



IEC 61400-6

Edition 1.0 2020-04

INTERNATIONAL STANDARD



**Wind energy generation systems –
Part 6: Tower and foundation design requirements**

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

ICS 27.180

ISBN 978-2-8322-8004-1

Warning! Make sure that you obtained this publication from an authorized distributor.

CONTENTS

FOREWORD.....	9
INTRODUCTION.....	11
1 Scope.....	12
2 Normative references.....	12
3 Terms and definitions	13
4 Symbols and abbreviated terms	17
4.1 Symbols.....	17
4.2 Abbreviated terms	19
5 Design basis including loading	20
5.1 General.....	20
5.2 Basis of design	20
5.2.1 Basic principles.....	20
5.2.2 Durability	21
5.2.3 Principles of limit state design	21
5.2.4 Structural analysis	21
5.2.5 Assessments by tests.....	22
5.3 Materials.....	22
5.4 Loads	22
5.4.1 Use of IEC 61400-1 or IEC 61400-2 load cases and partial safety factors for loads	22
5.4.2 Superseding of IEC 61400-1 or IEC 61400-2 partial safety factors for materials.....	22
5.4.3 Serviceability load levels	23
5.4.4 Load combinations in ULS	24
5.4.5 Structural damping values to be used in load calculations	25
5.4.6 Definitions and methods for use of internal loads	25
5.4.7 Definition of required load data for fatigue analysis	25
5.4.8 Definition of required load data for extreme load level.....	25
5.4.9 Vortex induced vibration.....	26
5.4.10 Loads due to geometric tolerances and elastic deflections in tower verticality	26
5.5 Load data and interface reporting requirements	27
5.5.1 Purpose	27
5.5.2 Wind turbine specification	27
5.5.3 Time history data	28
5.5.4 Load origins	28
5.5.5 Load components.....	28
5.6 General structural design requirements	28
5.6.1 Secondary structural influence	28
5.6.2 Fatigue analysis.....	28
5.7 Delivery documentation	28
6 Steel towers	29
6.1 General.....	29
6.2 Basis of design	29
6.3 Materials.....	29
6.3.1 General	29

6.3.2	Structural steels	29
6.3.3	Bolts and anchors	32
6.4	Ultimate strength analysis for towers and openings	32
6.4.1	General	32
6.4.2	Partial safety factors	32
6.4.3	Verification of ultimate strength	32
6.4.4	Tower assessment	32
6.4.5	Detail assessments	33
6.5	Stability	33
6.5.1	General	33
6.5.2	Partial safety factor	34
6.5.3	Assessment	34
6.5.4	Door frames/stiffeners	34
6.6	Fatigue limit state	35
6.6.1	General	35
6.6.2	Partial safety factor for materials	35
6.6.3	Assessment	36
6.6.4	Details	36
6.7	Ring flange connections	36
6.7.1	General	36
6.7.2	Design assumptions and requirements, execution of ring flanges	36
6.7.3	Ultimate limit state analysis of flange and bolted connection	38
6.7.4	Fatigue limit state analysis of bolted connection	38
6.8	Bolted connections resisting shear through friction	40
6.8.1	General requirements	40
6.8.2	Test-assisted design	41
6.8.3	Design without test	42
7	Concrete towers and foundations	42
7.1	General	42
7.2	Basis of design	42
7.2.1	Reference standard for concrete design	42
7.2.2	Partial safety factors	43
7.2.3	Basic variables	43
7.3	Materials	45
7.4	Durability	46
7.4.1	Durability requirements	46
7.4.2	Exposure classes	46
7.4.3	Concrete cover	46
7.5	Structural analysis	46
7.5.1	Finite element analysis	46
7.5.2	Foundation slabs	47
7.5.3	Regions with discontinuity in geometry or loads	47
7.5.4	Cast in anchor bolt arrangements	48
7.6	Concrete to concrete joints	48
7.7	Ultimate limit state	48
7.7.1	General	48
7.7.2	Shear and punching shear	48
7.8	Fatigue limit state	49
7.8.1	General	49

