Guide for the Certification of Offshore Wind Turbine Structures

Effective from 1 January 2018

Emirates Classification Society (Tasneef)
Aldar HQ 19th Floor,
Al Raha Beach, Abu Dhabi, UAE
Abu Dhabi, United Arab Emirates

Phone (+971) 2 692 2333
Fax (+971) 2 445 433
P.O. Box. 111155
info@tasneef.ae

GENERAL CONDITIONS

Definitions:

"*Administration*" means the Government of the State whose flag the Ship is entitled to fly or under whose authority the Ship is authorised to operate in the specific case.

"IACS" means the International Association of Classification Societies.

"*Interested Party*" means the party, other than the Society, having an interest in or responsibility for the Ship, product, plant or system subject to classification or certification (such as the owner of the Ship and his representatives, the ship builder, the engine builder or the supplier of parts to be tested) who requests the Services or on whose behalf the Services are requested.

"*Owner*" means the registered owner, the ship owner, the manager or any other party with the responsibility, legally or contractually, to keep the ship seaworthy or in service, having particular regard to the provisions relating to the maintenance of class laid down in Part A, Chapter 2 of the Rules for the Classification of Ships or in the corresponding rules indicated in the specific Rules.

"Rules" in these General Conditions means the documents below issued by the Society:

- (i) Rules for the Classification of Ships or other special units;
- (ii) Complementary Rules containing the requirements for product, plant, system and other certification or containing the requirements for the assignment of additional class notations;
- (iii) Rules for the application of statutory rules, containing the rules to perform the duties delegated by Administrations;
- (iv) Guides to carry out particular activities connected with Services;
- (v) Any other technical document, as for example rule variations or interpretations.

"*Services*" means the activities described in Article 1 below, rendered by the Society upon request made by or on behalf of the Interested Party.

"Ship" means ships, boats, craft and other special units, as for example offshore structures, floating units and underwater craft.

"*Society*" or *"TASNEEF"* means Tasneef and/or all the companies in the Tasneef Group which provide the Services.

"*Surveyor*" means technical staff acting on behalf of the Society in performing the Services.

Article 1

1.1. The purpose of the Society is, among others, the classification and certification of ships and the certification of their parts and components. In particular, the Society:
- (i) sets forth and develops Rules;
- (ii) publishes the Register of Ships;
- (iii) issues certificates, statements and reports based on its survey activities.

1.2. The Society also takes part in the implementation of national and international rules and standards as delegated by various G overnments.

1.3. The Society carries out technical assistance activities on request and provides special services outside the scope of classification, which are regulated by these general conditions, unless expressly excluded in the particular contract.

Article 2

2.1. The Rules developed by the Society reflect the level of its technical knowledge at the time they are published. Therefore, the Society, although committed also through its research and development services to continuous updating of the Rules, does not guarantee the Rules meet state-of-the-art science and technology at the time of publication or that they meet the Society's or others' subsequent technical developments.

2.2. The Interested Party is required to know the Rules on the basis of which the Services are provided. With particular reference to Classification Services, special attention is to be given to the Rules concerning class suspension, withdrawal and reinstatemen t. In case of doubt or inaccuracy, the Interested Party is to promptly contact the Society for clarification.
The Rules for Classification of Ships are published on the Society's website: www.tasneef.ae.

2.3. The Society exercises due care and skill:
- (i) in the selection of its Surveyors
- (ii) in the performance of its Services, taking into account the level of its technical knowledge at the time the Services are performed.

2.4. Surveys conducted by the Society include, but are not limited to, visual inspection and non-destructive testing. Unless otherwise required, surveys are conducted through sampling techniques and do not consist of comprehensive verification or monitoring of the Ship or of the items subject to certification. The surveys and checks made by the Society on board ship do not necessarily require the constant and continuous presence of the Surveyor. The Society may also commission laboratory testing, underwater inspection and other checks carried out by and under the responsibility of qualified service suppliers. Survey practices and procedures are selected by the Society based on its experience and knowledge and according to generally accepted technical standards in the sector.

Article 3

3.1. The class assigned to a Ship, like the reports, statements, certificates or any other document or information issued by the Society, reflects the opinion of the Society concerning compliance, at the time the Service is provided, of the Ship or product subject to certification, with the applicable Rules (given the intended use and within the relevant time frame).
The Society is under no obligation to make statements or provide information about elements or facts which are not part of th e specific scope of the Service requested by the Interested Party or on its behalf.

3.2. No report, statement, notation on a plan, review, Certificate of Classification, document or information issued or given as p art of the Services provided by the Society shall have any legal effect or implication other than a representation that, on the basis of the checks made by the Society, the Ship, structure, materials, equipment, machinery or any other item covered by such document or information meet the Rules. Any such document is issued solely for the use of the Society, its committees and clients or other duly authorised bodies and for no other purpose. Therefore, the Society cannot be held liable for any act made or document issued by other parties on the basis of the statements or information given by the Society. The validity, application, meaning and interpretation of a Certificate of Classification, or any other document or information issued by the Society in connection with its Services, is governed by the Rules of the Society, which is the sole subject entitled to make such interpretation. Any disagreement on technical matters between the Interested Party and the Surveyor in the carrying out of his functions shall be raised in writing as soon as possible with the Society, which will settle any divergence of opinion or dispute.

