

INTERNATIONAL STANDARD

NORME INTERNATIONALE



**Wind energy generation systems –
Part 3-2: Design requirements for floating offshore wind turbines**

**Systèmes de génération d'énergie éolienne –
Partie 3-2: Exigences de conception des éoliennes en mer flottantes**



THIS PUBLICATION IS COPYRIGHT PROTECTED

Copyright © 2025 IEC, Geneva, Switzerland

All rights reserved. Unless otherwise specified, no part of this publication may be reproduced or utilized in any form or by any means, electronic or mechanical, including photocopying and microfilm, without permission in writing from either IEC or IEC's member National Committee in the country of the requester. If you have any questions about IEC copyright or have an enquiry about obtaining additional rights to this publication, please contact the address below or your local IEC member National Committee for further information.

Droits de reproduction réservés. Sauf indication contraire, aucune partie de cette publication ne peut être reproduite ni utilisée sous quelque forme que ce soit et par aucun procédé, électronique ou mécanique, y compris la photocopie et les microfilms, sans l'accord écrit de l'IEC ou du Comité national de l'IEC du pays du demandeur. Si vous avez des questions sur le copyright de l'IEC ou si vous désirez obtenir des droits supplémentaires sur cette publication, utilisez les coordonnées ci-après ou contactez le Comité national de l'IEC de votre pays de résidence.

IEC Secretariat
3, rue de Varembe
CH-1211 Geneva 20
Switzerland

Tel.: +41 22 919 02 11
info@iec.ch
www.iec.ch

About the IEC

The International Electrotechnical Commission (IEC) is the leading global organization that prepares and publishes International Standards for all electrical, electronic and related technologies.

About IEC publications

The technical content of IEC publications is kept under constant review by the IEC. Please make sure that you have the latest edition, a corrigendum or an amendment might have been published.

IEC publications search - webstore.iec.ch/advsearchform

The advanced search enables to find IEC publications by a variety of criteria (reference number, text, technical committee, ...). It also gives information on projects, replaced and withdrawn publications.

IEC Just Published - webstore.iec.ch/justpublished

Stay up to date on all new IEC publications. Just Published details all new publications released. Available online and once a month by email.

IEC Customer Service Centre - webstore.iec.ch/csc

If you wish to give us your feedback on this publication or need further assistance, please contact the Customer Service Centre: sales@iec.ch.

IEC Products & Services Portal - products.iec.ch

Discover our powerful search engine and read freely all the publications previews, graphical symbols and the glossary. With a subscription you will always have access to up to date content tailored to your needs.

Electropedia - www.electropedia.org

The world's leading online dictionary on electrotechnology, containing more than 22 500 terminological entries in English and French, with equivalent terms in 25 additional languages. Also known as the International Electrotechnical Vocabulary (IEV) online.

A propos de l'IEC

La Commission Electrotechnique Internationale (IEC) est la première organisation mondiale qui élabore et publie des Normes internationales pour tout ce qui a trait à l'électricité, à l'électronique et aux technologies apparentées.

A propos des publications IEC

Le contenu technique des publications IEC est constamment revu. Veuillez vous assurer que vous possédez l'édition la plus récente, un corrigendum ou amendement peut avoir été publié.

Recherche de publications IEC -

webstore.iec.ch/advsearchform

La recherche avancée permet de trouver des publications IEC en utilisant différents critères (numéro de référence, texte, comité d'études, ...). Elle donne aussi des informations sur les projets et les publications remplacées ou retirées.

IEC Just Published - webstore.iec.ch/justpublished

Restez informé sur les nouvelles publications IEC. Just Published détaille les nouvelles publications parues. Disponible en ligne et une fois par mois par email.

Service Clients - webstore.iec.ch/csc

Si vous désirez nous donner des commentaires sur cette publication ou si vous avez des questions contactez-nous: sales@iec.ch.

IEC Products & Services Portal - products.iec.ch

Découvrez notre puissant moteur de recherche et consultez gratuitement tous les aperçus des publications, symboles graphiques et le glossaire. Avec un abonnement, vous aurez toujours accès à un contenu à jour adapté à vos besoins.

Electropedia - www.electropedia.org

Le premier dictionnaire d'électrotechnologie en ligne au monde, avec plus de 22 500 articles terminologiques en anglais et en français, ainsi que les termes équivalents dans 25 langues additionnelles. Egalement appelé Vocabulaire Electrotechnique International (IEV) en ligne.

INTERNATIONAL STANDARD

NORME INTERNATIONALE



**Wind energy generation systems –
Part 3-2: Design requirements for floating offshore wind turbines**

**Systèmes de génération d'énergie éolienne –
Partie 3-2: Exigences de conception des éoliennes en mer flottantes**

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

COMMISSION
ELECTROTECHNIQUE
INTERNATIONALE

ICS 27.180

ISBN 978-2-8322-9825-1

**Warning! Make sure that you obtained this publication from an authorized distributor.
Attention! Veuillez vous assurer que vous avez obtenu cette publication via un distributeur agréé.**

CONTENTS

FOREWORD.....	8
INTRODUCTION.....	11
1 Scope.....	12
2 Normative references	13
3 Terms and definitions	14
4 Symbols, units and abbreviated terms	26
4.1 General.....	26
4.2 Symbols and units.....	26
4.3 Abbreviated terms.....	27
5 Principal elements	28
5.1 General.....	28
5.2 Design methods.....	28
5.3 Safety level for FOWT.....	30
5.4 Safety classes for RNA and tower.....	30
5.5 Quality assurance	30
5.6 Rotor–nacelle assembly markings.....	30
5.7 Support structure markings	31
6 External conditions – definition and assessment.....	31
6.1 General.....	31
6.2 Wind turbine classes.....	31
6.3 Definition of external conditions at a FOWT site.....	32
6.3.1 General	32
6.3.2 Wind conditions	32
6.3.3 Marine conditions	33
6.3.4 Electrical power network conditions	40
6.3.5 Other environmental conditions	40
6.4 Assessment of external conditions at a FOWT site.....	41
6.4.1 General	41
6.4.2 The metocean database	41
6.4.3 Assessment of wind conditions	42
6.4.4 Assessment of marine conditions.....	44
6.4.5 Assessment of other environmental conditions	48
6.4.6 Assessment of electrical network conditions	49
6.4.7 Assessment of soil conditions.....	49
7 Structural design	50
7.1 General.....	50
7.2 Design methodology	51
7.3 Loads.....	51
7.3.1 General	51
7.3.2 Gravitational and inertial loads	51
7.3.3 Aerodynamic loads	51
7.3.4 Actuation loads.....	51
7.3.5 Hydrodynamic loads	52
7.3.6 Sea/lake ice loads	52
7.3.7 Other loads.....	52
7.4 Design situations and load cases	52

7.4.1	General	53
7.4.2	Power production (DLC 1.1 to 1.6).....	63
7.4.3	Power production plus occurrence of fault or loss of electrical network connection (DLC 2.1 – 2.6)	64
7.4.4	Start up (DLC 3.1 to 3.3).....	66
7.4.5	Normal shutdown (DLC 4.1 to 4.3)	67
7.4.6	Emergency stop (DLC 5.1).....	68
7.4.7	Parked (standstill or idling) (DLC 6.1 to 6.5)	68
7.4.8	Parked plus fault conditions (DLC 7.1 and 7.2)	69
7.4.9	Transport, assembly, maintenance and repair (DLC 8.1 to 8.4).....	70
7.4.10	Redundancy check and damage stability (DLC F1.1 to F2.3)	74
7.5	Load and load effect calculations	75
7.5.1	General	75
7.5.2	Relevance of hydrodynamic loads.....	75
7.5.3	Calculation of hydrodynamic loads.....	76
7.5.4	Calculation of sea/lake ice loads.....	77
7.5.5	Overall damping assessment for support structure response evaluations.....	77
7.5.6	Simulation requirements	78
7.5.7	Other requirements.....	82
7.6	Limit state analysis	83
7.6.1	Method	83
7.6.2	Ultimate strength analysis.....	86
7.6.3	Fatigue analysis	87
7.6.4	Serviceability analysis	88
8	Control system	89
9	Mechanical systems	90
10	Electrical system	91
11	Anchor design	91
12	Assembly, transport and installation	91
12.1	General.....	91
12.2	Planning	92
12.3	Environmental conditions	92
12.4	Documentation.....	92
12.5	Transport, receiving, handling and storage	93
13	Commissioning, operation and maintenance	93
13.1	General.....	93
13.2	Design requirements for safe operation, inspection and maintenance	93
13.3	Commissioning	94
13.3.1	General	94
13.3.2	Energization	95
13.3.3	Commissioning tests.....	95
13.3.4	Records.....	95
13.3.5	Post commissioning activities	95
13.4	Operator's instruction manual	95
13.4.1	General	95
13.4.2	Instructions for operations and maintenance record	96
13.4.3	Instructions for unscheduled automatic shutdown	96
13.4.4	Instructions for diminished reliability	96

13.4.5	Work procedures plan	96
13.4.6	Emergency procedures plan	97
13.5	Maintenance manual	97
14	Stationkeeping systems	98
14.1	General.....	98
14.2	Catenary, semi-taut or taut stationkeeping systems	98
14.3	Tendon systems.....	99
14.4	Synthetic mooring	99
14.5	Stationkeeping system hardware.....	99
14.6	Dynamic power cable	99
15	Floating stability	100
15.1	General.....	100
15.2	Intact static stability criteria	101
15.3	Quasi static evaluation.....	101
15.4	Dynamic response evaluation	102
15.5	Damage stability criteria	102
16	Materials	103
17	Marine support systems.....	103
17.1	General.....	103
17.2	Bilge system	103
17.3	Ballast system	103
Annex A (informative)	Key design parameters for a floating offshore wind turbine (FOWT)	104
A.1	Floating offshore wind turbine (FOWT) identifiers.....	104
A.1.1	General	104
A.1.2	Rotor nacelle assembly (machine) parameters.....	104
A.1.3	Support structure parameters	105
A.1.4	Wind conditions (based on a 10-min reference period and including wind farm wake effects where relevant)	105
A.1.5	Marine conditions (based on a 3-hour reference period where relevant)	106
A.1.6	Electrical network conditions at turbine.....	107
A.2	Other environmental conditions.....	107
A.3	Limiting conditions for transport, installation and maintenance	108
Annex B (informative)	Guidance on calculation of hydrodynamic loads	109
B.1	General.....	109
B.2	Morison's equation.....	109
B.3	Diffraction and radiation theory	109
B.4	Slam loading	110
B.5	Vortex-induced vibrations and motions.....	110
B.6	Appurtenances and marine growth	111
B.7	Global analysis and fatigue analysis methods	111
B.8	Breaking wave loads	112
B.9	Air gap.....	112
Annex C (informative)	Floating offshore wind turbine (FOWT) anchor design	113
Annex D (informative)	Statistical extrapolation of operational metocean parameters for ultimate strength analysis	114
D.1	General.....	114
D.2	Use of IFORM to determine 50-yr significant wave height conditional on mean wind speed	114

D.3	Examples of joint distributions of V and H_S and approximations to the environmental contour	116
D.4	Choice of sea state duration	118
D.5	Determination of the extreme individual wave height to optionally be embedded in SSS	119
Annex E	(informative) Corrosion protection	120
E.1	General.....	120
E.2	The marine environment	120
E.3	Corrosion protection considerations	121
E.4	Corrosion protection systems – Support structures	121
E.5	Corrosion protection in the rotor-nacelle assembly	122
Annex F	(informative) Prediction of extreme wave heights during tropical cyclones.....	123
F.1	General.....	123
F.2	Wind field estimation for tropical cyclones.....	123
F.3	Wave estimation for tropical cyclones	124
Annex G	(informative) Recommendations for alignment of safety levels in tropical cyclone regions.....	125
G.1	General.....	125
G.2	Global robustness level criteria	125
G.3	Design load cases.....	125
Annex H	(informative) Earthquakes.....	127
Annex I	(informative) Model tests	128
Annex J	(informative) Tsunamis	131
J.1	General.....	131
J.2	Numerical model of tsunami [51], [52]	131
J.3	Evaluation of variance of water surface elevation and current velocity [5]	134
Annex K	(informative) Redundancy of stationkeeping system.....	135
Annex L	(informative) Differing limit state methods in IEC and ISO standards	136
Annex M	(informative) Application of load and load effect logic to floating substructure design.....	138
M.1	General.....	138
M.2	Typical load computation setups	138
M.3	Applied example	139
Annex N	(informative) Guidance on simulation length and associated parameters	140
N.1	General considerations	140
N.1.1	General	140
N.1.2	Initial transient time	140
N.1.3	Low-frequency dynamics sampling	140
N.1.4	Reference period	140
N.2	Simulations for fatigue limit state analysis.....	141
N.2.1	General	141
N.2.2	Response variance and reference period	141
N.2.3	Statistical convergence of damage	141
N.3	Simulations for extreme limit state analysis.....	141
N.3.1	General	141
N.3.2	Characteristic extreme consistency with the reference period	142
N.3.3	Characteristic value variability	142

