature

Reference	Probability per vessel per year	Return period (years)
DNV-RP-F107: Probability of loss of control onboard when on collision course per pass (main reasons no crew on bridge, negligent/tired/drunk crew, accident or radar failure/poor visibility)	$2x10^{-4}$	5000
DNV-RP-F107: Machinery breakdown for single engine tankers in the north sea	$1.75x10^{-1}$	5.7
Kristoffersen & Monnier (1997) (SAFECO)	2.5x10-4	4000
DNV for Marine Coastguard Agency Probability of engine failure	$1.5x10^{-4}$	6667
Southampton Solent University, 15 years of Shipping Accidents: A review for WWF Average vessel loss rate per year (1997 to 2011)	$1.43x10^{-3}$	700
IMO, International Shipping Facts and Figures Average vessel loss rate per year (2006 to 2010)	$1.44x10^{-3}$	694
OGP Total loss per ship per year	$3x10^{-3}$	333

$P_{incident}$ has the greatest influence on the outcome of the probabilistic assessment. It is therefore critical to properly assess the probability that a vessel may have an incident which requires the use of an anchor. It is recognised that developing an accurate value for the probability of an incident is complex and that the availability of information varies significantly from location to location. In some locations the availability of incident data from National Authorities allows assessment of the number of incidents for a certain vessel type or class (e.g. Marine Accident Investigation Board (UK)). Alternatively, Lloyds Register annually publish both World Casualty Statistics and World Fleet Statistics which can be used to determine a frequency rate for a given region.

Where statistical data on the number of incidents is not available figures from the literature can be used. However, careful consideration is recommended to ensure that unrealistically low or high values are avoided. At it can be seen in table 7 the variability of failure rates found in the literature is striking with a range of return periods from 5 to 5000 years. This enhances the need for local investigation and should at least include the larger vessels since these will drive the decision on the acceptable risk and the mitigating measure. In addition, the behaviour of these vessels in emergencies should be assessed (see discussion on P_{WD}).

The selection of $P_{Incident}$ is critical and there is a risk of either over-conservativism or underestimation. It is recognised that selection of $P_{Incident}$ will prompt rigorous debate amongst stakeholders. The value may also vary along the proposed route. Several values for the $P_{incident}$ in table 7 especially those associated with probability of loss of control are calculated based on platform risk and/or grounding risk calculations and includes causes such as absence of crew, crew asleep, alcohol/drug abuse, which may not result in anchor drop but could result in collision or grounding. It is therefore strongly recommended to estimate local failure rates based on the local vessel traffic. In case values found in the literature are adopted this should be done with caution.

3.4.3. Anchor penetration

Being designed to penetrate the seabed to achieve a holding capacity, anchors may damage cables. All ships are fitted with anchors that may be deployed either as a temporary mooring, as part of a planned procedure, or for safety if the ship is at risk for some reason (for example loss of power). Anchor size requirements are based on various regulations including those published by Lloyds, American Bureau of Shipping and IACS. Using the IACS rules it is possible to determine the approximate size of anchors used by the vessels crossing the cable routes. The holding capacity of an anchor is determined by the soil conditions and by the geometry and weight of the anchor, which is proportional to the fluke length. The UHC of the anchor may be roughly estimated by assuming an efficiency factor multiplied by the anchor weight. However, the efficiency factor largely varies among the commonly available anchors (e.g. from 5 to 100) making this estimation uncertain. The size of the anchor (legal requirement) on a vessel is determined by its Equipment Number (EN) (equation 3).

Equation 3 Formula for the calculation of the Equipment Number (EN)

$$EN = DWT^{\frac{2}{3}} + 2.h.B + \frac{A}{10}$$

Where:

DWT	Vessel Deadweight
B (m)	Moulded breadth
H (m)	Effective height from the Summer Load Waterline to the top of the uppermost house
A (m^2)	Area in profile view of the hull, superstructure and houses above the Summer Load Waterline

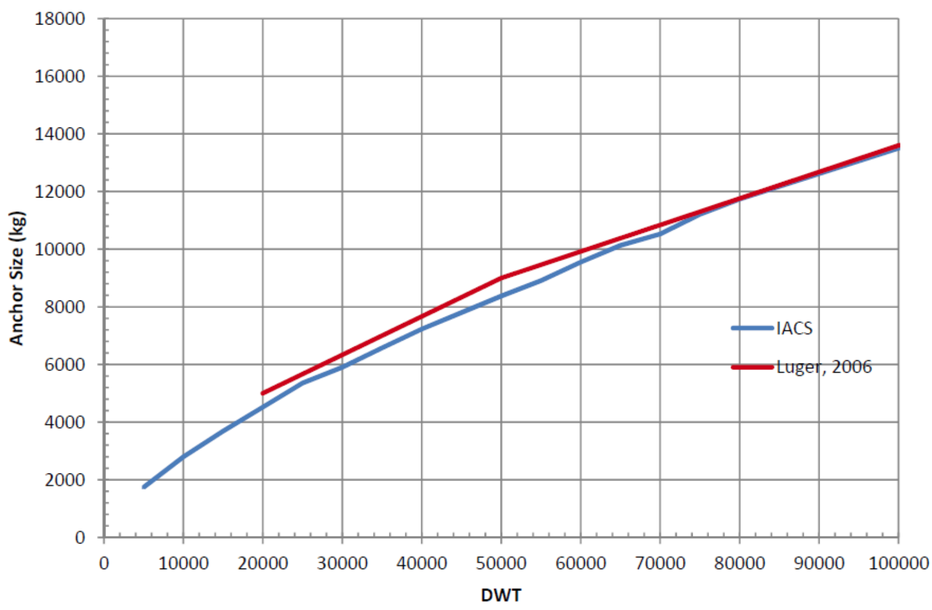


Figure 5 Relationship between Vessel DWT and Anchor Size

The EN is related to the displacement and sail area both above and below the waterline. The calculation includes parameters for breadth and effective height and therefore, the analysis should be considered an approximation; however the DWT represents approximately 2/3 of the classification value. Figure 5 illustrates the relationship between vessel DWT and anchor size. This relationship correlates well with anchor sizing proposed by Luger and that IACS rules result in broadly similar anchor sizes to Lloyds and DNV. Using this relationship and the distribution of vessels crossing the cable route, the distribution of anchor weights can be estimated.