3.3. The classification of a Ship, or the issuance of a certificate or other document connected with classification or certificati on and in general with the performance of Services by the Society shall have the validity conferred upon it by the Rules of the Society at the time of the assignment of class or issuance of the certificate; in no case shall it amount to a statement or warranty of seaw orthiness, structural integrity, quality or fitness for a particular purpose or service of any Ship, structure, material, equipment or machinery inspected or tested by the Society.

3.4. Any document issued by the Society in relation to its activities reflects the condition of the Ship or the subject of certification or other activity at the time of the check.

3.5. The Rules, surveys and activities performed by the Society, reports, certificates and other documents issued by the Society are in no way intended to replace the duties and responsibilities of other parties such as Governments, designers, ship builders, manufacturers, repairers, suppliers, contractors or sub-contractors, Owners, operators, charterers, underwriters, sellers or intended buyers of a Ship or other product or system surveyed.

These documents and activities do not relieve such parties from any fulfilment, warranty, responsibility, duty or obligation (also of a contractual nature) expressed or implied or in any case incumbent on them, nor do they confer on such parties any right, claim or cause of action against the Society. With particular regard to the duties of the ship Owner, the Services undertaken by the Society do not relieve the Owner of his duty to ensure proper maintenance of the Ship and ensure seaworthiness at all times. Likewise, the Rules, surveys performed, reports, certificates and other documents issued by the Society are intended neither to guarantee the buyers of the Ship, its components or any other surveyed or certified item, nor to relieve the seller of the duties arising out of the law or the contract, regarding the quality, commercial value or characteristics of the item which is the subject of transaction.

In no case, therefore, shall the Society assume the obligations incumbent upon the above-mentioned parties, even when it is consulted in connection with matters not covered by its Rules or other documents.

In consideration of the above, the Interested Party undertakes to relieve and hold harmless the Society from any third party claim, as well as from any liability in relation to the latter concerning the Services rendered.

Insofar as they are not expressly provided for in these General Conditions, the duties and responsibilities of the Owner and Interested Parties with respect to the services rendered by the Society are described in the Rules applicable to the specific Service rendered.

Article 4

4.1. Any request for the Society's Services shall be submitted in writing and signed by or on behalf of the Interested Party. Such a request will be considered irrevocable as soon as received by the Society and shall entail acceptance by the applicant of all relevant requirements of the Rules, including these General Conditions. Upon acceptance of the written request by the Society, a contract between the Society and the Interested Party is entered into, which is regulated by the present General Conditions.

4.2. In consideration of the Services rendered by the Society, the Interested Party and the person requesting the service shall be jointly liable for the payment of the relevant fees, even if the service is not concluded for any cause not pertaining to the Society. In the latter case, the Society shall not be held liable for non-fulfilment or partial fulfilment of the Services requested. In the event of late payment, interest at the legal current rate increased by 1.5% may be demanded.

4.3. The contract for the classification of a Ship or for other Services may be terminated and any certificates revoked at the request of one of the parties, subject to at least 30 days' notice to be given in writing. Failure to pay, even in part, the fees due for Services carried out by the Society will entitle the Society to immediately terminate the contract and suspend the Services.

For every termination of the contract, the fees for the activities performed until the time of the termination shall be owed to the Society as well as the expenses incurred in view of activities already programmed; this is without prejudice to the right to compensation due to the Society as a consequence of the termination.

With particular reference to Ship classification and certification, unless decided otherwise by the Society, termination of the contract implies that the assignment of class to a Ship is withheld or, if already assigned, that it is suspended or withdrawn; any statutory certificates issued by the Society will be withdrawn in those cases where provided for by agreements between the Society and the flag State.

Article 5

5.1. In providing the Services, as well as other correlated information or advice, the Society, its Surveyors, servants or agents operate with due diligence for the proper execution of the activity. However, considering the nature of the activities performed (see art. 2.4), it is not possible to guarantee absolute accuracy, correctness and completeness of any information or advice supplied. Express and implied warranties are specifically disclaimed.

Therefore, except as provided for in paragraph 5.2 below, and also in the case of activities carried out by delegation of Governments, neither the Society nor any of its Surveyors will be liable for any loss, damage or expense of whatever nature sustained by any person, in tort or in contract, derived from carrying out the Services.

5.2. Notwithstanding the provisions in paragraph 5.1 above, should any user of the Society's Services prove that he has suffered a loss or damage due to any negligent act or omission of the Society, its Surveyors, servants or agents, then the Society will pay compensation to such person for his proved loss, up to, but not exceeding, five times the amount of the fees charged for the specific services, information or opinions from which the loss or damage derives or, if no fee has been charged, a maximum of AED5,000 (Arab Emirates Dirhams Five Thousand only). Where the fees charged are related to a number of Services, the amount of the fees will be apportioned for the purpose of the calculation of the maximum compensation, by reference to the estimated time involved in the performance of the Service from which the damage or loss derives. Any liability for indirect or consequential loss, damage or expense is specifically excluded. In any case, irrespective of the amount of the fees charged, the maximum damages payable by the Society will not be more than AED5,000,000 (Arab Emirates Dirhams Five Millions only). Payment of compensation under this paragraph will not entail any admission of responsibility and/or liability by the Society and will be made without prejudice to the disclaimer clause contained in paragraph 5.1 above.

