



BSI Standards Publication

Cathodic protection of offshore wind structures

National foreword

This British Standard is the UK implementation of EN ISO 24656:2022. It is identical to ISO 24656:2022.

The UK participation in its preparation was entrusted to Technical Committee ISENF/8.

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offshore (ISO 24656:2022)

Kathodischer Korrosionsschutz von Offshore-
Windparkstrukturen (ISO 24656:2022)

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European foreword

This document (EN ISO 24656:2022) has been prepared by Technical Committee ISO/TC 156 "Corrosion of metals and alloys" in collaboration with Technical Committee CEN/TC 219 "Cathodic protection" the secretariat of which is held by BSI.

This European Standard shall be given the status of a national standard, either by publication of an identical text or by endorsement, at the latest by December 2022, and conflicting national standards shall be withdrawn at the latest by December 2022.

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The text of ISO 24656:2022 has been approved by CEN as EN ISO 24656:2022 without any modification.

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

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For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT) see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 156, *Corrosion of metals and alloys*, in collaboration with the European Committee for Standardization (CEN) Technical Committee CEN/TC 219, *Cathodic protection*, in accordance with the Agreement on technical cooperation between ISO and CEN (Vienna Agreement).

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

Cathodic protection (CP), possibly together with protective coating, is applied to protect the immersed external surfaces of offshore wind farm structures and appurtenances from corrosion due to seawater or seabed environments.

CP, possibly together with protective coating, can be applied to protect the internal flooded and seabed and sediment exposed surfaces from corrosion.

The general principles of CP in seawater are detailed in ISO 12473.

CP involves the supply of sufficient direct current to the surfaces of the structure in order to reduce the steel to electrolyte potential to values where corrosion is considered insignificant or acceptably low.

CP is designed to protect the submerged and buried areas of the structure from corrosion. The parts that are not permanently immersed will not be permanently protected by the CP system.

This document introduces guidance for the use of available metocean data to

- assess the CP demand of immersed and frequently wetted areas
- determine seawater flow velocities to assess the CP design parameters

This is in addition to the primary use of the metocean data in structural design.

This document does not require the CP designer to be expert in metocean data; it gives guidance on data which should be available from metocean specialists and which is required in the CP design process.

Cathodic protection of offshore wind structures

1 Scope

This document specifies the requirements for the external and internal cathodic protection for offshore wind farm structures. It is applicable for structures and appurtenances in contact with seawater or seabed environments. This document addresses:

- design and implementation of cathodic protection systems for new steel structures;
- assessment of residual life of existing cathodic protection systems;
- design and implementation of retrofit cathodic protection systems for improvement of the protection level or for life extension of the protection;
- inspection and performance monitoring of cathodic protection systems installed on existing structures, and
- guidance on cathodic protection of reinforced concrete structures.

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.

ISO 8501-1, *Preparation of steel substrates before application of paints and related products — Visual assessment of surface cleanliness — Part 1: Rust grades and preparation grades of uncoated steel substrates and of steel substrates after overall removal of previous coatings*

ISO 12473, *General principles of cathodic protection in seawater*

EN 12496, *Galvanic anodes for cathodic protection in seawater and saline mud*

ISO 12696, *Cathodic protection of steel in concrete*

ISO/IEC 17025, *General requirements for the competence of testing and calibration laboratories*

EN 60529, *Degrees of protection provided by enclosures (IP Code)*

IEC 61000-1-2, *Electromagnetic compatibility (EMC) — Part 1-2: General — Methodology for the achievement of functional safety of electrical and electronic systems including equipment with regard to electromagnetic phenomena*

IEC 61400-24, *Wind energy generation systems — Part 24: Lightning protection*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

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

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

3.1

atmospheric zone

zone located above the splash zone

3.2

buried zone

zone located under the seabed or expected scour level, whichever is lower

3.3

CP design life

time for which the CP is designed to protect the structure

Note 1 to entry: This may be different to the structure design life or structure service life.

3.4

doubler plate

plate welded onto a member to locally reinforce it or to isolate it from further welding work

3.5

electrolyte

medium in which electric current is transported by ions. In the context of this document, seawater or seabed

3.6

frequently wetted zone

FWZ

water level, WL(t), plus significant wave height, H_{mo}

Note 1 to entry: See [Annex B](#) for details.

3.7

free board level

FBL

water level for floating structures

Note 1 to entry: For calculation of frequently wetted zone, it will replace WL(t)

3.8

HAT

highest astronomical tide

level of the highest astronomical tide

3.9

hybrid cathodic protection system

system comprising both impressed current and galvanic anodes

3.10

inspection

examination of equipment to determine its continued performance characteristics, whether undertaken on a regular program basis or carried out as a simple operation

3.11

IR error

error in measured steel to electrolyte potential caused by the protection current or any other current flowing through the resistive environment

3.12

jacket structure

multi-legged lattice braced structure

3.13**J-tube**

curved tubular conduit designed and installed on a structure to support and guide cables

3.14**LAT****lowest astronomical tide**

level of the lowest astronomical tide

3.15**marine sediments**

top layer of the seabed composed of water saturated solid materials of various densities

3.16**metocean data**

meteorological and oceanographic data, often given as hourly statistics

3.17**monitoring**

activity continuously on-going or sporadically undertaken at fixed locations to determine the performance of a CP system or parameters related to the performance

Note 1 to entry: Typically, monitoring utilizes fixed sensors, the data from which can be data logged.

3.18**monopile**

foundation element driven or drilled into the seabed to support a transition piece and/or tower

3.19**over-polarization**

occurrence in which the structure to electrolyte potentials are more negative than those required for satisfactory cathodic protection

Note 1 to entry: Over-polarization provides no useful function and might even cause damage to the structure

3.20**owner**

structure owner, or developer or operator, all or any of which may have responsibility for matters related to corrosion protection

3.21**primary steel**

primary load carrying elements (monopile, jacket, hull and other steel structures)

3.22**re-polarization**

situation where the steel is polarized after a depolarization event

3.23**retrofit cathodic protection**

provision of CP equipment, either as a complete or a partial system, to an existing structure either to remedy CP performance deficiencies or to extend the CP system life

3.24**salinity**

quantity of inorganic salts dissolved in the seawater

Note 1 to entry: The standardised measurement is based on the determination of the electrical conductivity of the seawater.

Note 2 to entry: Salinity is expressed in grams per kilogramme (g/kg) or as parts per thousand (ppt or ‰).

3.25

scour

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

3.26

seabed

interface between seawater and solids of the *buried zone* ([3.2](#)) including the *marine sediments* ([3.15](#))

3.27

secondary steel

steel which is not primary steel, hence used for access (boat landing, ladders, decks and support for equipment)

3.28

shallow water

water of such depth that surface waves are noticeably affected by bottom topography

Note 1 to entry: Typically, this implies a water depth equivalent to half the wavelength^[33]. For all practical purposes in this document, it is understood as depth less than –30 m LAT

3.29

significant wave height

H_{mo}

mean level of the third largest waves in open sea

3.30

splash zone

external region of support structure that is frequently wetted due to the wave and tidal variations. A more detailed definition of splash zone is given in IEC 61400-3-1^[15]. In this document the frequently wetted zone is included as the upper boundary to which current demand for CP shall be included

3.31

structure service life

anticipated life of the windfarm structure.

Note 1 to entry: This includes a period for storage, transport, installation, operating the wind farm and a possible period for decommissioning

3.32

suction bucket

foundation element that is sucked into the seabed

3.33

surveying

process of carrying out inspection using a defined procedure

Note 1 to entry: In this document surveying is also used to describe the process of taking cathodic protection measurements, not using fixed and data logged sensors, but using a defined procedure