Alternatively once the EN is calculated the weight of the anchor can be estimated from the IACS tables (table 8). From the commonly available anchor catalogues it is possible to identify the distribution of the fluke length of anchors on vessels crossing the cable route. It should be noted that the fluke length can vary significantly depending on the manufacturer and type of anchor used, particularly where high holding power anchors (HHP) are in use. HHP anchors have been designed to be much smaller in weight for the same performance; however, the penetration depths do not vary with the EN. Having identified the fluke length of anchors anticipated in an area the potential penetration depth can be determined.

The nature of the seabed affects the potential penetration depth of an anchor; therefore an assessment of the seabed conditions along the route is important as part of the threat assessment. Work by the US Naval Civil Engineering Laboratory (NCEL) indicates that in sands and stiff clays the fluke tip penetration is limited to 1 fluke length (i.e. 1 time the fluke tip depth). In soft silts and clays anchor penetration is between 3 and 5 fluke lengths (i.e. 3-5 times the fluke tip depth). Table 9 illustrates an example of theoretical penetration depths for a range of anchor sizes.

Table 8 Anchor weight and equipment number relationship (IACS Requirements concerning Mooring, Anchoring and Towing)

E.N.	Stockless bower anchors		Stud link chain cable for bower anchors			
	No. *	Mass per anchor (kg)	Total length (m)	Min. dia. Mild steel Gr. 1 (mm)	Min. dia. Special quality Gr. 2 (mm)	Min. dia. Extra special quality Gr. 3 (mm)
1	2	3	4	5	6	7
205-240	3	660	302.5	26	22	20.5
240-280	3	780	330	28	24	22
280-320	3	900	357.5	30	26	24
320-360	3	1020	357.5	32	28	24
360-400	3	1140	385	34	30	26
400-450	3	1290	385	36	32	28
450-500	3	1440	412.5	38	34	30
500-550	3	1590	412.5	40	34	30
550-600	3	1740	440	42	36	32
600-660	3	1920	440	44	38	34
660-720	3	2100	440	46	40	36
720-780	3	2280	467.5	48	42	36
780-840	3	2460	467.5	50	44	38
840-910	3	2640	467.5	52	46	40
910-980	3	2850	495	54	48	42
980-1060	3	3060	495	56	50	44
1060-1140	3	3300	495	58	50	46
1140-1220	3	3540	522.5	60	52	46
1220-1300	3	3780	522.5	62	54	48
1300-1390	3	4050	522.5	64	56	50
1390-1480	3	4320	550	66	58	50
1480-1570	3	4590	550	68	60	52
1570-1670	3	4890	550	70	62	54
1670-1790	3	5250	577.5	73	64	56
1790-1930	3	5610	577.5	76	66	58
1930-2080	3	6000	577.5	78	68	60
2080-2230	3	6450	605	81	70	62
2230-2380	3	6900	605	84	73	64
2380-2530	3	7350	605	87	76	66
2530-2700	3	7800	632.5	90	78	68
2700-2870	3	8300	632.5	92	81	70
2870-3040	3	8700	632.5	95	84	73
3040-3210	3	9300	660	97	84	76
3210-3400	3	9900	660	100	87	78
3400-3600	3	10500	660	102	90	78
3600-3800	3	11100	687.5	105	92	81
3800-4000	3	11700	687.5	107	95	84
4000-4200	3	12300	687.5	111	97	87

Table 9 Example of a distribution of anchor sizes and maximum penetration depth

Vessel Size [DWT]	Estimated Displacement [t]	Estimated Anchor size [kg]	Fluke length [m]	Anchor Penetration Depth [m]	
				Sands	Soft Clay
500	850	335	0.70	0.49	1.60
1000	1700	524	0.81	0.57	1.86
2000	3400	825	0.94	0.67	2.16
3000	5100	1077	1.03	0.73	2.36
4000	6800	1302	1.10	0.77	2.52
5000	8500	1509	1.15	0.81	2.64
6000	10200	1702	1.20	0.85	2.75
8000	13600	2060	1.28	0.90	2.93
10000	17000	2388	1.34	0.95	3.08
15000	25500	3125	1.46	1.04	3.37

Anchor penetration trials undertaken by TenneT in loose to dense sands in the German Bight indicate that in granular material the penetration depth of 11 ton anchors is less than 1 m (including measurement uncertainties), much less than the expected theoretical result. If more trials are performed it may be proven that the suggested penetration depth of 3 to 5 fluke lengths in low strength material is potentially excessive.

3.5. FoS and specification of the *DoL*

At this stage the following should have been identified:

1. The penetration depth of external hazards against which mitigation is required;
2. Eventual constraints from natural hazards (e.g. sediment mobility of the site requiring an additional 0.4 m *DoL*);
3. Other constraints e.g. crossing of infrastructure.