5.3. Any claim for loss or damage of whatever nature by virtue of the provisions set forth herein shall be made to the Society in writing, within the shorter of the following periods: (i) THREE (3) MONTHS from the date on which the Services were performed, or (ii) THREE (3) MONTHS from the date on which the damage was discovered. Failure to comply with the above deadline will constitute an absolute bar to the pursuit of such a claim against the Society.

Article 6

6.1. These General Conditions shall be governed by and construed in accordance with United Arab Emirates (UAE) law, and any dispute arising from or in connection with the Rules or with the Services of the Society, including any issues concerning responsibility, liability or limitations of liability of the Society, shall be determined in accordance with UAE law. The courts of the Dubai International Financial Centre (DIFC) shall have exclusive jurisdiction in relation to any claim or dispute which may arise out of or in connection with the Rules or with the Services of the Society.

6.2. However,

(i) In cases where neither the claim nor any counterclaim exceeds the sum of AED300,000 (Arab Emirates Dirhams Three Hundred Thousand) the dispute shall be referred to the jurisdiction of the DIFC Small Claims Tribunal; and

(ii) for disputes concerning non-payment of the fees and/or expenses due to the Society for services, the Society shall have the right to submit any claim to the jurisdiction of the Courts of the place where the registered or operating office of the Interested Party or of the applicant who requested the Service is located.

In the case of actions taken against the Society by a third party before a public Court, the Society shall also have the right to summon the Interested Party or the subject who requested the Service before that Court, in order to be relieved and held harmless according to art. 3.5 above.

Article 7

7.1. All plans, specifications, documents and information provided by, issued by, or made known to the Society, in connection with the performance of its Services, will be treated as confidential and will not be made available to any other party other than the Owner without authorisation of the Interested Party, except as provided for or required by any applicable international, European or domestic legislation, Charter or other IACS resolutions, or order from a competent authority. Information about the status and validity of class and statutory certificates, including transfers, changes, suspensions, withdrawals of class, recommendations/conditions of class, operating conditions or restrictions issued against classed ships and other related information, as may be required, may be published on the website or released by other means, without the prior consent of the Interested Party.

Information about the status and validity of other certificates and statements may also be published on the website or released by other means, without the prior consent of the Interested Party.

7.2. Notwithstanding the general duty of confidentiality owed by the Society to its clients in clause 7.1 above, the Society's clients hereby accept that the Society may participate in the IACS Early Warning System which requires each Classification Society to provide other involved Classification Societies with relevant technical information on serious hull structural and engineering systems failures, as defined in the IACS Early Warning System (but not including any drawings relating to the ship which may be the specific property of another party), to enable such useful information to be shared and used to facilitate the proper working of the IACS Early Warning System. The Society will provide its clients with written details of such information sent to the involved Classification Societies.

7.3. In the event of transfer of class, addition of a second class or withdrawal from a double/dual class, the Interested Party undertakes to provide or to permit the Society to provide the other Classification Society with all building plans and drawings, certificates, documents and information relevant to the classed unit, including its history file, as the other Classification Society may require for the purpose of classification in compliance with the applicable legislation and relative IACS Procedure. It is the Owner's duty to ensure that, whenever required, the consent of the builder is obtained with regard to the provision of plans and drawings to the new Society, either by way of appropriate stipulation in the building contract or by other agreement.

In the event that the ownership of the ship, product or system subject to certification is transferred to a new subject, the latter shall have the right to access all pertinent drawings, specifications, documents or information issued by the Society or which has come to the knowledge of the Society while carrying out its Services, even if related to a period prior to transfer of ownership.

Article 8

8.1. Should any part of these General Conditions be declared invalid, this will not affect the validity of the remaining provisions.

Part A GENERAL
Chapter 1:
General Principles

1. Application

This document provides principles, technical requirements and guidance for the certification of offshore wind turbine structures.
These guidelines apply to steel fixed (bottom founded) structures and are to be used for the verification of structural components, support structures and foundations of offshore wind turbines, with specific focus given to bottom founded structures that are presently the typical configuration used for shallow waters.
In particular this document provides requirements for the following:

- design principles;
- selection of material;
- design loads;
- load effects analysis;
- steel structures design;
- foundation design;
- fabrication, installation and corrosion protection general requirements.

The guidelines do not apply to those components which are not essential for the structural integrity of the wind turbine offshore installation or to the system used to transfer the electric power generated by wind turbines, such as the cables laid on the seabed.

2. Amendments

Taking into account that the design technology of offshore wind structures is not only a complex technology but is rapidly evolving, these guidelines will be subject to review and updating as deemed necessary based both on experience and on future development.