3.34

tidal zone

zone located between LAT and HAT

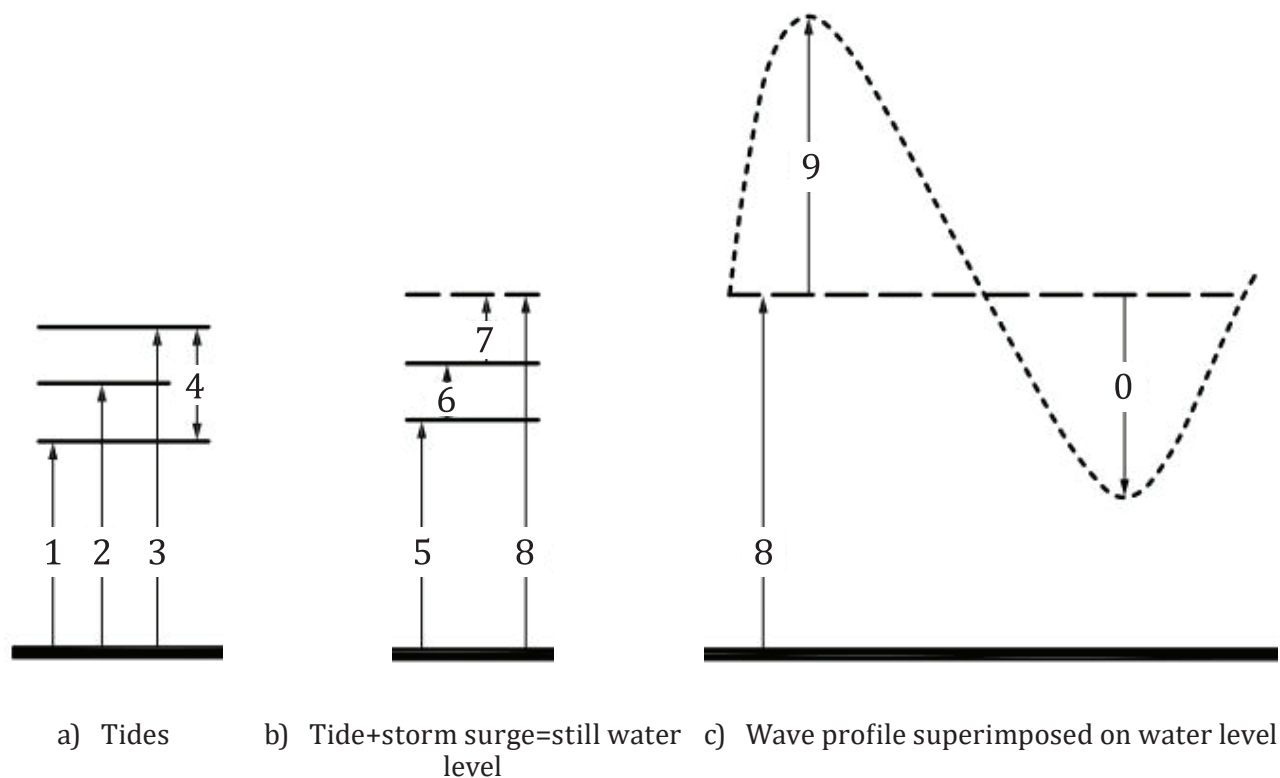
3.35

transition piece

intermediate structure between the monopile and the tower

3.36**wave crest and trough**

height of seawater above and depth of below still water level due to waves

Note 1 to entry: See [Figure 1](#) below.**Key****Key to distance elevation**

1 lowest astronomical tide (LAT)	6 tide associated with storm (shown positive but may be positive or negative)
2 mean sea level (MSL)	7 storm surge (shown positive but may be positive or negative)
3 highest astronomical tide (HAT)	8 still water (or "storm water") level
4 tidal range	9 crest elevation
5 tidal datum (commonly LAT or MSL but may be other)	0 trough elevation

Key line types

	seafloor
	tide levels
	surge or surge+tide levels
	wave profile

Figure 1 — Water depth, tides and storm surges, from ISO 19901-1^[10]**4 Symbols and abbreviations****4.1 Symbols**

<i>A</i>	Area, m ²
<i>C</i>	Anode cross section periphery, m
<i>c</i>	Coating degradation, %

ΔU	Driving potential, V
f_c	Coating breakdown factor
I	Current, A
$I_{\text{anode(initial)}}$	Initial current output of an individual galvanic anode material, A
$I_{\text{anode(final)}}$	Final current output of an individual galvanic anode material, A
I_{max}	Maximum protection current demand for a CP zone, A
$I_{\text{total(initial)}}$	Total current required for polarization of the structure, A
$I_{\text{total(final)}}$	Total current required for re-polarization of the structure, A
J	Current density, A/m ²
L	Anode body length, m
L_{initial}	Anode initial length, m
L_{final}	Anode final (or end of life) length, m
N	Number of anodes
Q	Practical electrochemical capacity for the anode alloy in the environment considered, Ah/kg
ρ	Resistivity of an electrolyte, Ωm . In this document resistivity may be of an electrolyte (sea or seabed) or a conductor material
R_a	Anode resistance to remote earth, Ω . In the context of this document, remote earth will be in seawater or seabed
r	Anode radius, m
R	Circuit resistance, Ω
S	Arithmetic mean of anode length and width, m
T	Temperature, $^{\circ}\text{C}$
T_{anode}	Effective lifetime of the anode, years
T_{design}	Required design life, years
U	Flow velocity (m/s)
u	Utilisation factor for CP design calculations
V_{initial}	Initial net volume of anode alloy (excluding the steel insert), m ³
V_{insert}	Volume of the insert only within the anode body, m ³
V_{final}	Final (or end of life) net volume of anode alloy, m ³
V_{gross}	Overall volume of the anode body including that portion of the insert only within the anode body, m ³
m_{anode}	Net mass of an individual galvanic anode material, kg
m_{total}	Minimum total net mass of galvanic anode material, kg

4.2 Abbreviations

ABS	Area Below Seabed
AC	Alternating Current
BEM	Boundary Element Method
CA	Corrosion Allowance
CP	Cathodic Protection
CP design life	Cathodic Protection design life
CPS	Cable Protection System
CSPE	Chlorosulfonated Polyethylene; alternatively abbreviated to CSP
DC	Direct Current
DO	Dissolved oxygen
EMF	Electromotive Force
EPR	Ethylene Propylene Rubber
ER	Electrical Resistance
FAT	Factory Acceptance Test
FBL	Free Board Level
FEM	Finite Element Method
FWZ	Frequently Wetted Zone
GACP	Galvanic Anode Cathodic Protection
HAT	Highest Astronomical Tide
HDPE	High Density Polyethylene
HMMPE	High Molecular Mass Polyethylene
HSC	Hydrogen Induced Stress Cracking
ICCP	Impressed Current Cathodic Protection
IEC	International Electrotechnical Commission
IMCA	International Marine Contractors Association
IP	Ingress Protection Rating
ISO	International Organization for Standardization
ITP	Inspection and Test Plan
LAT	Lowest Astronomical Tide
MIC	Microbially Influenced Corrosion

MMO	Mixed Metal Oxide
MP	Monopile
MSL	Mean Sea Level
MTL	Mean Tide Level
MWL	Mean Water Level
MDFT	Minimum Dry Film Thickness
NACE	National Association of Corrosion Engineers
NDFT	Nominal Dry Film Thickness
PTFE	Polytetrafluoroethylene
PVDF	Polyvinylidene Fluoride
PVC	Poly vinyl chloride
RCD	Residual Current Device
RMS	Root Mean Square
ROV	Remotely Operated Vehicle
S-N	Stress versus Number of cycles
SMS	Specified Minimum Yield Strength
TP	Transition Piece
TR	Transformer Rectifier
WTG	Wind Turbine Generator
XLPE	Cross-linked Polyethylene

5 Competence of personnel

Personnel who undertake the design (the CP designer), supervision of installation, commissioning, supervision of operation, inspections, measurements, monitoring and supervision of maintenance of CP systems shall have the appropriate level of competence for the tasks undertaken. This competence should be independently assessed and documented. The CP designer shall be competent to assess and determine the appropriate input parameters (such as steel current density, anode potential and anode electrochemical capacity) for the CP design based upon the type of structure, its exposure and the metocean data.

ISO 15257^[7] defines a method which may be utilized for assessing and certifying the competence of CP personnel.

Competence of CP personnel to the appropriate level for tasks undertaken should be demonstrated by certification in accordance with ISO 15257^[7] or by another equivalent prequalification procedure.

6 Structural considerations

6.1 Structures to be protected

Foundation structures are designed to support a tower and nacelle incorporating a turbine generator and wind driven rotor blades. The structure is subject to fatigue loading, which in many cases is the design driver.

This document can also be applied to the cathodic protection of other foundations associated with offshore wind power generation, such as transformer platform and meteorological mast foundations.

Offshore wind turbine foundation structures can comprise various primary steel structures such as large diameter monopile foundations driven into the seabed, lattice structures fixed to the seabed, floating structures, and concrete gravity-based structures.

NOTE The term “jacket” is commonly used to describe a lattice style structure comprising tubular legs stiffened with cross members. Jacket is the term used in the offshore oil and gas industry since the structure serves to enclose the conductor pipes.

This document defines the requirements for the CP of external and internal surfaces of offshore wind structures in contact with seawater and with seabed or sediment.

It addresses the following structures:

- monopile and transition piece foundations,
- mono bucket foundations,
- jacket structures with driven piles or suction buckets,
- floating structures,
- gravity-based reinforced concrete structures, and
- other foundations associated with offshore wind power generation.

This document addresses specific features of the above listed types of structure. The performance requirements are applicable to all offshore structures associated with generation of power from wind.

The various types of foundation structures, in common use, together with their corrosion strategies are illustrated in [Figure 2](#), [Figure 3](#), [Figure 4](#) and [Figure 5](#).

Monopile structures, [Figure 2](#), are one of the most common types of foundation structures for offshore wind turbines and have unique features which make special considerations necessary. Single large diameter steel piles (monopiles) are driven into the seabed to a defined level below seabed and with the top typically above MSL. Wind turbine towers are installed on an intermediate structure known as a transition piece (TP) or directly on the monopile (MP). The TP fits over the monopile, extending to some depth and is sealed where the overlap exists and grouted with a cementitious mortar. Alternatively, the TP is provided with a bottom flange and fitted on top of the MP with a top flange and bolted together.

