समुद्री ऊर्जा — तरंग, ज्वार और अन्य जल धारा परिवर्तक

भाग 10 समुद्री ऊर्जा परिवर्तक (एमईसीएस) के लिए मूरिंग प्रणाली का आँकलन

Marine Energy — Wave, Tidal and Other Water Current Converters

Part 10 Assessment of Mooring System for Marine Energy Converters (MECs)

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NATIONAL FOREWORD

This Indian Standard (Part 10) which is identical to IEC 62600-10 : 2021 'Marine energy — Wave tidal and other water current converters — Part 10: Assessment of mooring system for marine energy converters (MECS)' issued by the International Electrotechnical Commission (IEC) was adopted by the Bureau of Indian Standards on the recommendation of the Marine Energy Conversion Systems Sectional Committee and approval of the Electrotechnical Division Council.

The text of the IEC standard has been approved as suitable for publication as an Indian Standard without deviations. Certain conventions are, however, not identical to those used in Indian Standards. Attention is particularly drawn to the following:

a) Wherever the words 'International Standard' appears referring to this standard, they should be read as 'Indian Standard'; and

b) Comma (,) has been used as a decimal marker, while in Indian Standards the current practice is to use a point (.) as the decimal marker.

The Committee has reviewed the provisions of the following International Standards referred in this adopted standard and decided that they are acceptable for use in conjunction with this standard.

International Standard	Title
IEC TS 62600-1 : 2020	Marine energy — Wave, tidal and other water current converters — Part 1: Vocabulary
IEC TS 62600-2 : 2019	Marine energy — Wave, tidal and other water current converters — Part 2: Marine energy systems — Design requirements
IEC TS 62600-4 : 2020	Marine energy — Wave, tidal and other water current converters — Part 4: Specification for establishing qualification of new technology

For the purpose of deciding whether a particular requirement of this standard is complied with, the final value, observed or calculated expressing the result of a test, shall be rounded off in accordance with IS 2 : 2022 'Rules for rounding off numerical values (*second revision*)'. The number of significant places retained in the rounded off value should be the same as that of the specified value in this standard.

CONTENTS

INTRODUCTION

This document defines rules and assessment procedures for the design, installation and maintenance of mooring system with respect to technical requirements for floating marine energy converters.

The proposed work aims to bring together expert knowledge from the marine energy power and offshore engineering industries in order to formulate a guideline specification of the design, installation and maintenance requirements for mooring system of floating Marine Energy Converters.

In addition to safety and ocean environmental requirements, this document focuses on the strength requirements of mooring systems for Marine Energy Converters.

Indian Standard

MARINE ENERGY — WAVE, TIDAL AND OTHER WATER CURRENT CONVERTERS

PART 10 ASSESSMENT OF MOORING SYSTEM FOR MARINE ENERGY CONVERTERS (MECs)

1   Scope

The purpose of this document is to provide uniform methodologies for the design and assessment of mooring systems for floating Marine Energy Converters (MECs) (as defined in the TC 114 scope). It is intended to be applied at various stages, from mooring system assessment to design, installation and maintenance of floating Marine Energy Converters plants.

This document is applicable to mooring systems for floating Marine Energy Converters units of any size or type in any open water conditions. Some aspects of the mooring system design process are more detailed in existing and well-established mooring standards. The intent of this document is to highlight the different requirements of Marine Energy Converters and not duplicate existing standards or processes.

While requirements for anchor holding capacity are indicated, detailed geotechnical analysis and design of anchors are beyond the scope of this document.

2   Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC TS 62600-1: 2020, *Marine energy – Wave, tidal and other water current converters – Part 1: Vocabulary*

IEC TS 62600-2:2019, *Marine energy - Wave, tidal and other water current converters - Part 2: Marine energy systems - Design requirements*

IEC TS 62600-4:2020, *Marine energy – Wave, tidal and other water current converters – Part 4: Specification for establishing qualification of new technology*

3   Terms and definitions

For the purposes of this document, the terms and definitions given in IEC TS 62600-1 apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

4 Abbreviated terms

ALARP	As low as reasonably practicable
ALS	Accidental limit state
API	American Petroleum Institute
CALM	Catenary anchor leg mooring
CEC	Current Energy Converter
CFD	Computational fluid dynamics
DP	Dynamic positioning
FLS	Fatigue limit state
HAZID	Hazard Identification
HHP	High holding power
IEC	International Electrotechnical Commission
ISO	International Organisation for Standardisation
LTM	Long term mooring
MBL	Minimum breaking load
MEC	Marine energy converter
MEP	Marine environmental protection
MPM	Most probable maximum
PTO	Power take-off
PT	Project team
ROV	Remotely operated vehicle
SALM	Single anchor leg mooring
SF	Safety factor
SLS	Serviceability limit state
SPM	Single point mooring
TEC	Tidal Energy Converter
ULS	Ultimate limit state
UV	Ultraviolet
VIM	Vortex induced motion
VIV	Vortex induced vibration
WEC	Wave Energy Converter

5 Principal elements

5.1 General

The engineering and technical requirements to ensure integrity of a mooring system for a MEC are given in this document. This document is used in conjunction with IEC TS 62600-2.

5.2 Technology qualification

Technology qualification for mooring system components shall be completed in accordance with IEC TS 62600-4.

5.3 Safety and risk consideration

Understanding risk factors is important in quantifying the consequence class of the mooring design. The consequence class dictates the required level of safety of the mooring design. A mooring related risk assessment shall be completed. Guidelines for a mooring related risk assessment is discussed in more detail in Annex B. Additional guidelines for risk assessment can be found in IEC TS 62600-2:2019,5.4 and IEC TS 62600-4.

5.4 Safety levels

The assessment of consequences of failure shall cover all phases of MEC installation, operation, maintenance, and decommissioning, where the mooring system is affected or affects the overall system. Related consequences shall consider:

- Risk to life and injury

- Environmental impact

- Economic consequences

- Loss of public reputation and other political and societal consequences

The requirements in this document, including safety factors are intended to comply with 10^{-4} per year probability of failure for normal consequence class. This is in alignment with the objective of IEC TS 62600-2. However, a more conservative consequence class is provided along with associated safety factors that may be applicable for a smaller associated target probability of failure.

Where the risk can be controlled by short term deployments, or other factors, particularly for prototype deployments, a larger probability of failure may be tolerated. More information and guidance on safety and risk considerations can be found in Annex B.

5.5 Design procedure

The design process is iterative in nature. The potentially complex nature of MEC dynamic behaviour and external loading effects mean that careful consideration of the definition of environmental conditions, specific design load cases in the limit states required, and the limitations of analysis techniques used should be made. Guidance on environmental and site conditions are described in Clause 6.

The MEC mooring system design shall be regarded as completed when the integrity is verified by the limit state analysis described in Clause 7.

5.6 Inspection and maintenance requirements

The integrity of a station keeping system and its serviceability throughout the design service life are not only strongly dependent on a competent design, but also on the quality control exercised in manufacture, supervision on-site, handling during transport and installation, and the manner in which the system is used and maintained. Further information on inspection and maintenance requirements are described in Clause 8.

6 Environmental and site conditions

6.1 General

External conditions include metocean and other environmental factors that will vary based on location and should be considered on a site specific basis.

6.2 Primary environmental conditions

The environmental conditions described in 6.2 of IEC TS 62600-2:2019 shall be considered in the modelling, analysis, and prediction of environmental loads on and resulting dynamic response of MECs for the purpose of resolving the mooring design. The return periods for combinations of environmental conditions listed in 7.4 shall be used and are intended to align with IEC TS 62600-2:2019.

Wind, wave, current, water elevation variations, snow and ice, and other conditions at each site shall be considered. Guidelines for determining metocean conditions can be found in ISO 19901-1. Annex A.5.7 of ISO 19901-1:2005 provides guidance to establish metocean conditions with larger return periods. The confidence interval of statistical extrapolations to establish return periods from measured site specific data can have a significant effect on the return period values and should be selected carefully.

The return period of metocean conditions in the design load cases are a minimum. The sensitivity to the system response to return period can be considered.

6.3 Secondary environmental conditions

6.3.1 General

Secondary environmental conditions listed in 6.3 of IEC TS 62600-2:2019 shall be considered when the potential exists for significant effects on the MEC and mooring at the deployment site.

6.3.2 Marine growth

The type and accumulation rate of marine growth at a specific site can affect mass and hydrodynamic properties and therefore the dynamic response of the MEC and mooring lines. This shall be taken into consideration for mooring systems designed without any regular marine growth removal or protection plan. Indicative marine growth rates for a variety of locations can be found in ISO 19901-1. Increased line weight and drag coefficients representative of site-specific marine growth accumulation profiles should be considered.

6.3.3 Seabed conditions

Seabed conditions and type are required for anchor selection. More information on anchor selection can be seen in Annex C.

6.4 Site characteristics

6.4.1 General

Characteristics of the deployment site location may have special considerations that may directly affect the mooring design through various requirements or component selection.

6.4.2 Environmentally sensitive and protected areas and marine animals

Selected sites for MECs can be located near sensitive or protected habitats. Any device located in such a habitat can impact the ecology and environment via direct contact or indirectly by harassment. Mooring systems can have impact without a failure event. Consequences can include reduction in water quality from sediment churn and bottom scour due to normal mooring motion, marine life entanglement with mooring components, and habitat damage from anchor placement and installation activities. In addition, noise produced by strum, mooring line interaction with the seabed, and mooring component rattle can be considered harassment.

6.4.3 Nearshore impact

Nearshore impact is defined as impacts associated with any developmental activities related to the installation or operation of MECs that can take place in the area between the shoreline and

the area defined as the offshore zone. Nearshore impacts can have unintended consequences that can be financial, environmental, or societal. Nearshore impacts may include but are not limited to the following, listed in Table 1.

Table 1 – Potential nearshore impacts

Impact type	Description of impact
Noise	Noise generated during installation, recovery, or other operations involving the mooring system that can disturb marine life
Proximity	Dredging operations in coastal zones can disrupt MEC moorings or umbilical systems

6.4.4 Vandalism and misuse

Vandalism is the deliberate defacement, destruction, or theft of an existing MEC mooring system or mooring components. The misuse of floating structures as temporary tie-off buoys for sport and commercial vessels is common in nearshore areas. Accessibility of mooring components and connections should be considered.

6.4.5 Marine traffic

The type and frequency of other marine traffic traversing the site should be considered. For example, local or commercial fishing vessels can accidentally entangle in the MEC mooring system that could lead to failure. In addition, any restriction within the water column to mooring line components with regards to safe keel clearance regardless of limit state shall be considered. A notice to mariners should be filed with the applicable regional authority and nautical charts updated to reflect the location of the MEC and associated moorings.

6.4.6 Shallow water conditions

Synthetic ropes may contact the seabed during operations and installation if appropriately designed. Synthetic ropes should use protective jacket designs that have been tested and verified for specific conditions of sharp rocks or other features that could potentially cause damage to the lines.

7 Design load cases

7.1 General

Each mooring design will be a function of the site specific environmental conditions and specific MEC characteristics. Determining the mooring design that satisfies the limit states may not be obvious and may require an iterative process. Static, quasi-static, and dynamic analysis procedures can apply in the process.

The following subclauses elaborate on specific considerations for mooring design for MECs as well as clarifying analysis procedures and load cases.

7.2 Analysis procedure overview

The various limit states, ULS, ALS, FLS, and SLS, and associated load cases define the minimum set of criteria the mooring design shall satisfy. A recommended analysis procedure is summarized by the flow chart seen in Figure 1. This is the recommended procedure but is not necessarily the procedure that shall be used for design. This procedure is based on similar processes presented in IEC TS 62600-2:2019 and ISO 19901-7:2013. This procedure can be summarized as follows:

a) Determine site specific metocean and external conditions for the location.

b) Establish a conceptual mooring pattern. Properties of the mooring components shall be established. Mooring pretension should be considered including impacts due to water level variations and achievable installation tolerance.

c) Determine external loads on the mooring and MEC due to metocean and external conditions.

d) Complete an analytical or static analysis using mean environmental loading to allow rapid initial iteration on mooring components, pretensions, and mooring envelope. Iterate and modify the mooring design as needed.

e) Perform a dynamic analysis on the mooring system for each of the limit states considered.

f) If the resulting design criteria for any limit state are not satisfied, iterate on the mooring design concept or restart the process with a new mooring design concept.
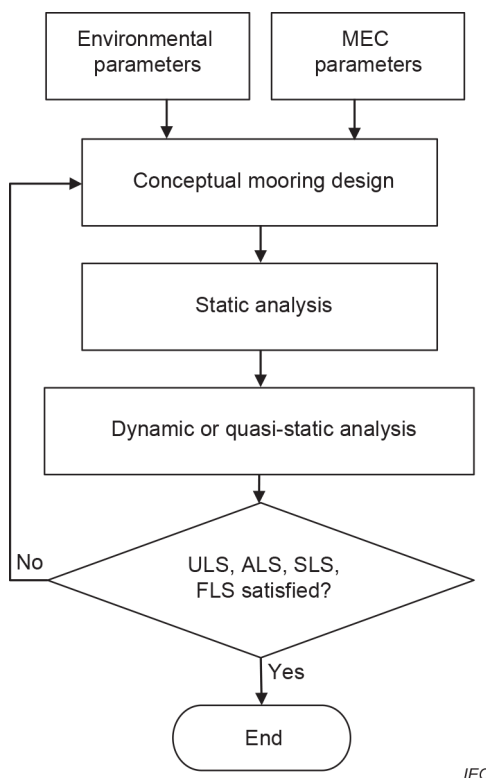
Figure 1 – Recommended conceptual mooring analysis procedure

7.3   Load categories

7.3.1   General

Environmental loads listed in IEC TS 62600-2:2019,7.2, and the effects described in this clause, shall be considered, unless they can be shown to have either no significant effect or are not applicable to the deployment site, in assessing the combined MEC system and mooring response. Further discussion on these environmental load types are discussed here. A range of possible combined loads may result:

a) Low frequency current, wind and wave drift loads.

b) Wave frequency loading.

c) High frequency VIV, seismic, PTO, ice and ship impact.

The combined assorted loadings, including those from winds, currents, and waves, on the MEC and mooring system are required to determine the motion response and mooring loads. The assorted loadings may be determined by relevant analytical, numerical, or experimental methods. Some loading can only be determined through the use of experimental methods or specialized software. Interaction between and directionality of wind, current, and waves shall be examined.

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7.3.2   Dynamic analysis of MEC response to environmental conditions

In comparison to static and quasi-static modelling, dynamic modelling considers the acceleration and velocity of all components in the system. Inertia, damping, and stiffness of the MEC and mooring as well as PTO effects may be incorporated in the dynamic model. Dynamic modelling may be coupled or uncoupled and performed in the frequency domain or the time domain. Time domain modelling is the preferred approach. For time domain modelling, the simulation time duration and time step should be considered such that all pertinent dynamic effects are captured. Adequate time domain simulation realizations shall be generated for each sea state to ensure consistent statistics of extreme peak responses. The frequency domain analysis may not accurately capture the peak resonance response of the system due to challenges incorporating nonlinear mooring response and loading effects in this technique.

Analysis techniques that can be shown to be more conservative than accepted time domain techniques may be used to evaluate the design load cases. Alternative analysis techniques or equivalent experimental evaluation of the defined load cases may be considered if the environmental effects cannot be practically evaluated by accepted time domain techniques.

Additional information on numerical modelling of these effects for mooring system design can be seen in Annex C.

7.3.3   Low frequency loads

7.3.3.1   Mean current and wind loads on mooring components

The effect of current actions on mooring lines and umbilical cables shall be evaluated. Actions on these entities due to currents can be calculated as a drag force.

7.3.3.2   Mean current and wind loads on MECs

As a guideline, the mean wind and current loading can be estimated with a drag force approximation.

7.3.3.3   Mean wave drift loads on MECs

The mean wave drift load is a time average load that arises from the effects such as but not limited to reflection of ocean waves on the floating MEC hull.

7.3.3.4   Low frequency wind, current, and wave loads on the MEC

The wave drift force can vary at low frequencies and can have effects proportional to the difference between frequencies of waves present in the spectrum. The geometry of the MEC can interact with prevailing wind direction to produce low frequency loading. The motion of the MEC and mooring system can also interact with prevailing current direction to produce low frequency loads. If the MEC mooring system has any low natural frequency, large motions and mooring loads can result. For example, in existing floating structure systems, low frequency yaw motions can result with a single point mooring system.