3. Governmental rules and International Standards

The application of the principles and technical requirements contained in this document is considered as part of the basis for obtaining Tasneef certification of the structure.
The certification of an offshore wind turbine with Tasneef or, more generally, any Tasneef act and decision does not relieve the interested parties from their duty of complying with any additional and/or more stringent requirements issued by the competent Administration and the relevant provisions for this application.
Moreover, general reference, and reference for matters not expressly specified or modified by these guidelines, is to be done to the International Standards Series IEC. in particular:
IEC EN 61400-3 Wind Turbines, Part 3: Design requirements for offshore wind turbines,
and the applicable requirements of:
IEC EN 61400-1 Wind Turbines, Part 1: Design requirements,
are to be complied with.

4. Alternative design criteria

Tasneef reserves the right to accept design criteria alternative to those mentioned in this document, provided it is satisfied that equivalent safety is achieved by such criteria.
The requirements of these guidelines are to be applied together with those of recognised design codes or standards.
Supplementary codes or standards used in the design are to be submitted to Tasneef for prior approval.
In the case of discrepancies between the requirements of codes or standards used and those of these guidelines, Tasneef may accept the former provided that, in its opinion, they ensure a global safety level equivalent to or higher than that resulting from the application of these guidelines. Preference will generally be given to codes or standards developed and used in the country where the structure is to be installed.

Part A Chapter 2: Terms and Definitions

1. General

The basic component of an offshore wind farm is the offshore wind turbine (OWT), defined as a wind turbine with a support structure subject to hydrodynamic loading (see also Fig. 1.1).

According to the IEC 61400-3 standard for offshore wind turbine design, the OWT can be split into the two following components:

- The rotor-nacelle assembly;
- The support structure,

for the main purpose of the assessment to the acting external loads.

Indeed, the hydrodynamic loads acting on the support structure of an offshore wind turbine are affecting the rotor-nacelle assembly only as indirect consequence of the response, particularly in terms of dynamic vibration, of the support structure.

The design of the support structure shall be based on the marine environmental conditions characteristic of the site where the offshore wind turbine will be installed.

On the other hand, wind conditions are the primary external conditions for the structural integrity of the rotor-nacelle assembly, although the marine conditions may also have an influence in some cases depending on the dynamic properties of the structure.

2. Definitions

For the purpose of this document, the following terms and definitions apply, in addition to those reported in IEC 61400-1 and IEC 61400-3.

2.1 Rotor-nacelle assembly

The RNA is the part of a wind turbine carried by the support structure and it includes:

- Rotor;
- Nacelle.

2.1.1 Rotor

The rotor is the part of the wind turbine consisting of the blades and the hub.

2.1.2 Nacelle-assembly

The nacelle-assembly is the collection of all components above the tower that are not part of the rotor.

This includes, principally, the drive train (shafts, couplings, gearbox, generator and brakes) and the nacelle enclosure.

2.2 Support structure

It is the portion of the offshore wind turbine made by the tower, the substructure and the foundation.

Different support structure concepts exist and they are specifically discussed in Chapter 5.

2.2.1 Tower

The tower is the part of the offshore wind turbine support structure connecting the substructure to the rotor-nacelle assembly.

2.2.2 Substructure

The substructure is the part of the offshore wind turbine support structure that is specifically submerged along the water depth, since it extends upwards from the seabed, connecting the foundation to the tower.

2.2.3 Foundation

The foundation is the part of the offshore wind turbine support structure which transfers the loads acting on the structure to the soil under the seabed.

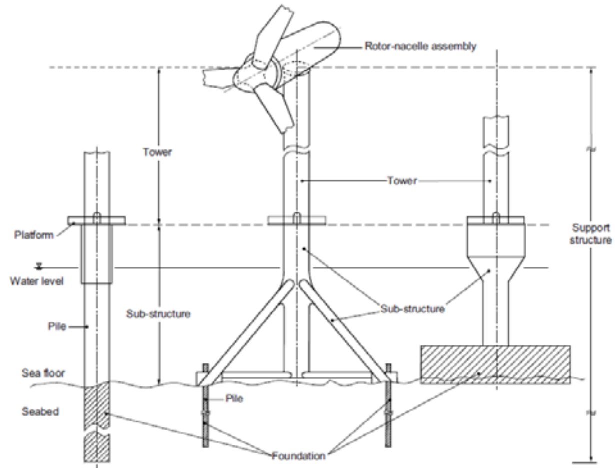

Fig. 1.1: Offshore wind turbine scheme

2.3 Design Life

The period of time between the commencement of construction and removal or breaking-up of the structure, which is subdivided into the following phases:

- Construction phase. This phase includes construction and assembly of the structure ashore or afloat;
- Transportation phase. This phase includes transportation of the structure or parts thereof, from the construction site to its final location including its possible loading on barges and mooring operations on the final location;
- Installation phase. This phase includes possible operations of launching, upending, submerging and positioning, piling, anchoring, ballasting, arrangements of nacelle, rotor, blades or other modular components, until the structure is ready to start its normal service operation;
- Operation phase. This phase starts with completion of installation and ends with removal or breaking-up of the structure;
- Removal phase. This phase includes removal of the structure from its location at the end of its operation.

2.4 Location

The geographical location where the wind turbine is finally installed to perform its design operation.