Based on the above and with the application of a suitable FoS the *DoL* can be specified. The application of the FoS is recommended due to:

- The inherent uncertainty in the soil profile along the cable route due to the variability of soil properties from single site investigation points;
- The inaccuracies in positioning and resolution of shallow geophysical surveys;
- Shipping data is normally based on limited sampling that may not be fully representative of the lifetime of the cable;
- The approximate manner in which anchor sizes are estimated;

- The inaccuracy of measurement of the *DoL*; and
- The uncertainty on the performance of burial equipment in terms of the achievable *DoL*.

The FoS may vary between projects and consideration should be given to the validity of a constant FoS particularly along long export or interconnector cables. An example of the factors that should be considered when selecting a FoS are:

- In areas of high shipping density the uncertainty in anchor sizing increases, therefore an increased FoS may be appropriate;
- The FoS should be varied based on the quality, appropriateness and distribution of the route survey data;
- FoS may vary based on sensitivity and variability checks of seabed strength;
- FoS may vary along the cable route or the infield array area according to factors that may influence the risk profile.

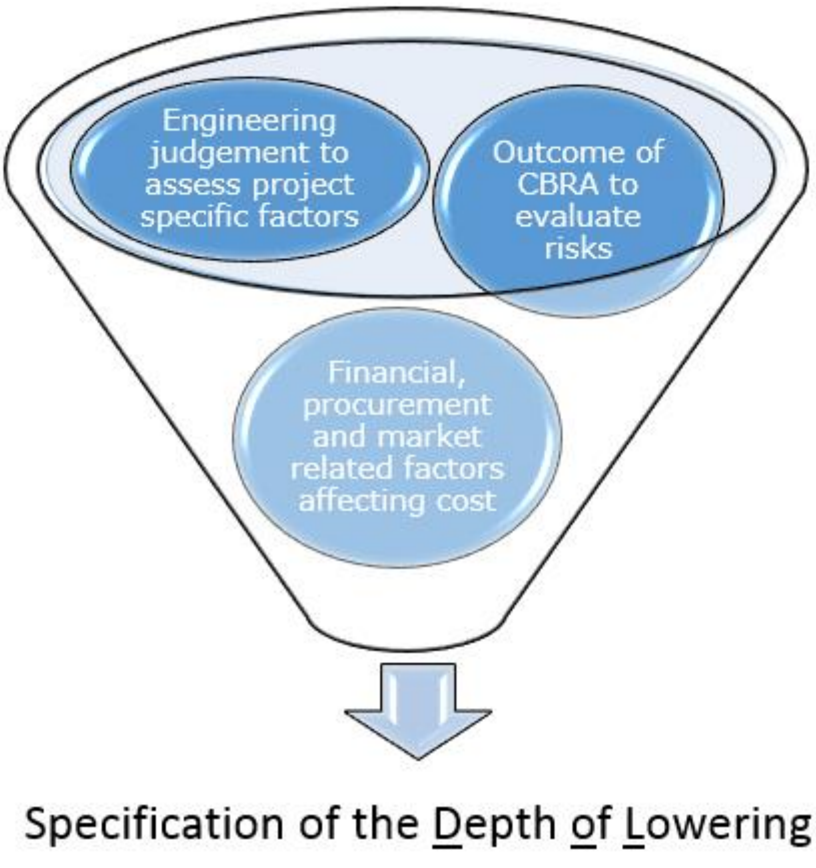


Figure 6 Main levers affecting the final specification of the DoL

No specific FoS is recommended in this document. The designers should choose a FoS based on their own acceptable risk profile, the local conditions and engineering judgement. In any case care should be taken not to specify a FoS which results in a target *DoL* which is not economically achievable. The selection of the FoS should aim to optimise cable protection without resulting in unjustified conservativism and an overly onerous installation cost.

3.6. Conclusions and recommendations

This application guide has provided a detailed explanation on how to apply the CBRA methodology in specifying the *DoL* for subsea cables. CBRA does not consider financial and other factors associated with the burial itself (required cost to achieve a certain protection level, vessel and burial tool availability, procurement strategy etc.) which are of utmost influence and importance in the final specification of the *DoL*.

The final *DoL* is derived by applying engineering judgement and carefully considering all the project specific surrounding and economic conditions alongside the outcome of CBRA.

Where the recommended minimum *DoL* is limited e.g. less than 0.3 m where only fishing is assessed as a threat, a minimum additional clearance of 0.3 m is recommended (FoS 2 in this case, however this is only an example) to avoid a *DoL* less than 0.5 m which is difficult to achieve in practice.

It is recognised that there may be uncertainty and/or debate regarding some of the input parameters. It is recommended to undertake sensitivity analysis in order to assess the potential implications of the parameters under consideration (e.g. $P_{Incident}$) and gain insights on the selection of the suitable values.

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Appendix A Motivation to develop CBRA

The CBRA methodology has been developed taking into account all the fundamental concepts already established in the industry from the experience accumulated from the protection of telecom cables, pipelines and umbilicals. CBRA advances these concepts by adding a pragmatic approach and novelties like the probabilistic risk assessment, ultimately proposing an innovative fit for purpose methodology for the assessment of the protection of subsea cables for offshore wind farms.

A.1. Superseding the Burial Protection Index

The BPI has been in use since the late 90's and was originally developed to assess the required protection level of fibre optic telecommunication cables. Although it has been widely applied to the 1st and 2nd generation offshore wind farms the BPI is now associated with conservativism and an inherently oversimplified approach that ignores the site specific factors and the real risk to which the cables are exposed. This often leads to over burial of cables. In summary the main limitations in the BPI include but are not limited to:

- It is a semi-qualitative approach;
- It is no longer widely used – individual risk based approaches have been developed by developers and consultancies;
- It only covers anchors of limited sizes with unclear definitions;
- It is conservative with regards to protection from fishing gear in soft clay sea beds;
- It ignores site specific factors like:
  - Water depth;
  - Probability of incidents involving anchors;
  - Frequency and size of vessels in transit;
  - Coastal erosion and changes in the seabed profile; and,
- It does not provide a means of quantifying the residual risk.