The TP is generally coated as it protrudes out of water, within and beyond the upper limit of full CP protection area, and therefore the coating jointly with a corrosion allowance comprises the corrosion protection strategy.

Generally, the required facilities for the operation of the foundations are pre-installed on the transition piece and/or the jacket structure including boat landings and ladders, grouting systems, boat fenders etc.

Jacket type foundations are similar to many offshore steel platforms and the provisions for CP are described in this document and in EN 12495^[18].

Floating structures, [Figure 4](#), are, as the name suggests, structures that are floating. They use chains or tethers to secure the structure to some seabed anchor.

Concrete gravity-based structures, [Figure 5](#), are placed on the seabed and are not normally considered in need of CP if

- designed according to EN 206^[14] jointly with the normative annexes for the relevant exposure classes,
- designed and constructed according to EN 1992-1-1^[15], and
- produced according to EN13670^[20] jointly with the normative annexes.

This document provides guideline for inclusion of CP on concrete structures for cases where premature deterioration has been observed or if an unacceptable risk of corrosion is considered.

This document also addresses the CP current demand of steel in concrete where the steel reinforcement is connected to steel elements that are not encased in concrete e.g. a steel monopile with a reinforced concrete gravity base.

Structural elements that are driven, drilled or sucked into the seabed such as piles or suction buckets, generally do not have anodes or other appurtenances fitted during installation, and hence it also prevents anodes and other appurtenances to be located below seabed level.

6.2 Materials

Offshore wind structures are mainly constructed from bare or coated carbon manganese steels with a specified minimum yield strength (SMYS) not exceeding 550 MPa.

Some parts of the structure can be made of metallic materials other than carbon manganese steel. The CP system shall be designed to ensure that there is complete control over any galvanic corrosion arising from this coupling and also any risk of hydrogen embrittlement, see ISO 12473.

Foundation structures such as monopiles, jackets and floating structures may be coated or partly coated in the immersed zone. The design of the CP shall take this into account.

Gravity based structures are generally made from reinforced concrete foundations, and the structure is placed on the seabed, hence the name gravity based. The tower is fitted to the top of the foundation.

6.3 Corrosion protection strategy

The selected strategy for an offshore wind turbine foundation structure is important since the levels of protection applied for the different structure areas (see [Figures 2 to 4](#)) feeds into the structural design, where the S-N curves used in the structural design are selected to match the environment anticipated over the structure service life.

NOTE Offshore steel wind foundations, are subject to fatigue loading and their design lives can be fatigue limited^[24], details fatigue design of offshore structures. Within this recommended practice are three major categories of S-N curves for carbon steel. These are S-N curves in air, S-N curves in seawater with cathodic protection and S-N curves for seawater with free corrosion. These curves are utilised in the structural design. The S-N curve 'seawater with cathodic protection' can be applied in the structural calculations, where the protective criteria are assumed fulfilled.

Three possible corrosion mitigation measures are possible: corrosion allowance, coatings and cathodic protection.

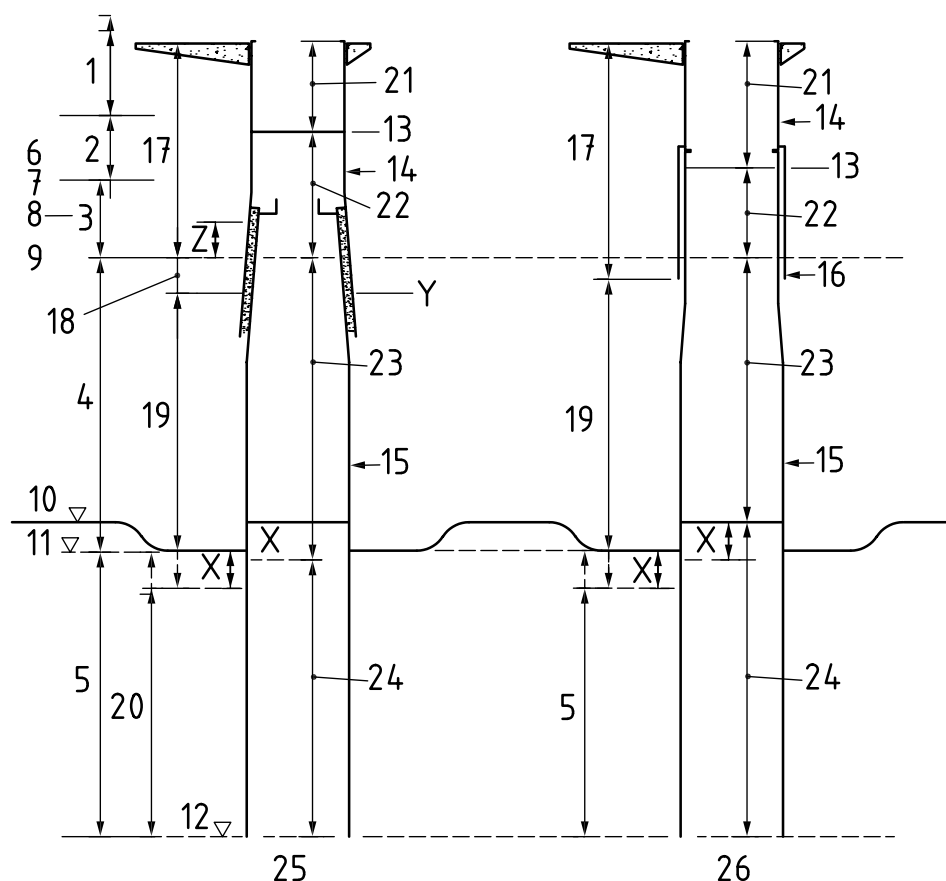
The role of cathodic protection is to minimise corrosion losses and to mitigate the effects of corrosion on structural design calculations in respect of fatigue. For parts of structures that are not cathodically protected, the wall thickness of structures may be increased to allow for corrosion losses during service. The additional thickness provides a Corrosion Allowance (CA). Typical areas where corrosion allowance is applicable are noted in [Figures 2 to 4](#).

Cathodic protection is often designed in combination with coatings. Cathodic protection does not need coatings to operate successfully, and coatings are optional in combination with cathodic protection as shown in [Figures 2 to 4](#). If coatings are not used, a higher current demand is needed to protect the structure in immersed and wetted areas.

ISO 12944-9^[5] provides guidance and requirements for coatings for offshore use and are further described in [Annex D](#). Coatings alone cannot be relied upon in fully immersed areas since some progressive breakdown can be anticipated throughout the structure service life. [Annex D](#) gives guidance for coating breakdown factors when used in combination with cathodic protection. The owner should be asked to accept the breakdown factors applied in the design.

Where cathodic protection is fully efficient (meeting the protective criterion), the S-N curve “protected in seawater” applies. Cathodic protection for offshore wind foundations may be provided by either galvanic anode CP systems, or impressed current CP systems, or a combination of both. At the time of selection of the CP system a risk and consequence evaluation shall be made which shall include assessments of, as a minimum:

- the time between installation of the foundation and setting the CP system to work;
- estimates of reliability of the alternative CP systems, the anticipated number of visits to each foundation during the structure service life for CP performance assessment, CP system maintenance and CP system repair or replacement;
- capital costs, operational costs and structural consequences of non-functional CP systems.