2.5 Water depth

The vertical distance from the sea bed to the minimum water level taking into account the effects, combined as necessary, of astronomical, wind and pressure differential tides.

2.6 Safety classes

An offshore wind turbine shall be designed according to one of the following safety classes *(ref. IEC 61400-3, Subclause 5.3):*

- A normal safety class is applied when a failure results personal injury or other social risk or economic consequence;
- A special safety class is applied when the safety requirements are determined by local regulations and safety requirements agreed by the manufacturer and the customer.

Wind turbine classes are defined in terms of wind speed and turbulence parameters ($\mathrm{V_{ref}}$ and $\mathrm{I_{ref}}$). Offshore wind turbines require wind turbine "class S" design, in which the design value shall be chosen by the designer and specified in the design documentation.
(ref. IEC 61400-3, Subclause 6.2).

Part B - STRUCTURES
Chapter 1:
General Analysis and Design Principles

1. General

1.1 Safety requirements

Offshore wind turbine structures are to be designed and constructed so as to ensure an acceptable standard with regards to safety of life at sea and to the prevention of environmental pollution and of possible major economic losses during all phases of the design life.
A support structure and its foundations are considered to have an acceptable level of safety when it is designed, constructed and inspected in compliance with the requirements of these guidelines and with those of supplementary codes mentioned in Part A, Chapter1,.

1.2 Functional requirements

The serviceability of the structure, i.e. the aptitude of the support structure to be properly operated in performing its design service, may require special design criteria.
The Designer or the Owner may specify functional requirements which are additional to those of these guidelines.

2. Methods of analysis and calculation

2.1 General

2.1.1
The safety verification of the wind turbine structure is to be performed by checking that stresses and structure dynamics do not exceed specified limit values.

2.2 Determination of loading effects

2.2.1
The determination of forces, moments, displacements, stresses and strains as well as the definition of corresponding resistance values are to be based upon accepted principles of static analysis, dynamic analysis and strength of materials.
The determination of stresses and strains is to be based on the theory of elasticity. Methods based on the theory of plasticity will be specially considered by Tasneef.

2.2.2
Physical and mathematical models used to analyse the structure and the idealisations of structures and of loadings are to be deemed acceptable by Tasneef and are to simulate and describe satisfactorily the behaviour of the actual structure and the anticipated relevant environmental conditions.

2.2.3
Possible effects of non-linearity in the geometry or materials which may significantly affect the safety of the structure are to be carefully considered. The influence of geometrical imperfections on the behaviour of the structure is also to be considered.

2.2.4
The effects of cyclic loads, which may cause damage due to fatigue, are to be determined in terms of magnitude and number of cycles; i.e. a long term distribution analysis of alternate stress magnitudes on the basis of the stress fluctuation anticipated during the design life of the structure.
The dynamic effects of cyclic loads, including motions and local vibrations caused by vortex shedding phenomena, are to be considered.

2.2.5
The response of structures subject to loads which may be considered random may be evaluated by either deterministic or statistical methods.

2.2.6
In case of fixed offshore installations, the dynamic statistical analysis of the support structure subject to wave actions is normally required when natural frequencies of the structure are close to those of waves having significant energy level.

2.2.7
Dynamic loading effects are to be determined using recognised methods of analysis and realistic assumptions with regard to wind oads, hydrodynamic and material properties and analytical models.
Linear and nonlinear loads and loading effects are to be taken into account.

2.3 Model tests

2.3.1
Tests on models shall satisfactorily simulate the behaviour of the structure or parts thereof and shall be carried out by recognised laboratories.

2.3.2
Model tests can be used either as calibration of analytical predictions, or to determine those responses not directly calculable.
Model tests may be specifically required by Tasneef.

2.3.3
When using results of model experiments which include either hydrodynamic or aerodynamic loadings, the following should be considered:

- possible errors due to scale effect (including effects of Reynolds Number dependent viscous effects);
- possible errors resulting from finite tank dimensions (wave reflection from side walls);
- possible errors resulting from limitations of the accuracy of modelling physical properties, parameters and dimensions;
- limitations on accuracy of experimental results due to finite record lengths, finite sample rates and numerical accuracy.

3. Design

3.1 General

3.1.1
Wind turbine structures are to be designed so as to minimise their sensitivity to environmental factors and service loads, and to facilitate their construction and inspection.

3.1.2
The design of the structure as a whole and of its components is to be such that normal operational is not impaired by structure motions and vibrations.

3.1.3
Structures which are subject to forces from mooring lines are to be designed to withstand the breaking load of such lines.

3.1.4
Due consideration is to be given to corrosion and adequate protection systems against corrosion are to be carefully examined in relation to the environmental parameters.

3.1.5
Secondary structures such as fenders, gangway ladders, etc. are to be designed so that possible failure due to accidental overload will not result in damage to the main structure or injury to personnel.

3.1.6
Structural connections and joints are to be designed, as far as practicable, to avoid complex structures and sharp section variations which may give rise to dangerous stress concentrations.
Transmission of primary tensile stresses through the thickness of plates is also to be avoided as far as practicable.
Where this is not practicable, the use of plates with through thickness properties is generally recommended.