When the BPI was adopted these limitations were addressed through the engineering judgement of the design team; however, this limits the standardisation of specifications and introduces uncertainty as it relies on the individual experience of the involved personnel and may either lead to conservatism or underestimation of the hazards. Finally, the BPI was developed to address the lack of detailed data for the installation of telecom cables (i.e. telecom cables are often thousands kilometres long with limited survey data, however often it is the situation that the water depth is such that no burial is required). This is a fundamental difference compared to offshore wind farms where high quality site specific data is potentially available and could/should be used to assess the "real and effective" risk to which cables are exposed. CBRA aims to establish this mind-set and this document aims to show how CBRA may be applied.

A.2. Superseding individual risk based approaches

The experience of the 1st and 2nd generation offshore wind farms showed that the lack of optimisation in the specification of the *DoL* increases the risks and costs associated with Cable installation. As a consequence the industry gradually shifted to risk based probabilistic approaches evaluating the effective risk profile and successively assessing the required protection level. These methodologies to a large extent were based on the following recommended practices (primarily the first one):

1. DNV-RP-F107 Risk assessment of pipeline protection, published in October 2010

2. DNV-RP-J301 Subsea power cables in shallow water renewable energy applications, published in February 2014

The DNV-RP-F107 is an extremely useful document adopted as the main reference for probabilistic risk approaches. Fundamental concepts were introduced including but not limited to:

- The ALARP risk mitigation approach;
- The systematic identification of hazards and corresponding mitigating measures in order to achieve an acceptable risk level; and,
- The categories of acceptable risk thus probabilities of occurrence for pipelines and umbilicals.

However, this recommended practice was developed for pipelines (as its title suggests) and therefore is not fully applicable to subsea cables. Its limitations include but are not limited to:

- Overall the document is driven by risks and consequences that are significantly different compared to offshore wind farms and subsea cables in general. For example damage to a pipeline can result in significant environmental damage as well as significant economic costs due to shutdown of offshore facilities and potentially a long lead time for replacement of damaged sections;
- A different range of activities take place around oil and gas platforms compared to offshore wind farms e.g. oil platforms are normally manned often with guard/standby vessels generally in deeper water opposed to offshore wind farms that are normally unmanned and this means that the vessel traffic around oil and gas platforms is fundamentally different compared to offshore wind farms;
- It does not provide guidance on how to perform a probabilistic risk assessment to assess the likelihood of an anchor strike. The latter together

with the risk from benthic fishing activity are the main anthropogenic hazards for which cable burial is adopted as a primary mitigating measure;

- The risk profile categories have been derived with different risks and consequences compared to offshore wind farms.

The DNV-RP-J301 published in February 2014 is a very comprehensive document virtually covering all the project stages of subsea cables in shallow water for renewable energy applications (design, manufacturing, installation and operation). However, in terms of the *DoL* specification it only provides valuable recommendations without proposing a methodology that specifies the *DoL*. These recommendations include but are not limited to (statements copied from the DNV-RP-J301):

- "The optimum depth of burial should be determined by applying a risk based approach, yielding an adequate and economical burial with a consistent level of protection"

- "Local regulations may require minimum burial depths and shallower burial may not be allowed. A risk based assessment may aid the discussion with the authorities and identify sections of the cable which should be buried shallower or deeper than the blanket requirement" (note from the authors: The German authorities reduced the *DoL* requirements based on a probabilistic risk based approach and large scale anchor trials (BSH 2015);

- The risk based approach regarding external aggression in a relatively stable seabed comprises the following steps:

    - Determination of the external aggression risk along the cable route (dropped anchor, dragged anchor, fishing gear interaction)
    - Determination of the ground properties along the cable route to assess potential penetration depths
    - Division of cable route into sections of similar risk profile
    - Application of a qualitative, semi-quantitative or quantitative method to determine a minimum burial depth

The CBRA methodology has been developed aiming to optimise the *DoL* based on the recommendations of both DNV recommended practices and on the accumulated experience in the industry. Where applicable CBRA introduced new approaches to bridge the gaps (e.g. for the probabilistic assessment of anchor strikes) and ultimately aims to establish itself as a robust, standardised and fit for purpose methodology used for the specification of the *DoL* of subsea cables for offshore wind farms.

Appendix B Description of the Risks

B.1. Natural Hazards

Natural hazards are not normally the main factors dictating the *DoL.* However, depending on site specific conditions they may affect the cable route and influence the *DoL* significantly. Careful, detailed and systematic assessment of these risks is strongly recommended to minimise the risk to the cable and to estimate changes to the risk profile over the lifetime.

B.1.1. Sediment Mobility

Sediment mobility is not in itself a threat to cable integrity. However, sediment mobility may affect the specified *DoL* of buried subsea cables resulting in exposure or additional covering of the cable over time, therefore changing the risk profile and potentially resulting in increased risk from anchor strike or risk of failure due to vortex induced vibration (strumming) of cable spans. In addition, a group of offshore structures (e.g. WTGs) may result in a global scour of the seabed among the structures potentially leading to exposure of cables.

Seabed features are usually classified in terms of the characteristic length, height and degree of mobility. Often it will be the situation that a dune or ripple moves laterally as well as vertically when it progresses. This means that the natural development of a cable on a relatively flat seabed will be to bury itself deeper rather than becoming exposed, although this behaviour heavily depends on local conditions.