7.3.4   Wave frequency loads on mooring components

Wave frequency loading on mooring components are a function of wave orbital velocities and accelerations and may cause dynamic loading on the mooring system.

7.3.5   Wave frequency loads on MEC

If the MEC geometry is large relative to the ocean wavelengths present, wave radiation and diffraction loading will have a significant influence on the MEC motion and mooring system response.

7.3.6 High frequency loading

7.3.6.1 Turbulence

Turbulence in high flow tidal zones may induce high frequency loading directly on the mooring lines or via the PTO response of the system. The implications for ultimate loads and fatigue life of the mooring lines should be assessed if there is significant turbulence in the flow at the site.

7.3.6.2 Vortex induced vibrations of mooring system and vortex induced motions of MECs

For mooring lines and umbilicals, the possibility of vortex induced vibrations (VIV) in areas with prevailing current should be considered due to potential impact on fatigue life. Fatigue life from direct VIV flexural vibration is mainly a concern at discontinuities such as connectors like sockets. Mooring lines with socket connections or other discontinuities should be assessed for fatigue life effects. Vortex induced motions (VIM) of the MEC with mooring system should be investigated.

Commercial software tools are available to evaluate VIV and VIM for certain offshore oil and gas systems but not necessarily for MEC technologies and their moorings. However, their applicability to MEC systems may be considered. Additional guidance on the effect of VIV and VIM can be found in DNVGL RP C205.

7.3.6.3 High frequency wave loads

Loading proportional to the sum of the frequencies of waves present in the spectrum can exist and should be considered in determining the response of systems with high natural frequencies.

7.3.6.4 MEC PTO response

The PTO system may have a significant influence on the dynamic response of the MEC and mooring system. The dynamic loading from the PTO on the system shall be considered.

7.4 Interaction with waves, currents, wind, water level and ice

7.4.1 General

If there is no other project site information available about the combination of the extreme environmental conditions, the return periods as stated in Table 2 can be used to derive environmental combinations for a 50 year return period.

Wind, wave, and current heading may be applied in co-linear fashion. However, depending on site-specific conditions or specific MEC characteristics, the combination of wind, wave, and current headings consistent with the metocean conditions at the site that results in the most severe response and mooring loads should be considered.

Note environmental combination ID 6 has a significantly different return period compared to the other conditions. The purpose of this combination is a robustness check to detect disproportionately large load increases. For example, in semi-submersible platforms, wave loads on the bottom surface of the deck will significantly increase loads on the system. These kinds of abrupt nonlinear increases in the nature of loads on the system can cause catastrophic failures. Environmental combination ID 6 has a significantly lower probability than 50 year return period because it is intended as an check for abnormal conditions. It is not intended to replicate the effect of extreme events such as a hurricane or tropical cyclone. A project site that may be susceptible to hurricane or tropical cyclone conditions may observe a coefficient of variation greater than 15 % in annual environmental condition maximums. Extra care should be used to ensure that the 500 year return period conditions are not unduly influenced by large variations in annual recorded maximums for a project site from extreme environmental hurricane and tropical storms.

Table 2 – Combinations of uncorrelated extreme events

Environmental combination ID	Environmental event and return period (years) to define characteristic value of corresponding load effect					
	Waves	Current	Water level	Wind	Ice	Dominating event
1	50	5	50	5	–	Ground swell
2	5	50	50	5	–	Sea currents
3	–	5	NWLR	5	50	Sea ice
4	50	5	50	50	–	Wind swell
5	-	50	50	5	-	River current
6	500	5	NWLR	500	-	Wind swell

7.4.2 Resonant response

Due to the potential complexity of MEC dynamic response, the environmental conditions that produce the most extreme response and mooring loads may not be obvious and may even be counter-intuitive.

A screening process should be performed to determine whether a particular wave period, which may be less than that associated with extreme conditions, generates the highest loads. Note that to maintain the environmental even return period, the associated wave height should be adapted for each associated wave period. This may be near MEC resonance in various degrees of freedom. Some WEC designs will resonate at specific wave periods and should be considered specifically.

7.4.3 Design return period for short term deployments

A short term deployment is significantly less than a typical MEC design service life. Short term deployments are intended to facilitate technology development and evaluation. Short term deployments may use a return period equal to 5 times the short term deployment life, with a minimum of 5 year return period and maximum of 50 year return period that corresponds to full design service life. These are intended as minimum requirements. The designer shall consider failure mode and effects when considering the environmental return period. Additional failure modes and effects analysis can be assessed using guidance from IEC 60812.

7.5 Mooring line components

7.5.1 General

Examples of mooring component types can be seen in Annex A. More detailed guidance is included for fibre ropes in Annex A.

7.5.2 Component strength

The minimum breaking load (MBL) of components can be provided by supplier technical specification sheets or from experimental measurements. Consideration should be given to flexural and chaffing effects of mooring components on MEC surfaces. As mooring line components wear, corrode, and fatigue, the MBL of the line components will decrease. Consequently, the reduction in MBL during the system's design life should be considered during the design of the mooring system otherwise planned replacement of the affected components may be required during the design life. The expected break strength of the components at the end of life should be used in the mooring analysis.

The dynamic MEC motion and consequent complex mooring interaction may require special consideration of selection of mooring components.

7.5.3 Component fatigue life

The fatigue damage accumulated in mooring components is the result of cyclic loading. Specific guidance for determining fatigue life can be found in Clause A.9 of ISO 19901-7:2013. However, an increased factor of safety fatigue life may be used to account for various factors such as inaccessibility of components for inspection, site specific environmental loading and unique PTO operational characteristics.

7.5.4 Redundancy

A redundant system is able to maintain the position of the MEC and the integrity of components, such as remaining mooring lines or umbilical cable, subject to the failure of one of its components. A loss of a component may be one mooring line.

Non-redundant mooring systems shall have special consideration to address ALS assessments. Moorings without sufficient redundancy are not always single point moorings. Non-redundant moorings shall not evaluate ALS design load cases involving a failed mooring line. However, non-redundancy shall be addressed through a safety factor larger than consequence class 2. The degree of increase of safety factor should be in accordance with a failure modes and effect analysis study. Failure modes and effects analysis can be assessed using guidance from IEC 60812.

7.5.5 Clearance

Contact between mooring lines and other mooring lines, the umbilical, the MEC and adjacent structures in all limit states shall be avoided. The required clearance can be determined on a case by case basis, but the minimum value should be considered on the basis of consequences of impact. Clearances should include consideration of the effect of marine growth accumulation. For locations sensitive to bottom disturbance by normal mooring motion and operating conditions, the mooring lines may need to be clear of contact from the seabed.

7.6 Umbilical considerations

7.6.1 Umbilical response

The umbilical is intended to carry a fluid or electrical power or both between the MEC and another location. A key output of the mooring analysis is the offset of the MEC for input to the design of the umbilical. The design of the mooring and umbilical may require an iterative approach to determine a suitable configuration for both items.

7.6.2 Umbilical strength

The umbilical strength and allowable bending radius should be provided by the manufacturer. Specific consideration shall be given to reduce stress concentration at umbilical termination or other areas of high curvature. Fatigue due to the dynamic motion responses should be carefully considered during the design of the umbilical lay-up and configuration.

7.6.3 Umbilical offset and clearance limits

The offset due to MEC movement in all limit state conditions shall be considered. The clearance between the umbilical and the mooring lines, seabed, MEC, and other potential hazards shall be considered.

The effect of the umbilical during ALS conditions shall be considered. ALS condition load cases may incur large MEC offsets, particularly for non-redundant systems, and may cause significant damage.

The installation and hook-up of umbilicals should be planned in consideration of any mooring, jack leg deployment, or live manoeuvring required by any maintenance or installation vessels.

Active control systems that can control mooring loads through PTO response or other mechanisms may be used to limit offsets of the system; however, consideration should be given to fault states of that control system that may result in larger excursions.

7.7 Limit states

7.7.1 General

The performance of a MEC with mooring system shall be described with reference to a specified set of limit states beyond which the MEC no longer satisfies design requirements. The following limit states shall be considered. Specific design load cases associated with each limit state to be considered are specified in Table 7 and Table 8.

7.7.2 Ultimate limit state (ULS)

This limit state corresponds to the intact mooring system's resistance to extreme expected actions, such as those arising from design environmental events. Consideration for the ULS shall be made to determine whether the extreme response corresponds to the MEC configured in survival or operational mode. The ULS for some MECs may occur at lower current or wave conditions than the extreme sea state or current 50-year return period level.

7.7.3 Accidental limit state (ALS)

The purpose of this limit state is to ensure the system can survive low probability events. Consideration for the ALS shall be made to determine whether the extreme response corresponds to the MEC configured in survival or operational mode.

For short term deployments of less than 1 year, the ALS may not be necessarily evaluated. The designer shall consider failure mode and effects when considering the consideration of evaluation of FLS. Additional failure modes and effects analysis can be assessed using guidance from IEC 60812.

7.7.4 Serviceability limit state (SLS)

This limit state represents mooring system installation, MEC installation and connection with mooring system, and operation and maintenance modes of the MEC. The effect on mooring components from commissioning, decommissioning, and delivery of MECs should be considered. If the duration of time the MEC is not connected is considerable, more detailed analysis of the mooring system in this configuration may be necessary.

7.7.5 Fatigue limit state (FLS)

The fatigue limit state refers to cumulative damage in the system components of the MEC due to environmental cyclical action. Consideration of the effect of the PTO on the FLS shall be made for those occurrences that are associated with the PTO being active. Consideration should be given to additional fatigue that could occur during periods of PTO fault. Guidance for various procedures to evaluate fatigue life can be found in Clause A.9 of ISO 19901-7:2013. This guidance includes information for the effect of mean tension on wire rope and chain components in calculating fatigue life. The effect of mean tension load on synthetic rope materials is significantly lower than metal components like wire and chain. The exception is some synthetic rope materials, such as aramids and LCAP, are susceptible to compression fatigue from low mean tension or slack events and shall be considered.

Fatigue life calculations should include damage expected in all conditions representative of the long term statistical occurrences of the local environment inclusive of both normal and extreme conditions expected during the duration of the deployment.

For short term deployments of less than 1 year, the FLS may not be necessarily evaluated. The designer shall consider failure mode and effects when considering the consideration of

evaluation of FLS. Additional failure modes and effects analysis can be assessed using guidance from IEC 60812.

7.7.6   Consequence class safety factors

The corresponding safety factors (SF) to be used for each consequence class are listed in Table 3. The SF are used to determine acceptable mooring line components. The consequence classes are defined in Clause B.5.

Table 3 – Consequence class associated safety factors for dynamic analysis techniques

Consequence class	ULS	ALS	SLS, FLS
2	2,2	1,25	1,0
1	1,67	1,25	1,0

Safety factors are a function of fundamental inherent uncertainties. Sources of uncertainty may include limitations of dynamic analysis techniques used to predict response of the system. Quasi-static and quasi-dynamic analysis may be used for preliminary analysis of permanent moorings only. Final permanent mooring installations shall be designed using dynamic analysis methods and corresponding safety factors.

Some MEC mooring systems may not incur significant accelerations. In these cases, a quasi-static or quasi-dynamic approach may be used if it can be shown, without significant correction factors, to produce consistent results to a dynamic model equivalent.

The fatigue life calculated from the results of FLS may be assessed using the process outlined in ISO 19901-7. Note the corresponding associated safety factor specified in ISO 19901-7 is applied to the fatigue life calculation and not to loads produced by the analysis process.

7.7.7   Mooring component failure

For each case to be studied, acceptable mooring component strength is achieved when the following relationships are satisfied:

$$\text{MBL / Design tension} > \text{SF} \qquad (1)$$

The tension is based on the Most Probable Maximum (MPM) dynamic tension. Guidance on computing the MPM may be found in Coles, 2001. Each design load case (DLC) specified is part of an associated limit state: ULS, SLS, ALS, FLS. The associated safety factor from Table 3 shall be applied in each case. The MBL associated with the expected corroded component size, if applicable, shall be used when assessing the strength criteria. Other degradation mechanisms (wear, abrasion, etc.) should be considered and appropriate component strength reductions incorporated to account for the condition at the end of life.

7.7.8   Anchor holding capacity

The holding capacity of anchors depends on sediment conditions and performance characteristics of the anchor. Safety factors for different anchor types are listed in Table 4, Table 5 and Table 6. If the anchor holding capacity is characterized at or near the intended site, or in a site with similar seabed conditions, and the mooring loads are well characterized with low uncertainty in ALS conditions, a minimum safety factor of 1 may be used. However, the nature of the failure mode of the anchor type should be considered when selecting the safety factor. Additional failure modes and effects analysis can be assessed using guidance from IEC 60812. Acceptable anchor holding capacity is achieved when the following relationship is satisfied:

$$\text{Anchor holding capacity / Design tension at anchor} > SF \qquad (2)$$

Safety factors indicated are generally for use with consequence class 1. For consequence class 2, higher safety factor should be used.

Short term deployments may use lower safety factors as indicated in Table 4. More information on short term deployments is in 7.4.3. The designer shall consider failure mode and effects when considering the safety factors. Additional failure modes and effects analysis can be assessed using guidance from IEC 60812.

Table 4 – Safety factors for holding capacity of drag anchors

Conditions	Minimum safety factor
Parmanent: Intact condition	1,5
Permanent: Redundancy check	1,0
Short term: Intact condition	1,0
Short term: Redundancy check	Not required

Table 5 – Safety factors for holding capacity of anchor piles and suction piles

Analysis condition	Permanent mooring		Short term deployment mooring	
	Vertical loading	Lateral loading	Vertical loading	Lateral loading
Intact condition	2,00	1,60	1,50	1,20
Redundancy check	1,50	1,20	1,20	1,00

Table 6 – Safety factors for holding capacity of gravity and plate anchors

Analysis condition	Gravity anchors				Plate anchors	
	Permanent mooring		Short term deployment mooring		Permanent mooring	Short term deployment mooring
	Vertical	Lateral	Vertical	Lateral		
Intact condition	2,00	1,60	1,50	1,20	2,00	1,50
Redundancy check	1,50	1,20	1,20	1,00	1,50	1,20

7.7.9 Load case modelling and simulation

Once a set of load cases has been defined, a numerical model or experimental test can be utilized to determine characteristic loads. Numerical simulations and experiments shall have the ability to model devices that are comprised of rigid bodies, power-takeoff (PTO) systems, mooring systems and the dynamic cable or umbilical as applicable. Simulations shall be performed by solving the governing MEC equations of motion in at least six degrees-of-freedom as applicable. Time domain analysis is the preferred technique. Frequency domain techniques can be used for mooring design if they can be shown to produce similar results to an equivalent time domain model or physical experiment responses.

When dynamic simulations or tests are used, the total period of load data for these cases shall be long enough to ensure statistical reliability of the estimated characteristic load effect. Multiple realizations shall be used only on ULS, SLS, or ALS DLC that significantly drive the mooring design. FLS cases should use single differing realizations for each environment considered.

– For load cases in the ULS categories for CECs (e.g., power production), at least six 10 min stochastic realizations are recommended for each mean current speed considered in the simulations. Constrained wave methods may be used for this purpose.

– For load cases in the ULS categories for WECs, at least six 3 h stochastic realizations shall be required for each sea state considered in the simulations. This requirement may be relaxed and shorter realizations may be used if the designer is able to demonstrate that the estimated extreme response is more conservative than that obtained with 3 h realizations. Guidance on estimating extreme response can be seen in Coles, 2001. Constrained wave methods may be used for this purpose.

– For ALS and transient load cases for MECs (e.g. stopping procedures) at least six 10 min simulations shall be carried out for each event at the given current speed and/or sea state. Transient load cases associated with PTO start or stop are not required if it can be shown the transient effect has no significant impact on the resulting mooring system loads.

7.7.10 Design conditions

7.7.10.1 General

Safety factors are based on the consequence class and associated limit states in the load case matrix Table 7 and Table 8. The load case matrix listed is adopted from IEC TS 62600-2:2019. The intent is that where applicable, load cases for general design requirements are evaluated in tandem with mooring system requirements. For each set of design conditions (normal operation, parked, fault, etc.), design load cases are defined. For each of these design load cases, limit states for consideration and environmental conditions are defined. Additional load cases specific to the mooring system and out of scope of IEC TS 62600-2:2019 are appended to Table 7 and Table 8.