7.8.2	Reinforcement and prestressing steel fatigue failure	49
7.8.3	Concrete fatigue failure	49
7.9	Serviceability limit state.....	50
7.9.1	Load dependent stiffness reduction	50
7.9.2	Stress limitation	50
7.9.3	Crack control	50
7.9.4	Deformations	51
7.10	Execution.....	51
7.10.1	General	51
7.10.2	Requirements	51
7.10.3	Inspection of materials and products	51
7.10.4	Falsework and formwork	51
7.10.5	Reinforcement and embedded steel.....	51
7.10.6	Pre-stressing	51
7.10.7	Precast concrete elements	52
7.10.8	Geometrical tolerances	52
8	Foundations – Geotechnical design.....	52
8.1	General.....	52
8.2	Basis of design	52
8.2.1	General	52
8.2.2	Geotechnical limit states	53
8.3	Geotechnical data	53
8.3.1	General	53
8.3.2	Specific considerations	55
8.4	Supervision, monitoring and maintenance of construction.....	56
8.5	Gravity base foundations.....	56
8.5.1	General	56
8.5.2	Ultimate limit state (ULS)	57
8.5.3	Serviceability limit state (SLS).....	60
8.6	Piled foundations	62
8.6.1	General	62
8.6.2	Pile loads.....	62
8.6.3	Ultimate limit state	63
8.6.4	Serviceability limit state.....	64
8.7	Rock anchored foundations	65
8.7.1	General	65
8.7.2	Types of rock anchor foundation.....	65
8.7.3	Geotechnical data	65
8.7.4	Corrosion protection.....	65
8.7.5	Anchor inspection and maintenance	66
8.7.6	Post tension tolerances and losses.....	66
8.7.7	Ultimate limit state	66
8.7.8	Serviceability limit state.....	67
8.7.9	Robustness check.....	67
8.7.10	Rock anchor design	68
9	Operation, service and maintenance requirements	70
9.1	Operation, maintenance and monitoring.....	70
9.2	Periodic structural inspections	70
9.3	Embedded steel structural section inspections	71

9.4	Bolt tension maintenance	71
9.5	Structural health monitoring.....	71
Annex A (informative)	List of suitable design codes and guidelines for the calculation basis	72
A.1	General.....	72
A.2	Reference documents	72
Annex B (informative)	List of material for structural steel	73
B.1	General.....	73
B.2	Structural steel.....	73
Annex C (informative)	Bolts.....	74
C.1	General.....	74
C.2	Reference documents	75
Annex D (informative)	Z-values for structural steel.....	76
D.1	General.....	76
D.2	Definition of Z-value according to Eurocode	76
D.3	Reference documents	76
Annex E (informative)	Simplified buckling verification for openings in tubular steel towers	77
Annex F (informative)	Fatigue verification.....	80
F.1	General.....	80
F.2	Specific details.....	80
Annex G (informative)	Methods for ring flange verification	81
G.1	Method for ultimate strength analysis according to Petersen/Seidel	81
G.1.1	Basics	81
G.1.2	Calculation method	81
G.1.3	Extension by Tobinaga and Ishihara	84
G.2	Method for fatigue strength analysis according to Schmidt/Neuper	85
G.2.1	Basics	85
G.2.2	Formulas for the tri-linear approximation.....	86
G.3	Reference documents	87
Annex H (informative)	Crack control – Guidance on 7.9.3	88
H.1	General.....	88
H.2	Crack control based on Eurocode 2	88
H.3	Crack control based on Japanese standards	88
H.4	Crack control based on ACI 318	89
H.5	Reference documents	89
Annex I (informative)	Finite element analysis for concrete.....	90
I.1	General.....	90
I.2	Order and type of elements	90
I.3	Constitutive modelling	91
I.4	Solution methods	91
I.5	Implicit approach.....	91
I.6	Steps in conducting of a finite element analysis	92
I.7	Checking results	92
I.8	Reference documents	93
Annex J (informative)	Tower-foundation anchorage	94
J.1	General.....	94
J.2	Embedded anchorages.....	94