The sediment mobility along a cable route is assessed with numerical modelling and **multiple** accurate bathymetric surveys. The surveys should ideally be completed a number of times, at the same and different times of year possibly recording significant weather events between surveys. The main aspects to consider include but are not limited to:

- Metocean conditions relevant to the particular section of the route;
- Eventual location of the section in the Surfing zone;
- Different Interface between the mobile layer and the underneath layer (friction factor between layers);
- Main seabed features (e.g. Sandwaves, Megaripples, Sandbars, Outcrops, Pit etc.); and,
- Potential for global scour between offshore structures;

CBRA does not discuss in detail or give any guidance on how to assess the sediment mobility. However, the importance of this factor is recognised and it is strongly recommended to accurately assess it with specific studies repeated in time. The layer of the mobile sediment and the pattern of its movement will influence the cable route and/or the specification of the *DoL*. Depending on various factors the *DoL* might increase or decrease or in some cases the cable route might be modified.

B.1.2. Seismic Activity

Although not considered a significant risk in the North Sea, if cables are installed in seismically active areas, bathymetric and sub-bottom profile data should be inspected for evidence of surface expressions of faulting. Fault movement might increase the length of cable required, causing tension or spanning of the cable. Seabed liquefaction is also a potential risk (also present due to the wave loading). Cable burial cannot normally be used to protect from damage due to ground movement, additional slack cannot normally be laid into a trench, and the constraint of backfill material will not allow the cable to move across a fault. Alternative cable routing should be considered in order to avoid high risk areas.

B.1.3. Submarine Landslide

Where evidence of submarine landslides is identified from survey data, cable routeing should be carefully considered. Dedicated geo-hazard studies should be completed. Cable burial may protect from submarine landslides if the base of the potential slide is identified and the cable is buried below this level. Particular care should be taken when burying cables at the top of a slope that shows evidence of previous slides. The trenching operations may remove material which results in slope instability. Where the risk from submarine landslides cannot be fully avoided, any future damage is likely to be treated as Force Majeure.

B.2. Anthropogenic Hazards

Anthropogenic hazards majorly influence the *DoL*. In most situations cable burial is anticipated to be the most effective mitigation method for fishing and shipping with route modification or exclusion zones to mitigate the risk from dredging/subsea mining.

B.2.1. Dredging/Aggregate Extraction/Subsea Mining

Dredging and aggregate extraction may pose a threat to submarine cables; however, cable burial is not normally adopted to mitigate this risk, as it is considered preferable to route away from these areas. Within UK waters, all active and historical dredging areas are known and are covered by detailed surveys to allow a certain amount of sediment to remain once a certain point is reached. All disposal sites are also known and these should be avoided (if possible).

Cable routes should avoid areas where aggregate extraction is occurring; alternatively a suitable exclusion zone should be agreed with consenting authorities and the owners of the extraction license. This is more likely to be achieved for future extraction sites.

Where a cable crosses a shipping lane or harbour approach that will be dredged to maintain access, it is recommended that cable installation is conducted immediately after the channel is dredged to its maximum depth or the specification of the *DoL* should allow for the maximum dredge depth as communicated by the relevant authorities. Port authorities should also be consulted over plans for future expansion and allow for burial below any future dredging depths.

Historical dumping grounds should generally be avoided as they may present a hazard to cables and the environment due to the risk of contamination and unknown obstructions.

B.2.2. Other existing and/or planned Cables, Umbilicals, Pipelines

Where the cable route crosses other subsea infrastructure (cable, pipeline etc.), the *DoL* of the cable is specified such to avoid interference with the existing infrastructure. Normally this means that the newer asset will be installed on top of the existing asset. If this results into a shallow *DoL* with an unacceptable residual risk, other mitigating measures should be adopted (e.g. mattresses, rock dumping). Where it is possible to foresee the requirement for other cables, pipelines or umbilicals to cross the proposed cable, it may be possible to increase the *DoL* of the cable in order to allow the burial of assets installed in the future. Whilst the onus is on the future cable or pipeline owner to provide appropriate protection, a collaborative approach is recommended using suitable crossing agreements which include appropriate risk assessments, as recommended by the ICPC Recommendations.

B.3. Risks not considered by CBRA

There are a number of hazards to cables that are not covered by CBRA since they are not normally mitigated by means of cable burial. However, these risks need to be addressed on a project by project basis. For example, unexploded ordnance (UXO) is a real and significant hazard to offshore projects and specific assessments and mitigations need to be considered (surveys, avoidance or removal). Similarly, construction activity represents a hazard to subsea cables with the vast majority of cable insurance claims relating to issues/incidents during construction (either directly during installation or during operation but caused by events occurring during the construction phase that led to cable damage). CBRA does not explicitly consider the risk from installation. It is recommended to develop project specific working procedures, non-generic method statements, risk assessments and protocols to mitigate construction risk as far as practically possible.

Appendix C Worked Example

The example aims to show how to use the CBRA methodology illustrating the process and highlighting important aspects. Since the objective is to illustrate the probabilistic assessment, the determination of the various parameters is performed in a rather simplistic manner. It is therefore expected that in real cases many parameters will be significantly different and more analysis will be required for their determination.

Step 1: Cable Routeing

A cable route is considered with two sections of sand, one section of soft clay and total length of 40 km.