Table 7 and Table 8 define a basic set of relevant design load cases for WEC and CEC mooring systems, respectively. Load cases that do not apply to the specific MEC shall not be evaluated. Furthermore, management and control strategies may be employed to reduce risk and therefore the associated design load cases do not apply and shall not be evaluated. Single fault conditions of the control system should be considered if relied upon. For example, a mooring disconnect system to avoid ice impact loads on the MEC as a management strategy would not require ice design load cases to be evaluated. However, if other realistic combinations lead to more severe loading, these shall also be considered. The basic set of design load cases is intended to identify and isolate design driving load cases. Load cases that can be shown to have no significant effect on the mooring system may not necessarily be evaluated.

The environmental conditions in Table 7 and Table 8 may be represented by a set of discrete values provided that the resolution is sufficient to assure accuracy of the calculation. In the definition of the design load cases, reference is made to the environmental conditions described in Clause 6.

In all design conditions, the designer shall ensure that the number and resolution of the normal and extreme sea states considered are sufficient to account for the fatigue damage associated with the long-term distribution of metocean parameters. Fatigue damage associated with extreme sea states can be significant for metal components such as chain, wire, connectors, and shall be included in fatigue damage calculations. The fatigue damage to synthetic rope in extreme sea states is significantly lower than metal components. The impact on fatigue life for synthetic rope may be ignored if it can be showed to be negligible for the particular synthetic rope considered.

7.7.10.2 Normal operation (DLC 1.1 to 1.3)

In this design condition, the MEC is in operation and connected to the electrical grid. The assumed MEC configuration shall take into account any imbalance of the PTO unit, where relevant. The maximum mass and hydrodynamic imbalances specified for manufacture shall be used in the design calculations.

In addition, deviations from theoretical optimum operating conditions, such as orientation errors (e.g. for tidal energy converters) control system delays, and pre-tension tolerances shall be taken into account in the analyses of operational loads.

This design condition includes loads resulting from wave loading and hydrodynamic turbulence (currents). Operational sea state (NSS) conditions shall be assumed for WECs and the turbulent current model (NTM) shall be considered for CECs.

For DLC 1.1, the significant wave height, peak spectral period and direction for each normal sea state shall be selected, together with the associated mean current speed, based on the long-term joint probability distribution of metocean parameters appropriate to the anticipated site (typically represented with an annual scatter diagram). Peak loading in the mooring system may occur in conditions with waves and no mean current or mean wind loading and should be considered.

Mean tension in the moorings may contribute significantly to fatigue life effects, especially for CECs. The FLS calculations shall account for the effect of mean tension as well as pre-tension imbalance due to reasonable installation constraints in metal mooring components, including chain, wire rope, connectors, etc. The effect of low mean tension or slack conditions may require consideration for compression fatigue evaluation for certain synthetic ropes including aramids and LCAP. However, the effect of mean tension in FLS calculations for synthetic rope can be ignored.

For DLC 1.2 (CECs), the significant wave height and peak spectral period for the maximum permitted normal sea state during power production shall be selected. Wave direction shall be varied from 0° to 360° in 30° steps. The worst case loading may not resolve in 30° step increments. Load cases with applicable wave directions in alignment with, and in between, mooring lines should be considered.

DLC 1.3 (CECs) embodies the requirements for maximum loading resulting from extreme turbulence conditions.

Table 7 – Design load cases for WECs

Design condition	DLC	Limit state	Wave conditions	Current conditions	Water level	Other conditions
1) Normal operation	1.1	ULS FLS SLS	OSS $H_{m0} = H_{rated}$	OCM $U = U_1$	NWLR	
	Ice	ULS FLS	No waves	OCM $U_{in} \le U \le U_{out}$	NWLR	Ice
2) Normal operation with fault	2.1	ULS FLS SLS	NWH $H_{m0} = H_{rated}$	OCM $U = U_1$	NWLR	Grid loss, grid failure, or fault in controller
3) Start procedures	3.1	ULS FLS SLS	NWH $H_{m0} = H_{rated}$	OCM $U = U_1$	NWLR	
4) Normal shut down procedures	4.1	ULS FLS SLS	NWH $H_{m0} = H_{rated}$	OCM $U = U_1$	NWLR	
5) Emergency shut-down procedures	5.1	ULS SLS	NWH $H_{m0} = H_{rated}$	OCM $U = U_1$	NWLR	
6) Parked/survival conditions	6.1	ULS FLS SLS	ESS $H_{m0} = H_{m50}$	ECM $U = U_5$	EWLR	Wind: EWM $(V = V_5)$
	6.2	ALS SLS	ESS $H_{m0} = H_{m50}$	ECM $U = U_5$	EWLR	Wind: EWM $(V = V_5)$ Grid loss
	6.3	ULS FLS SLS	OSS $H_{m0} = H_{rated}$	OCM $U = U_1$	NWLR	
	Ice	ULS	ESS $H_{m0} = H_{m50}$	ECM $U = U_5$	NWLR	Ice: $h = h_{50}$
7) Parked plus occurrence of fault	7.1	ULS FLS	ESS $H_{m0} = H_{m1}$	ECM $U = U_1$	EWLR	Wind: EWM $(V = V_1)$

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Design condition	DLC	Limit state	Wave conditions	Current conditions	Water level	Other conditions
8) Transport, installation and maintenance	8.1	ULS SLS	To be specified by the manufacturer			
	8.2	ULS SLS	ECM U = mean spring] flood, ebb, OE	ESS $H = H_{m1}$ 30° steps	EWLR	Locked state
	9.1	ALS	ESS $H_{m0} = H_{m500}$	ECM $U = U_5$	NWLR	Wind: EWM $(V = V_{500})$ intact mooring
9) Mooring	9.2	ALS	ESS $H_{m0} = H_{m50}$	ECM $U = U_5$	NWLR	Wind: EWM $(V = V_5)$ damaged stability

The following abbreviations from IEC TS 62600-2:2019 are used in Table 7:

ECM   extreme current model

ESS   extreme stochastic sea state

ETM   extreme turbulent current model

EWH   extreme steady wave height

EWM   extreme steady wind model

EWLR   extreme water level range

OSS   operational sea state

NTM   normal turbulent current model

OWH   operational wave height

NWLR   normal water level range

Table 8 – Design load cases for CECs

Design condition	DLC	Limit state	Current conditions	Wave conditions	Water level	Other conditions
1) Normal operation	1.1	ULS FLS SLS	NTM $U_{in} \leq U \leq U_{out}$ flood, ebb, OE	OSS $H = H_{m0}$	MTL ± Mean Range	
	1.2	ULS SLS	NTM $U_{in} \leq U \leq U_{out}$ flood, ebb, OE	OSS $H = H_{m0,out}$ Wave direction 0° to 360° in 30° steps	MTL ± Mean Range	
	1.3	ULS SLS	ETM $U_{in} \leq U \leq U_{out}$ flood, ebb, OE	OSS $H = H_{m0}$	MTL ± Mean Range	
2) Normal operation with fault	2.1	ULS FLS SLS	OCM or NTM $U_{rated} \leq U \leq U_{out}$ flood, ebb, OE	NWH $H = H_{m1}$ Worst direction from DLC 1.2	MTL ± Mean Range	Grid loss, grid failure, fault in controller, i.e. faults triggering the control system
	2.2	ULS SLS	OCM or NTM $U_{rated} \leq U \leq U_{out}$ flood, ebb, OE	NWH $H = H_{m1}$ Worst direction from DLC 1.2	MTL ± Mean Range	Safety system relevant faults, short circuit, brake failure
	2.3	ALS	OCM or NTM $U_{rated} \leq U \leq U_{out}$ flood, ebb, OE	NWH $H = H_{m1}$ Worst direction from DLC 1.2	MTL ± Mean Range	Accidental faults

Design condition	DLC	Limit state	Current conditions	Wave conditions	Water level	Other conditions
3) Start procedures	3.1	ULS FLS SLS	OCM or NTM $U_{rated} \leq U \leq U_{out}$ flood, ebb, OE	NWH $H = H_{m1}$ Worst direction from DLC 1.2	MTL ± Mean Range	CEC undergoing start-up
	3.2	ULS SLS	OCM or NTM $U_{rated} \leq U \leq U_{out}$ flood, ebb, OE	NWH $H = H_{m0,out}$ Worst direction from DLC 1.2	MTL ± Mean Range	
4) Normal shut-down procedures	4.1	ULS FLS SLS	OCM or NTM $U_{rated} \leq U \leq U_{out}$ flood, ebb, OE	NWH $H = H_{m1}$ Worst direction from DLC 1.2	MTL ± Mean Range	CEC undergoing shut-down
	4.2	ULS SLS	OCM or NTM $U_{rated} \leq U \leq U_{out}$ flood, ebb, OE	NWH $H = H_{m0,out}$ Worst direction from DLC 1.2	MTL ± Mean Range	
5) Emergency shut-down procedures	5.1	ULS SLS	OCM or NTM $U_{rated} \leq U \leq U_{out}$ flood, ebb, OE	NWH $H = H_{m1}$ Worst direction from DLC 1.2	MTL ± Mean Range	TEC undergoing emergency shut-down, rapid shut-down, etc.

Design condition	DLC	Limit state	Current conditions	Wave conditions	Water level	Other conditions
6) Parked/ survival conditions	6.1a	ULS SLS	ECM; U = peak spring; flood, ebb, OE	ESS; H = H_{m5}; most probable direction(s)	EWLR	Wind: EWM ($V=V_5$)
	6.1b	ULS SLS	ECM; U = peak spring; flood, ebb, OE	ESS; H = H_{m50}; most probable direction(s)	EWLR	Wind: EWM ($V=V_{50}$)
	6.2	ULS SLS	worst combination of current and wave from DLC 6.1a and 6.1b; $U \leq U_{in}$, $U_{out} \leq U$; flood, ebb, OE	worst combination of current and wave from DLC 6.1a and 6.1b; H = H_{m0}	EWLR	Wind: EWM ($V=V_5$); Grid loss; for CEC with yaw system
7) Parked with fault	7.1	ULS SLS	ETM; U = mean spring; worst direction from DLC 6.1	ESS; H = H_{m1}; worst direction from DLC 6.1a	EWLR	Wind: EWM ($V=V_1$)
	7.2	ULS FLS SLS	NTM; $U_{in} \leq U \leq U_{out}$; flood, ebb, OE	NWH; H = H_{m1}	associated tidal height	grid loss
8) Transport, installation and maintenance	8.1	ULS SLS	To be specified by the manufacturer			
	8.2	ULS SLS	ECM; U = mean spring$_1$; flood, ebb, OE	ESS; H = H_{m1}; 30° steps	EWLR	Locked state

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Design condition	DLC	Limit state	Current conditions	Wave conditions	Water level	Other conditions
9) Mooring	9.1	ALS	ECM $U = U_{500}$	ESS $H_{m0} = H_{m5}$	NWLR	Wind: EWM ($V = V_5$) intact mooring
	9.2	ALS	$U = U_5$	$H_{m0} = H_{m500}$		Wind: EWM ($V = V_{500}$)
	9.3	ALS	ESS $H_{m0} = H_{m50}$	ECM $U = U_5$	NWLR	Wind: EWM ($V = V_5$) damaged stability

The following abbreviations from IEC TS 62600-2:2019 are used in Table 8:

ESS   extreme stochastic sea state

ETM   extreme turbulent current model

EWH   extreme steady wave height

EWM   extreme steady wind model

EWLR   extreme water level range

OCM   normal steady current model

ECM   extreme current model

OSS   operational sea state

NTM   normal turbulent current model

OWH   operational wave height

NWLR   normal water level range

OE   maximum allowable orientation error

7.7.10.3   Normal operation with fault (DLC 2.1 to 2.3)

Any fault in the control system (including control induced failures that lead to uncontrolled excitations) as well as faults causing trigger of the safety system or any fault in the PTO unit (e.g. generator short circuit in electrical systems) that is significant to the MEC loading shall be assumed to occur during power production. It may be assumed that independent faults do not occur simultaneously.

For DLC 2.1, the occurrence of a fault in the control system shall be analysed. Exceedance of the limiting values of the control system (over-speed, stroke length limitation, etc.) shall be investigated.

For DLC 2.2, the occurrence of faults triggering the safety system or faults in the PTO that are considered to be rare events shall be analysed. Exceedance of the limiting values for the safety system (over-speed, stroke length limitation, overpower, short circuit, vibrations, shock, runaway of the blade pitch, failure of a braking system, etc.) shall be investigated.

If a fault causes an immediate shut-down or the consequent loading can lead to significant fatigue damage, the probable number of shut-downs and the duration of this extraordinary design condition shall be considered.

For DLC 2.3, accidental events are considered.

7.7.10.4   Start-up (DLC 3.1 to 3.2)

This design condition includes all events resulting in loads on the MEC mooring system during the transitions from any standstill or idling condition to power production.

For all start-up and shutdown procedures, the probable number of events shall be considered. Normal sea state (NSS) conditions shall be assumed for WECs and the turbulent current model (NTM) shall be considered for CECs. The significant wave height, peak spectral period and direction for each normal sea state shall be selected, together with the associated mean current speed, based on the long-term joint probability distribution of metocean parameters appropriate to the anticipated site.

7.7.10.5   Normal shut-down (DLC 4.1 to 4.2)

This design condition includes all the events resulting in loads on the MEC mooring system during normal transitions from power production to a stand-by condition (standstill or idling).

If applicable, further shutdown procedures shall be taken into account due to site-specific requirements, such as shadow criteria or conditions for installation within a MEC array (curtailment strategy).

7.7.10.6   Emergency shut-down (DLC 5.1)

This design condition covers manual actuation of the emergency shutdown system. For this load case, the PTO unit shall be brought to a standstill (or idling in case of MECs without braking devices).

7.7.10.7   Parked during survival conditions (DLC 6.1 to 6.2)

For this design condition, the PTO is in standstill or idling mode. For some designs, the MEC may be operational and connected to the electrical grid. Extreme environmental conditions with a return period of at least 50 years shall be considered for this design condition.

Either the steady current model or the turbulent current model shall be used. If the steady current model is used, the appropriate correction to the current speed may be considered to account for the effect of turbulence.

Additionally, either regular waves and/or irregular sea state shall be considered where appropriate.

Stochastic waves are recommended for global hydrodynamic loads and motions, with the appropriate control and PTO settings. Regular waves are more appropriate for specific phenomena, such as slamming and wave breaking.

The 50-year return period of the significant wave height for WECs and the 50-year return period of the mean current speed for the CECs shall be considered. For some MECs a lesser environment may result in higher loading. Conditions up to the 50 year environment should be screened to confirm the controlling conditions.

7.7.10.8 Parked during normal conditions (DLC 6.3)

For this design condition, the PTO unit is in stand-by mode (standstill or idling) in normal environmental conditions.

Irregular sea state conditions shall be assumed. The significant wave height, peak spectral period and direction for each normal sea state shall be selected, together with the associated mean current speed, based on the long-term joint probability distribution of metocean parameters appropriate to the anticipated site. The designer shall ensure that the number and resolution of the normal sea states considered are sufficient to account for fatigue damage associated with the long-term distribution of metocean parameters.

7.7.10.9 Parked with an idling fault (DLC 7.1 to 7.2)

This design condition considers deviations from normal behaviour of a parked MEC resulting from the occurrence of a fault in the PTO unit. If any fault produces deviations from the normal behaviour of the MEC mooring system in parked conditions, the possible consequences shall be considered. The designer shall consider parking failure, which may include the inability to park during severe conditions.

The fault condition shall be combined with extreme environmental conditions and a return period of 1 year.

If a grid failure may occur and no backup energy system or redundant electricity supply is provided, the behaviour of mechanical brakes and the safety system shall be considered in the load assumptions. The probability and the possible duration of such failures shall be investigated and considered including fatigue implications. The safety of the MEC and mooring system shall be independent of the grid.

Either a steady or turbulent current model shall be used for design conditions. If the steady current model is used, correction to the current speed may be considered to account for the effect of turbulence.

Additionally, irregular sea state shall be considered.

The 1-year return period of the significant wave height for WECs and the 1-year return period of the mean current speed for CECs shall be considered.

7.7.10.10 Transport, installation and maintenance (DLC 8.1 to 8.2)

Long periods where the MEC is not fully installed or is without grid connection shall be considered if there is any potential effect on the mooring system. The intent is to determine any effect on wear and fatigue life of the system in its incomplete commissioned state.