3.1.7

Wind turbines support structures constructed to be operated in locations where low temperatures may occur are to be designed to avoid configurations which may give cause to ice accumulation on structures and machinery.
Possible impacts of floating blocks of ice against the structures located in the splash zone are also to be considered.

3.2 Protection against accidental damage

3.2.1

In order to protect the structure against accidental damage, the following two principles are to be considered:

- Reduction in damage probability;
- Reduction in damage consequences.

3.2.2

The structural configuration is to be designed taking account of the possibility of accidental damage.

3.3 Accessibility for inspection

3.3.1

The support structure is to be designed to minimise the number of structural members which are not accessible for inspection and repair.
For structural members which are not accessible for inspection, Tasneef may specify additional more stringent requirements concerning their strength (particularly with respect to the fatigue limit state) and the maintenance of their original functional characteristics.

Part B Chapter 2: Environmental Conditions

1. General

The design of the support structure and the rotor-nacelle assembly of an offshore wind turbine shall be based on site-specific external conditions.
It shall be demonstrated that the offshore site-specific external conditions do not compromise the structural integrity of the turbine.

2. RNA environmental conditions

Wind conditions are the primary external conditions to consider for the structural integrity of the rotor-nacelle assembly, although the marine conditions may also have an influence in some cases depending on the dynamic properties of the structure.

2.1 Wind characterization

The wind regime, according to IEC 61400-1, Subclause 6.3 is to be characterized as follows:

- Normal wind conditions that are assumed to occur more frequently than once per year during normal operation;
  (ref. IEC 61400-1, Subclause 6.3.1)
- Extreme wind conditions that are defined with a 1-year or 50-year recurrence period.
  (ref. IEC 61400-1, Subclause 6.3.2)

In general, the wind climate is characterized by:

- U_{10} the 10-minute mean wind speed (or V_{ref} for the conditions above mentioned).
- σ_U the standard deviation of the wind speed.

The wind conditions include a constant mean flow combined, in many cases, with either varying deterministic gust profile or with turbulence.
In all cases, the inclination of the mean flow with respect to a horizontal plane is zero.

2.1.1 Wind mean speed

U_{10} varies from one 10-minute timeframe to the next and this variability can be represented in terms of a Weibull distribution.

$$F_{U_{10}}(u) = 1 - e^{-\left(\frac{u}{A}\right)^k}$$

The slope parameter k and the scale parameter A are site and height-dependent coefficients.

For onshore plants, the scale parameter A at height z can be calculated as follows:

$$A = A_H \frac{\ln \frac{z}{z_0}}{\ln \frac{H}{z_0}}$$

z_0 is the terrain roughness parameter which is defined as extrapolated height at which the mean wind speed becomes zero, (logarithmic variation with height adopted). The sea surface roughness parameter is deeply analyzed in Paragraph 2.1.2.1.

A_H is the scale parameter at a reference height H. For engineering calculation, the following approximation can be applied:

$$A = A_{10} \left(\frac{z}{H}\right)^{\alpha}$$

α depends on the terrain roughness. A height dependent expression for α is obtained if the logarithmic and exponential expressions for A given above are combined.

$$\alpha = \frac{\ln\left(\frac{\ln \frac{z}{z_0}}{\ln \frac{H}{z_0}}\right)}{\ln \frac{z}{H}}$$

As an alternative to the previous expression for α, values for α are tabulated below.

Terrain type	$z_0[\mathrm{m}]$	α
Plane ice	0,00001	0
Coastal areas with onshore wind	0,001	0
Open country without significant buildings and vegetation	0,01	0
Cultivated land with scattered buildings	0,05	0,16
Forests and suburbs	0,3	0,30
City centres	1-10	0,40

2.1.1.1 Sea surface roughness parameter

For offshore locations where the terrain consists of the sea surface, the roughness parameter z_0 is not constant, but depends on the wind speed, the height over the terrain, water depth and wave field.

A widely used expression for the roughness parameter z_0 of the open, deep sea far from land is given by Charnock's formula.

$$z_0 = A_c \frac{(u^*)^2}{g}$$

$$g = \text{gravity acceleration } (9{,}81\ \mathrm{m}/sec^2)$$

$$A_c = 0{,}011$$

$$u^* = \sqrt{\frac{\tau}{\rho}}$$

u^* is the frictional velocity, τ is the surface shear stress at sea surface and ρ is the air density.

Charnock's formula can be applied to near-coastal locations provided that $A_c = 0{,}034$ is used.
Charnock's formula leads to the following expression for the roughness parameter.

$$z_0 = \frac{A_c}{g}\left(\frac{\kappa\, U_{10}}{\ln\frac{z}{z_0}}\right)^2$$

The determination of z_0 and of the distribution of U_{10} involves an iterative procedure.
Indicative values of the roughness parameter z_0 are given in the following table.

Terrain type	$z_0[\mathrm{m}]$	α
Open sea without waves	0,0001	0
Open sea with waves	0,0001-0,003	0,12

2.1.2 Wind speed standard deviation

For a given value of U_{10}, the standard deviation σ_U exhibits a natural variability of the wind speed from one 10-minute timeframe to another, known as turbulence.
σ_U can be well-represented by a lognormal distribution:

$$F_{\sigma_u|U_{10}}(\sigma) = \Phi\left(\frac{\ln\sigma - b_0}{b_1}\right)$$

where b_0 and b_1 are site-dependent coefficients.