Figure 7 Cable route and seabed conditions for the example

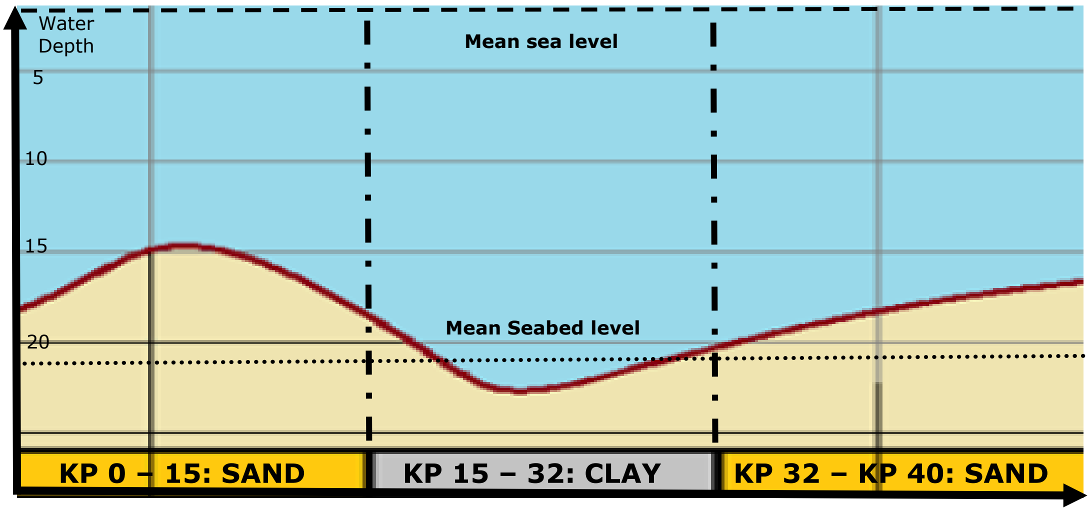


Table 10 Breakdown of the route and soil type

Route Section (KP)	Water depth	Dominant Seabed
0 – 15	15 – 18m	Sand
15 – 32	18 – 23m	Soft Clay
32 – 40	12 – 20m	Sand

Step 2: Data Collation

Table 11 Input assumptions for the example

Parameter	Value
$P_{Incident}$	$1.43x10^{-3}$ per vessel per year
V_{ship}	2 Knots

Survey data is available informing on the sediment mobility of the site. Data for the vessel traffic has been gathered (Figure 8) and the anchor sizes have been estimated alongside the maximum penetration depth and the $D_{Ship\ Drag}$ (Table 13). It should be highlighted that in this example it was chosen to assume a different $D_{Ship\ Drag}$ for the probabilistic calculation. In order to make the assessment more conservative an alternative is to take the $D_{Ship\ Drag}$ of the largest anchor and perform the computation for all anchor sizes with the same $D_{Ship\ Drag}$. The estimation of the $D_{Ship\ Drag}$ is not a straightforward task as it depends on the anchor geometry and the soil properties. In this exercise it was estimated using equation 2 on the assumption that the efficiency factor of all anchors is 5 for clay and 10 for sand.

The value of the $P_{Incident}$ and the value to of the V_{ship} to be used in the probabilistic assessment have been determined based on the site conditions and the engineering judgement (table 11).

Step 3: Assessment of the Seabed Conditions

The seabed has no mobile sediment. The water depth in the 3 sections of this example is reported in Table 10. The seabed shape has slopes.

Step 4: Identification and Assessment of the Risks

For simplification it is assumed that sediment mobility studies and site surveys have demonstrated that there is no sediment mobility risk present at this cable route. In addition the only anthropogenic risks present are the risk from fishing and the risk from shipping (table 12).

The vessel traffic of the route is illustrated in figure 8 for each section. The assumed vessel incident failure rate $P_{Incident}$ and V_{Ship} are specified in table 11 and the estimated $D_{Ship\ Drag}$ and P_{WD} are given in table 13.