Key

X user defined as upper limit of where CP protective criterion is to be met

Y user defined as lower limit of coating

Z user defined as lower limit of where CP protective criterion is to be met

1 atmospheric zone

2 splash zone

3 tidal zone

4 immersed zone

5 buried zone

6 FWZ_{50 %} (above HAT)

7 HAT

8 MSL

9 LAT

10 seabed level

11 scour level

12 pile toe level

13 lower internal platform

14 transition piece

15 monopile

16 skirt

17 external: CA + coating

18 external: CP + coating

19 external: CP + optional coating

20 external: CA to be considered

21 internal: coating

22 internal: CA + coating

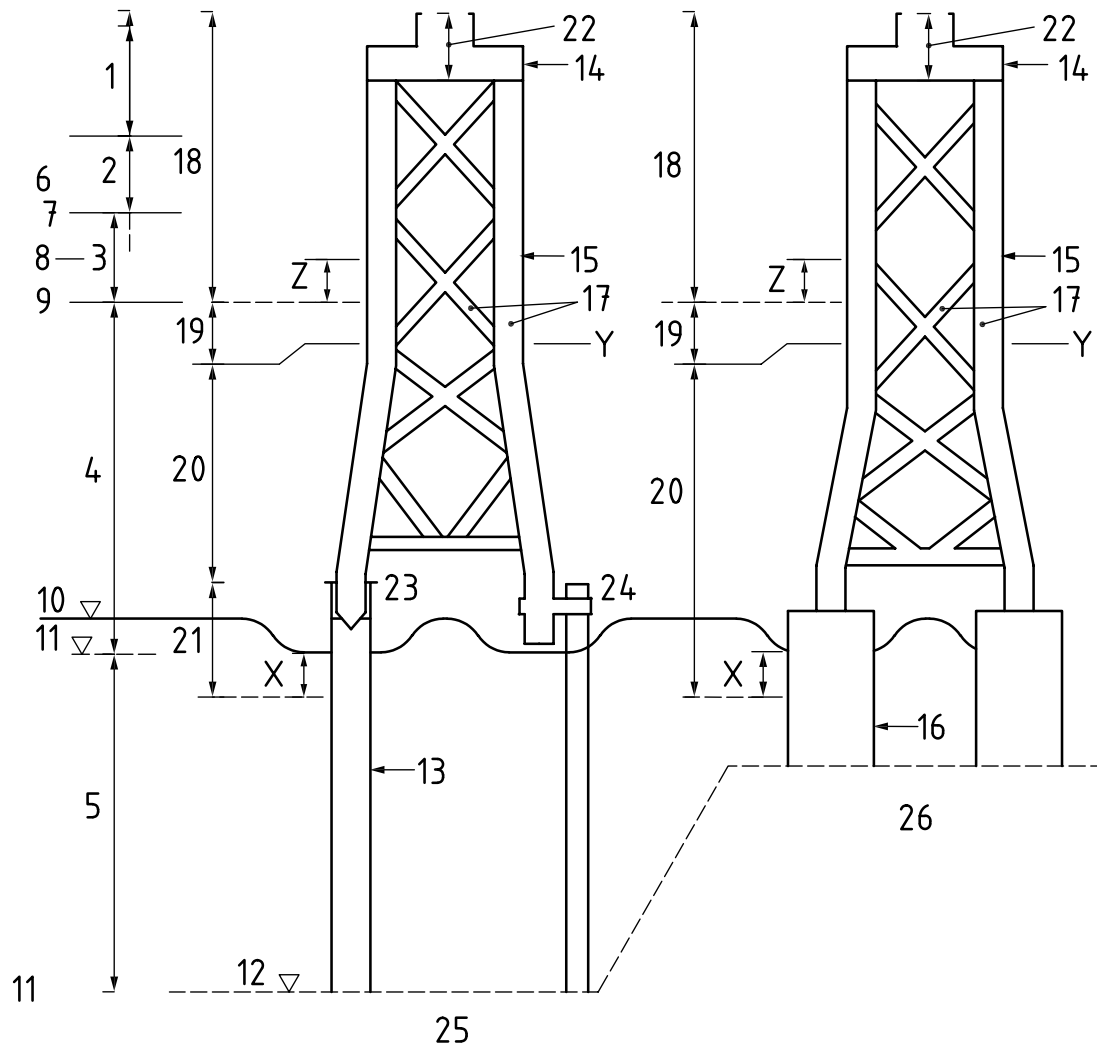
23 internal CA + optional coating and/or CP

24 internal: CA to be considered

25 MP/TP foundation grouted

26 MP/TP foundation bolted

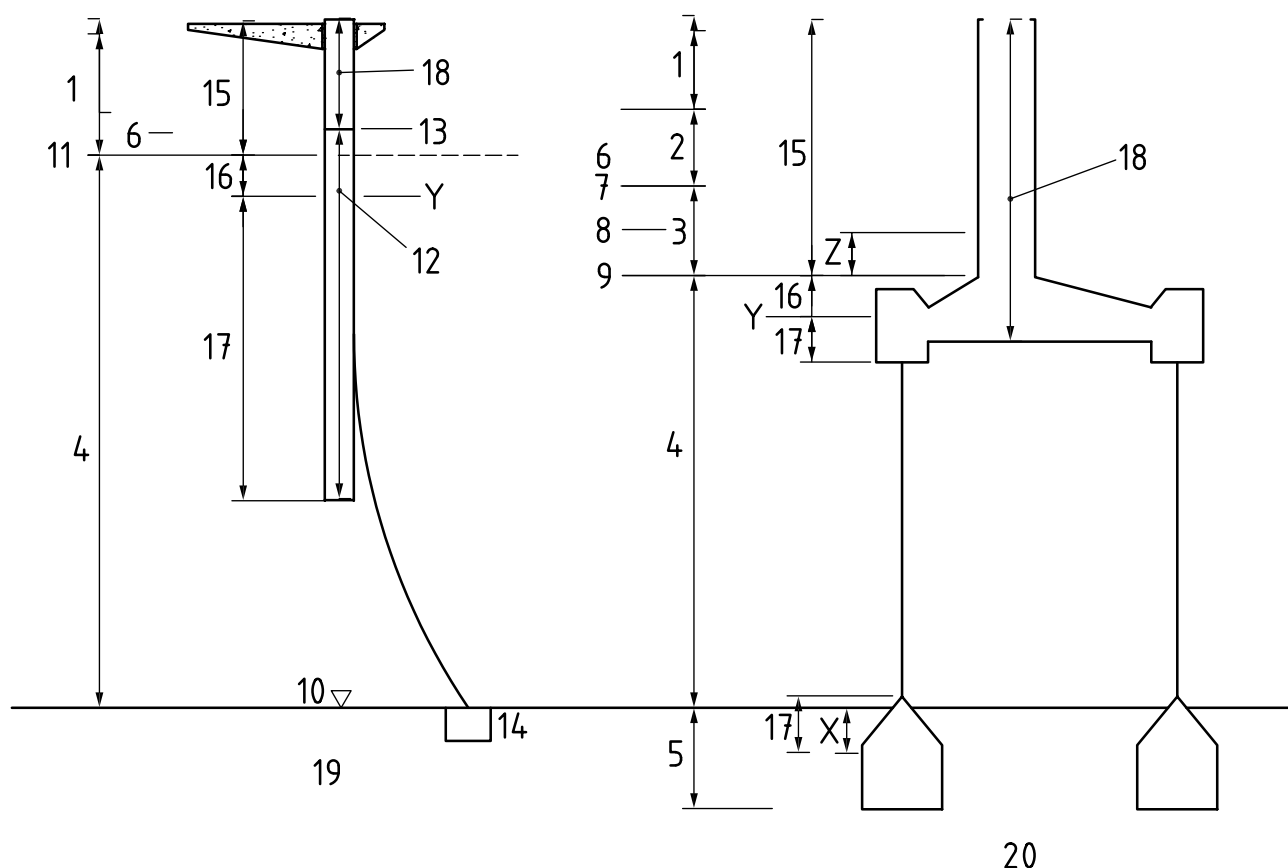
Figure 2 — Corrosion protection strategy for monopile, left side grouted, right side bolted with TP including skirt



Key

X	user defined as upper limit of where CP protective criterion is to be met
Y	user defined as lower limit of coating
Z	user defined as lower limit of where CP protective criterion is to be met
1	atmospheric zone
2	splash zone
3	tidal zone
4	immersed zone
5	buried zone
6	FWZ ₅₀ % (above HAT)
7	HAT
8	MSL
9	LAT
10	seabed level
11	scour level
12	pile toe level
13	pile
14	transition piece
15	jacket
16	suction bucket
17	sealed compartment
18	external: CA + coating
19	external: CP + coating
20	external: CP + optional coating
21	external: CP
22	internal: coating
23	pile option 1
24	pile option 2
25	piled jacket
26	suction bucket jacket

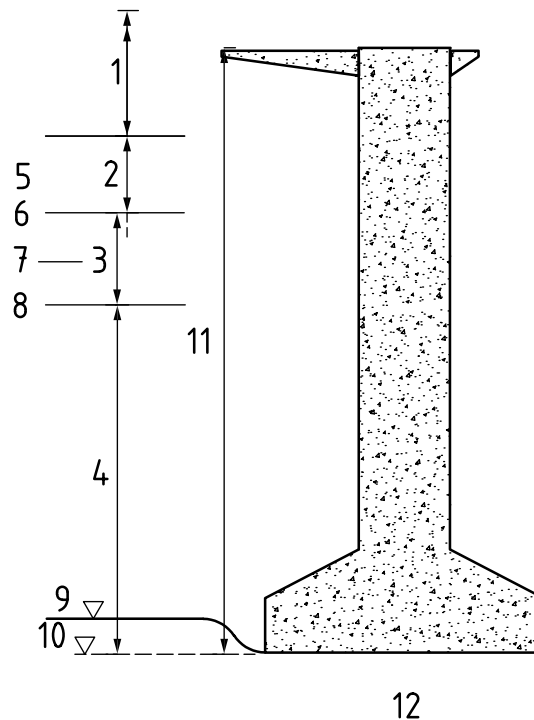
Figure 3 — Corrosion protection strategy for piled jacket or suction bucket jacket foundation



Key

- | | | | |
|----|---|----|--------------------------------------|
| X | user defined as upper limit of where CP protective criterion is to be met | | |
| Y | user defined as lower limit of coating | | |
| Z | user defined as lower limit of where CP protective criterion is to be met | | |
| 1 | atmospheric zone | 11 | rise and fall of spar with sea level |
| 2 | splash zone | 12 | sealed |
| 3 | tidal zone | 13 | lower internal platform |
| 4 | immersed zone | 14 | anchor |
| 5 | buried zone | 15 | external: CA + coating |
| 6 | FWZ _{50 %} (above HAT) | 16 | external: CP + coating |
| 7 | HAT | 17 | external: CP + optional coating |
| 8 | MSL | 18 | internal: coating |
| 9 | LAT | 19 | floating spar |
| 10 | seabed level | 20 | floating TLP (tension leg platform) |

Figure 4 — Corrosion protection strategy for floating foundation, left side floating spar, right side floating TLP



Key

- 1 atmospheric zone
- 2 splash zone
- 3 tidal zone
- 4 immersed zone
- 5 FWZ₅₀ % (above HAT)
- 6 HAT
- 7 MSL
- 8 LAT
- 9 seabed level
- 10 scour level
- 11 external: optional CP
- 12 gravity based foundation

Figure 5 — Corrosion protection strategy for reinforced concrete gravity-based foundations

7 Cathodic protection criteria

7.1 Temporary protection

Temporary cathodic protection, to achieve the protection criteria, see 7.2 and 7.3 to the immersed and buried surfaces detailed in Figure 2, Figure 3, Figure 4 and Figure 5, shall be provided for the period between construction and commencement of operation of CP (impressed current or galvanic) unless it can be demonstrated that any corrosion occurring before cathodic polarization protection does not compromise the structural integrity. A strategy could be to coat fatigue sensitive areas such as welds and nodes to protect these against corrosion, until power is available.