The coefficient b_0 can be interpreted as the mean value of $\ln\sigma_U$ and b_1 can be interpreted as the standard deviation of $\ln\sigma_U$.
The mean value $E[\sigma_U]$ and the standard deviation $D[\sigma_U]$ can be calculated as follows:

$$E[\sigma_U] = e^{(b_0+\frac{1}{2}b_1)}$$

$$D[\sigma_U] = E[\sigma_U]\sqrt{e^{b_1^2} - 1}$$

Since a lognormal distribution for σ_U conditioned by U_{10} may underestimate the higher values of σ_U, a more appropriate distribution model for σ_U is reported by the following Frechet distribution of σ_U conditioned by U_{10}:

$$F_{\sigma_U|U_{10}}(\sigma) = e^{-\left(\frac{\sigma_0}{\sigma}\right)^k}$$

The distribution parameter k can be solved implicitly and the distribution parameter σ_0 using Gamma function Γ.

$$\left(\frac{D[\sigma_U]}{E[\sigma_U]}\right)^2 = \frac{\Gamma\left(1-\frac{2}{k}\right)}{\Gamma\left(1-\frac{1}{k}\right)} - 1$$

$$\sigma_0 = \frac{E[\sigma_U]}{\Gamma\left(1-\frac{1}{k}\right)}$$

Based on boundary-layer theory, the mean value of the standard deviation σ_U can be derived for homogenous terrain at height z.

$$E[\sigma_U] = U_{10} A_x \,\kappa \frac{1}{\ln \frac{z}{z_0}}$$

A_x is a constant that depends on z_0.

A conservative fixed choice for σ_U is practical for design purposes, thus a characteristic value can be estimated as:

$$\sigma_{U,c} = U_{10} \frac{1}{\ln \frac{z}{z_0}}$$

Characteristic standard deviation values shall be used for the wind speed:

$$\sigma_{U,c} = I_{T,15} \frac{U_{10,15} + aU_{10}}{a+1}$$

$$U_{10,15} = 15 \text{ m/s}$$

$I_{T,15}$ or I_{ref} (above mentioned) is the characteristic value of the turbulence intensity at 15 m/s and a is the slope parameter.

2.1.3 Turbulence intensity

(ref. IEC 61400-1, Table1)

The turbulence intensity I_T is defined as the ratio between the standard deviation σ_U of the wind speed and the 10-minute mean wind speed U_{10}.
The phenomenon of wind turbine influenced turbulence is known as a wake effect.
Wake effect shall be considered when turbines are installed behind other turbines with a distance of less than twenty times the rotor diameter.

The following method can be used to consider the wake effects.

The free flow turbulence intensity I_T is modified by the wake turbulence intensity $I_{T,w}$ to give the total turbulence intensity $I_{T,tot}$.

$$I_{T,tot} = \sqrt[m]{(1 - N \cdot p_w) I_T^m + p_w \sum_{i=1}^{N} {I_{T,w}}^m \cdot s_i}$$

$$p_w = 0{,}06$$

$$s_i = \frac{x_i}{D}$$

$$I_{T,w} = \sqrt{\frac{1}{(1{,}5 + 0{,}3\, s_i \sqrt{v})^2} + I_T^2}$$

N	Number of closest neighbouring wind turbines;
m	Wöhler (S-N fatigue) curve exponent corresponding to the material of the considered structural component (normally m = 3 for steel);
v	Free flow mean wind speed at hub height;
p_w	Probability of wake conditions;
x_i	Distance to the i-th turbine;
D	Rotor diameter;
$I_{T,w}$	Maximum turbulence intensity at hub height on the centre of the wake.

If the wind farm consists of more than five rows with more than five turbines in each row, or if the distance between the turbines in the rows that are located perpendicular to the predominant wind direction is less than three times the diameter, the increase in mean turbulence intensity is to be taken into account.
In this case the free flow turbulence I_T is substituted with $I_T{}^*$, where x_r is the distance within row and x_f is the distance between rows.

$$I_T{}^* = \frac{1}{2}\sqrt{{I_w}^2 + {I_T}^2} + I_T$$

$$I_w = \frac{0{,}36}{1 + 0{,}08\sqrt{s_r s_f v}}$$

$$s_r = \frac{x_r}{D}$$

$$s_f = \frac{x_f}{D}$$

In addition to the turbulence in the direction of the mean wind (longitudinal), there will be turbulence also laterally and vertically.

2.1.4 Stochastic turbulence model

The spectral density of the wind speed process expresses how the energy of the wind turbulence is distributed between various frequencies. Spectral moments are useful for representation of the wind speed process $u(t)$.

2.1.4.1 Kaimal spectrum

(ref. IEC 61400-1, Annex B)

Frequently used models that satisfy the norm requirements are the Mann uniform shear turbulence and the Kaimal spectrum and the exponential coherence model.