Annex O (informative) Estimation of wave directional spreading by long wave method / single point measurement	143
O.1 Background.....	143
O.2 Linear free-wave extraction.....	144
O.3 Second-order calculation	144
Annex P (informative) Direction spreading function	146
Annex Q (informative) Concrete structures design	147
Q.1 General.....	147
Q.2 Design load cases.....	147
Q.2.1 Limit states in reinforced concrete design	147
Q.2.2 ULS, ALS and FLS load cases	148
Q.2.3 SLS load cases.....	148
Q.2.4 Load factors	148
Q.3 Design criteria	149
Q.3.1 Material factors.....	149
Q.3.2 ULS, ALS, FLS verifications.....	149
Q.3.3 SLS: Watertightness verification	150
Q.3.4 SLS: Crack-opening verification.....	150
Q.3.5 SLS: Limitation of stresses	150
Annex R (informative) Relationship between peak wave period and significant wave height in the sea areas affected by swell.....	151
R.1 General.....	151
R.2 Relationship between wave height and wave period in the sea areas affected by swell	151
Annex S (informative) Application of damage stability criteria	152
S.1 Objective	152
S.2 Scenario of loss of floating stability.....	152
S.3 Flow of application of new damage stability criteria	152
S.4 Definition of target probability of failure (PS).....	153
S.5 Definition of collision probability (P1)	154
S.6 Definition of total loss probability by ship collision (P2)	156
S.6.1 Concept of estimation of P2 and PT.....	156
S.6.2 Simplification of FEM analysis	156
S.6.3 Estimation of P2 by limit curve.....	158
S.7 Additional countermeasure to reduce P2.....	159
Bibliography.....	160
 Figure 1 – Parts of a floating offshore wind turbine (FOWT).....	16
Figure 2 – Rigid-body motion degrees of freedom of a floating substructure; <i>illustration by Alfred Hicks, National Renewable Energy Laboratory</i>	17
Figure 3 – Design process for a floating offshore wind turbine (FOWT).....	29
Figure 4 – Definition of water levels	38
Figure 5 – Top-down view of nacelle yaw and nacelle yaw misalignment in a simulation	62
Figure 6 – The two approaches to calculate the design load effect.....	84
Figure D.1 – Example of the construction of the 50-year environmental contour for a 3-hour sea state duration	115
Figure J.1 – The calculated result of Equation (J.8)	133

Figure M.1 – Example of load and load effect workflow for a hybrid "beams" and "nodes" floating substructure model setup	139
Figure O.1 – A typical 60-min (full-scale) time history spectrum with $H_s = 6,18$ m and $T_p = 10,36$ s recorded at the Ocean Engineering Wide Tank, University of Ulsan, Korea (South)	143
Figure R.1 – The relationship between significant wave height and significant wave period based on the measurement at Fukushima offshore site [2]	151
Figure S.1 – Concept flow of application of new damage stability criteria	153
Figure S.2 – Concept image of the approaching frequency	155
Figure S.3 – Concept of estimation of P2 and PT in a strict way.....	156
Figure S.4 – Concept of a limit curve	158
Figure S.5 – Concept of the probability of total loss probability by ship collision.....	158
Table 1 – Conversion between extreme wind speeds of different averaging periods.....	42
Table 2 – Design load cases	56
Table 3 – Safety factor for yield stress	87
Table G.1 – Additional load cases for tropical cyclone affected regions	126
Table L.1 – Mapping of limit states in ISO 19904-1 Table 4 and load cases from IEC 61400-3-2	137
Table Q.1 – Partial factors γ_F for actions for different limit states	149
Table Q.2 – Material factors γ_m for different limit states and materials	149
Table Q.3 – Allowable crack-width for different exposure zones	150
Table S.1 – Annual reliability of offshore structures	154

INTERNATIONAL ELECTROTECHNICAL COMMISSION

WIND ENERGY GENERATION SYSTEMS –**Part 3-2: Design requirements for floating offshore wind turbines**

FOREWORD

- 1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as "IEC Publication(s)"). Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
- 2) The formal decisions or agreements of IEC on technical matters express, as nearly as possible, an international consensus of opinion on the relevant subjects since each technical committee has representation from all interested IEC National Committees.
- 3) IEC Publications have the form of recommendations for international use and are accepted by IEC National Committees in that sense. While all reasonable efforts are made to ensure that the technical content of IEC Publications is accurate, IEC cannot be held responsible for the way in which they are used or for any misinterpretation by any end user.
- 4) In order to promote international uniformity, IEC National Committees undertake to apply IEC Publications transparently to the maximum extent possible in their national and regional publications. Any divergence between any IEC Publication and the corresponding national or regional publication shall be clearly indicated in the latter.
- 5) IEC itself does not provide any attestation of conformity. Independent certification bodies provide conformity assessment services and, in some areas, access to IEC marks of conformity. IEC is not responsible for any services carried out by independent certification bodies.
- 6) All users should ensure that they have the latest edition of this publication.
- 7) No liability shall attach to IEC or its directors, employees, servants or agents including individual experts and members of its technical committees and IEC National Committees for any personal injury, property damage or other damage of any nature whatsoever, whether direct or indirect, or for costs (including legal fees) and expenses arising out of the publication, use of, or reliance upon, this IEC Publication or any other IEC Publications.
- 8) Attention is drawn to the Normative references cited in this publication. Use of the referenced publications is indispensable for the correct application of this publication.
- 9) IEC draws attention to the possibility that the implementation of this document may involve the use of (a) patent(s). IEC takes no position concerning the evidence, validity or applicability of any claimed patent rights in respect thereof. As of the date of publication of this document, IEC had not received notice of (a) patent(s), which may be required to implement this document. However, implementers are cautioned that this may not represent the latest information, which may be obtained from the patent database available at <https://patents.iec.ch>. IEC shall not be held responsible for identifying any or all such patent rights.

IEC 61400-3-2 has been prepared by IEC technical committee 88: Wind energy generation systems. It is an International Standard.

This first edition cancels and replaces IEC TS 61400-3-2, published in 2019. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to IEC TS 61400-3-2:

- a) The relevant contents of IEC 61400-3-1 have been migrated into IEC 61400-3-2, making IEC 61400-3-2 a self-standing document that does not have to be read directly in conjunction with IEC 61400-3-1.

- b) Several modifications have been made regarding metocean conditions in Clause 6 considering the nature of FOWT and the offshore site where FOWT will be installed, including: (1) the importance of wave directional spreading has been highlighted as it may result in larger loads for FOWT, including the addition of the new informative Annex O and Annex P and (2) the characteristic of swell has been explained, which may be relevant for some FOWT projects, including the addition of new informative Annex R regarding the characteristic of swell.
- c) Subclauses 7.1, 7.2, 7.3, 7.4 and 7.5 have been changed to include a revised DLC table and its related descriptions, including amongst others updated requirements on directionality, wave conditions, redundancy check and damage stability cases, and a robustness check case; further updates are made related to guidance and necessities provided on load calculations and simulation requirements.
- d) Subclause 7.6 has been updated with guidance on fatigue assessment along with clarifications on serviceability analysis and the applicable material for WSD; related Annex L has been updated and a new Annex M has been added for clarification of the safety factors and load and load effect approach for floating substructures.
- e) The concept of floater control system that will interact with the wind turbine controller has been introduced in Clause 8.
- f) Clause 11 has been renamed from "Foundation and substructure design" to "Anchor design" and requirements for the transient conditions have been added.
- g) A more detailed clause regarding concrete design has been added to Clause 16 together with an informative Annex Q.
- h) Clause 15 has been updated with the aim to improve ease of use, using experience from oil and gas and considering unique wind turbine characteristics; updates included guidance for TLPs, damage stability, dynamic stability, testing and the addition for Annex S regarding how to analyse collision probability.

This International Standard is to be read in conjunction with IEC 61400-1, *Wind energy generation systems – Part 1: Design requirements*.

The text of this International Standard is based on the following documents:

Draft	Report on voting
88/1028/FDIS	88/1050/RVD

Full information on the voting for the approval of this International Standard can be found in the report on voting indicated in the above table.

The language used for the development of this International Standard is English.

This publication was drafted in accordance with the ISO/IEC Directives, Part 2, and developed in accordance with the ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/publications.

A list of all parts of the IEC 61400 series, published under the general title *Wind energy generation systems*, can be found on the IEC website.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under webstore.iec.ch in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn, or
- revised.

IMPORTANT – The "colour inside" logo on the cover page of this document indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

INTRODUCTION

This part of IEC 61400 outlines the minimum design requirements for floating offshore wind turbines (FOWT) and is not intended for use as a complete design specification or instruction manual.

Several different parties may be responsible for undertaking the various elements of the design, manufacture, assembly, installation, erection, commissioning, operation and maintenance of a FOWT and for ensuring that the requirements of this document are met. The division of responsibility between these parties is a contractual matter and is outside the scope of this document.

Any of the requirements of this document may be altered if it can be suitably demonstrated that the safety of the system is not compromised. Compliance with this document does not relieve any person, organization, or corporation from the responsibility of observing other applicable regulations.

WIND ENERGY GENERATION SYSTEMS –

Part 3-2: Design requirements for floating offshore wind turbines

1 Scope

This part of IEC 61400 specifies requirements for assessment of the external conditions at a floating offshore wind turbine (FOWT) site and specifies essential design requirements to ensure the engineering integrity of FOWTs. Its purpose is to provide an appropriate level of protection against damage from all anticipated hazards during the planned lifetime.

This document focuses on the engineering integrity of the structural components of a FOWT but is also concerned with subsystems such as control and protection mechanisms, internal electrical systems and mechanical systems.

A wind turbine shall be considered as a FOWT if the floating substructure is subject to hydrodynamic loading and supported by buoyancy and a stationkeeping system. A FOWT encompasses five principal subsystems: the RNA, the tower, the floating substructure, the stationkeeping system and the onboard machinery, equipment and systems that are not part of the RNA.

The following types of floating substructures are explicitly considered within the context of this document:

- ship-shaped structures and barges,
- semi-submersibles (Semi),
- spar buoys (Spar),
- tension-leg platforms/buoys (TLP / TLB).

This document can be utilized for structural types other than listed above, but special consideration may be needed to support novel features to achieve the same target safety level. These other structures can have a great range of variability in geometry, materials and structural forms and, therefore, can be only partly covered by the requirements of this document. In other cases, specific requirements stated in this document can be found not to apply to all or part of a structure under design. In all the above cases, conformity with this document will require that the design is based upon its underpinning principles and achieves a level of safety equivalent, or superior, to the level implicit in it.

This document is applicable to unmanned floating structures with one single horizontal axis turbine. While generally applicable, additional considerations may be needed, e.g., for multi-turbine units on a single floating substructure, vertical-axis wind turbines, FOWTs with shared moorings, spinning spars, floating structures without a stationkeeping system, or combined wind/wave energy systems.

This document is to be used together with the appropriate IEC and ISO standards mentioned in Clause 2. In particular, this document is fully consistent with the requirements of IEC 61400-1. In the event of requirements that may conflict between this document and the normative references, the requirements stated in this document supersede those of the references.

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 60721 (all parts), *Classification of environmental conditions*

IEC 61400-1:2019, *Wind energy generation systems – Part 1: Design requirements*

IEC 61400-3-1, *Wind energy generation systems – Part 3-1: Design requirements for fixed offshore wind turbines*

IEC 61400-13, *Wind turbines – Part 13: Measurements of mechanical loads*

IEC 61400-15-1, *Wind energy generation systems – Part 15-1: Site suitability input conditions for wind power plants*¹

IEC 61400-24, *Wind turbines – Part 24: Lighting protection*

IEC TS 61400-30:2023, *Wind energy generation systems – Part 30: Safety of wind turbine generators – General principles for design*

ISO 2394, *General principles on reliability for structures*

ISO 2533, *Standard Atmosphere*

ISO 18692-1, *Fibre ropes for offshore stationkeeping – Part 1: General specification*

ISO 18692-2, *Fibre ropes for offshore stationkeeping – Part 2: Polyester*

ISO 18692-3, *Fibre ropes for offshore stationkeeping – Part 3: High modulus polyethylene (HMPE)*

ISO 19900, *Petroleum and natural gas industries – General requirements for offshore structures*

ISO 19901-1, *Petroleum and natural gas industries – Specific requirements for offshore structures – Part 1: Metocean design and operating conditions*

ISO 19901-4, *Petroleum and natural gas industries – Specific requirements for offshore structures – Part 4: Geotechnical and foundation design considerations*

ISO 19901-6, *Petroleum and natural gas industries – Specific requirements for offshore structures – Part 6: Marine operations*

ISO 19901-7, *Petroleum and natural gas industries – Specific requirements for offshore structures – Part 7: Stationkeeping systems for floating offshore structures and mobile offshore units*

ISO 19902, *Petroleum and natural gas industries – Fixed steel offshore structures*

¹ Under consideration. Stage at the time of publication: IEC/AFDIS 61400-15-1:2023.