Figure 8 Vessel traffic per section of the considered cable route

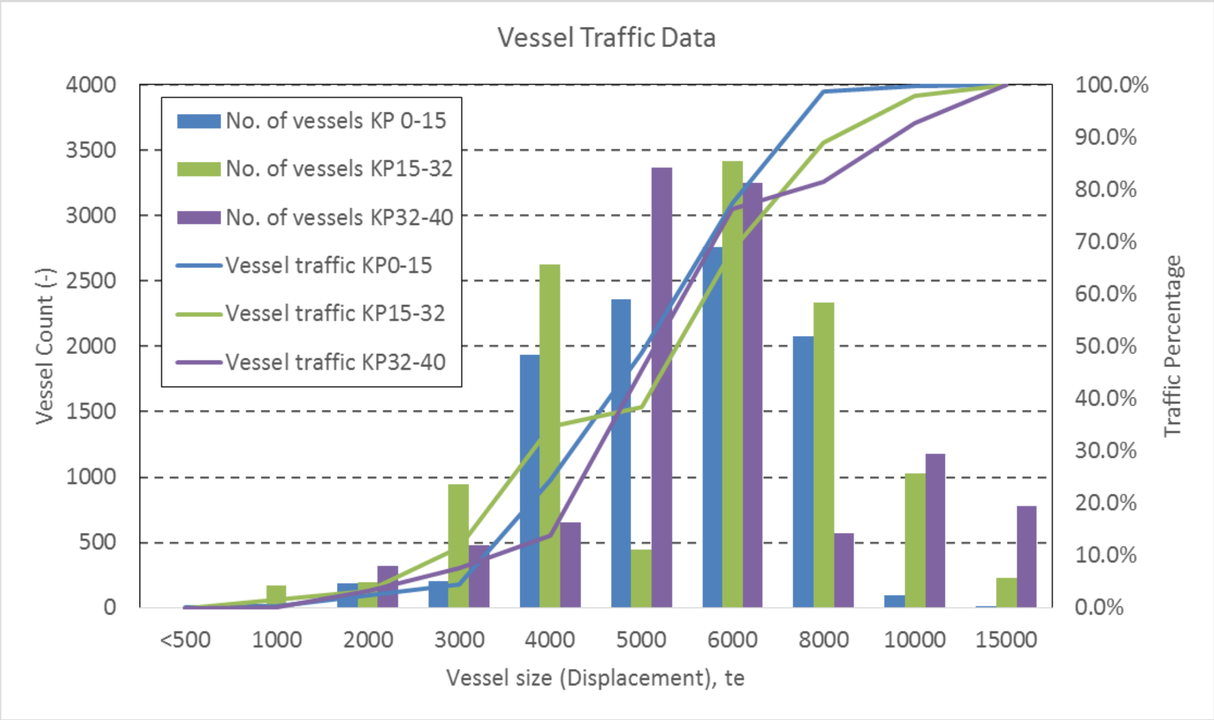


Table 12 Assessment of the route specific risks

SOURCES	Hazard	Cable Risk		
	Description	Risk	Mitigation	Residual Risk
Soil conditions				
Mobile Sediment	Sand wave or megaripple mobility could cause deburial or increased burial of the cable	0	Sediment mobility study has shown that there is no evidence of mobile sediment at the site	0
Anthropogenic				
Fishing	On bottom fishing activity limited to water depths of <50 m. Snagging of cables with fishing gear and damage during retrieval of gear.	4	Cable burial below depth of fishing. Maximum penetration of the fishing gear 0.3 m, thus minimum DoL 0.6 m with 0.3 m FoS.	0
Shipping /Anchors	Major shipping lanes passing through the site.	7	Cable burial below anchor penetration depth. CBRA to assess the risk and amount of mitigation measure. Application of FoS on the outcome of the DoL.	2

Step 5: Probabilistic Risk Assessment

The risk assessment indicated that vessel anchors are a threat to the cable and recommended burial as a mitigation. The probability of an anchor deployment in the vicinity of the cable was calculated using equation 1 undertaking the steps described in section 3.4.3 (subsection on the acceptable risk) to determine the initial risk for surface laid cable. The results are shown in table 14.

Table 13 Estimation of the $D_{Ship\ Drag}$ and P_{WD} for the vessels/anchor sizes of interest

DWT (Tons)	Estimated anchor weight (kg)	$D_{Ship\ Drag}$ Sand (m)	$D_{Ship\ Drag}$ Clay (m)	P_{WD}		
				KP 0-15 (15-18m)	KP 15-32 (18-23m)	KP32-40 (12-20m)
500	335	6.6	13.2	0.1	0.1	0.1
1000	524	8.4	16.9	0.1	0.1	0.1
2000	825	10.7	21.4	0.2	0.1	0.3
3000	1,077	12.3	24.6	0.2	0.1	0.3
4000	1,302	13.6	27.2	0.2	0.1	0.3
5000	1,509	14.7	29.3	0.4	0.3	0.5
6000	1,702	15.6	31.2	0.4	0.3	0.5
8000	2,060	17.2	34.3	0.5	0.4	0.6
10000	2,388	18.5	37.0	0.6	0.5	0.7
15000	3,125	21.2	42.4	0.7	0.6	0.8

Table 14 Results of the probabilistic assessment

DWT (Tons)	Probability of anchor deployment in the vicinity of the cable		
	KP 0-15	KP 15-32	KP 32-40
500	2.80E-08	3.77E-08	1.62E-08
1000	2.93E-07	3.23E-06	7.71E-08
2000	2.21E-06	4.51E-06	5.68E-06
3000	2.75E-06	2.54E-05	9.60E-06
4000	5.72E-05	4.99E-05	1.93E-05
5000	7.53E-05	2.12E-05	3.59E-05
6000	9.36E-05	2.84E-05	1.38E-04
8000	9.69E-05	6.27E-05	3.19E-05
10000	6.07E-06	1.04E-04	2.37E-04
15000	1.33E-06	3.23E-05	7.19E-05
Probability scenario	Overall probability and return period in the route section		
Total probability*	3.36E-04	3.32E-04	5.50E-04
Overall return period (years)	2978	3016	1819

*Total probability calculated as sum of the individual probabilities

Table 15 *DoL* specification mitigating the risk from anchors without FoS

Acceptable Return Period (years)	% of vessels against which mitigation is required KP			Vessel size (DWT) and anchor size to protect cable from KP			Depth of Lowering to protect from emergency anchoring (Unfactored) KP		
	0 - 15	15 - 32	32 - 40	0 - 15	15 - 32	32 - 40	0 - 15	15 - 32	32 - 40
25	0.0%	0.0%	0%	-	-	-	-	-	-
100	0.0%	0.0%	0%	-	-	-	-	-	-
250	0.0%	0.0%	0%	-	-	-	-	-	-
500	0.0%	0.0%	0%	-	-	-	-	-	-
1,000	0.0%	0.0%	0%	-	-	-	-	-	-
2,500	0.0%	0.0%	27%	-	-	6,000 te, 1702 kg	-	-	0.85
5,000	40.4%	39.7%	64%	5,000 te, 1509 kg	4,000 te, 1302 kg	10,000 te, 2388 kg	0.81	2.52	0.95
10,000	70.2%	69.8%	82%	6,000 te, 1702 kg	8,000 te, 2060 kg	15,000 te, 3125 kg	0.85	2.93	1.05
25,000	88.1%	87.9%	93%	8,000 te, 2060 kg	10,000 te, 2388 kg	15,000 te, 3125 kg	0.90	3.08	1.05
50,000	94.0%	94.0%	96%	8,000 te, 2060 kg	10,000 te, 2388 kg	15,000 te, 3125 kg	0.90	3.08	1.05
100,000	97.0%	97.0%	98%	8,000 te, 2060 kg	15,000 te, 3125 kg	15,000 te, 3125 kg	0.90	3.37	1.05