If coatings alone are used before cathodic protection is applied, it may be necessary to undertake an assessment of probable coating damages, its distribution and corrosion, before cathodic protection is commissioned.

7.2 Steel structures

The required structure to electrolyte potential limits for a range of metals and alloys in seawater are detailed in ISO 12473.

NOTE 1 In this document, all potentials are referenced to the silver/silver chloride/seawater reference electrode (Ag/AgCl/seawater) except when otherwise stated.

The accepted criterion for protection of carbon manganese steels in aerated seawater is a protection potential more negative than $-0,80$ V measured with respect to (wrt) Ag/AgCl/seawater reference electrode. This corresponds approximately to $+0,23$ V when measured wrt pure zinc electrode (e.g. alloy type Z2 as defined in EN 12496:2013, Clause 2 or $+0,25$ V when measured wrt zinc electrode made with galvanic anode alloy types Z1, Z3 or Z4 as defined in EN 12496.

When different metals and alloys are in electrical contact, the protection potential shall be sufficiently negative to control any galvanic corrosion of the less noble of them. In practice, the less noble metal is usually carbon steel, where $-0,80$ V is appropriate.

Ag/AgCl/seawater reference electrodes are sensitive to seawater salinity. A correcting factor shall be applied when not used in 3,5 % seawater salinity. Guidance to conversion between reference electrodes and correction factors are given in ISO 12473:2017, Annex C.

The protection potential of steel in anaerobic environments and where there is a risk of Microbially Influenced corrosion (MIC) shall be more negative than $-0,90$ V wrt Ag/AgCl/seawater, unless another criterion can be justified.

A negative limit of $-1,10$ V wrt Ag/AgCl/seawater is recommended in order to avoid coating disbondment. For conventional steels with a SMYS equal or lower than 550 MPa (grade S355 per EN 10025^[17]), there is no enhanced risk of cracking at this negative limit. This limit will not be exceeded on structures protected by zinc or aluminium galvanic anodes, see ISO 12473.

Where there is a possibility of hydrogen induced stress cracking (HISC) and hydrogen embrittlement, which may be adversely affected by cathodic protection to excessively negative values, a safe, less negative potential limit shall be adopted. If insufficient documentation is available for a given material, this specific negative potential limit relative to the metallurgical and mechanical conditions shall be determined by mechanical testing at the polarized potential limit. These potential limits apply to all cathodically protected structural components, including fasteners.

Ferritic and ferritic-pearlitic structural steels with specified minimum yield strength (SMYS) up to at least 550 MPa have proven compatibility with CP systems, provided they are manufactured and fabricated according to relevant standards. However, laboratory testing has demonstrated susceptibility to HISC during extreme conditions of yielding. All welding should be executed according to a qualified procedure with 350 HV10 as an absolute upper limit. With a qualified maximum hardness in the range 300 HV10 to 350 HV10, design measures should be implemented to avoid local yielding.

Austenitic stainless steels and nickel-based alloys are generally considered immune to HISC in the solution annealed condition. Similarly, welding or hot forming according to an appropriate procedure does not induce HISC sensitivity. Bolts of AISI 316 stainless to ISO 3506-1^[2], grade A4, property class 80 and lower, i.e., up to SMYS 640 MPa, have proven immunity to HISC with a negative limit of $-1,10$ V wrt Ag/AgCl/seawater.

Martensitic carbon, low-alloy and stainless steels can present HISC at steel to electrolyte potentials less negative than $-1,10$ V Ag/AgCl/seawater in materials with an actual YS of about 700 MPa and hardness of about 350 HV10, respectively. Untempered martensite is especially prone to HISC. Welding of materials susceptible to martensite formation should be followed by post welding heat treatment to reduce heat-affected zone (HAZ) hardness and residual stresses from welding. The same recommendations for hardness limits and design measures as for ferritic steels apply. Bolts in martensitic steel heat treated to SMYS up to 720 MPa, e.g. ASTM A193^[21] grade B7 and ASTM A320^[22] grade L7 have proven immunity to HISC with a negative limit of $-1,10$ V wrt Ag/AgCl/seawater.

Failures due to inadequate heat treatment have occurred and for critical applications, batch testing should be employed to verify a maximum hardness of 350 HV10.

Ferritic-austenitic (duplex) stainless steels are potentially susceptible to HISC, independent of SMYS, typically 400 MPa to 550 MPa or specified maximum hardness. Welding may cause increased HISC susceptibility in the weld metal and in the HAZ adjacent to the fusion line. This is related to an increased ferrite content rather than hardness. Qualification of welding should prove that the maximum ferrite content in the weld metal and the inner HAZ, about 0,1 mm wide can be effectively controlled. Ferrite contents of maximum 60 % to 70 % are typically specified. Coarse microstructure is more susceptible because HISC propagates preferentially in the ferrite phase. Design precautions should include measures to avoid local plastic yielding^[26].

NOTE 2 There is no generally recognised test method to verify CP compatibility of different metallic materials. Constant extension rate testing, also referred to as slow strain rate testing, is applicable to compare HISC susceptibility of materials of the same type, e.g., relative susceptibility of martensitic steels. For more quantitative testing, uni-axially loaded tensile specimens, with constant load, 4-point bend specimens with constant displacement, crack tip opening displacement (CTOD) and other testing configurations have been applied at controlled CP conditions. Such testing is, however, beyond the scope of this document.

For steels with a SMYS higher than 550 MPa, a negative limit of potential in the range $-0,83\text{ V}$ to $-0,95\text{ V}$ wrt Ag/AgCl/seawater shall be applied, as specified in ISO 12473. Where potential limits are not defined in ISO 12473 the specific negative potential limit relative to the metallurgical and mechanical conditions shall be determined by testing the material/environment combination at the polarized potential limit. These potential limits apply to all cathodically protected structural components, including fasteners.

Potential limits for high strength steels may also apply to fastener materials.

High strength steels, corrosion resistant alloys (stainless steels and copper alloys), particularly high strength and high hardness materials, may be adversely affected by cathodic protection in accordance with the protection criteria above. ISO 12473 provides guidance as do References ^[53]^[28] and ^[26].

The general guidance is that if the SMYS is $\leq 550\text{ MPa}$ and the hardness is below 350 HV10, cathodic protection is safe to the above criteria limits. But particular materials and their metallurgical condition may be sensitive to hydrogen induced stress cracking (HISC) at less negative values.

7.3 Reinforced concrete structures

Steel reinforced concrete structures or parts of structures fabricated from steel in concrete might not require cathodic protection, see ^{6.1}. However, if their reinforcement is electrically continuous with parts of a steel structure that do require CP, the reinforcement will be a 'drain' on the CP system. In such cases the provision of CP current shall be in accordance with ISO 12696 for 'cathodic prevention'.

If CP of steel in concrete is required for durability of the structure or parts of the structure, it shall be designed in accordance with ISO 12696.

No instant off steel to electrolyte (concrete) potential more negative than $-1,10\text{ V}$ wrt Ag/AgCl/0,5 M KCl for plain reinforcing steel or $-0,90\text{ V}$ for prestressing steel shall be permitted.

The required structure to electrolyte potential limits for reinforcement in concrete structures are detailed in ISO 12696.

ISO 12696 also details the appropriate reference electrodes to be used in reinforced concrete.

8 Cathodic protection design

8.1 Objectives

The objective of a CP system is to deliver sufficient current to each part of the structure and appurtenances in need of protection, in order to meet the potential criteria. The anodes shall be

distributed so that the structure to electrolyte potential of each part of the structure to be cathodically protected is within the limits given by the protection criteria throughout the CP design life, see [Clause 6](#).

The design objectives may be achieved by the design of a CP system using either an impressed current or a galvanic anode system or a combination of both (hybrid systems).

8.2 Design considerations

8.2.1 General

CP systems may be combined with a coating system which will reduce the amount of protective current required and lead to more uniform distribution of the current.

ISO 12944-9^[5] specifies the performance requirements for protective paint systems for offshore and related structures to be used in corrosivity class CX (offshore) and immersion conditions Im4 as defined in ISO 12944-2^[4].