Installation of the mooring system itself may introduce significant loading on the components. The effect on wear and fatigue life on mooring components due to installation operations, including, but not limited to pretensioning or proof loading, shall be considered.

If mooring components are used in any towing operation, the effect on wear and fatigue life of the mooring shall be considered. Reduced survivability may be in the form of reduced fatigue life, or general component wear. Although the period to be considered shall be case-specific, a period of 3 months may be used as a guide.

7.7.10.11 Accident limit states (DLC 9.1 to 9.3)

The mooring installation process is defined in part by a finite weather window. In this finite weather window, a partial mooring configuration is established. This partial mooring configuration is the minimum mooring configuration acceptable for short term adverse weather conditions. Design load cases to evaluate the partial mooring configuration in short term adverse weather conditions shall be evaluated.

REC systems may be subject to 500 year current representing extreme river flood. The driving factor for mooring design is water level and flow speed. Debris in the 500-year flood event could be a source of additional load on the mooring system, if applicable. Engineering judgement should be used based on the MEC structural arrangement regarding additional loads that could be induced by debris accumulating on device during the extreme flood event.

TEC systems may be placed in exposed areas. The robustness check on 500 year return period wave condition shall be checked. The 500 year current may not necessarily drive design for many TEC systems but should be checked if extreme flooding is a possibility. Debris in the 500-year flood event could be a source of additional load on the mooring system, if applicable. Engineering judgement should be used based on the MEC structural arrangement regarding additional loads that could be induced by debris accumulating on device during the extreme flood event.

Damaged stability ALS cases should consider FMEA to determine appropriate load cases. This may include load cases evaluating loads in the mooring with one line removed. It may include load cases with some specific damage to the MEC device. Additional failure modes and effects analysis can be assessed using guidance from IEC 60812.

8 In-service inspection, monitoring, testing, and maintenance

8.1 General

This clause gives a brief overview for maintenance and inspection requirements. Existing standards should be considered for appropriate rigorous and complete inspection regime. Guidance for maintenance and inspection requirements may be found in API RP 2I.

Rigorous and effective inspection of mooring hardware is required because mooring failures can result from corroded or physically damaged mooring components, defective connecting hardware, or mooring components of inferior quality.

The measures to be considered in the design of a permanent mooring system to minimize component deterioration generally include means to address corrosion and bending stresses.

Suitable means to address corrosion include:

a) Cathodic protection of major components (e.g. chain, wire rope, connecting hardware, submersible buoys and anchors).

b) Sheathing of wire rope.

c) Jacketing and filtering of ropes.

d) Protective coatings.

e) Galvanization of components (in particular wire ropes).

f) Electrical bonding or isolation between dissimilar materials.

g) Oversizing and/or replacing components based on expected corrosion rates.

Suitable means to minimize bending stresses in the mooring lines:

h) Adequate sizes of bending shoes and/or fairleads.

i) Bend stiffeners near terminations.

More detailed information, including photographic examples, is available in API RP 2I.

8.2 Anchor proof loading

All anchors shall be subject to load testing after initial installation. For systems where the mooring line is attached to the anchor below the mudline, the load testing is completed to embed anchor, establish reverse catenaries through the sediment, and straighten the mooring. Loads on the anchor should be a significant portion of expected holding capacity held for 15 min. Following any substantial changes, whether by intent, environment, or accident, a further load test may be required subject to the outcome of a risk assessment. Specific test procedures for moorings can be found in 10.4.6 of ISO 19901-7:2013.

Proof loading may not be practical depending on the specific MEC. If the integrity of individual anchors can be proven in an alternative method than direct mooring proof loading, then these methods may be used. This may be particularly useful for different anchor types such as pile or rock anchors.

Synthetic ropes may not practically be able to remove new rope construction elongation before installation. If synthetic ropes are used in the mooring, the proof load procedure shall account for new rope construction elongation.

8.3 Component replacement

8.3.1 General

A specification for the inspection, inspection intervals, and discard criteria for mooring line components should be considered.

Outline procedures for the replacement of any components should be considered as part of the spares and maintenance strategy.

8.3.2 Fibre rope component inspection and replacement

For maintenance and inspection refer to ISO 9554:2019, Annex C and ISO 18692-1 2018.

8.3.3 Inspection and predictive procedures

The development of predictive procedures or non-destructive tests (NDT) to decide when synthetic ropes should be taken out of service is of primary importance. Widely available field data is lacking while extrapolation of laboratory-based models to full-scale with sufficient confidence is difficult. Moreover, available life prediction techniques still require extensive validation.

Mooring lines are subject to both short-term and long-term degradations during their service life. Short-term degradation can result from accidents, mishandling and operational problems. Long-term degradation can result from wear, fatigue, interaction with sea-water, including wetting and drying cycles, and any combination of these mechanisms. Rope manufacturers will typically provide guidelines for retirement, which may be used to cover particular aspects specific to the rope design.

For uncoated ropes the detection of some forms of short-term damage can be relatively easy by inspection, particularly for unjacketed rope because they take highly visible forms such as kinks, bends, bird cages, crushing, cork screwing and broken strands. The detection of long-term internal degradation poses the greatest challenge for inspection. This can rarely be observed externally, especially in rope designs that incorporate a jacket or may become covered in marine growth.

While some NDT techniques can detect global changes in wire rope modulus, no currently implemented technique can detect local changes in fibre rope moorings. For example, fatigue degradation limited to a 10 mr length located near the end of a 1 km line would change the global modulus by less than 1 %, but could have catastrophic consequences at the local level. Research studies have begun to investigate the use of ultrasonic and acoustic emission techniques in an attempt to address this concern. Ultrasonic techniques introduce high frequency sound waves that reflect from discontinuities while acoustic emission approaches listen for the noises made by the microscopic and macroscopic changes occurring during degradation process. At time of publication, neither of these techniques have been successfully implemented offshore.

At present, synthetic ropes cannot be easily inspected after deployment or with great accuracy because their removal for examination is a difficult operation that could cause damage to the rope. Therefore, reliance should be placed on solid design and fabrication, care in installation and visual monitoring. This means that design of permanent mooring systems should consider redundant mooring legs or establish retirement criteria by phased removal and testing of mooring line sections. Both techniques are expensive and unsatisfactory: also visual monitoring has important limitations in fibre ropes protected by opaque jackets or covered by marine growth and in any case in the inspection of terminations even when spliced.

To this end, the current objective of technological improvements is the development of efficient NDT systems able to detect and localize the initiation of rope degradation. There are past and ongoing studies using Optical Time Domain Reflectometry (ODTR) and these are showing promise as potential NDT methods (see O'Hear 2003, Gordelier *et al.*, 2020). Tracking of line usage through load monitoring, residual strength testing programs, and operations specific modeling (i.e., applied tension, time, and temperature) can be implemented to support lifecycle prediction and/or monitoring. These methods will typically be highly influenced by the specifics of the system and rope design, often requiring development in accordance with individual project efforts.

8.4 In air and splash zone mooring line sections

All mooring components and hardware that are located above water, where an interface is made with the floating structure, should be inspected visually. Deterioration from interaction with the mooring components with the MEC structure, seawater or other external effects may occur. Some examples of deterioration include corrosion, marine growth, bending fatigue failure at mooring or umbilical terminations, broken wire rope strands, and chain link wear, fatigue cracking, and loose studs.

8.5 Submerged mooring line sections

The submerged hardware, terminations, and section of mooring line that extends from the MEC to a connector within surface diving limits can be inspected using surface divers, by an ROV using an underwater video camera, or other appropriate inspection methods. The remaining sections of mooring line can be inspected using an ROV with a video camera system. The

inspections shall be recorded for later analysis and to form a baseline for assessing the degradation of the system.

In case where an ROV is not available, there should be a plan to inspect subsurface components. Where sheathed mooring lines are installed, it is not possible to determine the condition of the material beneath the sheath. The purpose of this inspection is then to verify the integrity of the sheath to ensure that it is not cracked, torn, or chafed. For electrically isolated components, the integrity of anodes should be monitored.

The entire length of chain components should be inspected to check for abrasive wear, corrosion, and missing studs, where possible.

Chain near the sea bed is subject to greater wear and abrasion due to contact. An allowance for this possibility may be made by increasing the diameter of this section of chain. Knowledge or an estimate of the corrosion or wear rate is necessary to increase the diameter of components accordingly.

In order to facilitate inspection of chain near the bottom surface, it may be necessary to apply higher tensions in the mooring line than those normally present under operating conditions.

8.6   Commissioning and decommissioning procedures

Damage during deployment and retrieval is possible unless strict procedures are followed.

The installation operations shall define the safe operating limits of the components and installation equipment, with due account for the environmental conditions and wave and tidal sites. All procedures should, wherever practical, have stopping points where the operation can be made safe in the case of, for example, tidal current strength rising above the installation limit.

The decommissioning of the mooring system shall take into account the degraded state of the mooring components and marine growth when disconnecting and recovering onboard.

Annex A
(informative)

Moorings and anchoring systems

A.1 Types of moorings and anchoring systems

A.1.1 General

This clause provides an overview of mooring and anchor types that may be used with floating MECs. Floating structure station keeping systems vary depending on the characteristics of the structure and on the environmental conditions. Single point moorings are frequently used for floating structures where greater freedom in motion is required, while spread moorings are used mostly on structures when maintaining a particular orientation is important.

The mooring components, anchor types, and sizing depend on the site requirements, design, and MEC power capture considerations.

Additional background information on mooring types are available in many resources available online for marine renewables including the Advanced Anchoring and Mooring Study 2009.

A.1.2 Mooring systems

A.1.2.1 General

Examples of existing mooring system types for floating structures are described in the following subclauses. These examples are not exhaustive.

A.1.2.2 Spread moorings (catenary, taut-line and semi-taut-line)

Spread moorings are often used when weathervaning, or rotation movement of a floating structure such that it aligns to a wind or current load so as to minimize drag loading, is not desirable. Spread moorings can incorporate chain, wire rope, synthetic rope, or various combinations of materials. Spread mooring systems may use taut, semi-taut, or catenary systems. A spread moored configuration can be seen in Figure A.1.
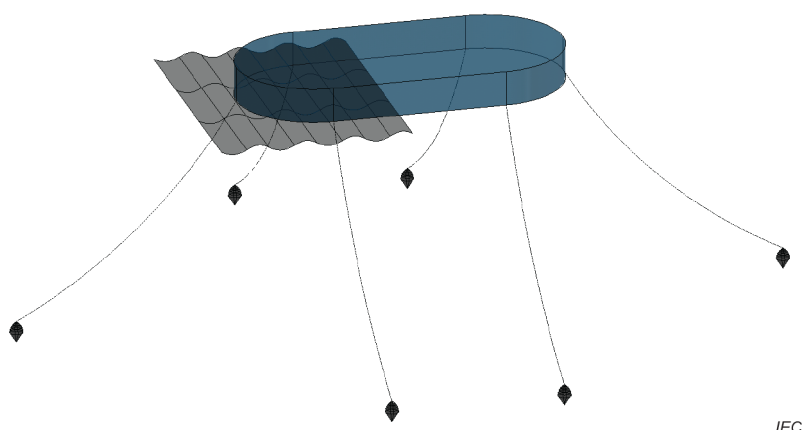

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Figure A.1 – Spread mooring configuration

A.1.2.3 Single point moorings (SPM)

Single point moorings allow floating structures to weathervane. A floating structure may directly connect to the mooring system or to an intermediary moored buoy. There is wide variety in the

design of single point moorings but they all essentially perform the same function. Examples of typical single point mooring systems are described below.

a) Catenary anchor leg mooring (CALM)

A CALM system consists of a large buoy that supports a number of catenary mooring lines. The floating structure is connected to the buoy by a single connection point as indicated in Figure A.2.
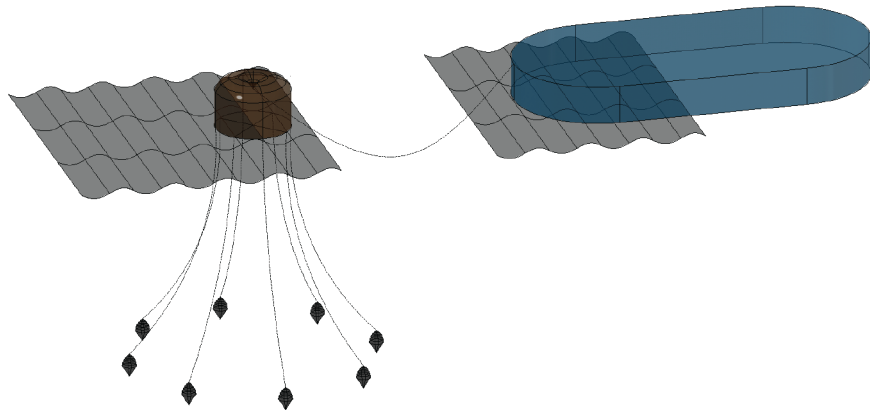

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Figure A.2 – Catenary anchor leg mooring configuration

b) Single anchor leg mooring (SALM)

A SALM system consists of a large buoy that supports a single taut vertical mooring line. The buoy floatation induces tensions that tend to restore the buoy to the vertical position. The floating structure is connected to the buoy by a single connection point as indicated in Figure A.3.
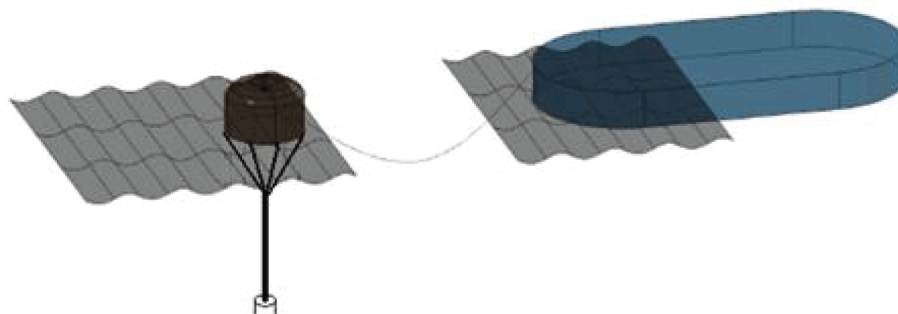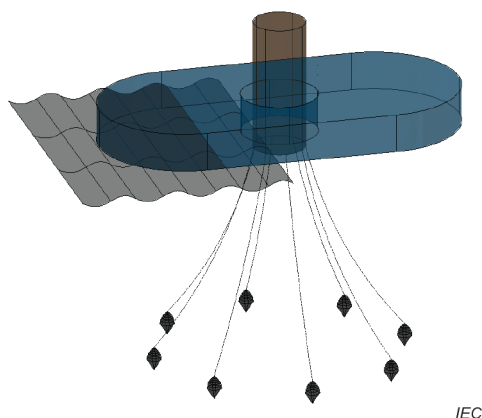

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Figure A.3 – Single anchor leg mooring configuration

c) Turret mooring

A turret mooring system consists of lines that are attached as in a CALM or SALM buoy system. The turret is attached to the floating structure via a bearing joint or other linkage that allows relative yaw motion as indicated in Figure A.4.

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Figure A.4 – Turret mooring configuration

A.2 Mooring line components

A.2.1 General

Mooring lines for floating structures are usually made up of wire rope, chain, synthetic fibre rope or a combination thereof. Many possible combinations of line type, size and location, and size of clump weights or buoys can be used to achieve the required mooring performance. The following subclauses provide an illustration of common mooring components.

The selection of mooring components shall be based on design objectives. The mooring components should meet material, manufacture, and testing requirements specified in applicable certification rules. Mooring component properties (e.g. MBL, weight, etc.) shall be based on manufacturer specific data. An adequate inspection and maintenance program shall be developed to monitor for loss of integrity or damage where practical with monitoring, such as with ROV systems as possible, in-service. The components suitability for mobile or long term mooring (LTM) deployments shall be considered. More information on aspects of component selection can be found in A.1.7 and A.11.1 of ISO 19901-7:2013. The following sections provide more information to help with component selection.

A.2.2 Chain

Chain size is defined by the bar diameter of the chain links. Diagrams of studless and studlink chain can be seen in Figure A.5. Various grades of chain are available from U-grades (normally used for ship chain) to the higher grade of ORQ, R3, R3S, R4, R4S, and R5.