Step 6: Identification of the Acceptable risk

The probability of anchor impact is relatively high with average return periods in the range of ~1800 to ~3000 years. This is due to the intense vessel traffic (>9,000 vessels in KP 32-40) and the conservative parameters adopted in the assessment. As there are currently no guidelines as to acceptable risk, the required *DoL* for a range of acceptable return periods are detailed in the table below. The project team and stakeholders must decide the most appropriate acceptable return period to optimise the burial depth with respect to operational risk against installation risk and cost

The results in table 15 indicate that for acceptable return periods less than or equal to 1,000 years there is no requirement to protect from emergency anchoring as the probability of occurrence is below the level of acceptable risk. In this case the *DoL* is therefore is a function of the fishing risk. For illustrative purposes two different acceptable return periods were selected in the example.

Step 7: Specification of the *DoL*

The example shows a slightly different outcome for each zone

- KP 0-15: The larger acceptable return period results in an increase in the recommended *DoL*. This increase is not significant, however, it may reduce the number of suitable trenching options or require multi-pass operations increasing the installation risk and cost.
- KP 15-32: The larger acceptable return period results in a significant increase in the recommended *DoL*, which could result in limited burial options or requirements for addition protection
- KP 32-40: The larger acceptable return period results in a slight increase in the recommended *DoL* which would not be anticipated to significantly affect trenching options.

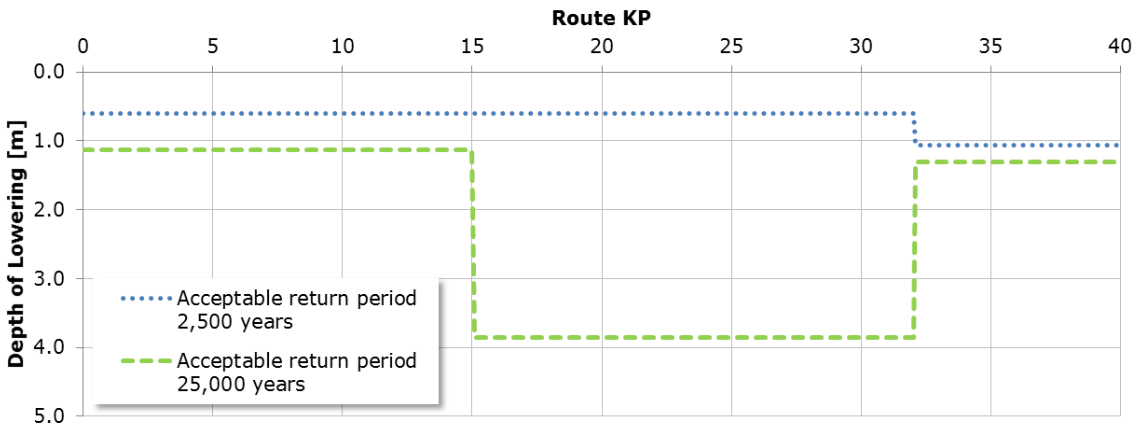
Accepting a higher residual risk can reduce the required burial depth by 10% to 300% potentially reducing installation cost and risk, however, the residual risk could be orders of magnitude higher. Therefore it is vital the project team and stakeholders fully understand the cost and risk consequences of when determining the *DoL* and the residual risk.

Table 16 Final *DoL* specification including FoS

Route Section (KP)	Dominant Seabed	Mobile Sediment Depth	Fishing Threatline	Anchor Threatline		Factored DoL*	
				2,500yr	25,000yr	2,500yr	25,000yr
0 – 15	Sand	0 m	0.3 m	0 m	0.9 m	0.6 m	1.13 m
15 – 32	Soft Clay	0 m	0.3 m	0 m	3.08 m	0.6 m	3.85 m
32 – 40	Sand	0 m	0.3 m	0.85 m	1.05 m	1.06 m	1.32 m

*Including an example of the application of a FoS

Figure 9 *DoL* specification with FoS and varying acceptable return period



Discussion on the example

From the example it clearly emerges the influence of two main factors in the outcome of CBRA:

- The $P_{Incident}$ which practically sets the order of magnitude of the result;
- The acceptable return period which determines the required amount of mitigating measures.

Currently there is no power cable industry guidance on what could be a commonly adopted framework of acceptable return period (thus risk) as it exists for pipelines in the oil and gas industry. As a consequence it is of utmost importance to define the acceptable risk through the engagement of the stakeholders involved in the project. For the specification of the *DoL*, a FoS should be applied to the outcome of CBRA. The FoS is chosen based on the engineering judgement. Successively as depicted in figure 6, this result is evaluated together with economic, market, procurement and other project specific factors and finally the *DoL* is specified.

Table 17 Sensitivity of $P_{Incident}$ and P_{WD}

Parameter	Value	Average return period in the route section		
		KP 0-15	KP 15-32	KP 32-40
$P_{Incident}$	$1.75x10^{-1}$ per vessel per year	2978	3016	1819
	$1.43x10^{-3}$ per vessel per year	362,013	366,598	221,125
V_{ship}	2 knots	2978	3016	1819
	4 knots	1489	1508	910

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