ISO 19903, *Petroleum and natural gas industries – Concrete offshore structures*

ISO 19904-1, *Petroleum and natural gas industries – Floating offshore structures – Part 1: Ship-shaped, semi-submersible, spar and shallow-draught cylindrical structures*

ISO 19906, *Petroleum and natural gas industries – Arctic offshore structures*

ISO 29400, *Ships and marine technology – Offshore wind energy – Port and marine operations*

API RP 2T, *Planning, Designing, and Constructing Tension Leg Platforms*

IMO *International Code on Intact Stability*, 2008 (2008 IS CODE), 2020 Edition

IMO *2009 MODU CODE*, 2020 Edition

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 61400-1 and the following apply.

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

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

3.1

air gap

clearance between the highest water surface that occurs during the extreme environmental conditions and the lowest exposed part not designed to withstand wave impingement

3.2

anchor

device attached to the end of the mooring line or tendon and partially or fully buried in the seabed to limit the movement of the mooring line or tendon and to transfer loads to the seabed

Note 1 to entry: Available options for anchoring floating structures include drag anchors, anchor piles (driven, jetted, suction, torpedo/gravity-embedded and drilled and grouted), and other anchor types such as gravity anchors and plate anchors.

3.3

blade pitch

rotational motion of the blade relative to the hub to control the angle between the blade and the wind

3.4

co-directional

acting in the same direction

3.5 control system

system implementing the turbine and FOWT support structure control functions, including sensors, logic elements, actuators, communication networks, and power supplies

Note 1 to entry: The intent of the control system is to control operation of the turbine and FOWT support structure by active and passive means to optimize the power yielding and keep the operating parameters within the limits assumed in the structural design of the whole FOWT. The control system is likely to include control loops for normal operation as well as alarms and shutdown mechanisms to ensure that limits are not exceeded.

Note 2 to entry: There may be a separate control system for turbine operation and the FOWT support structure.

3.6 current

flow of water past a fixed location usually described in terms of a current speed and direction

3.7 diffraction

physical phenomenon describing the influence of a floating substructure on the incoming wave field

Note 1 to entry: Diffraction constitutes part of the wave excitation hydrodynamic load on the floating substructure.

3.8 design wave

deterministic wave with a defined height, period and direction, used for the design of an offshore structure

Note 1 to entry: A design wave may be accompanied by a requirement for the use of a particular periodic wave theory.

3.9 designer

party or parties responsible for the design of a FOWT

3.10 dynamic power cable

dynamic and submerged electrical cable feeding or collecting power from a floating substructure, the dynamic part being located from the hang-off of the floating substructure to either the touch-down point or to another floating substructure

3.11 environmental conditions

characteristics of the environment (wind, air and sea temperature, waves, sea currents, water level, sea/lake ice, marine growth, scour and overall seabed movement, etc.) which may affect the behaviour of a FOWT

3.12 external conditions

external factors affecting operation of a FOWT, including environmental conditions, electrical network conditions, and other climatic factors (temperature, snow, ice, etc.)

3.13 extreme significant wave height

significant wave height of the sea state over the reference period with an annual probability of exceedance of $1/N$ ("return period": N years), extrapolated from the extreme distribution of significant wave height at the site

3.14

extreme wave height

individual wave height (generally the zero up-crossing wave height) with an annual probability of exceedance of $1/N$ ("return period": N years)

3.15

fast ice cover

rigid continuous cover of ice not in motion

3.16

fetch

distance over which the wind blows over the sea with approximately constant wind speed and direction

3.17

fixed offshore wind turbine

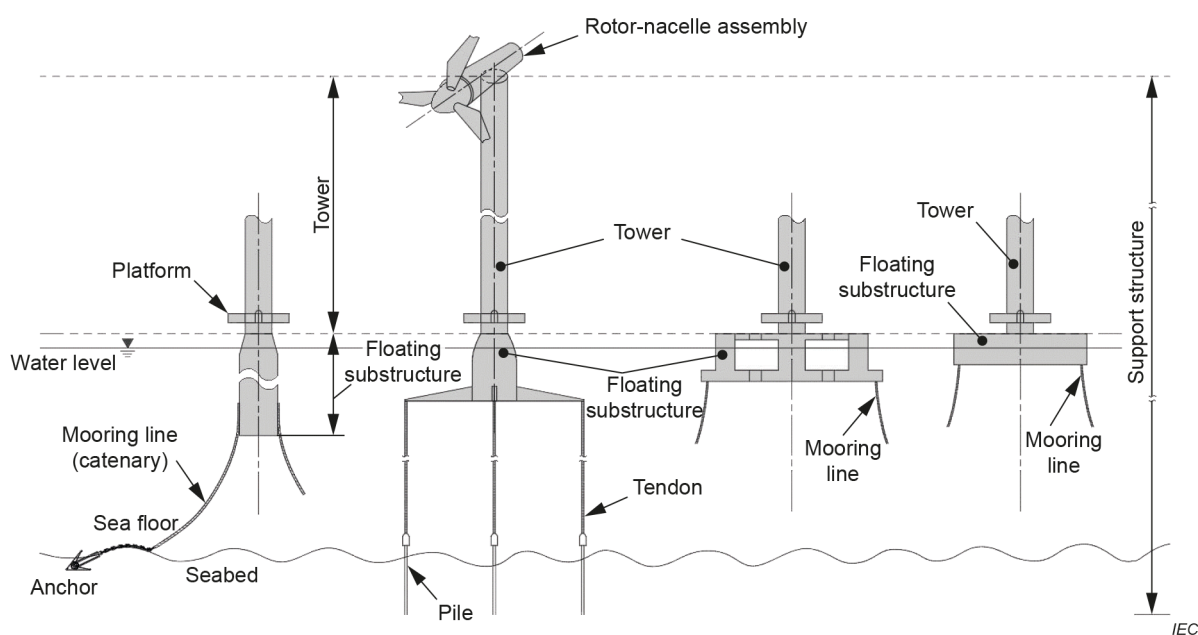
wind turbine with a substructure that is subject to hydrodynamic loading and is founded on the seabed

3.18

floating offshore wind turbine

wind turbine with a floating substructure that is subject to hydrodynamic loading and is supported by buoyancy and a station-keeping system

Note 1 to entry: Different FOWT support structure concepts are shown in Figure 1 together with the other parts of a FOWT support structure.



From left to right: Spar, TLP, Semisubmersible and Barge.

Figure 1 – Parts of a floating offshore wind turbine (FOWT)

3.19

floating offshore wind turbine site

location or intended location of an individual FOWT either alone or within a wind farm

3.20

floating stability

ability of a floating substructure to generate restoring moment after deviation from an equilibrium floating position

Note 1 to entry: Generally, verification of floating stability applies to both intact and damage conditions.

3.21

floating substructure

part of a FOWT support structure that floats above the sea floor, connects to the tower and stationkeeping system, and consists of a buoyant structure for supporting operational loads

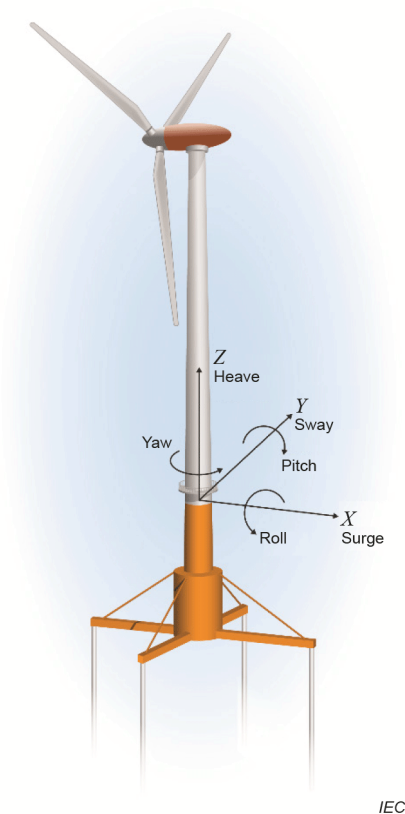
Note 1 to entry: A floating substructure can also be referred to as a hull. Different floating substructure concepts are shown in Figure 1 together with the other parts of a FOWT.

3.22

heave

translational up or down motion of the floating substructure

Note 1 to entry: The six rigid-body motion degrees of freedom of a floating substructure – surge, sway, heave, roll, pitch and yaw – are illustrated in Figure 2.



IEC

Figure 2 – Rigid-body motion degrees of freedom of a floating substructure; *illustration by Alfred Hicks, National Renewable Energy Laboratory*

Note 2 to entry: The coordinate system shown in Figure 2 is for reference only and may be defined by the designer.

3.23

highest astronomical tide

highest still water level that can be expected to occur under any combination of astronomical conditions and under average meteorological conditions

Note 1 to entry: Storm surges, which are meteorologically generated and essentially irregular, are superimposed on the tidal variations, so that a total still water level above highest astronomical tide may occur.

3.24

hindcasting

method of simulating historical (metocean) data for a region through numerical modelling

3.25

hub height

height of the centre of the swept area of the wind turbine rotor above the mean sea level

3.26

hummocked ice

crushed ice and ice floes piled up into ridges when large ice floes meet with each other or with a rigid obstacle, for example a floating substructure

3.27

ice floe

sheet of ice in size from metres to several kilometres, not rigidly frozen to a shore, still or in motion

3.28

icing

build-up of a cover of ice or frost on parts of a FOWT that can result in added loads and/or changed properties

3.29

land-locked waters

waters almost or entirely surrounded by land

3.30

load effect

effect of a single load or combination of loads on a structural component or system, for example internal force, stress, strain, motion, etc.

3.31

lowest astronomical tide

lowest still water level that can be expected to occur under any combination of astronomical conditions and under average meteorological conditions

Note 1 to entry: Storm surges, which are meteorologically generated and essentially irregular, are superimposed on the tidal variations, so that a total still water level below lowest astronomical tide may occur.

3.32

manufacturer

party or parties responsible for the manufacture and construction of a FOWT

3.33

marine conditions

characteristics of the marine environment (waves, sea currents, water level, sea/lake ice, marine growth, seabed movement and scour, etc.) which may affect the behaviour of a FOWT

3.34**marine growth**

surface coating on structural components caused by plants, animals and bacteria

3.35**mean sea level**

average level of the sea over a period of time long enough to remove variations due to waves, tides and storm surges

3.36**mean zero crossing period**

average period of the zero-crossing (up or down) waves in a sea state

Note 1 to entry: Relations exist between mean zero crossing period and peak period.

3.37**metocean**

abbreviation of meteorological and oceanographic

3.38**misaligned (for wind and waves)**

acting from different directions

3.39**mooring system**

passive type of stationkeeping system that typically comprises mooring lines, anchors, connectors and hardware and may include other components such as buoys, clamped weights, turrets, disconnecting system, etc.

3.40**moving ice**

portions of sea/lake ice that move under the action of wind and/or currents

3.41**multi-directional (for wind and waves)**

acting in multiple directions

3.42**nacelle yaw**

for turbines with an active or passive nacelle-yaw control mechanism, degree of freedom determining the orientation of the RNA with respect to the tower (and by extension the floating substructure)

3.43**operational draft**

draft of the floating substructure, measured from the bottom of the keel to the SWL without environmental excitation (no wind, no wave and no current), in operational conditions, meaning in-place with the wind turbine, stationkeeping system and dynamic power cable fully installed and ballasted for operation

Note 1 to entry: Operational draft is generally a fixed value for a given FOWT design. However, it may have a small range of values for specific FOWT designs, for example, depending on tide level ranges for a TLP or depending on variations in marine growth.

3.44

operational limit

value of a certain physical parameter defined in the design basis such as acceleration, inclination, heel, displacement, excursion, frequency, rpm, voltage, strain, pressure, wind speed, wave height, etc. that satisfies the most demanding of the prescribed operating criteria for a specified FOWT to ensure its operation within acceptable Reliability and Safety criteria

3.45

peak wave period

period of the peak energy in the wave spectrum

3.46

pitch

floating substructure rotational motion about an axis aligned with the sway direction

Note 1 to entry: The six rigid-body motion degrees of freedom of a floating substructure – surge, sway, heave, roll, pitch and yaw – are illustrated in Figure 2.