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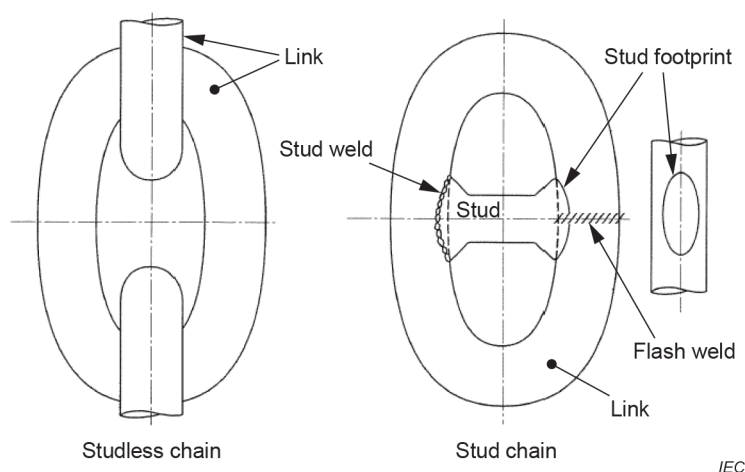
Figure A.5 – Studless and studlink chain

The length of chain links have been standardised with an overall length of 6 times the nominal bar diameter and 3,6 and 3,35 times the bar diameter for overall width for studded and studless chain, respectively. To facilitate connection to other items, both chain types are often terminated in slightly larger end links which are matched to LTM shackle designs.

When selecting chain, the choice of studded versus studless can be a key aspect. While studded has greater fatigue life, a lost, damaged, or misaligned stud can reduce fatigue life to less than that of studless chain. Studless chain can be easier to handle compared to studlink since there is room in the link to attach a lifting point.

Corrosion allowance should be taken into account for LTM systems. Consideration of the location of the system should be factored as it has been noted that the corrosion rate of chain can be high in highly oxygenated environments. Guidance for corrosion rates can be seen in DNVGL OS E301, section 5.2. This corrosion will lead to a loss of strength which shall be accounted for in the design. Out of plane bending and wear considerations of chain links at connection to the hull should be investigated, if applicable. Additional guidance on out of plane bending can be seen in ISO 19901-7. Certified marine grade chain should be used. Guidance for chain certification can be seen in ISO 1704.

A.2.3 Wire rope

Wire rope has a lower weight per unit length than chain, lower stiffness, and similar breaking loads. Common wire ropes used in offshore mooring lines are six strand, spiral strand, and multi-strand as seen in Figure A.6. The wire rope is terminated with a socket for connection to the other components in the mooring system. Special consideration is required to protect wire rope components from coming in contact with the sea bed, from abrasion damage and corrosion.
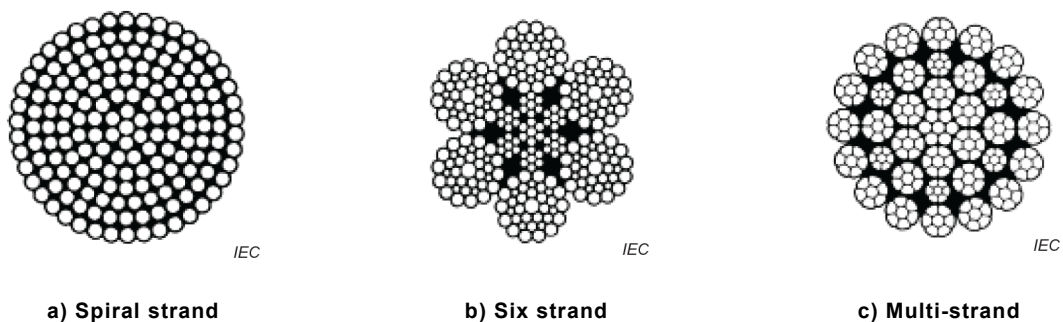

a) Spiral strand   b) Six strand   c) Multi-strand

Figure A.6 – Typical wire rope construction

The different constructions of wire rope behave differently, especially with regards to the torque and twisting response and hence should not be used in the same mooring leg. The spiral strand wire is torque balanced and does not twist appreciably under load, whilst six strand rope will twist significantly.

The six strand wire is susceptible to corrosion, whereas spiral strand wire has significantly greater longevity, especially if supplied with an external sheath.

Certified marine grade wire rope should be used. Guidance for wire rope certification can be seen in ISO 2232 and ISO 10425.

A.2.4 Synthetic rope

A.2.4.1 General

Synthetic ropes are made of one or more synthetic polymer fibers, which are twisted and/or braided to form a rope structure. Synthetic materials may be advantageous to chain and wire rope when rope handling, buoyancy, stiffness, corrosion, or fatigue life are critical. Common

fiber types for use in mooring applications include nylon, polyester, and high modulus polyethylene (HMPE), although aramid and LCP materials are also sometimes used. Properties of these fibers may vary significantly between manufacturers and grades.

Performance characteristics are driven primarily by the fiber type, construction (twist levels, braid angles, number of strands, orientation of strands, jacket, substrand construction, arrangement of fibers), and coating. Unlike wire rope or chain, elevated temperatures may modify performance or endurance characteristics of some synthetic fibers. Though uncommon for submerged moorings, elevated temperatures above 50 °C are especially critical for HMPE fiber ropes, which are more prone to creep. For nylon ropes, the hydrophilic effects of water should be considered for both breaking strength and fatigue characteristics.

A wide variety of synthetic rope options exist. Consult rope manufacturers for specific and detailed performance characteristics. More information on mooring with synthetic rope can be found in ISO 19901-7. More information on general specifications of fibre rope can be seen in ISO 9554.

Filter cloth is required where a fibre rope may be exposed to seabed particles. Guidance for filter clothes and their description can be seen in ISO18692-2 2019.

The initial selection of mooring line material should be included as part of the overall system design to ensure an appropriate solution provides the required stiffness, linear density, tensile strength, and damage resistance properties. Different synthetic fibre materials can offer a wide range of stiffness properties, from well below that available for steel solutions to comparable values. Selection of the synthetic fibre material will also have a drastic impact on the linear density for a given tensile strength target. In the case where abrasion is expected to be a major factor in wear generation (i.e. operation at or below the mudline), synthetic fibre ropes can be designed to include protective jacketing to increase abrasion resistance when required, however this will have an impact on other operational considerations including inspection.

Bending performance is related to the strength and fatigue life for tension members required to route through a fairlead. Synthetic fibre ropes are being developed for use through a fairlead for permanent moorings and may require a low friction polymer lining and exterior HMPE wear sleeving.

While variability of the mooring line design can affect performance characteristics in the specific system integration, Table A.1 provides a general comparison of broad attributes across material types. This can function as a starting point for consideration and selection should be predicated by details of each individual system and solution.

Table A.1 – Generalized comparison of mooring line material characteristics

	Stiffness	Linear density	Abrasion resistance	Bending performance
Chain	High	Very high	High	Low to high
Wire rope	High	High	High	Moderate to high
Synthetic rope	Low-high	Med-low	Low-medium	Moderate to high

A.2.4.2 Construction of synthetic fibre ropes

Various techniques are used to convert fibres into ropes. Unlike steel wire, fibres can tolerate substantial twist during manufacture, and this expands the range of possibilities for the rope construction.

The main assembly methods for assembling a structure out of base fibre material is through twisting into a yarn, binding a collection of fibre together in an outer jacket, or encapsulating in a resin.

Parallel yarns can be assembled by extruding or over-braiding an outer jacket. Since these jackets have a relatively large cross-sectional area they result in ropes of large diameter and weight. Consequently, this technique is rarely used.

A.2.4.3   Rope types

A.2.4.3.1   General

Rope constructions are divided into the broad categories as listed below:

a) Parallel core.

b) Stranded (Wire rope construction) and laid.

c) Plaited and braided.

A.2.4.3.2   Parallel yarn and parallel strand

Parallel core ropes comprise of an inner core constructed from a number of parallel-arranged sub-ropes that are typically 3-strand twisted or 12-strand braided - both with low constructional helix angles. An illustration of parallel yarn rope can be seen in Figure A.7. The sub-ropes are designed to produce balanced torque and twist characteristics. This type of rope construction can be used as inserts in chain systems, but not wire rope systems, unless the rope is specifically designed for torque matching. Torque matching may not be possible due to the limitation in the amount of torque that can be generated.

To contain the core, provide suitable handling properties and protect against external damage a braided jacket is plaited around the completed core construction. Groupings of cover yarns, typically 2, 3 or 4, form clockwise and anti-clockwise plaits for braiding, thus maintaining the neutral torque and twist balance of the rope. An illustration of parallel core rope can be seen in Figure A.8.
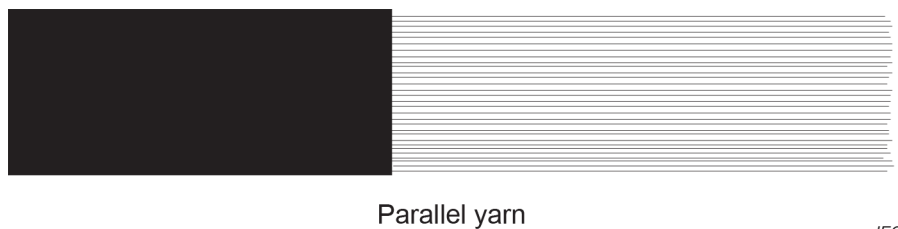

Parallel yarn

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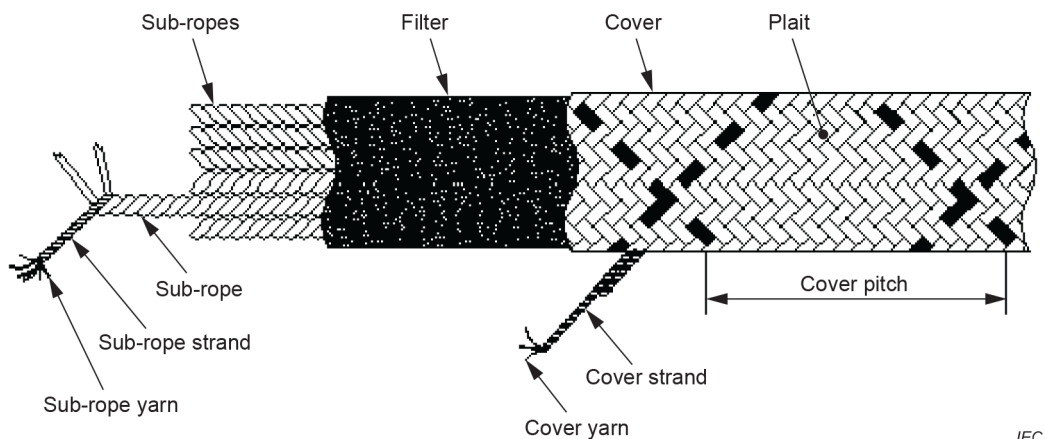**Figure A.7 – Parallel yarn rope**

Figure A.8 – Parallel core rope

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A.2.4.3.3 Stranded or laid

In a stranded construction, twisted strands are arranged in one or more concentric rings around a central core strand. The core strand may or may not be designed to carry load. Common constructions are 6+1 (six strands around the core); 12+6+1 (twelve strands around six strands); and 18+12+6+1. The 18+12+6+1 construction can be seen in Figure A.9.
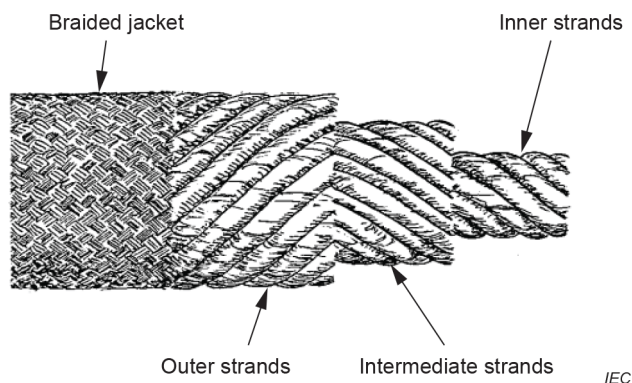

Figure A.9 – Rope construction with 18+12+6+1 format

Laid rope constructions may be supplied with a braided polyester or nylon jacket. Extrusions and polyurethane coatings have also been used. A combination of both a braid and an extrusion or coating makes an extremely tough jacket.

Laid constructions are an old design and were originally made by hand from natural fibres. They are made with a substantial amount of twist, 30^0 or more. This gives them structural integrity and they do not need external jackets to hold them together. The most common laid constructions are 3 and 4 strand. The 3 strand lay produces significant torque, but the 4 strand can be designed with very low torque. A sample of 3 strand rope construction can be seen in Figure A.10.

Figure A.10 – Three strand laid construction
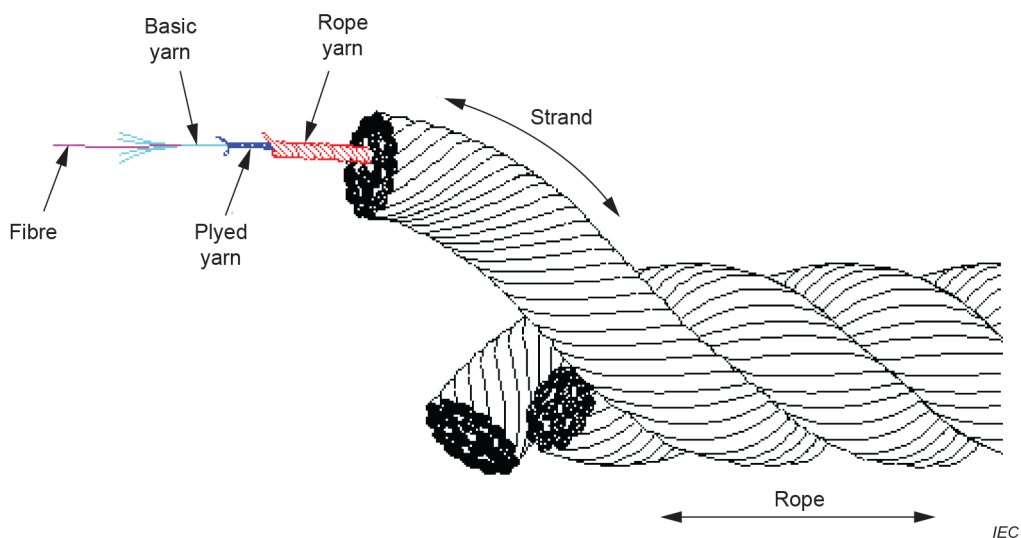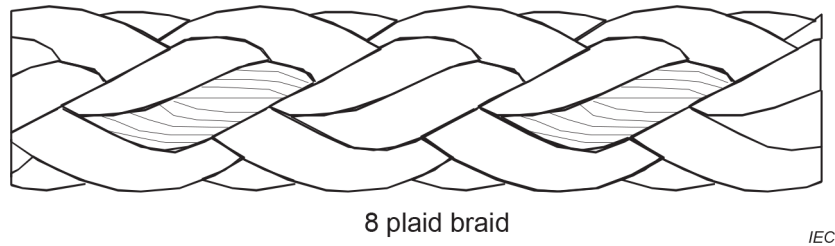
A.2.4.3.4 Plaited and braided

Plaited ropes are sometimes described as square braids. They are produced on a plaiting machine containing eight reels, each containing one strand. Frequently, as in the eight strand x-plaited rope, groups of two reels interweave as a pair around the other pairs of reels to produce an eight strands rope of a somewhat square cross-section.

8 plaid braid

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Figure A.11 – Rope with 8 plait braid construction

Braids can be either solid or circular. The construction is robust and tolerates rude handling. Plaited and braided ropes are naturally torque balanced which can be a desirable feature for this application and are normally available in either 8 or 12 strand constructions. However, this also means that, with a small amount of imposed rotation, half the strands are unloaded and the rope can lose up to half its strength. The 8 and 12 strand ropes without any additional protection are easily inspectable as there is no protective sheath covering the load bearing components. An 8 plaid braid construction can be seen in Figure A.11.

Braid on braid

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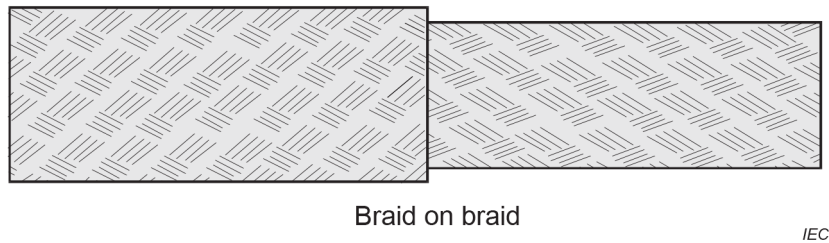
Figure A.12 – Rope with braid on braid construction

Double braid or braid on braid consists of an outer braid over an inner braid as seen in Figure A.12. These are more compact than single braids and can be designed either to have the outer braid support the load under applied tension or function solely as a protective layer around a load-bearing core.