This document introduces the concept of a frequently wetted zone (FWZ) to recognize the full impact of water flow rate, tidal ranges and wave height on CP requirements. This concept is important to offshore wind turbine foundation structures. It is an essential part of the required CP design calculations, see [8.6](#) and [Annex B](#).

Offshore wind turbine foundations are exposed to variable seawater velocities as a result of tidal variations and wave actions. Further, the location of a structural member in flowing water also results in increased flow velocity around the same member.

Because each offshore wind farm is in a geographically unique location in respect of these features, each CP design shall be based on the metocean data unique to that particular location, see [Annex B](#).

The CP system shall be designed with due regard to environmental conditions, see [8.6](#).

Current drain to all surface areas below seabed level and above the fully protected area including the frequently wetted area shall be taken into account when calculating CP current requirements.

Current drain to structures which cannot be directly fitted with anodes such as anchors and mooring chains shall also be taken into account when calculating CP current requirements. The distribution of current, its attenuation and the ability of the CP system to provide relatively uniform current density to all immersed surfaces shall be assessed and ensured e.g. by mathematically modelling the CP system, using appropriate and proven input parameters in order to indicate the distribution of current and structure to electrolyte potential values over the structure under conditions that reflect the full CP design life.

The required inputs to the design which shall be considered and documented are detailed generally in [Clause 15](#) and particularly in [6.3](#). Each step of the CP system design shall be undertaken and checked in accordance with a fully documented design plan and the final CP design shall be fully documented in a CP design report.

A quality management system and an environmental management system shall be used in conjunction with this document.

ISO 9001^[3] constitutes a suitable quality management systems standard which may be used, and ISO 14001^[6] gives guidance on the selection and use of an environmental management system. CP designs should be subject to quality management and include an assessment of environmental impact.

The annulus between a TP skirt internal surface and the MP external surface, see [Figure 2](#), for the bolted MP/TP, may present particular difficulties in respect of CP design. The environment within the annulus may have features of both 'external' and 'internal' CP. The CP design shall document the specific design parameters used for such an annulus. The corrosion assessment should take into account any area within the annulus that is above the water level.

8.2.2 External cathodic protection

CP shall be applied to the external immersed or partially immersed surface of steel structures. Monopiles and tubular piled jackets may be coated, partially coated or bare. In the case of monopile (MP) structures the transition piece is generally coated.

Both galvanic anode CP systems and impressed current CP systems can protect an offshore wind turbine foundation structure against corrosion.

For galvanic anode systems intended for MP installations, the time between driving the monopiles and protecting the MPs with CP should be minimised, or other corrosion mitigations employed.

Early corrosion may have an impact on structural integrity.

In the case of ICCP systems, the CP designer (see [Clause 5](#)), in conjunction with structural engineering, shall determine if temporary CP will be necessary to cover the period between foundation installation and the ICCP system becoming operational.

The possibility of power disruptions or intermittent failures to either temporary or permanent ICCP systems shall also be considered.

8.2.3 Internal cathodic protection

8.2.3.1 Monopiles

Experience has shown that it is difficult to completely seal the internal space in monopiles when J-tubes are routed inside the MP and some oxygenation of water should be expected. Even if completely sealed, entry for inspection will introduce oxygen.

Where CP is installed in closed compartments, ventilation shall be included in the structural design to prevent build-up of gases and consequent risk of an explosive mixture. All CP systems generate hydrogen. Aluminium anodes generate more hydrogen than zinc anodes. Impressed current anodes generate chlorine gas as well as hydrogen gas on the protected steel and this may be particularly corrosive to the “head space” immediately below the airtight deck. There can be an incensive spark risk with both hydrogen (with oxygen in air) and with chlorine (with hydrogen).

In closed monopiles without water replenishment aluminium galvanic anodes should not be used due to known acidification issues^{[33][34]} and hydrogen gas generation and ICCP systems should not be used due to potential safety hazards from chlorine and/or hydrogen gas generation. Zinc anodes may be used with measures to prevent risks from hydrogen gas build up.

Where perforations are introduced into the monopile to ensure a flow of oxygenated seawater, the perforations shall be of sufficient size to preclude their accidental sealing by marine growth or calcareous deposits. The extent of water replenishment in the water column inside the monopile shall be confirmed based on water flow studies.

If CP is not employed internally, the use of protective coatings should be considered and fixed monitoring of the internal environment and corrosion rates at sensitive locations, above and below water and just below the internal seabed/sediment level of representative structures should be considered. Inspection procedures shall be appropriate to ensure detection of localized corrosion before this can impact the structure service life.

Internal CP designs require particular attention to distribution of structure to electrolyte potential over the surface within restricted electrolyte volumes, see [9.6](#) and EN 17243. Mathematical modelling of the CP system [see [Annex I](#)] is recommended.

8.2.3.2 Flooded compartments in jacket structures

For jacket legs with welded and valve sealed flooded compartments with no oxygen access after time of sealing, oxygen will be available for corrosion processes for a relatively short period until it is

consumed. The level and extent of corrosion and the impact of corrosion on the structural integrity in this period shall be considered.

NOTE As an example of impact of oxygen only: For a 2 m diameter vertical tubular with 10 m water column (with 8 ppm dissolved oxygen) and 5 m of air (20,9 % oxygen) a total reduction of wall thickness of 26 µm based on uniform corrosion can be expected before the available oxygen is fully depleted. If corrosion is taking place primarily in the upper meter of column, the corresponding reduction in wall thickness would be 260 µm.

When a jacket has flooded compartment(s) which are not sealed and there is continual replenishment of oxygenated seawater, CP is required. The CP current densities are reduced due to reduced seawater velocities compared with conditions externally. The possible locations for installation of anodes in such a case makes the possibility of uneven potential distribution and attenuation significant and this shall be considered. Further information is given in EN 17243.

8.3 CP Design life

The CP design life is normally specified by the owner. Due to the unmanned and multiple remote installations of offshore wind turbine structures in a wind farm asset it is inevitable that regular access may be difficult and limited. It is normal practice therefore for the CP design life to be for the entire anticipated life of the offshore wind turbine structure.

The CP design life should include both the installation period as well as offshore wind farm turbine operating lifetime. If there is a period without protection before installation and commissioning of the CP system or before energizing (for impressed current systems), then this shall be considered in connection with the structural design. In addition, service life for the decommission phase may be considered. If it is envisaged that the effective life of the CP system will be shorter than that of the structure (including installation and decommissioning periods) then this shall be justified and documented in the design report, see [15.1](#) and provision for replacement or retrofit as appropriate included in the design.

8.4 Surface area considerations

8.4.1 General

To calculate the CP current demand, it is necessary first to determine the surface area of the structure to be protected. This includes areas where the protective criteria are to be met and areas which will drain current.

Design drawings of the structure to be protected should be the basis of the surface area calculation. Information on the extent and type of coatings if any and any associated appurtenances shall be included in the CP design report.

It may be practical to apply some simplification when calculating surface areas for complex structural parts. However, such simplifications shall be conservative to ensure that the resultant calculated current demand is not underestimated. If necessary, an additional contingency factor should be considered, if the exact dimensions of all immersed components are not known.

8.4.2 Structure subdivision

Structures to be protected should be divided into separate CP zones, which can be considered independently with respect to CP design, although electrically connected.

A schematic representation of different zones requiring separate consideration due to installation depth characteristics is indicated in [Figure 2](#), [Figure 3](#), [Figure 4](#) and [Figure 5](#).

[Annex C](#) gives indicative design current density and data for use in the buried zone and for different marked-up seawater flow velocity rates (see [8.6](#)).

Surface area calculations and their separation into various zones shall be documented in the CP design report. Reference shall be made to structural drawings including revision numbers and all items affecting CP current demand shall be included in the calculation.

For piled structures, including monopile foundations, all surface areas that will receive CP current shall be considered, irrespective of any assessment that may infer that the corrosion rate or corrosion risk is low for driven piles into the seabed. CP current will be distributed to the driven pile surfaces and if these surfaces are not included in the CP design there will be a current deficit in the overall CP system design. This shall apply to both internal and external CP designs.

To what extent coatings are provided below seabed/scour depth is for the corrosion protection designer (see [Clause 5](#)) to decide. Any global and local scour shall be included into the CP design, the immersed zone for surface area calculations shall include the level to seabed plus maximum scour depth.

Where scour protection is placed internally, due to the constrained electrolyte, it may affect the electrolyte resistivity, and this should be considered. Externally, due to the huge volume of electrolyte, any issues are normally insignificant.

Anchoring systems on floating offshore wind structures shall be considered as separate zones and shall have their own independent CP systems.

8.5 Environmental factors

8.5.1 General

This document is applicable to the immersed and buried parts of any offshore wind turbine structure located in seawater of all compositions and for all soil types.

For surfaces that are alternately immersed and exposed to the atmosphere, CP is only effective when the immersion time is sufficiently long for the steel to become and be maintained polarized.

CP is effective to bare (uncoated) steel. It is also often used, and is effective, in combination with protective coatings (paints) which reduce the required CP current requirements and improve current distribution.