3.47

power collection system

electrical system that collects the power from one or more FOWTs

Note 1 to entry: The power collection system includes all electrical equipment connected between the wind turbine terminals and the network connection point. For offshore wind farms, the power collection system may include the connection to shore.

3.48

radiation (hydrodynamic)

physical phenomenon describing the wave field generated by the oscillation of a floating substructure in water

Note 1 to entry: Radiation depends on the floating substructure degree of freedom and oscillation frequency. The most common hydrodynamic load components of radiation are added mass and radiation damping.

3.49

recognized classification society

member of the International Association of Classification Societies (IACS), with recognized and relevant competence and experience in floating structures

3.50

redundancy (for stationkeeping system)

state of a FOWT stationkeeping system when following a loss of one mooring line or tendon, the FOWT will be kept within a confined area by the damaged stationkeeping system and will not interfere with other structures, such that no further consequences of the loss of the mooring line or tendon will take place

Note 1 to entry: Dynamic infield power cable rupture and power shutdown due to FOWT drift-off may be an accepted solution based on owner/developer approval.

3.51

reference period

period during which stationarity is assumed for a given stochastic process, for example wind speed, sea elevation or response

3.52

refraction

process by which wave energy is redistributed as a result of changes in the wave propagation velocity due to variations in water depth and/or current velocity

3.53**roll**

floating substructure rotational motion about an axis aligned with the surge direction

Note 1 to entry: The six rigid-body motion degrees of freedom of a floating substructure – surge, sway, heave, roll, pitch and yaw – are illustrated in Figure 2.

3.54**rotor–nacelle assembly**

part of a FOWT carried by the support structure

3.55**scantling**

sizing of plates, girders and stiffeners of floating substructures

3.56**sea floor**

interface between the sea and the seabed

3.57**sea floor slope**

local gradient of the sea floor, for example associated with a beach

3.58**sea/lake ice**

frozen seawater or lake freshwater

3.59**sea state**

condition of the sea in which its statistics remain stationary

3.60**seabed**

materials below the sea floor in which a support structure is founded

3.61**seabed movement**

movement of the seabed due to natural geological processes

3.62**scour**

removal of seabed soils by currents and waves or caused by structural elements interrupting the natural flow regime above the sea floor

3.63**semisubmersible**

floating substructure normally consisting of a top structure with a number of widely spaced, large cross-section, supporting columns connected to submerged pontoons or heave plates

Note 1 to entry: Pontoon/column geometry is usually chosen to minimize global motions in a broad range of wave frequencies.

3.64**shallow water**

depth in which the presence of the seabed has a pronounced effect on the wave hydrodynamics

3.65**significant wave height**

statistical measure of the height of waves in a sea state, defined as either the average height of the highest one third of the zero up-crossing waves or as $4 \times \sigma_\eta$ where σ_η is the standard deviation of the sea surface elevation

Note 1 to entry: The former height is called the statistical significant wave height (usually denoted $H_{1/3}$ ², while the latter height is called the spectral significant wave height (denoted by H_s or H_{m0}).

3.66**significant wave period**

statistical measure of the period of waves in a sea state, defined as the average period of the highest one third of the zero up-crossing waves, denoted $T_{1/3}$

Note 1 to entry: Relations exist between the peak period T_p and $T_{1/3}$.

3.67**spar**

deep-draught, small water-plane area floating substructure

3.68**splash zone**

external region of the FOWT support structure that is frequently wetted due to turbine operation, wave, tidal variations and floating substructure motions

Note 1 to entry: To define upper and lower limit of the splash zone, the following parameters shall be considered where applicable to the specific FOWT support structure type:

- the highest still water level with a return period of 1 year increased by the crest height of a wave with height equal to the significant wave height with a return period of 1 year,
- the lowest still water level with a return period of 1 year reduced by the trough depth of a wave with height equal to the significant wave height with a return period of 1 year,
- the shallowest and deepest operational draft, and
- the per direction average heel angle of the floating substructure during normal turbine operation.

Areas of the support structure that are only wetted during major storms (beyond a return period of 1 year) are not considered in the splash zone.

3.69**stationkeeping system**

system capable of limiting the excursions and/or accelerations of the FOWT within prescribed limits and maintaining the intended orientation

Note 1 to entry: A stationkeeping system may differ from a mooring system in the case of active thrusters, tendons, etc.

3.70**still water level**

abstract water level calculated by including the effects of tides and storm surge but excluding variations due to waves

Note 1 to entry: Still water level can be above, at, or below mean sea level.

3.71**storm surge**

change in water level caused by atmospheric change and/or wind associated with a storm

² In deep water, $H_{1/3} \approx 0,956 H_s$ regardless of wave spectral form (ISO 21650:2007).

3.72**structural dynamics model**

numerical model or sequence of models used to compute the physics-based response of the FOWT structure, including the environmental excitation (wind, waves, current), control actions and full-system structural response (rotor, drivetrain, nacelle, tower, floating substructure, and stationkeeping system)

3.73**support structure**

part of FOWT consisting of the tower, floating substructure, and stationkeeping system

SEE: Figure 1.

3.74**surge**

translational fore or aft motion of the floating substructure

Note 1 to entry: The six rigid-body motion degrees of freedom of a floating substructure – surge, sway, heave, roll, pitch and yaw – are illustrated in Figure 2.

3.75**sway**

translational side-to-side motion of the floating substructure

Note 1 to entry: The six rigid-body motion degrees of freedom of a floating substructure – surge, sway, heave, roll, pitch and yaw – are illustrated in Figure 2.

3.76**swell**

sea state in which waves generated by winds remote from the site have travelled to the site, rather than being locally generated

3.77**tendon**

collection of components of a stationkeeping system that forms a tensioned vertical or near-vertical link between the TLP-type floating substructure and the anchor on and beneath the sea floor for the purpose of providing stationkeeping and floating stability to FOWTs

3.78**tension leg platform**

vertically moored, buoyant, compliant structural system wherein excess buoyancy of the floating substructure (in excess of weight and tendon loads) maintains tension in the mooring system

3.79**tidal current**

current resulting from tides

3.80**tidal range**

vertical distance between the highest astronomical tide and the lowest astronomical tide

3.81**tides**

regular and predictable movements of the sea generated by astronomical forces

3.82**tower**

part of a FOWT support structure which connects the floating substructure to the rotor-nacelle assembly

3.83

tsunami

long period sea waves caused by rapid vertical movements of the sea floor

3.84

uni-directional (for wind and waves)

acting in a single direction

3.85

upwell

wave elevation relative to the floating substructure

3.86

water depth

vertical distance between the sea floor and the still water level

Note 1 to entry: As there are several definitions for the still water level (see 3.70) there can be several water depth values.

3.87

wave crest elevation

vertical distance between the crest of a wave and the still water level

3.88

wave direction

mean direction from which the wave is travelling

3.89

wave height

vertical distance between the highest and lowest points on the water surface of an individual zero up-crossing wave

3.90

wave period

time interval between the two zero up-crossings which bound a zero up-crossing wave

3.91

wave spectral peak frequency

frequency of the peak energy in the wave spectrum, the inverse of the wave peak period

3.92

wave spectrum

frequency domain description of the sea surface elevation in a sea state

3.93

wave steepness

ratio of the wave height to the wave length

3.94

weather downtime

one or more intervals of time during which the environmental conditions are too severe to allow for execution of a specified marine operation

3.95

weather window

interval of time during which the environmental conditions allow for execution of a specified marine operation

3.96**wind profile – wind shear law**

mathematical expression for assumed wind speed variation with height above still water level

Note 1 to entry: Commonly used profiles are the logarithmic profile (equation (1)) and the power law profile (equation (2)).

$$V(z) = V(z_r) \times \frac{\ln(z/z_0)}{\ln(z_r/z_0)} \quad (1)$$

$$V(z) = V(z_r) \times \left(\frac{z}{z_r} \right)^\alpha \quad (2)$$

where

$V(z)$ is the wind speed at height z ;

z is the height above the still water level;

z_r is a reference height above the still water level used for fitting the profile;

z_0 is the roughness length;

α is the wind shear (or power law) exponent.

3.97**wind sea**

sea state being generated by local winds

3.98**yaw**

floating substructure rotational motion about an axis aligned with the heave direction

Note 1 to entry: The six rigid-body motion degrees of freedom of a floating substructure – surge, sway, heave, roll, pitch and yaw – are illustrated in Figure 2.

3.99**zero up-crossing wave**

portion of a time history of wave elevation between zero up-crossings

Note 1 to entry: A zero up-crossing occurs when the sea surface rises (rather than falls) through the still water level.

4 Symbols, units and abbreviated terms

4.1 General

For the purposes of this document, the symbols and abbreviated terms given in IEC 61400-1 and the following apply:

4.2 Symbols and units

A_C	Charnock's constant	[-]
d	water depth	[m]
$f_{\text{low frequency}}$	upper end of low-frequency range	[Hz]
f_p	wave spectral peak frequency	[Hz]
g	acceleration due to gravity	[m/s ²]
H	individual wave height	[m]
H_B	breaking wave height	[m]
H_N	individual wave height with a return period of N years	[m]
H_s	spectral significant wave height	[m]
H_{sN}	spectral significant wave height with a return period of N years	[m]
$H_{1/3}$	statistical significant wave height	[m]
k	wave number	[-]
K_{max}	accumulated freezing degree-days	[°C]
L_k	velocity component integral scale parameter	[m]
$p(V_{\text{hub}})$	probability density function of hub height wind speed	[-]
R_d	design value for component resistance	[-]
R_k	characteristic value for component resistance	[-]
S_d	design value for load effect	[-]
$S.F.$	safety factor	[-]
S_k	characteristic value for load effect	[-]
S_η	single sided wave spectrum	[m ² /Hz]
t	time	[s]
T	wave period	[s]
T_p	peak spectral period	[s]
T_z	mean zero-crossing wave period	[s]
U_N	current velocity, with a return period of N years	[m/s]
U_{ss}	sub surface current velocity	[m/s]
U_w	wind-generated current velocity	[m/s]
V_N	expected extreme wind speed (averaged over 10 min), with a return period of N years	[m/s]
V_{eN}	expected extreme wind speed (averaged over 3 s), with a return period of N years	[m/s]
z	vertical distance above SWL	[m]

α	wind speed power law shear exponent	[-]
η	sea surface elevation relative to SWL	[m]
κ	von Karman's constant	[-]
λ	wave length	[m]
θ_c	current direction	[°]
θ_w	wave direction	[°]
θ_{wm}	mean wave direction	[°]
$\sigma_{\text{allowable}}$	allowable stress	[N/m ² or Pa]
σ_{buckling}	allowable buckling stress	[N/m ² or Pa]
σ_y	specified minimum yield strength	[N/m ² or Pa]
σ_{cr}	critical compressive buckling stress or shear buckling stress	[N/m ² or Pa]
σ_η	sea surface elevation standard deviation	[m]
τ	temperature	[°C]

4.3 Abbreviated terms

COD	co-directional
CPT	cone penetration test
DLC	design load case
ECD	extreme coherent gust with direction change
ECM	extreme current model
EDC	extreme direction change
EOG	extreme operating gust
ESS	extreme sea state
EWLR	extreme water level range
EWM	extreme wind speed model
EWS	extreme wind shear
FMEA	failure modes and effects analysis
FOWT	floating offshore wind turbine
HAT	highest astronomical tide
IACS	International Association of Classification Societies
IMO	International Maritime Organization
ITTC	International Towing Tank Conference
LAT	lowest astronomical tide
MIC	microbiologically influenced corrosion
MIS	misaligned
MODU	mobile offshore drilling unit
MSL	mean sea level
MUL	multi-directional
NCM	normal current model

NSS	normal sea state
NTM	normal turbulence model
NWLR	normal water level range
NWP	normal wind profile model
RCS	recognized classification society
RNA	rotor-nacelle assembly
SSS	severe sea state
SWL	still water level
TLB	tension-leg buoy
TLP	tension-leg platform
UNI	uni-directional
WSD	working stress design

5 Principal elements

5.1 General

The engineering and technical requirements to ensure the safety of the structural, mechanical, electrical and control systems of a FOWT are given in this document. This specification of requirements applies to the design, manufacture, transport (including towing), assembly, installation and manuals for operation and maintenance of a FOWT and the associated quality management process. In addition, safety procedures, which have been established in the various practices that are used in the transport, assembly, installation, operation and maintenance of a FOWT, are taken into account.

5.2 Design methods

This document requires the use of a structural dynamics model to predict design load effects. Such a model shall be used to determine the load effects for all relevant combinations of external conditions and design situations as defined in Clause 6 and Clause 7 respectively. A minimum set of such combinations has been defined as load cases in this document.

The design of the support structure of a FOWT shall be based on site-specific external conditions. These shall therefore be determined in accordance with the requirements stated in Clause 6. The conditions shall be summarized in the design basis.