A.2.4.3.5   Fibre material

Synthetic rope is made from man-made fiber and can be made with a variety of material types, each with its own unique properties. Material types for mooring ropes are polyester, nylon, HMPE, liquid crystal polyester LCAP, PEN polyester, aramid, polyolefin, polypropylene, PBO, carbon/glass fiber and carbon composite. Mechanical properties such as tenacity, modulus, linear density, environmental resistance, and fatigue life, vary widely across these material types and will have a major impact on the performance that can be achieved as a component in any mooring system. A comparison of general material properties are available in ISO 9554:2019. A summary of common properties can be seen in Table A.2.

Table A.2 – Properties for selection of synthetic fibre

Fibre type	Strength N/mm²	Elongation %	Modulus N/mm²	Density g/cc	Strength g/den	Strength cN/Tex
PBO (HM)	5 800	2,5	280 000	1,56	42,1	372
PBO (SM)	5 800	4,0	180 000	1,56	42,1	372
HMPE	3 400	3,7	85 000	0,97	39,7	351
Aramid HS	3 350	4,0	60 000	1,44	26,4	233
Aramid Copolymer	3 500	4,0	73 000	1,39	28,5	252
Aramid HM	2 850	2,4	110 000	1,45	22,3	197
Aramid SM	2 850	3,7	60 000	1,44	22,4	198
Liquid Crystal Polyester	2 800	3,3	65 000	1,41	22,5	199
Steel	2 160	1,1	200 000	7,86	3,1	27
Polyester (PEN)	1 100	6,0	18 000	1,38	9,0	80
Polyester (PET)	1 050	12,5	9 000	1,38	8,6	76
Nylon	850	18,0	5 500	1,14	8,4	75
Polypropelyne	590	15,0	3 933	0,89	7,5	66
Polyethelyne	410	10,0	4 100	0,92	5,0	45

A.2.4.3.6 Comparative fibre properties

ISO 9554:2019, Annex A provides comparative values but does not include a ranking against steel. Table A.3 provides a relative ranking of synthetic materials as compared to steel. Note that design specifics for synthetic rope products (i.e., fibre lubricant, strand jacketing) can have an impact on these rankings. For example, nylon products with strand jackets have been observed to achieve a fatigue life higher than comparable polyester rope designs.

UV due to sunlight exposure is not typically an issue for large fibre ropes used in moorings. It is generally considered a surface effect and depending on material can only affect exposed material up to a certain depth, on the order of a few millimeters. Application specific exposure levels should be considered as well as the structure and yarn path for exposed strands. In cases where UV degradation is anticipated to be a major concern, incorporation of a protective outer rope jacket in the rope design can fully protect the rope.

Table A.3 – Generalized comparison of common rope relevant material properties

Material	Tenacity	Specific gravity	Elongation	Tension fatigue resistance	Creep resistance	Critical temperature
Polyester	Medium	High	Medium	Very high	High	Medium
Nylon	Medium	Medium	High	Very high	Medium	Medium
HMPE	High	Low	Low	Very high	Low	Low
Aramid	High	High	Low	High	High	High
LCP	Medium	High	Low	High	High	High
Polypropylene	Low	Low	Medium	High	Low	Low
Steel wire	Low	Very high	Low	Moderate	Very high	Very high
Chain	Very low	Very high	Low	Low	Very high	Very high

A.2.4.3.7   Determination of physical properties

Physical measurements of the rope product can have an impact on incorporation of the mooring line within the constraints of the system. Rope diameter is typically reported as a nominal value due to the variability of the measurement when various load conditions are applied. Due to the presence of void space within the structure of a new rope that has never been subjected to tensioning, it can be necessary to consider this value under various load conditions and histories. Linear density is generally only required for the definition of rope design and mass of rope for transport and handling. Synthetic lines do not have any significant catenary effect on mooring system response. Determination of rope diameter, linear density, and lay length is fully described in ISO 2307.

Rope break strength main requirements is provided in ISO18692-2 2019 applicable for very large polyester ropes intended for permanent moorings of very large floaters. An alternate method for the determination of break strength ISO 2307 which is more applicable to smaller ropes used in general shipping. Special consideration should be given to nylon break strength due to the related response for this material when exposed to water. ISO 9554 provides a method for determination of break strength using a statistical approach and also for a wider range of materials and constructions with in an informative annex that is more economically applicable to small to moderate size ropes.

Elongation and stiffness (Flory *et al.* 2004) response is critical for many operational considerations. While this is predicated in general terms by the load bearing fibre material selection, the structure of the rope will have an influence on the final static and dynamic stiffness observed. One method for evaluation of fibre rope stiffness is described in ISO 18692-1 2018 which is a generic loading regime which was written for oil and gas floating production vessels. The loading regime to test rope stiffness should be based on the actual WEC device, metocean and location numerical modelled line load response which may be completely different to an oil and gas vessel. This may not be feasible, so alternative design methods may be used on stiffness properties to enable designs to proceed with adequate accuracy. Accuracy of stiffness properties may affect accurate displacement and motion offsets more than peak loads in the mooring system.

Other characteristics that may be critical to consider during the rope selection process include tension-tension fatigue, axial compression resistance, static bend fatigue, and cyclic bend fatigue. Resistance to these modes of degradation are highly dependent in the system and intended design life. Depending on the specific system requirements, determination of the optimal product solution may require non-standard evaluation. Some relevant test methods are captured in ISO 18692 and ISO/TS 17920 and can be used as an initial point of reference.

Further information on the test method of year over year abrasion is provided in CI 2009N for nylon. This test should be considered to ensure satisfactory marine grade lubricant is specified.

Due to the extensive fatigue life of polyester (Banfield 2005) as compared to steel wire and chain, it is not expected to be a limiting factor of any mooring system design. More recent data on nylon has also supported a very long fatigue life (Ridge, Banfield and Mackay 2010), providing the fibre has a marine grade lubricant and a long lay (low twist) design. Highly twisted nylon ropes will generally provide a slightly longer fatigue life as compared to steel wire and should not be used for permanent mooring design unless test data verifies adequate fatigue life.

Axial compression is not an issue for polyester, nylon and HMPE. There is no requirement to count number of cycles or set lower limits for minimum tensions. Yarn buckling data Flory and Banfield (2017) show that the effect is very severe in aramids, which will begin to lose significant strength around 22 000 cycles, HMPE 110 000 cycles and polyester 500 000 cycles. Nylon has the highest performance with little effect even at 1 million cycles. Thus, cycles and minimum tension is only required for aramids.

Low tension regimes in the mooring system may not allow fibres in new ropes to properly set. This may result in a significant reduction of breaking load from manufacturer reported MBL values.

A.2.4.3.8   Fibre rope terminations

The feasibility of using synthetic fibres for the construction of ropes suitable for mooring line application depends on the availability of efficient rope terminations. There are various methods available for terminating synthetic fibre ropes. The most common are:

–   eye spliced;

–   resin potted;

–   spike in socket (also called barrel-and-spike).

For synthetic fibre ropes both eye spliced and resin potted terminations are traditionally used. The barrel-and-spike termination is used for parallel-yarn ropes.

Of the three termination types, only the spliced eye has been qualified for strength and resistance to hysteresis heating at sizes appropriate for very large moorings up to 2 500 t. The barrel-and-spike has been strength tested on Kevlar fibre rope at over 1 400 t.   Several companies are developing resin socket terminations. A general problem with systems that are dependent on friction or bonding to the rope circumference is that they will lose efficiency at large sizes. This can be avoided by applying processes that allow for splitting the overall rope structure into smaller components, which is an inherent feature of splices, and can be achieved with resin sockets. However, this makes this termination type complex and expensive and has no testing or field experience to date.

Splicing techniques (the most common type by far) are efficiently used for terminations of large ropes in all constructions (except parallel yarn).   Testing and qualification is commonly performed by manufacturers allowing for reliable specifications based on the material, construction, and splice method utilized.

The strength efficiency of conventional potted-socket terminations falls off for large fibre ropes, mainly because distortion of the resin relaxes tension in yarns at the centre of the rope and thus increases tension in the outer yarns. Some manufacturers have developed special sockets but these are limited in supply and size, test data and field experience.

Not all cases require a full strength termination. For example, in the case of a rope being utilized on a winch drum or capstan, much of the tension is taken up in the wraps between direct load application and the final attachment point. In these cases, a simple mechanically applied compression termination may be suitable, however anticipated load transfer for the worst-case scenario should be considered. This can be performed through a calculation based on minimum potential wraps and the material coefficient of friction.

Termination fatigue is not an issue for spliced ropes as that is how the fatigue curve has been developed (Banfield *et al.* 2005, Ridge *et al.* 2010). It is important that the spliced termination follow best practice and suitable design of splice for the rope construction, which should include aspects of tuck length, number of tucks, tuck angle, and type of tapering. These are proprietary ropemaker aspects and may vary from one design to another.   For resin socket and barrel and spike the similar applies, in terms of load transfer from fibre to socket/spike, material roughness, and shape of the spike. Furthermore, when bending of the rope at the exit of the termination, bending relief maybe required. For these terminations particular care should be taken with abrasion at the tip of the spike and exit of the socket has been adequately addressed.

A.2.5   Elastic tethers

Highly elastic materials are available for mooring components. These components may have an elongation of 200 % to 400 % before failure. Because of the significant elongation, the stiffness of individual elastic tethers is significantly lower in comparison to synthetic rope, wire, and chain. However, this can be adjusted through construction of components using parallel arrays of elastic tethers.

Elastic tether materials have been successfully used in long term deployments in various industries, including for wave energy applications. However, limited information is available from international standards on these materials. Durability, fatigue, and nonlinear stretch properties should be carefully considered before using in long term deployments.

A.2.6   Clump weights

Concentrated or distributed weights can be added to mooring lines to produce desired performance characteristics. Using clump weights in a mooring line design shall require consideration of potentially adverse effects, such as increased use of connecting hardware, installation complexity, maintenance and inspection requirements, dynamic response and possible interaction with the seabed which can result in damage or loss of the clump weight.

The addition of a clump weight may cause a large angle change to the mooring line at a single point and thus localised wear may be significantly increased. This should be accounted for in the design.

A.2.7   Buoyancy aids

Concentrated or distributed buoyancy aids can be added to mooring lines to produce desired performance characteristics. The depth rating of the buoyancy module shall be considered to avoid damage or loss of buoyancy through compressive creep or water absorption. Loss of buoyancy can have a significant impact on the performance of the mooring system.

Using buoyancy aids in a mooring line design shall require consideration of potentially adverse effects, such as increased use of and complex loading on connecting hardware, installation complexity, maintenance and inspection requirements, and dynamic effect of the buoy on the mooring, drag forces, and navigation hazard of shallow or partial submergence.

A.2.8   Connectors and accessories

The number of connectors should be minimized for safety, fatigue, and operational and maintenance considerations. Connectors with the designation LTM are used for permanent mooring systems and are of a more robust design.

Failure modes due to connector interaction and other accessories, such as material hardness, contact area, and electric potential differences, as well as interaction with the seabed, shall be considered. Special attention should be paid to securing details as to ensure the connectors do not accidently come apart. Shackles should be double secured with bolts/lock nuts, bent bars, etc. instead of cotter pins. Corrosion of the securing system should be considered. Several examples of connectors can be seen in Figure A.13. It should be noted that some of these items, such as Kenters, Baldt, and swivel shackles, may not be suitable for LTM in excess of 1 to 2 years due to poor fatigue performance.

Some connectors may include load monitoring instrumentation. If any load monitoring instrumentation is in the load path of the mooring, it shall be designed to the same structural strength and standard of design as the other mooring components used.
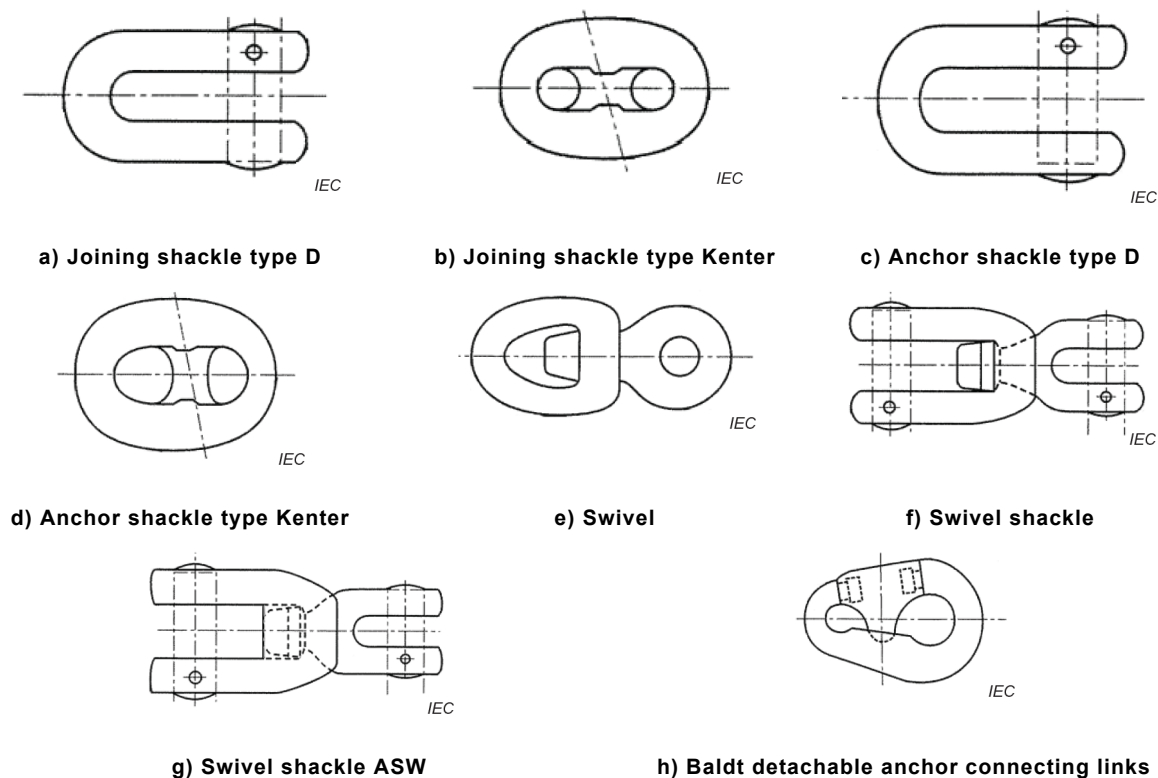
a) Joining shackle type D   b) Joining shackle type Kenter   c) Anchor shackle type D

d) Anchor shackle type Kenter   e) Swivel   f) Swivel shackle

g) Swivel shackle ASW   h) Baldt detachable anchor connecting links

**Figure A.13 – Types of connectors**

A.3 Anchors

A.3.1 General

Various anchor types and selection criteria are discussed.

A.3.2 Drag embedment anchor

A drag embedment anchor is designed to penetrate into the sediment as it is pulled horizontally along the seabed. Two fundamental types of drag anchor are the stockless and the High Holding Power (HHP). The stockless anchor is traditionally used as a ships anchor as it is easy to deploy and recover but limited in holding capacity. The HHP anchor requires careful positioning but generates a high holding capacity due to the large surface area bearing against the soils when embedded.

By design, when employing drag embedment anchors, the mooring line should generally not have any uplift at the anchor location in order to avoid a reduction in holding capacity, which may cause the anchor to dislodge from the sediment. The vertical load resistance of the drag embedment anchors, although limited, may be considered in the design and the manufacturer may provide a maximum angle between mooring line an anchor installation plan without causing any uplift of the anchor. In addition, out of plane lateral loading can also cause the anchor to fail. An example of a HHP drag embedment anchor can be seen in Figure A.14.