Friction between the driven part of the structure and the soil can damage coating applied to the structure. [Annex D](#) provides guidance for coating break-down factors that may be applied.

The application of coatings can be precluded by the need for friction between the structure element and the seabed, for example, suction buckets.

Design current densities and therefore the total CP current demand depend upon the seawater velocity, the seawater temperature, erosion, dissolved oxygen content, and the ability to build up and maintain protective calcareous deposits on bare metal surfaces. Some informative guidance is given in [Annex C](#).

The environmental factors listed below that affect CP current requirements and the ability of CP systems to provide this current shall be assessed. These effects are significant in the determination of adequate CP for offshore wind foundations. The effects of significant reduction in anode current output caused by anodes close to each other shall be calculated, see [E.1.8](#). The effects of current and potential attenuation over the steel structure from close to the anodes to points most remote from anodes shall be calculated, see [Annex E](#).

8.5.2 Seawater flow velocity

CP current density requirements for both initial polarization and maintenance of polarization throughout life vary significantly with seawater flow velocity. [Figure 6](#) describes the increase in velocity vertically from seabed/scour level upwards and [B.7](#) describes horizontal flow rate effects. Horizontal velocity will accelerate around vertical tubulars and, for CP design purposes, the determined velocity at varying depths, see [8.6.2](#) shall be marked-up as indicated in [Annex B](#) and [Figure 6](#) in order to determine the appropriate CP current density required.

8.5.3 Electrolyte resistivity

Electrolyte electrical resistivity is of importance in the design of galvanic anode systems since it is a factor in the calculation of anode to remote seawater resistance and hence anode current output, see [Annex E](#). For impressed current anodes the electrical resistivity shall be taken into account during system design to provide sufficient output voltage. However, electrolyte resistivity also affects distribution of current from anodes and hence the degree of structure polarization. Higher resistivity results in polarization over a shorter distance from the anodes.

Seawater electrical resistivity (ρ in Ωm) is dependent on seawater salinity and temperature. In open seawater the value of salinity is reasonably constant within a relatively narrow limit, as shown in [Annex E](#). However, in some offshore wind farm locations, for example inshore areas (particularly near river estuaries and where tidal currents are significant) or in areas affected by snow melts/seasonal freshwater ingress (e.g. Baltic Sea and Caspian Sea), resistivity may vary considerably both with location and with time. In some conditions there can be stratification of different salinity at different depths, causing variations in resistivity with depth.

All of these factors shall be taken into account in the CP design.

Resistivity values shall be based on actual data from the specific location and the data shall reflect the mean and variation over an annual period and any variation with depth. The resistivity corresponding to an average temperature for the coldest month of the year (or the month with the highest electrical resistivity due to a combination of temperature and freshwater dilution of the salinity) shall be used in the design. In the absence of measured seawater electrical resistivity, accurate assessment shall be by use of local salinity and temperature measurements and [Annex E](#).

If anodes are to be installed in the seabed sediment, the seabed resistivity shall be determined or estimated by the CP designer (see [Clause 5](#)) in the absence of measured values. If actual data are not available for sediment resistivity, a default value of $5 \times$ seawater resistivity used for the design shall be used.

8.5.4 Seawater temperature

Temperature has a significant effect on seawater resistivity, See [8.5.3](#), on levels of dissolved oxygen and on calcareous deposit formation. The range of temperatures to be anticipated for the structure shall be considered in the CP design.

Increasing water temperature decreases oxygen solubility and therefore reduces CP current density required. It however also increases the corrosion rate and increases the CP current density required.

Thus, the effects of seawater temperature on CP designs are complex and they shall be addressed in detail. [Annex C](#) provides informative guidance regarding the impact of temperature on CP design parameters.

Decreasing temperatures increase the solubility of the calcareous deposits and affects their formation rate and morphology reducing the protective nature of the deposits given in ISO 12473.

8.5.5 Calcareous deposits

Calcareous deposits on the structure surface occur as a result of cathodic reactions during the CP process, see ISO 12473. The current requirement to protect a structure is decreased when calcareous deposits have formed. The mean current density is largely determined by the nature of the calcareous deposits for steel in seawater when effective CP has been achieved.

Allowance shall be made for the influence of water flows, suspended silts, sands, ice or by ice flows on stability of calcareous deposits. The stability of calcareous deposits is also affected by storms. Guidance is given in [Annex D](#) and Reference [\[35\]](#).

8.6 Protection current demand

8.6.1 General

The current demand of each metallic component of the structure is the product of its surface area exposed to the electrolyte and the selected current density. The demand can be reduced by the presence of coatings where appropriate. The term “current density” is the CP current per uncoated unit surface area of the structure being protected. The selected current density is that which is required to achieve and maintain polarization of the structure to be protected.

The current densities shall be selected either from proven experience from similar installations in the same locality, from full scale testing or based on published data relating measured environmental conditions to current density for instance as detailed in [Annex C](#).

Caution should be exercised in using ‘proven design practice’ from past projects if the CP performance of these past projects has not been accurately assessed. The assessment should include potential surveys, fixed potential monitoring (data logging) and current or current density measurements or surveys that verify the effectiveness of the design in delivering full conformity with CP design criteria for all times of the year, with all environmental conditions.

The current demand calculations shall include the initial (or polarization), the mean (or average) and the final (or re-polarization) current densities, informative values given in [Annex C](#).

For galvanic anodes, the initial and final current requirements shall be used to determine anode number and geometry based on anode resistance calculations, see [Annex E](#).

The mean current demand often called maintenance current demand shall be used to determine the requirement of total galvanic anode mass i.e. net mass of the cast alloy required for the design life.

For impressed current the anode design shall be based on the maximum calculated current requirement of the initial and final current values with an added contingency factor. A minimum factor of 25 % is recommended, see [10.2.2](#).

While coatings are not necessary for effective CP, they are often used in conjunction with CP to reduce the current demand and improve current distribution/reduce attenuation, see [Annex E](#).

For coated structures the CP design shall take into account the increased current demand over time as the coating loses its electrical resistance effectiveness. This is achieved by the application of a coating breakdown factor in the formulae for current demand calculation, see [8.6.2](#). [Annex D](#) explains the process of coating breakdown and has suggested coating breakdown factors and breakdown rates for a range of coating systems which may be suitable for use for offshore wind turbine foundation structures.

8.6.2 Calculation of current demand, external surfaces

For external surfaces, the frequency of wetting of the structure shall be included in the design.

For driven or drilled piles, suction buckets or anchors below the seabed, their full external surface area shall be included in the CP design, refer to [8.4](#). Guidance on which items are to be cathodically protected and which items only act as a drain on the CP system is provided in [Table C.4](#). Any anode support structure shall also be included in the CP current calculation requirement.

To account for the effect of seawater velocity, metocean data shall be used to derive a marked-up seawater flow velocity profile across the water depths. Recommended methodology is described in [Annex B](#). The upper water level shall be the frequently wetted zone at 50 percent non-exceedance level, $FWZ_{50\%}$.

The current demand shall be calculated based on the surface area including the frequently wetted zone (FWZ), to structure pile toe level or suction bucket toe level. The structure should, as a minimum, be divided into the following zones:

- a) $FWZ_{50\%}$ to $FWZ_{5\%}$

- b) FWZ_{5 %} to seabed/scour
- c) Seabed/scour to pile toe/suction bucket level

The current demand shall be calculated for the initial, mean and final (re-polarization) event.

The total current demand shall be calculated as the sum of current demands from each of the zones, defined above from FWZ_{50 %} to toe level.

The total current, I_{total} , required shall be calculated as given in [Formula \(1\)](#):

$$I_{\text{total}} = I_{\text{zone(FWZ 50 \% to FWZ 5 \%)}} + I_{\text{zone(FWZ 5 \% to seabed-scour depth)}} + I_{\text{zone(seabed-scour depth to toe level)}} \quad (1)$$

i.e. summation over the individual zones.

The zone FWZ_{5 %} to seabed/scour shall be subdivided into zones of maximum 10 m depth to account for changes in marked-up seawater flow velocity, see [Figure 6](#).

The 10-meter increments may be adjusted if the marked-up flow velocity profile provides justification for this, for instance where the profile is very steep, larger increments may be used.