The design of the FOWT support structure shall include the design of the stationkeeping system per Clause 14 and consider floating stability per Clause 15. The offset requirements, metocean conditions and corresponding loads on the floating substructure induced by the dynamic power cable system and the potential for clashing with the floating substructure and stationkeeping system shall be taken into account. Consideration shall be given to the submerged weight, mechanical response characteristics and hang-off location.

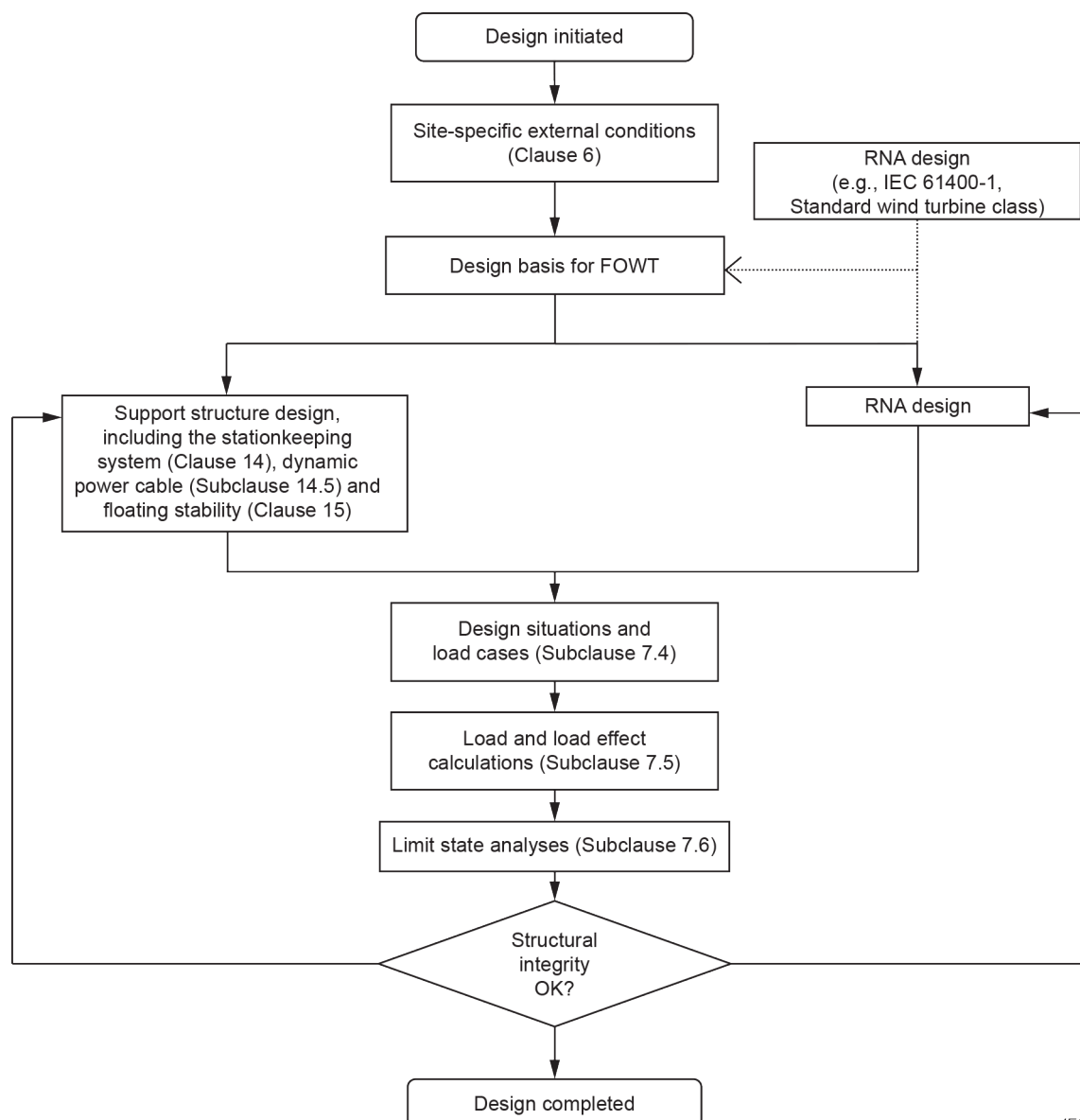
In the case of the rotor–nacelle assembly, which may have been designed initially on the basis of a standard wind turbine class as defined in IEC 61400-1:2019, 6.2, it shall be demonstrated that the FOWT support structure and the site-specific offshore conditions do not compromise the RNA structural integrity. The demonstration shall comprise a comparison of loads and deflections in the RNA calculated for the specific FOWT support-structure and the specific site conditions with those calculated during initial design.

The design of the control and protection system (see Clause 8), mechanical systems (see Clause 9) and electrical system (Clause 10) shall be verified taking account of the dynamic response of the FOWT.

The design process for a FOWT is illustrated in Figure 3. The figure indicates the key elements of the design process and identifies the corresponding relevant clauses of this standard. The process is iterative and shall incorporate load and load effect calculations for the complete wind turbine comprising the integrated support structure and rotor–nacelle assembly. The structural design of a FOWT may be regarded as completed when its structural integrity has been verified based on the limit state analyses defined in 7.6.

Data from full-scale testing of the RNA shall be used to increase confidence in predicted design values and to validate structural dynamics models and design situations. Data from full-scale testing of the FOWT support structure may similarly be used, if available. Guidance relating to the measurement of mechanical loads for full-scale wind turbine testing is available in IEC 61400-13. Data from model-scale testing should be used to confirm the response of a particular floating substructure configuration, to validate structural dynamics models and design situations, and to confirm that no extraordinary or unexpected behaviour of the tested configuration occurs (see Annex I).

Verification of the adequacy of the design shall be made by calculation and should be supported by testing. For guidance regarding how model tests can be utilized in the design process, see Annex I.



IEC

Figure 3 – Design process for a floating offshore wind turbine (FOWT)

5.3 Safety level for FOWT

The safety level of the FOWT designed according to this document shall be at or exceed the level inherent in IEC 61400-1.

The FOWT is unmanned-except for occasional inspection and maintenance visits-and the consequences of a potential failure of a FOWT are considered as moderate. This characterization corresponds to the medium (L2) exposure level as defined in ISO 19900 series. Care should be taken because ISO 19901-7 and ISO 19904-1 standards do not specify safety factors and return periods for medium (L2) exposure level. As a consequence, return periods, safety factors and methods provided in the present standard differ from those found in ISO 19900 series. Considering the FOWT as an L2 structure is equivalent to the safety level discussed in IEC 61400-1. Additional considerations for ISO 19900 series and IEC 61400 series approach for limit state analyses are provided in Annex L.

5.4 Safety classes for RNA and tower

An RNA shall be designed according to one of the following two safety classes:

- a normal safety class that applies when a failure results in risk of personal injury or other social or economic consequence;
- a special safety class that applies when the safety requirements are determined by local regulations and/or the safety requirements are agreed between the manufacturer and the customer.

Partial safety factors for normal safety class RNAs are specified in IEC 61400-1.

Partial safety factors for special safety class RNAs shall be agreed upon between the manufacturer and the customer. An RNA designed according to the special safety class shall be classified as a class S wind turbine as defined in IEC 61400-1.

IEC 61400-1 defines safety levels consistent with the safety level defined in clause 5.3 for the FOWT. Safety classes from IEC 61400-1 can be applied to the tower.

5.5 Quality assurance

Quality assurance shall be an integral part of the design, procurement, manufacture, installation, commissioning, operation and maintenance, and decommissioning of FOWTs and all their components.

5.6 Rotor–nacelle assembly markings

The following information, as a minimum, shall be prominently and legibly displayed on the indelibly marked rotor–nacelle assembly nameplate:

- RNA manufacturer and country;
- model and serial number;
- production year;
- rated power;
- reference wind speed, V_{ref} ;
- hub height operating wind speed range, $V_{in} - V_{out}$;
- operating ambient temperature range;
- IEC wind turbine class (see IEC 61400-1);
- rated voltage at the wind turbine terminals;
- frequency at the wind turbine terminals or frequency range in the case that the nominal variation is greater than 2 %.

5.7 Support structure markings

The following information, as a minimum, shall be prominently and legibly displayed on the indelibly marked FOWT support structure (including floating substructure) nameplate:

- draft marking (combined load line markings for operating in sea operation);
- unit identification;
- company and registered owner identification;
- markings required by local authorities.

6 External conditions – definition and assessment

6.1 General

FOWTs are subjected to environmental and electrical conditions, including the influence of nearby turbines, that may affect their loading, durability and operation. To ensure the appropriate level of safety and reliability, environmental, electrical and soil parameters shall be taken into account in the design and shall be explicitly stated in the design documentation.

The environmental conditions are divided into wind conditions, marine conditions (waves, sea currents, water level, sea/lake ice, marine growth, seabed movement and scour) and other environmental conditions. The electrical conditions refer to the electrical power network conditions. Soil properties are relevant to the design of the FOWT anchor and stationkeeping system.

The structural integrity shall be demonstrated taking proper account of the environmental conditions at each specific site at which the FOWT will be subsequently installed.

The design process for a FOWT is shown in Figure 3. The assessment of site-specific external conditions is the first step in the design process and forms the basis for the design. This clause therefore specifies both the definition and assessment of the external conditions.

The external conditions are subdivided into normal and extreme categories. The normal external conditions generally concern recurrent structural loading conditions, while the extreme external conditions represent rare external design conditions. The design load cases shall consist of critical combinations of these external conditions for specified joint return periods with wind turbine operational modes and other design situations.

The definition and assessment of the normal and extreme external conditions to be considered in design are specified in 6.2 to 6.4.

The abbreviations added in parentheses in the subclause headings in the remainder of this clause are used for describing the external conditions for the design load cases defined in 7.4.

6.2 Wind turbine classes

The external conditions to be considered in design are dependent on the intended site or site type for a FOWT installation. In IEC 61400-1 wind turbine classes are defined in terms of wind speed and turbulence parameters. The intention of the classes is to cover most onshore applications. IEC 61400-1 includes a specific class for tropical cyclone conditions ("T class"). Additional guidance on tropical cyclone conditions is available in Annex G of this document.

There are some principal differences between offshore and onshore wind conditions. However, for a FOWT the definition of classes in terms of wind speed and turbulence parameters remains appropriate as the basis of design of the rotor–nacelle assembly (RNA). As stated in 5.2 it shall be demonstrated subsequently that site-specific external conditions do not compromise the structural integrity of the rotor–nacelle assembly.

The manufacturer shall in the design documentation describe the models used and values of essential design parameters. Where the models described in Clause 6 are adopted, a statement of the values of the parameters will suffice. The design documentation should contain the information listed for guidance in Annex A.

6.3 Definition of external conditions at a FOWT site

6.3.1 General

A FOWT shall be designed to safely withstand the wind conditions and marine conditions adopted as the basis of design.

The wind regime and marine conditions for load and safety considerations are divided into the normal conditions which occur frequently during normal operation of a FOWT, and the extreme conditions which are defined as having a 1-year or 50-year return period. A 500-year return period is also used for a robustness check of the FOWT support structure.

NOTE The normal range of water levels is, however, defined in this document as the variation in water level with a return period of 1 year, refer to 6.3.3.4.2.

The extreme conditions are intended to produce N -year ($N = 1, 50$ or 500) return period load effects (cross-sectional loads, deformations, etc.). Combining marginal N -year events directly will in general produce load effects of longer return period than N years. The more environmental parameters that are combined in this way, the more conservative the design potentially becomes. For the assessment of the combined wind and marine environment, several parameters are relevant for the load effects of offshore turbines. Thus for FOWT design, the assessment of joint environmental conditions by specifying associated conditions instead of direct combinations of marginal conditions of equal return period is appropriate. The N -year response can alternatively be determined using a response based long-term analysis where all the actual metocean parameters are taken into account at each time step of a storm. Care should be taken however that rare combination of events may be difficult to extrapolate. API RP 2MET can be used for guidance.

To determine joint environmental conditions for design, the approach of environmental contours can be used. The joint environmental conditions to be designed for are then defined as those among all conditions on the environmental contour that cause the most extreme response for the given return period. The possible dynamic response shall be considered in the assessment. By this approach joint wind speeds, wave heights, wave periods, water levels, directional relations etc. may be established.

The application of the method of environmental contours, or other probabilistic methods, generally requires information defining the long-term joint probability distributions of wind and marine conditions. In practice not all environmental conditions are typically measured simultaneously. Environmental contours are instead developed for subsets of parameters – e.g. wave heights and water level, wave height and wave period, etc.

The following clauses define the predominant marginal extreme conditions to consider as a minimum, e.g., N -year return wind and marine conditions. Conditions to associate with these shall be established. In the absence of sufficient information to develop site-specific environmental contours, conservative alternatives are provided.