J.3	Bolted anchorages	95
J.4	Grout	95
J.5	Anchor bolts	95
J.6	Embedded ring	95
J.7	Anchorage load transfer	96
Annex K (informative)	Strut-and-tie section	97
K.1	General	97
K.2	Example of a rock anchor foundation	98
K.3	Reference documents	101
Annex L (informative)	Guidance on selection of soil modulus and foundation rotational stiffness	103
L.1	General	103
L.2	Soil model	103
L.3	Dynamic rotational stiffness	105
L.4	Static rotational stiffness	106
L.5	Reference documents	107
Annex M (informative)	Guidance for rock anchored foundation design	108
M.1	General	108
M.2	Corrosion protection	108
M.2.1	Standard anchors	108
M.2.2	Corrosion protection of bar anchors	109
M.3	Product approval	110
M.4	Rock anchor design	110
M.5	Grout design	110
M.6	Testing and execution	110
M.7	Suitability/performance test	111
M.8	Acceptance/proof test	111
M.9	Supplementary extended creep tests	111
M.10	Reference documents	111
Annex N (informative)	Internal loads – Explanation of internal loads	112
Annex O (informative)	Seismic load estimation for wind turbine tower and foundation	114
O.1	General	114
O.2	Vertical ground motion	114
O.3	Structure model	114
O.4	Soil amplification	115
O.5	Time domain simulation	116
O.6	Reference documents	116
Annex P (informative)	Structural damping ratio for the tower of wind turbine	117
P.1	General	117
P.2	First mode structural damping ratio	117
P.3	Second mode structural damping ratio	118
P.4	Higher mode damping	118
P.5	Reference documents	119
Annex Q (informative)	Guidance on partial safety factors for geotechnical limit states	120
Q.1	General	120
Q.2	Equilibrium	120
Q.3	Bearing capacity	120
Q.4	Sliding resistance	121

Q.5 Overall stability	121
Q.6 Reference documents	122
Bibliography	123
 Figure 1 – Flange notations as an example of an L-flange	31
Figure 2 – Door opening geometry	35
Figure 3 – Flange gaps k in the area of the tower wall	37
Figure 4 – Bolt force as a function of wall force	39
Figure 5 – S-N curve for detail category 36.....	40
Figure 6 – Thermal effects around tower cross-section	44
Figure 7 – Illustration of rock anchor length.....	70
Figure E.1 – Circumferentially edge-stiffened opening	78
Figure E.2 – Definition of W_s and t_s according to JSCE	79
Figure G.1 – Simplification of system to segment model	81
Figure G.2 – Locations of plastic hinges for different failure modes	82
Figure G.3 – Geometric parameters	83
Figure G.4 – Modification factor λ for different α [1].....	85
Figure G.5 – Tri-linear approximation of the non-linear relation between bolt force and tension force of the bolted connection	86
Figure K.1 – Example for the design of a deep beam using the strut-and-tie method.....	97
Figure K.2 – Simple shapes of strut-and-tie models	97
Figure K.3 – Three examples for carrying load in a deep beam	98
Figure K.4 – Strut-and-tie models for a rock-anchor foundation.....	100
Figure K.5 – Top tie reinforcement in a rock-anchor foundation.....	101
Figure L.1 – Example stress-strain relationship for soil	103
Figure L.2 – Loading and unloading behaviour of soil	104
Figure L.3 – Variation of shear modulus with soil strain.....	105
Figure L.4 – Reduction in rotational stiffness due to load eccentricity	106
Figure L.5 – Illustrative example of reduction in foundation rotational stiffness due to increasing load eccentricity	107
Figure M.1 – Section through rock and anchor.....	108
Figure M.2 – Typical anchor configuration with corrosion protection	109
Figure N.1 – Representation of internal loads	113
Figure O.1 – Structure model for response spectrum method	115
Figure P.1 – First mode damping ratio for the steel tower of wind turbine	118
 Table 1 – Flange tolerances	37
Table 2 – Summary of geotechnical limit states	53
Table B.1 – National and regional steel standards and types	73
Table C.1 – Comparison of bolt material in ISO 898-1, JIS B1186 and ASTM A490M-12.....	74
Table E.1 – Coefficients for Formula (E.3).....	78
Table H.1 – Limit value of crack width based on Japanese standards [1].....	89
Table P.1 – Damping coefficients	117