The current for the subzones from FWZ_{5 %} to seabed/scour shall be calculated as given in [Formula \(2\)](#):

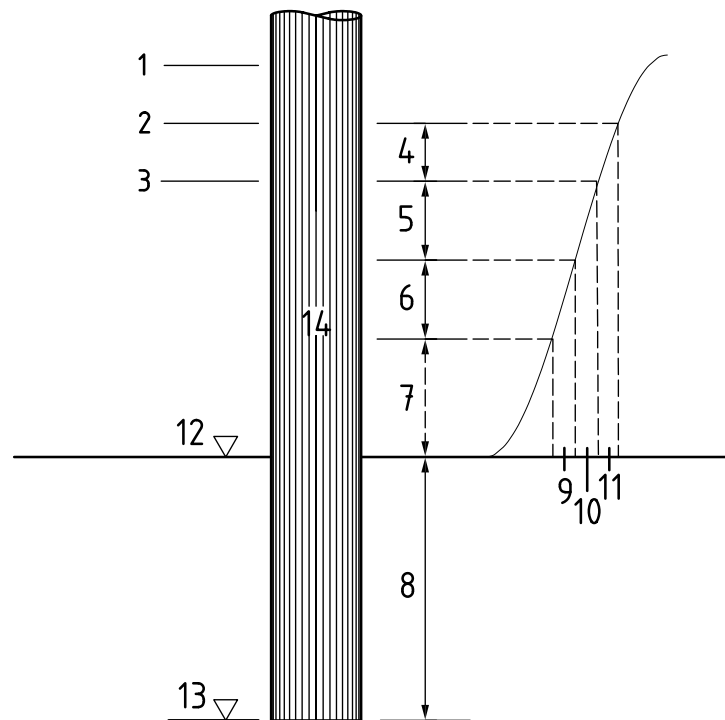
$$I_{\text{zone}} = j_{\text{zone}} \cdot A_{\text{zone}} \cdot f_c \quad (2)$$

where

- I_{zone} is the current in A,
- j_{zone} is the current density in A/m²,
- A_{zone} is the surface area of the zone in m²,
- f_c is the coating breakdown factor, for uncoated bare steel parts of the structure, $f_c = 1$

The current densities for the initial, mean and final (re-polarization) events for structural steel foundations shall be calculated:

- Below seabed/scour: For instance, as per the guidance in [C.4](#).
- Above seabed/scour: The derived marked-up seawater flow velocity profile shall be used to find the current density for instance as provided in [C.2](#) for each of the above zones. The marked-up seawater flow velocity in the vertical centre of the zone shall be used as basis.



Key

1	FWZ ₉₅ %	8	A_{BS} , m ²
2	FWZ ₅₀ %	9	U_{CP2} , m/s
3	FWZ ₅ %	10	U_{CP1} , m/s
4	$A_{(FWZ50 \% - FWZ5 \%)}$, m ²	11	$U_{CP(FWZ50 \% - 5 \%)}$, m/s
5	$A_{1.(FWZ5 \% - \text{max. 10 m below FWZ5 \%})}$, m ²	12	seabed/scour
6	$A_{2.(\text{max. 10 m below FWZ5 \%} - \text{max. 20 m below FWZ5 \%})}$, m ²	13	toe
7	$A_{z.(\text{to seabed})}$, m ²	14	structure

Figure 6 — Steel structure areas and zones relative to seawater flow velocity

[Figure 6](#) shows the structure to the left with structure levels on the y-axis: toe, seabed/scour and levels for frequently wetted zones (FWZ_{5 %}, FWZ_{50 %} and FWZ_{95 %}). [Annex B](#) provides information on how to derive the frequently wetted zone based on metocean data.

A represents the surface areas in the individual zones to subdivide the structure into:

- $A_{FWZ(50\% - 5\%)}$,
- $A_{FWZ(5\% - \text{Max } 10 \text{ m below FWZ } 5\%)}$,
- $A_{FWZ(\text{Max } 20 \text{ m below FWZ } 5\% - \text{Max } 10 \text{ m below FWZ } 5\%)}$, etc until seabed or scour depth, and
- A_{BS} for below seabed.

The X-axis represents the marked-up seawater flow velocity as defined and derived as detailed in [Annex B](#). Above seabed/scour the marked-up seawater flow velocity ($U_{CP(FWZ50\% - 5\%)}$, U_{CP1} , U_{CP2} , etc) as shown on the X-axis shall be used to find the current density for instance as shown in [C.2](#) for that given zone. U_{CP} is the vertical centre of the zone to be used in the calculations.

Below seabed, the surface area may be subdivided as shown [C.4](#) with the corresponding current densities shown. Guidance on calculation of current densities for reinforced concrete foundations can be found for instance based upon [C.5](#).

8.6.3 Calculation of current demand, internal surfaces

Internally, the surface areas for compartments with free-flowing seawater shall extend to the highest internal water level, which for free-flowing conditions will be HAT.

Flow inside a monopile is dependent on the size, number, and location of the openings in the surface and the sea state outside the monopile. In order to estimate the appropriate current densities a detailed study of the seawater flow velocity within the structure is required along with study of the environmental factors, dissolved oxygen concentration, pH, salinity etc.

Guidance on current requirements for different dissolved oxygen contents can be found for instance in [Annex C](#).

8.7 Electrical continuity and continuity bonds

Where the foundation structure incorporates bolted flange to flange connections or where a welded jacket structure is used, the electrical continuity in the structure may allow for adequate current flow from the anodes to the structure.

Electrical continuity bonding shall be established between the MP and TP where the MP and TP are grouted, and where either

- external galvanic anodes are welded to the TP,
- internal galvanic anodes are connected to the TP, or
- impressed current systems are utilized with the negative return or 'drain point' connected to the TP, or all

These continuity bonds shall be designed so that the full current from both an external and internal CP system can be carried between the MP and TP and that the voltage drop across the bonds and connection points is not such that it adversely affects the CP system performance. The continuity bond design (cross section, length and contact resistances) shall meet the requirements of the CP and the electrical safety and earthing for lightning purposes.

Some redundancy in the provision of continuity bonds is recommended. Design of the continuity bond may be based on a total of 10 mV voltage drop across all the parallel connections using the maximum design CP current (see [8.6](#)). This recommendation is relevant to galvanic anode systems in which case the design driving voltage for the anodes for galvanic anode systems shall be reduced accordingly (see [Clause 10](#) for ICCP systems).

If the connection is bolted, the connection shall be made using appropriate methods to avoid loosening as a result of vibration and deterioration due to corrosion.

NOTE Direct pin brazing ensures a metallurgical bond between the copper core of the cables and the steel of the MP and TP and is a suitable low resistance connection method.

Bond resistance measured using AC or DC resistance measurement methods is not an accurate measure because of the many parallel connection points through, for example continuity bonds and wedges etc. and should always be conducted in conjunction with visual inspection of the bond integrity. Current flowing across the bonds can be measured using a high accuracy DC clamp meter.

Material selection and corrosion protection of the contact points shall be chosen so that the connection is durable, reliable and maintainable over the CP design life, bearing in mind that these connections often are placed above water and will not receive protective current, but they will be in a humid, saline and sometimes tidal exposure area.

These details shall be documented in the CP Design Report along with the extent to which the volt drop in cable bonds between TPs and MPs and between anode cages or arrays and MPs has been calculated, which reduces galvanic anode currents and what provision has been made in the design to remedy this.

8.8 Current drains and interactions

Current can be drained by structures or elements of the structure that are not intended to be fully protected by the CP system.

NOTE 1 Examples are

- cable protection systems,
- cable armouring,
- the area of the foundation or structure above and below the level where full protection is required, and
- mooring and anchor chains.

These items shall be documented and considered in the CP design and an additional current demand as appropriate to the particular circumstance shall be applied to the calculated additional surface areas.

The amount of current that will be drained, depends on the surface area and local environment. Some indicative current densities are given in [Annex C](#) if actual measured data or experience from other nearby structures is not available. Mathematical modelling may indicate the amount of current likely to be drained, see [Annex I](#).

NOTE 2 Theoretically all structures in a typical windfarm development will be electrically interconnected via the armouring of the array cables. In practice there is no evidence of significant currents flowing between adjacent structures; the electrical resistance of the steel wire armour and the localized distribution of external anodes dictate that one structure will not significantly affect its neighbour's CP system performance.

The interconnection between structures should be acknowledged and could, theoretically, affect any future novel foundation designs or CP systems.

8.9 Installation considerations during design

For jacket structures, galvanic anodes and ICCP anodes with their cables and conduits can be installed in the fabrication yard before launch. Mathematical modelling see [Annex I](#) can be used to predict the distribution of potential and inform the optimum choice of anode location.

For monopile or transition piece structures, due to installation constraints during pile driving, galvanic and ICCP anodes are not normally pre-installed on driven monopiles. Anodes are either fixed to the transition piece or separate anode cages on the monopile or anode array on the seabed are used. These shall be electrically connected to the MP at the offshore site after driving operations are completed.

In this case the uniform distribution of potential is more difficult. Inadequate anode distribution and attenuation of current and potential over monopile surfaces apply equally to ICCP systems as to GACP systems. Mathematical modelling at the design stage can optimize the design in respect of adequate current and potential distribution across the structure, see [Annex I](#), allowing optimum placement of anodes and minimize the risk of under or over-polarization.

The CP design shall ensure that anodes and monitoring systems are installed where the possibility of disturbance or damage from external sources is minimal and, where appropriate, anode replacement is facilitated.

For the internal protection of MP/TP foundation structures, anodes may be suspended from the deck of the transition piece or from the lower internal platform. The suspension of anodes will take place after the monopile has been driven into the seabed and the TP has been installed.

Either the time between installation of monopiles and transition piece may be significant, or the coupling of anodes to the structure is completed sometime after installation, or both.

The periods where the CP system is not operational should be recognized and any effect on structural integrity should be accounted for in the structural design.