6.3.2 Wind conditions

The wind parameters defined in IEC 61400-1 are appropriate for the offshore environment. Site-specific conditions representative of the FOWT site shall be assessed in accordance with the requirements stated in 6.4.3.

It should be ensured that the representation of the power spectrum of the turbulence and the sampling of turbulence by the rotor in the low-frequency range are adequate to obtain suitable excitation of low-frequency modes of the FOWT.

6.3.3 Marine conditions

6.3.3.1 General

Care should be taken when the combined wind and wave input to the load simulations is defined so as not to disregard important sea states.

The effect of swell is not explicitly included in standard wave spectrum based on a single significant wave height and period, but may not be negligible in the area where swell exists and considered appropriately. The effect of swell may affect the response of FOWT in conjunction with low-frequency responses of FOWTs and multi directionality of the wave spectrum, i.e., the prevailing wave direction may be different for wind wave and swell. Wind-wave misalignment cases leading to bi-directional wave loading may require specific attention for FOWTs and shall be taken into account. This may be particularly important for load cases driving tower-base fatigue.

The marine conditions described in this subclause include waves, sea currents, water level, sea ice, marine growth, scour and seabed movement. Other external conditions relevant to the offshore environment are defined in 6.3.5.

6.3.3.2 Waves

6.3.3.2.1 General

Waves are irregular in shape, vary in height, length and speed of propagation, and may approach a FOWT from one or more directions simultaneously. The features of a real sea are best reflected by describing a sea state by means of a stochastic wave model.

The stochastic wave model represents the sea state as the superposition of many small individual frequency components, each of which is a periodic wave with its own amplitude, frequency and direction of propagation; the components have random phase relationships to each other. A design sea state shall be described by a wave spectrum, S_{η} , together with the significant wave height, H_s , a peak spectral period, T_p , and a mean wave direction, θ_{wm} , or a peak wave direction, θ_{wp} . Where appropriate, the wave spectrum may be supplemented with a directional spreading function. Standard wave spectrum formulations are provided in ISO 19901-1.

Periodic or regular waves can be used as an abstraction of a real sea for design purposes with appropriate justification. A deterministic design wave shall be specified by its height, period and direction.

The correlation of wind conditions and waves shall be taken into account for the design of a FOWT. This correlation shall be considered in terms of the long-term joint probability distribution of relevant parameters, e.g.:

- mean wind speed, V ;
- significant wave height, H_s ;
- peak spectral period, T_p ; and
- water depth, d .

The joint probability distribution of these parameters is affected by local site conditions such as fetch, water depth, bathymetry, etc. The distribution shall therefore be determined from suitable long-term measurements and/or by the use of numerical hindcasting techniques whichever is appropriate, refer to 6.4.4.

The correlation of normal wind conditions and waves shall also consider wind-wave misalignment, i.e. consideration of mean wind and wave directions (separation of wind sea and swell may also be considered). The multi-directional distributions of wind and wave directions can have an important influence on the loads acting on the support structure. The importance of this influence will depend on the nature of the wind and wave directionality and on properties of the support structure such as eigenfrequencies, modal damping, mode shapes and geometrical symmetry. The designer may, in some cases, demonstrate by appropriate analysis that it is conservative and therefore acceptable to assume that the wind and waves are aligned (co-directional) and acting from a single, worst case direction (uni-directional).

Alternatively, the designer may demonstrate by appropriate analysis that it is conservative and therefore acceptable to assume that the wind and waves are misaligned and acting from two, worst case directions (for example, 90° misalignment may be the worst case because of the consequential lack of aerodynamic damping). The assumptions regarding wind and wave directions are considered for each design load case in 7.4.

When taking account of the wind and wave misalignment, particular care shall be taken to ensure that the directional data and wind turbine modelling techniques are reliable, refer to 7.5.

The combined extreme event of wind, waves, water level, and other relevant parameters shall ensure that global extreme environmental actions with return periods of 1 year and 50 years are considered. The geometric and dynamic properties of the support structure may imply that several combined events shall be specified.

Wave models are defined in 6.3.3.2.2 to 6.3.3.2.5 in terms of sea state representations including stochastic linear wave models and regular non-linear design waves. The stochastic wave models shall be based on a wave spectrum appropriate to the site anticipated for the FOWT.

As long as the sea state is stationary, H_s and T_p are independent of reference period. To determine the joint probability distribution of V_{hub} , H_s , and T_p , a one hour averaging period shall be used to define the mean wind speed against which to correlate the significant wave height and peak spectral period.

In any cases, the spreading of the wave may be important for the load calculation of FOWT and should be considered. Neglect of the spreading may cause less conservative results, e.g., the underestimation of fluctuating yaw motion of the floating substructure, which is different from fixed wind turbines. See Annex O, Annex P and ISO19901-1 for more detailed information on wave spreading.

6.3.3.2.2 Normal sea state (NSS)

The significant wave height, peak spectral period and direction for each normal sea state shall be selected, together with the associated mean wind speed, based on the long-term joint probability distribution of metocean parameters appropriate to the anticipated site.

For fatigue load calculations, the designer shall ensure that the number and resolution of the normal sea states considered are sufficient to account for the fatigue damage associated with the full long-term distribution of metocean parameters.

For ultimate load calculations, the normal sea states considered shall be those sea states characterised by the expected value of the significant wave height, H_s , and peak spectral period, T_p , conditioned on a given value of mean wind speed. The designer shall take account of the range of peak spectral period, T_p , appropriate to each significant wave height. Design calculations shall be based on values of peak spectral period which result in the highest loads acting on the FOWT.

6.3.3.2.3 Severe sea state (SSS)

The severe sea state model shall be considered in combination with normal wind conditions for calculation of the ultimate loading of a FOWT during power production. The severe sea state model associates a severe sea state with each mean wind speed in the range corresponding to power production. The significant wave height, $H_{s,SSS}(V)$, for each severe sea state shall in general be determined by extrapolation of appropriate site-specific metocean data such that the combination of the significant wave height and the mean wind speed has a return period of 50 years. It is recommended that the extrapolation of metocean data be undertaken using the so-called Inverse First Order Reliability Method (IFORM). This method is described in Annex D which also gives guidance on how to determine $H_{s,SSS}(V)$ from site-specific environmental conditions. Alternative methods for environmental contours are also introduced in Annex D.

To improve convergence, the severe sea state may optionally include the extreme individual wave height that, in combination with the associated wave period and the mean wind speed, has a return of 50 years. In this case, the designer shall take account of the range of wave period, T , appropriate to each extreme wave height. In the absence of a more sophisticated probabilistic assessment, design calculations shall assume values of wave periods within this range that result in the highest loads acting on a FOWT.

For all mean wind speeds, the unconditional extreme significant wave height, H_{s50} , with a return period of 50 years may be used as a conservative value for $H_{s,SSS}(V)$. Similarly, it is conservative to adopt the extreme individual wave height H_{50} for the extreme individual wave height in the severe sea state. This approach may be used in the absence of information defining the long-term joint probability distribution of wind and waves.

6.3.3.2.4 Extreme sea state (ESS)

The extreme sea state model shall be considered for combined global environmental actions with return periods of 1 year, 50 years and 500 years. The designer may need to investigate a number of extreme sea states combined with, for example, different water levels to determine the appropriate extreme sea state(s) for design, refer 6.3.3.4.3 and 6.3.3.3.5. The extreme significant wave height (H_{s500} , H_{s50} or H_{s1}) shall be included in the sea state and the extreme individual wave height (H_{500} , H_{50} or H_1) may optionally be included to improve convergence. In this case, the designer shall take account of the range of wave period, T , appropriate to each extreme wave height. Design calculations shall assume values of wave periods within this range that result in the highest loads acting on a FOWT.

The extreme sea state(s) shall be determined from analysis of appropriate site-specific metocean data (i.e. measurements and/or hindcast data) for the FOWT site, refer to 6.4.4.

In the absence of information defining the long-term joint probability distribution of extreme wind and waves, it shall be assumed that the extreme 10-min mean wind speed with a 50-year return period occurs during the extreme 3-hour sea state with a 50-year return period. The same assumption shall apply with regard to the combination of the extreme 10-min wind speed and the extreme 3-hour sea state each with a 1-year return period. When used, the extreme individual wave height shall be assumed to occur at a random time during the simulation of the extreme sea state.

6.3.3.2.5 Breaking waves

The influence of breaking waves shall be assessed during the design of a FOWT. Breaking waves are classified as spilling, plunging or surging, the first two types being relevant to sites suitable for FOWTs. The water depth, sea floor slope and wave period determine whether the form of the breaking wave is expected to be spilling or plunging. In addition, wave breaking may be triggered by the presence of the structure itself.

Guidance is provided in Annex B relating to the calculation of the loading applied by a breaking wave to a FOWT support structure.

6.3.3.3 Sea currents

6.3.3.3.1 General

Although sea currents may, in principle, vary in space and time, they are generally considered as a horizontally uniform flow field of constant velocity and direction, varying only as a function of depth. The following components of sea current velocity shall be taken into account:

- sub-surface currents generated by tides, storm surge and atmospheric pressure variations, etc.;
- wind-generated, near-surface currents.

The total current velocity is the vector sum of these components. Wave induced water particle velocities and current velocities shall similarly be added vectorially. The influence of sea currents on the relationship between wave length and wave period is generally small and may be neglected, refer to ISO 19901-1, A.8.4.3 for further guidance. Other site-specific current components may exist, such as near shore, wave induced surf currents running parallel to the coast.

6.3.3.3.2 Sub-surface currents

The sub-surface current profile may be characterised by a simple power law over the water depth d , where the current velocity $U_{ss}(z)$ is defined as a function of height z above SWL:

$$U_{ss}(z) = U_{ss}(0) \left[(z + d)/d \right]^{1/7} \quad (3)$$

The 1-year and 50-year return period values of the sea surface velocity $U_{ss}(0)$ may be determined from analysis of appropriate measurements at the FOWT site, refer to 6.4.4.3.

In general, it is conservative to assume that the sub-surface currents are aligned with the wave direction.

6.3.3.3.3 Wind-generated, near-surface currents

The wind-generated current may be characterised as a linear distribution of velocity $U_w(z)$ reducing from the surface velocity $U_w(0)$ to zero at a depth of 20 m below SWL:

$$U_w(z) = U_w(0) (1 + z/20) \quad (4)$$

At sites where the water depth is less than 20 m, the wind-generated current velocity at the sea floor will be non-zero.

The wind-generated sea surface current velocity may be assumed to be aligned with the wind direction, and may be estimated from

$$U_w(0) = 0,01 V_{1\text{-hour}}(z = 10 \text{ m}) \quad (5)$$

where $V_{1\text{-hour}}(z = 10 \text{ m})$ is defined as the 1-hour mean value of wind speed at 10 m height above SWL.

The 1-year and 50-year return period values of $V_{1\text{-hour}}(z = 10 \text{ m})$ may be determined from analysis of appropriate measurements at the FOWT site. These wind speeds may then be used with equation (5) to estimate the 1-year and 50-year return values of wind-generated sea surface current velocity.

6.3.3.3.4 Normal current model (NCM)

The normal current model is defined as the appropriate site-specific combination of wind-generated currents and tidal currents. The normal current model excludes storm-generated sub-surface currents. Normal tidal currents shall be accounted for as the mean of tidal current speeds.

The normal current model shall be assumed for those load cases involving normal and severe wave conditions (NSS, SSS) and for each load case the velocity of the wind-generated currents may be estimated from the relevant mean wind speed, refer to 6.3.3.3.3.

6.3.3.3.5 Extreme current model (ECM)

The extreme current model shall be considered for those ultimate load cases associated with extreme wave conditions (ESS). Currents associated with ESS shall result in combined global environmental actions with return periods of 1 year, 50 years and 500 years and are denoted by U_1 , U_{50} and U_{500} , respectively. Load calculations shall be undertaken based on the currents which result in the highest loads acting on a FOWT.

These extreme values shall be determined from analysis of appropriate site-specific metocean data (i.e. measurements and/or hindcast data) for the FOWT site, refer to 6.4.4.

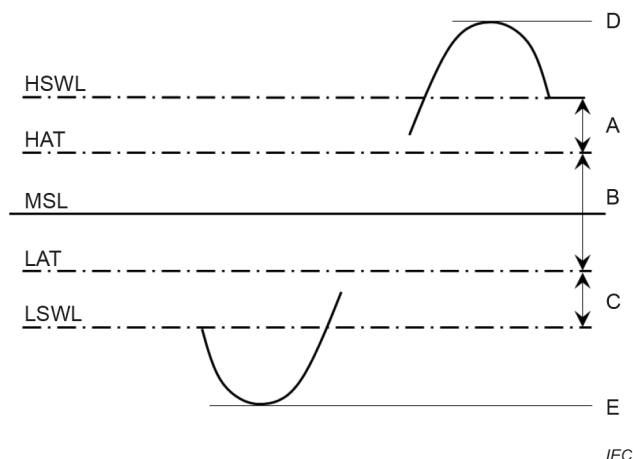
In the absence of information defining the long-term joint probability distribution of extremes it is conservative to apply currents with return period of 1 year and 50 years and to assume the current to be co-directional with the waves.