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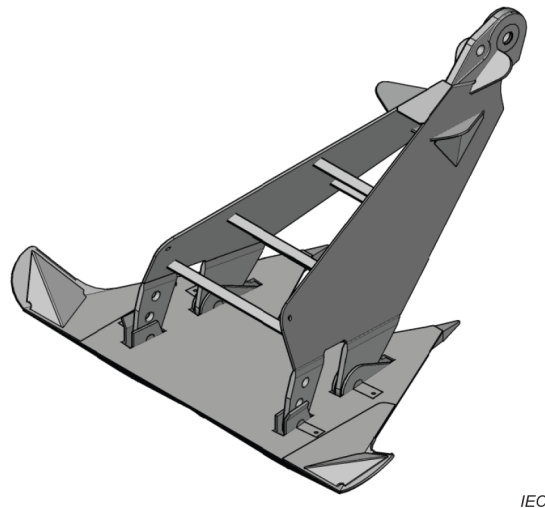
Figure A.14 – Drag embedment anchor

The holding capacity is a function of the soil, with stiffer soils giving higher load capacity. If the soils are very hard, or rock, the anchor may only partially embed, resulting in reduced holding capacity or failure to embed.

A.3.3 Pile anchor

A pile anchor is a rod or pipe that is driven into the seabed by a piling hammer, vibrator, drilling, or other means. The holding capacity of the pile is generated by the friction of the sediment along the pile, lateral sediment resistance, or a grouted bond with the rock. A capacity to resist both out of plane lateral and vertical loads is possible depending on pile design. A schematic of a pile anchor can be seen in Figure A.15.


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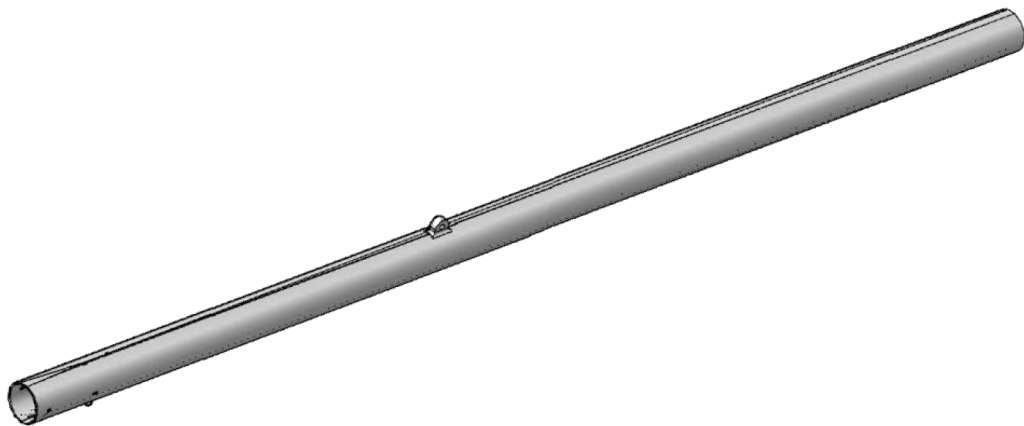
Figure A.15 – Pile anchor

Design of pile anchors requires knowledge of the strength of the sediment and therefore core samples are usually required to ensure the pile can be installed to the required depth. The size of the installation equipment required should be considered early in the design, since the cost of the hammers or drills and ships to deploy them may be prohibitively expensive.

A.3.4 Suction anchor

The suction anchor is forced into the seabed by the pressure differential created by pumping out the seawater from the caisson during installation. This pressure differential is limited to the

depth of the water above the anchor and so installation in shallow water can prove difficult. Suction anchors are generally not suitable for hard, rocky, or gravel seabed.

The holding capacity of the suction anchor is generated by the friction of the sediment along the caisson wall, lateral sediment resistance, and reversed end bearing effects. A capacity to resist both out of plane lateral and vertical loads is possible depending on suction anchor design. A schematic of a suction anchor can be seen in Figure A.16.

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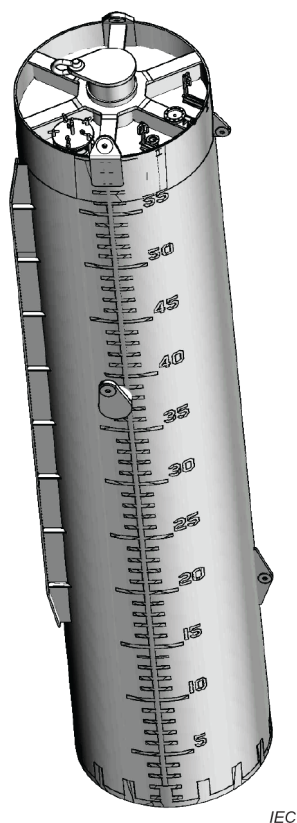
Figure A.16 – Suction anchor

A.3.5   Gravity installed anchor

Gravity installed anchors are installed as projectiles that penetrate the sea floor under velocity. The holding capacity of the anchor is generated by the friction of the sediment and lateral sediment resistance. A capacity to resist both out of plane lateral and vertical loads is possible depending on anchor design. A schematic of a gravity installed anchor can be seen in Figure A.17.
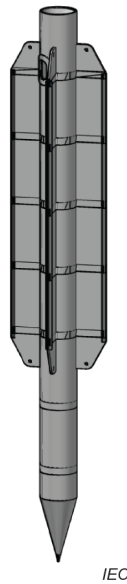
IEC

Figure A.17 – Gravity installed torpedo anchor

Gravity installed anchors rely on high velocity to achieve sufficient penetration and hence are generally used in deep water with a sand or soft clay seabed and are not suitable for very hard, rocky, or gravel soils. A rotating load point on a gravity installed anchor can accommodate out of plane loading experienced during a large excursion event. A sample gravity anchor can be seen in Figure A.18.
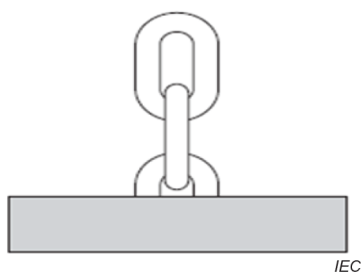

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Figure A.18 – Gravity installed anchor with rotating load arm

A.3.6   Gravity anchor

The holding capacity of a gravity anchor is generated by the submerged weight of the anchor material used and by the friction from the seabed. Steel, concrete, and confined rubble are examples of materials that may be used. A schematic of a gravity anchor can be seen in Figure A.19.

IEC

Figure A.19 – Gravity anchor

The dimensions of the gravity anchor may be significantly larger than many other designs and in shallow water or in areas with strong currents, environmental loading from wind and waves may have a significant impact on holding capacity.

A.3.7 Plate anchor

Plate anchors can be installed by drag embedment or by being vertically driven into place followed by a keying process. The holding capacity of the plate anchor is generated by sediment resistance against the plate surface. Significant vertical holding capacity is possible. A capacity to resist out of plane lateral loads is possible depending on plate anchor design. A schematic of a plate anchor can be seen in Figure A.20.


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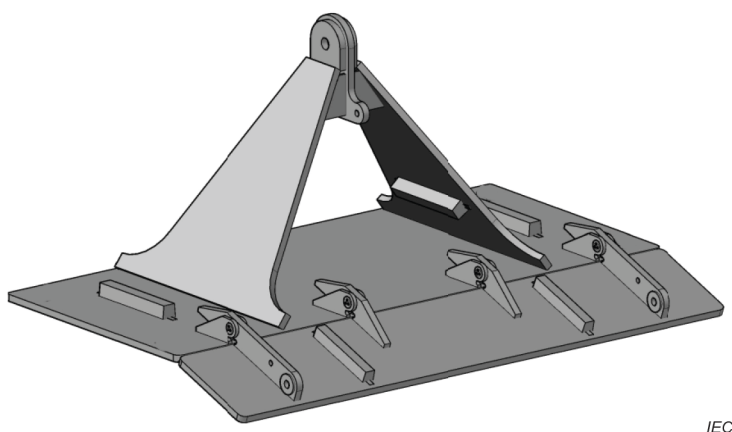
Figure A.20 – Suction or pile driven plate anchor

A.3.8 Screw and rock anchors

A screw anchor may be used for particular sediment types and for special applications. Holding capacity is generated by friction and lateral sediment reaction against the anchor surface. Depending on the screw anchor design, vertical and out of plane lateral holding capacity is possible.

A rock anchor is driven into the soil. Holding capacity is generated by expansion of the head of the anchor after installation depth is reached.

A schematic of a screw anchor can be seen in Figure A.21. A rock anchor can be seen in Figure A.22.
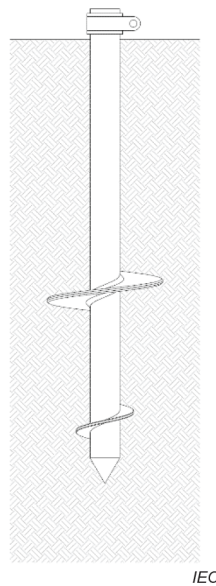
Figure A.21 – Screw anchor
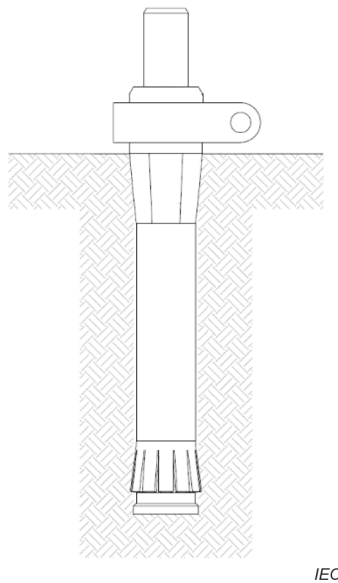
Figure A.22 – Rock anchor

A.3.9   Type selection

In selecting the appropriate anchor type, consideration shall be given to the mooring system configuration and design characteristics (load, out of plane lateral, and uplift), site-specific seabed conditions, direct loading from current and wave action, removal and installation constraints. The above considerations as well as the site specific risk profile will dictate anchor selection.

A.3.10   Holding capacity

A.3.10.1   General

For all anchors, the design load and holding capacity shall be clearly defined for all limit state conditions. The holding capacity may be determined from anchor manufacturer or standard design tables and semi-empirical models. Generic manufacturer holding capacity curves may

not be a conservative approach. Sample anchor data can be found in A.10.4 of ISO 19901-7:2013.

In some cases, accurately predicting or assessing the anchor holding capacity can be impractical or impossible. Characterizing holding capacity or key characteristics of the anchor type can be used to design and assess the anchor.

These characterizations of the anchor can be used to assess the holding capacity of the anchor without any further additional safety factor required. Additional safety factors may be used if there is uncertainty in the dynamic loads, hydrodynamic loads on the anchor itself, load angles in the moorings or if there is uncertainty in the nature of the failure mode of the anchor type.

Particular consideration should be given to possible dynamic and direct environmental loading on the anchor and the influence on sediment and rock conditions. The dynamic and cycling fatigue loading on the anchor type and resulting holding capacity and failure mode should also be considered. Additional failure modes and effects analysis can be assessed using guidance from IEC 60812.

A.3.10.2 Gravity anchors

Measurement of the holding capacity of a gravity anchor may be done on land or in water if the ground conditions are similar to the intended installation site. Assessment of gravity anchor load holding capacity shall include an assessment of external forces, such as hydrodynamic loads, acting on the gravity anchor in addition to the mooring load.

A.3.10.3 Rock anchors

Drilled rock anchors shall have validated knowledge of capacity of the anchors derived from experimental load testing. Where possible, full-scale land-based testing in similar geotechnical conditions should be conducted prior to installation to provide baseline design information for comparison.

Drill logs for installed anchors shall be generated during installation for comparison to the expected geotechnical conditions and previous experience in similar rock quality. Where drill logs indicate a failure to achieve the expected geotechnical engagement, the anchor shall be considered not to be capable of generating sufficient load holding capability.

A.3.11 Sediment and rock conditions

Site-specific sediment and rock data should be obtained in order to evaluate the performance of the anchors. Installation calculations and ultimate holding capacity calculations should utilize the lower and upper bound site-specific data to develop anchor performance envelopes.

A.3.12 Fluke setting

Some anchor types have an adjustable fluke feature allowing the angle or exposed area of fluke to be adjusted for various sediment conditions. The fluke setting features and installation implications should be considered.

A.3.13 Installation

Each anchor type has different installation techniques to consider. A detailed installation plan, including allowable tolerances, should be prepared during the design phase. The field layout and surrounding infrastructure should be considered when planning the installation. As the time of year may indicate the installation weather windows, the necessary anchor setup time should also be specified and taken into account.

A.3.14 Proof loading

Some anchor types require proof loading as an integral part of the installation process to ensure proper embedment. It is important that the minimum required proof load is determined for each application and included in the installation plan.

A.3.15 Directional anchor loading

Structural and geotechnical capacities should be considered for each design based on the maximum expected out of plane lateral, uplift, and horizontal loading in all limit states. Some deployments may require multiple attachment points to a single anchor and all loading combinations shall be considered and the possible geotechnical effect to the seabed or sediment.

A.3.16 Failure mode

The failure mode of the anchor and the implications in ALS should be considered on a site specific basis. Additional failure modes and effects analysis can be assessed using guidance from IEC 60812.

A.3.17 Environmental loading

Anchors for a MEC system may be large or placed in shallow water or areas subject to tidal and wave action. The loading from environmental effects including wind, waves, and current shall be considered as it may have a significant effect on holding capacity. Reduced holding capacity due to scour may also result.

A.3.18 Failure point

A specific design failure point between the anchor, mooring line, and structure interface should be incorporated into the design. This controls the point of failure and limits catastrophic MEC hull or anchor damage. Additional failure modes and effects analysis can be assessed using guidance from IEC 60812.

Annex B
(normative)

Safety and risk considerations

B.1 General

This annex provides guidance for the consideration of safety and risk associated with MEC mooring systems. Fundamental aspects of determining probability of a mooring failure and the associated consequences are discussed. The goal is to identify potential risks before the mooring system design is finalized and installed. Identifying site-specific risks facilitates the selection of a consequence class and the associated safety factors to be used for the mooring system.

Additional information on risk assessment as well as technology qualification for use in mooring systems can also be found in IEC TS 62600-4.

B.2 Risk

B.2.1 General

A basic description and background of risk is provided in the following subclauses for introductory purposes from API RP 2SK. Acceptable risk levels vary from region to region depending on governing body regulations and requirements. Consideration shall be given to ensure compliance with all applicable rules for the region and operation.

B.2.2 Definition

The description of risk is provided in this document to assist in the specific context of evaluating mooring designs. Risk is the potential of an adverse event occurring that leads to an undesirable outcome or consequence. In general, a risk assessment should study the probability of event occurrence, related consequences, and potential risk mitigation measures.

$$\text{Risk} = \text{[Probability of an undesirable event occurring]} \times \text{[Anticipated consequence if that event occurred]} \tag{B.1}$$

Mooring risk scenarios can be complex and involve multiple events in succession. In a situation with multiple risk events, the total risk is the sum of the risks for each different accident, provided that the consequences are of the same type:

$$\text{Risk} = \text{For all accidents} \sum (\text{[Probability of an undesirable event occurring]} \times \text{[Anticipated consequence if that event occurred]}) \tag{B.2}$$

B.2.3 Consequence types

B.2.3.1 General

In general, the types of consequence to be considered in MEC mooring system risk assessments, at a minimum, include:

a) Health and safety effects.
b) Damage to MEC, mooring components, or other assets.

c) Environmental effects.

d) Financial loss.

e) Damage to corporate or industry reputation.

A mooring system failure can include any single or multiple mooring component or anchor structural or geotechnical failure. When considering adverse MEC events as a result of a mooring failure, the immediate surface, subsurface, and device itself, along with all appurtenances, should be considered. The surrounding surface and subsurface region of the MEC location should be considered to cover reasonable consequence scenarios.

B.2.3.2   General risk mitigation

When performing a MEC mooring risk assessment, it is important to understand the risk exposure for each specific location and system. Risk may be reduced to tolerable levels by decreasing the probability of an undesirable event occurring and/or by minimizing the consequence should that event occur. Acceptable or tolerable risk levels for a particular MEC mooring project may be based on industry, corporate, certifying authority, and/or government criteria depending on the location. It is up to the responsible party to ensure all potential risks are considered and mitigated during design (i.e. before installation) to tolerable levels that are as low as reasonably practicable (ALARP). It is a conservative approach is to ensure failure is ALARP.

B.2.3.3   ALARP principle

Thorough consideration with regards to the design, planning, and operations should be given to reduce risk of mooring failure. However, it may be shown that the benefit of further risk reduction is outweighed by the effort or resources required to implement the mitigating measure. The magnitude of consequence due to a mooring failure can vary considerably based on many site-specific elements, and therefore so may the risk level of what is considered to be ALARP.