Table Q.1 – Minimum partial safety factors for the equilibrium limit state (European and North American practice).....	120
Table Q.2 – Minimum partial safety factors on for the equilibrium limit state (JSCE)	120
Table Q.3 – Minimum partial material and resistance factors for the bearing resistance limit state, ULS	121
Table Q.4 – Minimum partial material and resistance factors for the sliding resistance limit state, ULS	121
Table Q.5 – Minimum partial material and resistance factors for the overall stability limit state, ULS	122

INTERNATIONAL ELECTROTECHNICAL COMMISSION

WIND ENERGY GENERATION SYSTEMS –

Part 6: Tower and foundation design requirements

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) Attention is drawn to the possibility that some of the elements of this IEC Publication may be the subject of patent rights. IEC shall not be held responsible for identifying any or all such patent rights.

International Standard IEC 61400-6 has been prepared by IEC technical committee TC 88: Wind energy generation systems.

The text of this standard is based on the following documents:

FDIS	Report on voting
88/751/FDIS	88/754/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.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

Future standards in this series will carry the new general title as cited above. Titles of existing standards in this series will be updated at the time of the next edition.

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

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

The contents of the corrigendum of November 2020 have been included in this copy.

IMPORTANT – The 'colour inside' logo on the cover page of this publication 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 document has been developed for the design of onshore wind turbine towers and foundations that will build on and complement the IEC 61400-1 relating to design criteria and provide a complete set of technical requirements for the structural and geotechnical design. The requirements are also applicable to wind turbines covered by IEC 61400-2. It is envisaged that the proposed work will be followed by the development of another part, directed towards the design of offshore support structures, thus also complementing IEC 61400-3-1.

Civil engineering practices associated with the scope of the standard have regional variations. It is not the intention of this document to conflict with those practices but to supplement them particularly in ensuring that all important features of typical wind turbine towers and foundations are fully and correctly considered. To this end, the relevant parts in existing standards for design of steel and concrete structures and for geotechnical design have been identified for participating countries and regions.

The principles included in this document apply to the sections of the tower of an offshore fixed structure above the splash zone if the loading has been calculated according to IEC 61400-3-1.

This document will include the evaluation and calibration of partial safety factors for material strengths to be used together with the safety elements in IEC 61400-1 and IEC 61400-2 for loads and for verification of static equilibrium.

WIND ENERGY GENERATION SYSTEMS –

Part 6: Tower and foundation design requirements

1 Scope

This part of IEC 61400 specifies requirements and general principles to be used in assessing the structural integrity of onshore wind turbine support structures (including foundations). The scope includes the geotechnical assessment of the soil for generic or site specific purposes. The strength of any flange and connection system connected to the rotor nacelle assembly (including connection to the yaw bearing) are designed and documented according to this document or according to IEC 61400-1. The scope includes all life cycle issues that may affect the structural integrity such as assembly and maintenance.

The assessment assumes that load data has been derived as defined in IEC 61400-1 or IEC 61400-2 and using the implicit reliability level and partial safety factors for loads.

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

IEC 61400-2, *Wind turbines – Part 2: Small wind turbines*

IEC 61400-3-1:2019, *Wind energy generation systems – Part 3-1: Design requirements for fixed offshore wind turbines*

ISO 2394:2015, *General principles on reliability for structures*

ISO 22965-1, *Concrete – Part 1: Methods of specifying and guidance for the specifier*

ISO 22965-2, *Concrete – Part 2: Specification of constituent materials, production of concrete and compliance of concrete*

ISO 22966, *Execution of concrete structures*

ISO 6934 (all parts), *Steel for the prestressing of concrete*

ISO 6935 (all parts), *Steel for the reinforcement of concrete*

ISO 9016:2012, *Destructive tests on welds in metallic materials – Impact tests – Test specimen location, notch orientation and examination*

ISO 12944 (all parts), *Paints and varnishes – Corrosion protection of steel structures by protective paint systems*

EN 1993-1-9:2005, *Eurocode 3: Design of steel structures – Part 1-9: Fatigue*

EN 1993-3-2:2006, *Eurocode 3: Design of steel structures – Part 3-2: Towers, masts and chimneys – Chimneys*