6.3.3.4 Water level

6.3.3.4.1 General

The water depth range shall be determined where relevant for FOWT design.

Different water levels are illustrated in Figure 4.



Key

HSWL	highest still water level	A	positive storm surge
HAT	highest astronomical tide	B	tidal range (equal to NWLR, see clause 6.3.3.4.2)
MSL	mean sea level	C	negative storm surge
LAT	lowest astronomical tide	D	maximum crest elevation
LSWL	lowest still water level	E	minimum trough elevation

Figure 4 – Definition of water levels

6.3.3.4.2 Normal water level range (NWLR)

The normal water level range shall be assumed equal to the long-term difference between highest astronomical tide (HAT) and lowest astronomical tide (LAT).

The NWLR shall be assumed for those fatigue and ultimate load cases involving the normal sea state model (NSS) based on the joint probability distribution of sea state conditions and wind speed (H_s , T_p , V_{hub}). The NWLR range shall also be assumed for ultimate load cases associated with

- severe sea state (SSS);
- wave conditions with a return period of 1 year.

Ultimate load calculations shall be undertaken based on either the water level within the NWLR that results in the highest loads, or by appropriate consideration of the probability distribution of water levels within the NWLR.

For ultimate load cases associated with the severe stochastic sea state (SSS) model, the water levels corresponding to NWLR may cause the wave heights to be depth-limited. If this is the case, and in order to avoid the wave heights being depth-limited, a higher water level within the extreme water level range (EWLR) shall then be assumed.

For the calculation of the hydrodynamic fatigue loads the designer may in some cases demonstrate by means of an appropriate analysis that the influence of water level variation on fatigue loads is negligible or can be accounted for in a conservative manner by assuming a constant water level greater than or equal to the mean sea level.

6.3.3.4.3 Extreme water level range (EWLR)

The extreme water level range shall be assumed for ultimate load cases associated with wave conditions with a return period of 50 years (ESS). Combination with ESS shall result in combined global environmental actions with a return period of 50 years. The designer may need to investigate a number of representations of the ESS combined with different water levels. Load calculations shall be undertaken based on the water levels which result in the highest loads acting on a FOWT. The relevant design driving water levels shall be determined for calculation of the hydrodynamic loading, ice loading and the buoyancy of the floating substructure.

In the absence of the long-term joint probability distribution of metocean parameters including water level, the designer shall at least undertake calculations based on the following water levels:

- highest still water level with a return period of 50 years, based on an appropriate combination of highest astronomical tide and positive storm surge;
- lowest still water level with a return period of 50 years, based on an appropriate combination of lowest astronomical tide and negative storm surge;
- water level associated with the highest breaking wave load.

6.3.3.5 Sea/lake ice

At some locations, loading of the floating support structure of a FOWT due to sea/lake ice can be critical. The ice loads may be associated with static loading from a fast ice cover, or dynamic loading caused by wind and current induced motion of ice floes. Moving ice floes impacting the floating support structure over a considerable period of time may result in significant loading. A site-specific assessment of the occurrence and properties of the sea/lake ice shall be undertaken as stated in 6.4.4.5.

6.3.3.6 Marine growth

Marine growth influences the mass, the geometry, and the surface roughness of the floating substructure and the stationkeeping and dynamic cable systems of a FOWT. Consequently, marine growth may influence hydrodynamic loads, dynamic response, accessibility and the rate of corrosion of the structure.

Marine growth may be considerable at some locations and shall be taken into account in the design of the FOWT support structure.

Marine growth is broadly divided into "hard" (generally animal such as mussels and barnacles) and "soft" (seaweeds and kelps), where hard growth is generally thinner but rougher than soft growth. Marine organisms generally colonize a structure soon after installation but the growth rate tapers off after a few years.

The nature and thickness of marine growth depends on the structural member's position relative to the sea level, orientation relative to dominant current, age and maintenance strategy; but also on other site conditions such as salinity, oxygen content, pH value, current, and temperature.

The corrosion environment is normally modified by marine growth in the upper submerged zone and the lower part of the splash zone of the FOWT support structure. Depending on the type of marine growth and other local conditions, the net effect may be either to enhance or retard corrosion attack. Enhancement of corrosion processes by marine growth (e.g. through corrosive metabolites) is commonly referred to as Microbiologically Influenced Corrosion (MIC). Marine growth may further interfere with systems for corrosion control, including coatings/linings and cathodic protection.

Due to the uncertainties involved in assumptions regarding marine growth, a strategy for inspection and possible removal of marine growth should be planned as part of the FOWT design. The frequency, inspection method and growth removal criteria shall be based on the impact of marine growth on the structural reliability of a FOWT, and the extent of experience with marine growth under the specific conditions prevailing at the site.

6.3.3.7 Seabed movement and scour

The anchors of a FOWT shall be designed taking account of the influence of seabed movement and scour. The analysis of seabed movement and scour, and the design of appropriate protection shall conform to the requirements of ISO 19901-4 and ISO 19901-7. Requirements regarding the assessment of seabed conditions are stated in 6.4.4.7.

6.3.4 Electrical power network conditions

The conditions at the FOWT terminals are to be determined for the specific installation as described in 6.4.6.

6.3.5 Other environmental conditions

Environmental (climatic) conditions other than wind and marine conditions can affect the integrity and safety of a FOWT, by thermal, photochemical, corrosive, mechanical, electrical or other physical action. Moreover, combinations of the climatic parameters may increase their effects.

The following other environmental conditions shall at least be taken into account and the action taken stated in the design documentation:

- air temperature;
- humidity;
- air density;
- solar radiation;
- rain, hail, snow and ice;
- ice and snow accumulation;
- chemically active substances;
- mechanically active particles;
- salinity causing corrosion;
- lightning;
- seismicity causing earthquakes and/or tsunamis;
- water density;
- water temperature.

The climatic conditions taken into account shall be defined in terms of either representative values or limits of the variable conditions. The probability of simultaneous occurrence of climatic conditions shall be taken into account when the design values are selected.

Variations in the climatic conditions within the normal limits which correspond to a 1-year return period, or more often, shall not interfere with the designed normal operation of a FOWT.

Unless correlation exists, other extreme environmental conditions according to 6.4.5.3 shall be combined with the normal wind conditions according to IEC 61400-1 and normal marine conditions according to 6.3.3.

Specific attention should be paid to the assessment of the seismic analysis in the case of TLP/TLB-type floating substructures, see Annex H.

6.4 Assessment of external conditions at a FOWT site

6.4.1 General

The external conditions at a FOWT site shall be assessed in accordance with the requirements of the following subclauses.

The partial safety factors for loads referenced in 7.6.2.2 assume that the site assessment of the normal and extreme metocean conditions has been carried out according to the minimum requirements of this Subclause 6.4.

6.4.2 The metocean database

A site-specific metocean database shall be established containing information on

- wind speeds and directions;
- significant wave heights, wave periods and directions;
- correlation of wind and wave statistics;
- current speeds and directions;
- water levels;
- occurrence and properties of sea/lake ice and occurrence of their drift directions and drift speeds;
- occurrence of icing of the turbine and its FOWT support structure;
- other relevant metocean parameters such as air and water temperatures and densities, water salinity, site bathymetry, marine growth, etc.

The database may be established from site-specific measurements supported, where appropriate, by numerical simulations (hindcasts). If site-specific measurements are used, the results shall generally be correlated with data from a nearby location for which long-term measurements exist, unless the results can otherwise be shown to be conservative. The monitoring period for the site-specific measurements shall be sufficient to ensure reliable statistics for the individual parameters as well as the joint probability distribution of these parameters. If only correlation analysis of measured data is to be undertaken, the location of the long-term measurements should be less than 50 km from the prospective FOWT site and the water depth, the fetch and the bathymetry should be similar at the two locations. When correlating the long-term data with the wind turbine site-specific short-term data, care should be taken that the correlation is adequate and that the uncertainty of the correlation analysis can be estimated. Should the location of the long-term measurements be more than 50 km from the prospective wind turbine site, it is advisable also to undertake numerical simulations (hindcasts) to estimate the site's metocean statistics. Long-term site-specific measurements shall not generally be required when correlation with suitable long-term data from a nearby location is undertaken or when numerical tools can be reliably applied for transposing the long-term data to the wind turbine site.

Time series measurements may be of particular importance in order to characterise wave heights, periods and wave spectra at shallow water sites.

When assessing the quality and quantity of data, special attention should be given to the adequacy of the data with respect to extrapolation to very infrequent events.

6.4.3 Assessment of wind conditions

6.4.3.1 General

The site wind parameters shall be either measured and extrapolated, or calculated using appropriate methods (e.g. monitoring measurements made at the site, long-term records from local meteorological stations, simulation models or local codes and standards). The methods described in 11.3 of IEC 61400-1:2019 and IEC 61400-15-1 apply with the deviations specified below.

Values of the following parameters shall be estimated at the wind turbine site in addition to those specified in IEC 61400-1:

- extreme 10-min average wind speed $V_{1,\text{hub}}$ at hub height with a return period of 1 year;
- wind speed standard deviation $\hat{\sigma}$ from the ambient turbulence (estimated as the mean value of the standard deviation of the longitudinal component) and the standard deviation $\hat{\sigma}_\sigma$ of $\hat{\sigma}$ at V_{hub} between V_{in} and V_{out} and V_{hub} equal to V_{ref} .

High values of wind shear have been reported for extended periods of time for certain areas in connection with highly stratified flow or severe roughness changes. However, for the gust models which employ the mean wind profile (i.e. EOG, ECD, EWS as defined in IEC 61400-1) the shear may be assumed equal to the mean wind shear. This is justified because these models are concerned with gusts generated by turbulence, which implies that shear values associated with high turbulence levels are appropriate.

The interval of any wind speed bin used in the above shall be 2 m/s or less, and the wind direction sectors shall be 30° or less. IEC 61400-1 requires that all parameters, except for air density, be available as functions of wind direction and given as 10-min averages. Because the offshore environment generally exhibits less directional variation than the onshore environment, providing omnidirectional information for parameters such as shear and turbulence is acceptable unless precluded by coastal effects for near-shore sites or nearby obstacles.

The site extreme wind parameters shall be either:

- measured in the range of 0,2 V_{ref} to 0,4 V_{ref} and extrapolated, or
- derived from a correlation analysis of short-term monitoring measurements made at the site and long-term records from local meteorological stations, or from local codes or standards, or
- based on experience of nearby sites. In this case the assumption of similarity between the sites is to be justified.

Where site-specific extreme average wind speeds are available only for averaging periods longer than 10 min, the conversion factors stated in Table 1 may be used to estimate the extreme 10-min average wind speed. The factors in this table give the ratio between the extreme wind speed for a given averaging period and the extreme 10-min average wind speed.

Table 1 – Conversion between extreme wind speeds of different averaging periods

Averaging period	10 min	1 h	3 h
Correction factor relative to extreme 10-min average wind speed	1,00	0,95	0,90

The long-term probability distribution of mean wind speed, V_{hub} , may be assumed to be independent of averaging period for periods in the range between 10 min and 3 h³.

6.4.3.2 IEC 61400-1 wind conditions applied to rotor-nacelle assembly design

In the case that the wind conditions specified in IEC 61400-1 are used as the basis of design of the rotor–nacelle assembly, the following variations to the parameter values may be assumed:

- the inclination of the mean flow with respect to a horizontal plane is zero;
- the wind profile, $V(z)$, denotes the average wind speed as a function of height, z , above the still water level. In the case of standard wind turbine classes, the normal wind speed profile is given by the power law:

$$V(z) = V_{\text{hub}} \left(z/z_{\text{hub}} \right)^{\alpha} \quad (6)$$

where, for normal wind conditions, the power law exponent, α , is 0,14.

6.4.3.3 Assessment of ambient free stream turbulence

The value of the ambient free stream turbulence standard deviation shall be determined using appropriate statistical techniques applied to measured and preferably de-trended data. Where topographical (shore line) or other local effects may influence the turbulence intensity, these effects shall be represented in the data. The characteristics of the anemometer, sampling rate and averaging time used to obtain measured data shall be taken into account when evaluating the turbulence intensity.