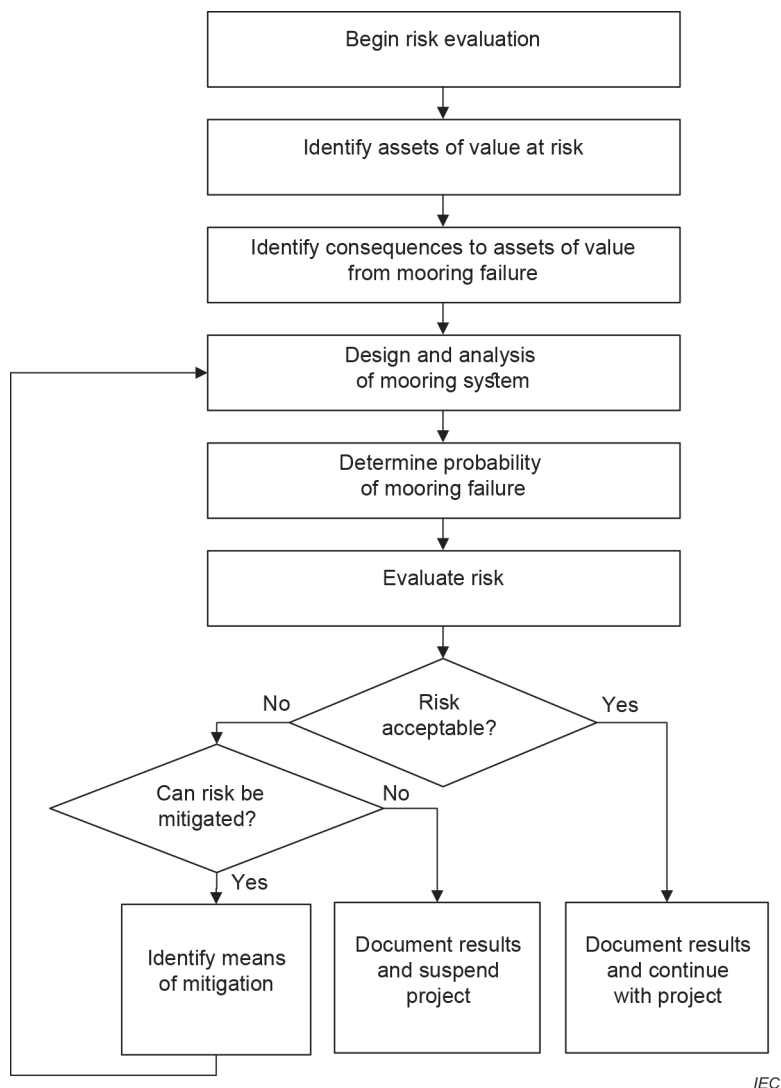## B.3   Risk assessment methodology

B.3.1   General

This clause provides information on the basic considerations and methodology of a risk assessment relating to the mooring of a MEC. The fundamental considerations in determining the probability of a mooring failure and the related consequence are discussed. This clause is not intended to specify exactly how to perform the risk assessment or limit the user to any specific format for analysis and results.

B.3.2   Methodology flowchart

B.3.2.1   General

The purpose of the risk assessment methodology described herein is to give some level of guidance in assessing the probability of a MEC experiencing a mooring failure and the related consequences of such an event. The consequences of a mooring failure to the MEC itself can vary based upon the type of MEC and is the responsibility of the owner and operator to properly consider.

Figure B.1 illustrates the general methodology used to evaluate the risk associated with a MEC mooring failure with regards to assets of value at risk. Assets of value may be related to loss of income or property, environmental impact, or endangering human life.

Figure B.1 – General risk methodology flowchart

B.3.2.2   Basic considerations

Generally, risk assessments can be carried out on a qualitative or quantitative basis. This document outlines the approach for a quantitative risk assessment. A Hazard Identification (HAZID) study should still be completed to identify broad risks and develop measures to mitigate those risks for any operation. Typically, a HAZID is a qualitative assessment of consequence events using some form of risk matrix to categorize the events based on the probability of occurrence. For guidelines on performing HAZID studies, see ISO 17776.

B.3.2.3   Probability assessment

Determining the probability of the initial event and then subsequent events is a crucial part of determining the risks involved with a moored MEC. For a moored MEC risk assessment, the initial event is mooring failure.

The probability of the initial mooring failure occurring shall consider the environmental return period, associate line capacity, load factors, material factors, and service life duration. The longer the MEC is deployed, the more likely a particular design event will be exceeded. The probability (P) of exceeding a particular design environment with return period (T) over the service life (n) of the MEC can be determined using the following relationship:

$$P = [1-(1-1/T)^n]$$

Alternatively, the probability of the initial mooring failure can be calculated through a reliability analysis. The detail level of such an analysis can vary, but at a minimum the uncertainty in mooring component strength and environmental loads should be considered.

B.3.2.4   Consequence classification assessment

For each location, it is important to fully understand and consider the possible consequences in the event of a mooring failure. Quantitatively, consequences are usually considered from a financial loss perspective. Some consequences, such as loss of life, are difficult to quantify, but should be considered in any comprehensive risk study. Multiple successive consequences should be considered to the extent practical.

B.4   Consequence considerations for mooring failure

Consequence considerations should be taken into account during the design phase. The considerations should be focused on the identification of the consequences to assets of value in the event of mooring system failure. Consequences can be categorized based on the description of the exposure or hazard and can be defined by the following, see Table B.1.

Table B.1 – Consequence categories

Consequence category	Possible related consequence
Person	Injury or fatality
Financial	Loss of production, cost of repair, compensation
Property	Damage to device or third party property
Environmental	Possible injury, harassment, or death of local ecosystems
Societal	Negative public perception

Each consequence category should be assessed for each consideration. Considerations for consequence assessment are addressed below.

B.5   Consequence classification

B.5.1   General

The purpose of increased minimum safety factor requirements for higher consequence systems is to reduce the probability of a mooring failure. MEC consequence classifications include class 1 and class 2.

General guidance for selecting mooring consequence class based on consequence categories previously defined is listed below. The most limiting of any single consequence category shall determine the consequence class of the mooring system location.

For consequence class 2, possible outcomes of a mooring system failure may include potential loss of human life, significant damage to marine environments, blockage of high traffic navigable waterways, and substantial financial or third party property damage. Target annual probability of failure for this consequence class is 10^{-5}.

For consequence class 1, possible outcomes of a mooring system failure may include minimal chance of human injury, minimal environmental impact, minimal navigable waterway impact, and minimal financial or property damage. Target annual probability of failure for this consequence class is 10^{-4}.

B.5.2 Consequence impact considerations

B.5.2.1 General

There are many factors that should be considered when determining the level of consequence, some of which are identified in the following subclauses.

B.5.2.2 Subsurface infrastructure, pipelines, umbilical, cables

Subsurface infrastructure can be considered as any man made structure placed on the bottom surface, including pipelines, subsea cables, etc. A mooring failure can result in dragging mooring line components or anchors across the bottom surface, causing damage or destruction to surrounding subsurface infrastructure or areas of environmental or archaeological importance. The probability of subsurface infrastructure damage, in the event of a mooring failure, can be affected by:

a) Distance away from MEC site.

b) Anchor and mooring components choice.

c) Diameter of pipeline or cables.

d) Mooring system robustness.

e) Concentration of infrastructure in an area.

An example of how probability is affected can be explained by distance away from the MEC site. The greater the distance from the MEC mooring location to a pipeline or cable can indicate a lower probability of dragging an anchor and/or mooring components and causing damage to the infrastructure. The consequence assessment of these events may include the cost of repair or replacement, delay of production, and possibly causing an environmental incident.

B.5.2.3 Surface structures

Surface risk can include damage to surface asset systems such as moorings or damage associated with any hull to structure interaction. The probability of complete structure loss may not be as high for MECs due to the smaller target of the structure compared to its mooring. The probability of surface structure damage can be based on the location and the distance to the asset.

The financial consequence of interacting and colliding with other surface structures such as vessels, or other MECs may be considered. Both direct collision to these structures and interaction damage to the associated ancillaries such as the moorings, risers, power cables, etc., may be accounted for in the cost impact. Replacement or repair, delay of production, or causing a possible environmental incident may be included in the consequence assessment.

B.5.2.4 Waterway navigation impacts

There are consequences associated with the failure of mooring of any man-made offshore structure in navigable waters. Mooring failure can physically affect:

a) Commercial shipping.

b) Governing authority operations.

c) Recreational boating.

d) Fishing (commercial and recreational).

The consequences can vary depending on the project phases, including installation, operations and decommissioning.

B.5.2.5 Environmentally sensitive and protected sites

Partial and complete mooring failures can cause the MEC to move into and through a sensitive or protected habitat. Normal operation of the MEC may cause impairments to water use and quality due to continual bottom disturbance from mooring lines.

B.5.2.6 Archaeological sites

A bottom surface hazard survey should be completed prior to the installation of the MEC. The requirement of a hazard survey may vary from region to region. In regions where archaeological finds are protected, a discovery of manmade debris may indicate the presence of a shipwreck or a find of archaeological importance. Minimum clearance distances for anchor placement or grounded lengths of the mooring system from an archaeological find may be determined by the governing body of a region to minimize disturbance.

B.5.3 Risk mitigation considerations

B.5.3.1 Mitigation overview

Risk tolerance varies from project to project based on a number of design considerations and drivers. Although this specification sets out minimum technical requirements, the circumstances for a particular project may warrant additional risk mitigation considerations to minimize risk to tolerable levels for the various stakeholders. The following subclauses address the reduction of risk event probability and consequence.

B.5.3.2 Probability reduction

The probability of mooring system failure can be reduced through various design strategies that achieve higher return periods at the required factor of safety (reliability level) for the respective consequence class. Consideration should be given to the duration of the anticipated service life. The longer the MEC is deployed, the more likely a particular design event will be exceeded. The probability (P) of exceeding a particular design environment with return period (T) over the service life (n) of the MEC can be determined using the following relationship:

$$P = [1-(1-1/T)^n]$$

For example, a design return period of 50 years and an anticipated design service life of 25 years, there is a 40 % probability that the design environment will be equalled or exceeded during service. There is a risk based decision to be made by the project stakeholders.

B.5.3.3 Consequence reduction

Consequence class is defined by the location of the MEC and the associated consequence categories previously discussed. A careful consideration of available locations and their associated consequence categories should be completed before selecting the final location. Mooring system design failure points can be adjusted to minimize the consequence of a mooring failure and reduce the risk to tolerable levels

B.5.4 Risk acceptance

B.5.4.1 Acceptance overview

After identification of all risks involved, it shall be decided whether each particular risk is tolerable or not. Regardless, risk reduction measures should always be considered and evaluated for each identified risk. Depending on the geographical region, ruling authorities may have their own acceptance and approval criteria. Acceptable levels of MEC mooring failure risk can generally be based on the experience and level of acceptability established by other offshore systems and industries. Stakeholders may have different internal risk acceptance criteria based on the type of consequence. Determining what level of risk is tolerable may be

based on consideration and weighing of known requirements and the benefits versus cost/effort/resources of additional risk mitigating measures.

The risk assessment process can be iterative. It should be repeated each time with consideration to the proposed mitigating measures until the risk level is acceptable. Both preventative (e.g. strengthening the mooring system to reduce failure probability) and mitigation (e.g. choosing a synthetic line component to reduce severity of consequence in the event of a failure) measures can be used to reduce risk to tolerable levels.

It is also important to recognize that a risk reduction measure for one scenario can actually increase risk associated with another scenario in some cases.

B.5.4.2   Documentation

The basis, assumptions, and results of the risk assessment shall be thoroughly documented with full traceability. Conclusions and all measures taken to reduce risk shall be clearly explained. The fundamentals and results of the analysis should be clear, even to persons that may not be familiar with the project.

Annex C

(informative)

Numerical modelling considerations

C.1 General

This annex provides information on various modelling techniques that are used to study the dynamics of floating structures. Special care is required in understanding the capabilities and limitations of the modelling method used due to the additional complexity introduced by MECs.

C.2 Mooring, umbilical, and dynamic cable models

C.2.1 General

Nonlinear behaviours shall be considered to gauge the most appropriate mooring model to use to determine the dynamic mooring system response. Some examples of nonlinear behaviours in mooring systems include variation in mooring geometry due to extreme storm conditions or shallow operating depths, mooring component material properties, mooring drag and damping induced by viscous hydrodynamic effects on the lines, and seabed contact. Installation tolerances shall be considered in the model.

C.2.2 Static and catenary models

A static line or static catenary model may be used to initially produce mooring position and tension based on the distributed weight and stiffness of the line. This model cannot address dynamic effects such as mooring inertia or viscous damping effects on the MEC. A quasi static analysis may use a static line model in conjunction with a dynamic MEC model. This approach may produce significantly different results than a dynamic line model.

C.2.3 Discrete models

These models discretize the mooring lines, umbilicals, and dynamic cables. These models may be based on finite segment, finite difference, finite element techniques. The results of these models usually produce converging results as the discretization density of the model increases. The effects of internal axial, bending, and torsion loads of the mooring components and umbilical can be incorporated. Most dynamic effects and nonlinearities can be addressed by discrete models.

C.2.4 Floating unit numerical models

C.2.4.1 General

A model may consist of limited degrees of freedom ranging from a single motion mode to all six degrees of freedom. If the system has an articulated mechanism, the degrees of freedom considered may be more than six. The floating unit model shall include all degrees of freedom that affect the motion of the system and induce significant mooring reaction loads.

C.2.4.2 Small body approximation and Morison-type hydrodynamic loading

C.2.4.2.1 General

When a MEC representative dimension is small relative to the incident wavelengths present in the ocean, wave diffraction effects can be neglected and viscous and inertia effects dominate. The Morison equation produces hydrodynamic loading on the MEC as a function of relative velocity, acceleration, and hydrodynamic drag and added mass coefficients for the structure of interest. Hydrodynamic coefficients for common geometric shapes are available in the literature

and standards. Ideally, coefficients can be determined through numerical or experimental methods.

Wave radiation effects may not be insignificant but in general they act as a damping mechanism and as a result it may be considered conservative to neglect them for the purpose of a mooring design.

C.2.4.2.2 Linearized hydrodynamic loading

When a MEC representative dimension is large relative to incident wavelengths, diffraction effects will dominate. It is common to resolve diffraction loads through a numerical solver based on potential flow theory. Potential flow solvers that use a strip-theory approach can only be applied to slender floating structures. On the other hand, potential flow solvers that use a panel method approach are not subject to any such geometric constraint. Diffraction loads can change significantly if the MEC has a relative speed to the water. Potential flow solutions usually do not account for strong viscous effects like flow separation or skin friction which may be accounted for by other means. Other assumptions, limitations, and linearization of a wave radiation and diffraction solver should be checked with the particular requirements of a MEC unit for validity.

C.2.4.2.3 Nonlinear hydrodynamic and hydroelastic loading

Computational fluid dynamics (CFD) techniques that account for viscous and rotational effects in more detail than potential theory are evolving. Principally, CFD could solve the fluid dynamics problem fully and directly in some situations. However, these techniques can be extremely computationally intensive and in many cases are impractical to use for design purposes due to their complexity and long simulation run times.

C.2.4.2.4 Coupled and uncoupled analysis

An uncoupled analysis considers a floating MEC response either neglecting the mooring and umbilical restoring forces or using a linear stiffness to represent them. The resulting MEC motion response is then used to determine maximum mooring loads accordingly. In contrast, a coupled or global response analysis directly incorporates the mooring and MEC models. An uncoupled analysis is usually less complex due to the ability to compartmentalize the floating device and mooring models. When nonlinear mooring dynamic behaviour begins to have a substantial influence on MEC and PTO response, a coupled analysis shall be used. In shallow water conditions or when significant water elevation changes relative to water depth occur, significant mooring variations are expected and a coupled analysis shall be used.

C.2.4.2.5 Quasi static and quasi dynamic analysis

A quasi static approach uses RAO information to drive deflection of the mooring in different sea states to assess mooring loads. A quasi dynamic approach uses a dynamic MEC model along with a static line model. In both cases, the inertia and acceleration of the lines are ignored. This may produce substantial different results than a dynamic line model.

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Amendments Issued Since Publication

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