Where no site data for turbulence is available, the turbulence standard deviation σ_1 may be estimated using the surface roughness parameter z_0 derived from the Charnock expression for atmospheric conditions that are near-neutral:

$$z_0 = \frac{A_C}{g} \left[\frac{\kappa \times V_{\text{hub}}}{\ln(z_{\text{hub}}/z_0)} \right]^2 \quad (7)$$

where

g is the acceleration due to gravity;

κ 0,4 is von Karman's constant, and

A_C is Charnock's constant.

A_C 0,011 is recommended for open sea and $A_C = 0,034$ may be used for near-coastal locations. The surface roughness parameter and resulting turbulence standard deviation calculated using the Charnock equation apply for open sea conditions. Care should be taken in cases where the influence of shore topology and onshore roughness may lead to higher values of turbulence standard deviation. Use of the higher value of the coefficient is recommended unless site specific data confirm otherwise.

³ This assumption might not be valid at the tail of long-term probability distribution, for mean wind speeds exceeding V_{out} .

The roughness of the sea surface increases with wind speed and thus the turbulence intensity will increase as a function of wind speed in near-neutral conditions. At many offshore sites, it has been found that average turbulence intensity offshore is high at low wind speeds, decreases to a minimum at wind speeds of approximately 8 to 12 m/s (at 10 m reference height) and then increases slowly with increasing wind speed.

The roughness parameter is found by solving the above implicit equation and, in turn, the standard deviation of the longitudinal wind speed component may be calculated from

$$\sigma_1 = \frac{V_{\text{hub}}}{\ln(z_{\text{hub}}/z_0)} + 1,28 \times d \times I_{15} \quad d = 4 \text{ m/s} \quad (8)$$

where I_{15} is the average value of hub height turbulence intensity determined at $V_{\text{hub}} = 15 \text{ m/s}$. The use of the assumption of near-neutral conditions (as equation (7)) will, in general, give low average values for the standard deviation of the longitudinal wind speed component and is not valid for representing tropical cyclone conditions⁴.

Models accounting for non-neutral atmospheric conditions offshore have been proposed. The models in "H. Wang, R. J. Barthelmie, S. C. Pryor and H. G. Kim, *A new turbulence model for offshore wind turbine standards*, Wind Energy, Volume 17, Issue 10, pages 1587–1604, October 2014" may be applied if no other information is available. They represent three different levels of turbulence spanning the range from far offshore to very near-shore with complex terrain onshore. Care shall be taken when justifying the level to adopt.

In the absence of suitable site-specific data to estimate the turbulence standard deviation with a 1-hour averaging period, this may be assumed to be related to the 10-min average turbulence standard deviation by

$$\sigma_{i,1\text{-hour}} = \sigma_{i,10\text{-min}} + b; \quad b = 0,2 \text{ m/s} \quad (9)$$

6.4.3.4 Assessment of wake effects from neighbouring wind turbines

The assessment of wake effects from neighbouring wind turbines shall be undertaken in accordance with the requirements stated in IEC 61400-1. Guidance is provided in IEC 61400-1:2019, Annex E, regarding site-specific conditions.

6.4.4 Assessment of marine conditions

6.4.4.1 Assessment of extreme wave conditions

The following extreme sea state parameters shall be estimated:

- the significant wave height with a return period of 500 years assuming a 3 h reference period, H_{s500} ;
- the significant wave height with a return period of 50 years assuming a 3 h reference period, H_{s50} ;

⁴ The standard deviation $4\text{m/s} \times I_{15}$ in equation (8) differs from $1,44\text{m/s} \times I_{15}$ specified in IEC 61400-1 because significantly larger standard deviations have been recorded at some offshore locations. Hence, this parameter should be carefully evaluated for the specific site, accounting for available information from similar or neighbouring sites. Further, the specification of Weibull-distributed turbulence intensity in the IEC 61400-1 class definition is not generally valid offshore, which influences the assessment of ETM.

- the significant wave height with a return period of 1 year assuming a 3 h reference period, H_{s1} ;
- the extreme individual wave height with a return period of 500 years, H_{500} and the associated range of wave periods;
- the extreme individual wave height with a return period of 50 years, H_{50} and the associated range of wave periods;
- the extreme individual wave height with a return period of 1 year, H_1 and the associated range of wave periods;
- the extreme crest height with a return period of 50 years.

The extreme significant wave height and the extreme individual wave height may be determined in several ways. The most appropriate approach is based on statistical analysis of peak storm significant wave heights of the metocean database above a certain threshold. The extreme individual wave heights may be established by convolution of the long-term distribution of the significant wave height H_s and peak spectral period T_p , with the conditional short term distribution of individual wave height H given the significant wave height H_s . Reference is made to Clause 8 of ISO 19901-1. The extreme wave heights may, however, be limited by water depth.

Breaking waves may occur at the site of a FOWT depending on the water depth, sea floor slope, wave height, period and steepness.

Annex F provides guidance on assessment of extreme wave conditions during tropical cyclone conditions.

In the case that the metocean data is insufficient to assess the extreme wave height and the range of associated wave periods, for deep water it may be assumed that:

$$H = 1,86 H_s \quad (10)$$

which is obtained as the most probable maximum wave in a 3-hour reference period sea-state with significant wave height H_s assuming a Rayleigh distribution of wave heights and 1 000 waves, i.e. the 0,1 % exceedance quantile of the Rayleigh distribution. Associated with this wave height, the following wave period range can be applied

$$11,1 \sqrt{H_s/g} \leq T \leq 14,3 \sqrt{H_s/g} \quad (11)$$

It should be noted that the equation above is the relation for wind generated waves. A FOWT may be installed at sites where swell may have a significant impact on FOWT response. In such sites, longer periods than the value specified in equation (11) may be observed. For details, see Annex R.

For a given wave height, the wave period has a depth-dependent lower limit which is determined from the breaking wave height limit. Note that in deep water the ratios H_{50}/H_{s50} and H_1/H_{s1} are usually in the range 1,9 to 2,0. For shallow water sites where measurements are not available, H_{50} and H_1 shall be assumed equal to the breaking wave height in cases where the latter is less than 2,0 times the value of the appropriate H_s .

6.4.4.2 Assessment of normal wave conditions

For the normal sea states, the site-specific metocean database shall be analysed in order to establish the long-term joint probability distribution of the following parameters:

- mean wind speed at hub height, V_{hub} ;
- significant wave height, H_s ;
- peak spectral period, T_p .

Note that this is a minimum requirement and in the case where the use of standard wave spectrum is not appropriate, more wave parameters or discrete wave spectrum including two dimensional spectrum of frequency and direction may be considered. For example, in case swell and wind-induced wave are both dominant and spectrum with two peak is used for design, additional parameters are needed.

In 6.3.3.2.2 defining NSS a 1-hour averaging period is required for the establishment of the long-term joint probability distribution of V_{hub} , H_s , and T_p . If the available joint statistical data for V_{hub} , H_s , and T_p are based on a different averaging period, the data shall be converted to be based on a 1-hour averaging period for the wind speed. The correlation between V_{hub} , H_s , and T_p may increase with a longer averaging period because the build-up of waves under the influence of wind happens over a period of hours. However, depending on the specific characteristics of the site, the correlation may not change significantly with the averaging period and therefore it may be reasonable to assume that the long-term joint probability distribution of V_{hub} , H_s and T_p is independent of averaging period.

If necessary, the joint probability distribution shall be extended to include wind and wave directions although site-specific measurements allowing the derivation of the joint occurrence of these five parameters are often not available⁵. The resolution of the joint probability distribution shall be such that the interval of any wind speed bin shall be 2 m/s or less, the interval of any significant wave height bin shall be 0,5 m or less, and the interval of any wave period bin shall be 0,5 s or less. The intervals of significant wave height and wave period bins may be increased if the calculated fatigue loads are not less conservative; this may be demonstrated using appropriate representative values. If directional data are available, the widths of wind and wave direction sectors shall be 30° or less.

6.4.4.3 Assessment of currents

In addition to their impact on the loading of the support structure of a FOWT, currents affect the location and orientation of boat landings and fenders and may create seabed scouring.

Sea currents shall be assessed taking into account components associated with tidal, storm surge, wind-generated currents and ocean currents, where these are relevant to the wind turbine site. The velocity and directional characteristics of each significant component of sea current at the site shall be separately assessed.

Extreme sea surface current velocities having 1 year, 50 year and 500 year return periods shall be determined from analysis of the site-specific metocean database.

⁵ It is noted that an assumption of co-directionality of wind and waves may not be conservative for sites where large misalignment between wind and wave directions is common.

Generally, there is no requirement for assessment of site-specific variation of current velocity with depth and the standard profiles provided in 6.3.3.3 may be assumed. However, measurements of site-specific current amplitude and direction are recommended to improve upon the standard profiles. For single point moored floating substructures, the surface current is especially important. For floating substructures with deep draft, the depth variation of current is especially important.

6.4.4.4 Assessment of water level, tides and storm surges

The mean and fluctuation in water level at the wind turbine site shall be assessed in order to determine the following parameters:

- mean sea level (MSL);
- highest astronomical tide (HAT) and lowest astronomical tide (LAT);
- highest still water level (HSWL) including positive storm surge;
- lowest still water level (LSWL) including negative storm surge.

These parameters shall be determined from the site-specific metocean database. Accurate estimates of storm surge require a long data set. Long-term measurements or hindcasts available from a nearby location may be used together with correlation techniques to derive the site-specific storm surge characteristics.

6.4.4.5 Assessment of sea/lake ice

At sites where ice is expected to occur, its physical properties shall be taken into consideration for the design of support structures of FOWT.

The site-specific properties of the ice should be described in the design documentation.

There are several parameters to be assessed, some of which can be measured, others calculated from empirical formulae and others determined from sources of historical data such as ice atlases.

The most relevant parameters are listed below:

- sheet ice thickness with a 50-year return period, h_{50} ;
- the dimensions of thick ice features of finite extent (such as ridges) entrained within the ice which may interact with the structure, including the consolidated layer thickness h_c , with a 50-year return period;
- ice strength coefficient C_R ;
- ice density;
- current speed at 1 m below ice lower surface;
- wind speed at 10 m above surface, acting on the ice sheets and ridges;
- water level fluctuation;
- water salinity;
- water density;
- air density;
- freezing degree-days;
- wind drag coefficient C_W ;
- current drag coefficient C_C ;
- frequency of ice concentrations.

6.4.4.6 Assessment of marine growth

The thickness of marine growth and its dependence on depth below sea level shall be assessed based on applicable recommendations, local experience and existing measurements. Site-specific studies may be necessary to establish the nature, likely thickness and depth dependence of marine growth.

NOTE Information regarding marine growth is available for some areas (North Sea, Persian Gulf, West African coast, Gulf of Mexico, coast of California, East coast of Canada), refer to ISO 19901-1.

6.4.4.7 Assessment of seabed movement and scour

The stability of the seabed shall be assessed. It shall be determined whether the bathymetry and soil configuration at the site require consideration of the possibility of slope failure, slides, cavity failure or erosion phenomena. Settlement and soil liquefaction shall in general be taken into account for the design of gravity base anchors.

Based on observations, sea floor variations can usually be characterised as a combination of the following:

- local scour characterised by steep sided scour pits around structural elements such as piles and pile groups when used as anchors;
- global scour characterised by shallow scoured basins of large extent around a structure, possibly caused by overall structure effects, multiple structure interaction, or wave-soil-structure interaction;
- overall seabed movement of sand waves, ridges and shoals which would occur in the absence of a structure. Such movements can result in the lowering or rising of the sea floor, or repeated cycles of these. The addition of man-made structures may change the local sediment transport regime which can aggravate erosion, cause accumulation, or have no effect.

Seabed movement and scour can result in removal of vertical and lateral support for anchors, causing undesirable settlements and displacements of shallow anchors, overstressing of anchor elements and change of the dynamic properties of the FOWT. Where scour is a possibility, it shall be taken into account in design and/or its mitigation shall be considered. In general, the assessments shall follow the procedures outlined in ISO 19901-4, Subclauses 6.3.4 and 6.3.5.

The extent of scour and the required scour protection at the FOWT site shall be determined:

- on the basis of previous records from nearby sites or sites with similar sea floor characteristics;
- from model tests; or
- from calculations calibrated by prototype or model tests.

6.4.5 Assessment of other environmental conditions

6.4.5.1 General

The parameters specified in 6.3.5 shall be assessed.

6.4.5.2 Other normal environmental conditions

Normal values for the environmental parameters given below may be assumed as follows:

- ambient air temperature range of $-10\text{ }^{\circ}\text{C}$ to $+30\text{ }^{\circ}\text{C}$;
- relative humidity of up to 100 %;
- solar radiation intensity of $1\,000\text{ W/m}^2$;
- air density of $1,225\text{ kg/m}^3$;
- water density of $1\,025\text{ kg/m}^3$;
- water temperature range of $0\text{ }^{\circ}\text{C}$ to $+30\text{ }^{\circ}\text{C}$.