The following expression for the Kaimal spectrum.

$$S_k(f) = \sigma_k^2 \frac{4\,\frac{L_k}{U_{10}}}{\left(1 + 6\frac{f\,L_k}{U_{10}}\right)^{\frac{5}{3}}}$$

S_k is the single-sided velocity components spectrum.

σ_k is the velocity component integral scale parameter.

k is the index referring to the velocity component direction (longitudinal, lateral, upward).

λ is the turbulence scale parameter.

The turbulence spectral parameters are given for each velocity component k=1,2,3.

	1	2	3
σ_k	σ_1	$0{,}8\,\sigma_1$	$0{,}5\,\sigma_1$
L_k	$8{,}1\,\lambda$	$2{,}7\,\lambda$	$0{,}66\,\lambda$

At any point in time, there will be variability in the wind speed from one point to another. The closer together the two points are, the higher is the correlation between their respective wind speed. The wind speed will form a random field in space.
A commonly used model for the autocorrelation function of the wind speed field can be derived from the following exponential coherence model to account for the spatial correlation structure of the longitudinal velocity component.

$$\mathrm{Coh}(r,f) = e^{-c\cdot f\cdot\frac{r}{u}}$$

Where r is the distance between the two points, u is the average wind speed over the distance r, f is the frequency and c is the non dimensional decay constant which reflects the correlation length of the wind speed field.

2.1.5 Extreme wind conditions

The extreme wind conditions are normally referred (according to (ref. IEC 61400-1, subclause 6.3.2) to a 50-year return period.
The characterization of a 50-year wind speed requires an extreme value analysis of available wind speed data.
It has been proven useful to carry out such an extreme value analysis on the frictional velocity pressures derived from the wind speed data, rather than on the wind speed data themselves.
For this purpose, the observed wind speeds $u(z)$ are transformed to friction velocity u^* through the following inverse formula:

$$u^* = \frac{\kappa\, u(z)}{\ln\left(\frac{z}{z_0}\right)}$$

Von Karman's constant $\kappa = 0{,}4$ and neutral atmospheric conditions are assumed.

The friction velocities u^* derived from the above transformation refer to the prevailing local roughness z_0.
It is often desirable to transform the friction velocities to data related to a reference roughness $z_0 = 0.05$ m, which is different from the true local roughness parameter.
This can be done by geostrophic mapping, thus utilising the fact that the geostrophic wind speed G is constant and equal for every roughness z_0.

$$G = \frac{u^*}{\kappa}\sqrt{\left(\ln\left(\frac{u^*}{f\,z_0}\right) - A\right)^2 + B^2}$$

$$A = 1{,}8$$

$$B = 4{,}5$$

$$f = 1{,}2\ 10^{-4}\ \mathrm{rad/s}$$

f is the Coriolis parameter and it is referred to a latitude of 55.5°.
The geostrophic wind speed G is calculated explicitly by the given formula when the true roughness z_0 and the corresponding u^* are given. For this value of G, the same formula is used to implicitly solve a new value of u^* that corresponds to the desired new reference roughness z_0.
When the friction velocities have been determined from the wind speed data as described above, the corresponding velocity pressure q is calculated.

$$q = \frac{1}{2}\rho(u^*)^2$$

The q data are grouped into n subrecords of a specified duration and the maximum value of q in each of the n subrecords is extracted. When the duration is one year, these n maximum values of q constitute an empirical distribution of the annual maximum velocity pressure. The velocity pressure q is expected to follow a Gumbel distribution.

$$F(q) = e^{-e^{-\frac{q-b}{a}}}$$

The parameters a and b are determined fitting to the n observations of the annual maximum velocity pressure: b is interpreted as the value of q which has recurrence period of one year.
The value of q that has a recurrence period of T years can be found using the following formula, where T_0 is 1 year.

$$q_T = b + a\ln\frac{T}{T_0}$$

The previous formula can be used to find the 50-year velocity pressure q_{50}.
The corresponding 10-minute mean wind speed $U_{10,T}$ with recurrence period T at height z and terrain roughness z_0 can be found.

$$U_{10,T} = \frac{1}{\kappa}\sqrt{\frac{2q_T}{\rho_0}}\ln\frac{z}{z_0}$$

When the wind speed with a 50-year recurrence period is given, i.e. $U_{10,50}$, the wind speed with recurrence period T years can be found.

$$U_{10,T} = U_{10,50}\sqrt{0{,}57 + 0{,}11\ln\frac{T}{\ln\frac{1}{p}}}$$

p is the probability of no exceedances in T years and n is the number of exceedances per year, given by $p = e^{-nT}$.

2.1.6 Wind shear

(ref. IEC 61400-1, Subclause 6.3.2.6)

Wind shear is defined as the variation of the wind speed with the height: it is important for large and flexible rotors.

Wind shear profiles can be derived from logarithmic model modified by a stability-corrected logarithmic wind shear profile as follows.

$$u(z) = \frac{u^*}{\kappa}\left(\ln\frac{z}{z_0} - \psi\right)$$

$\psi > 0$ for unstable conditions
$\psi < 0$ for stable conditions
$\psi = 0$ for neutral conditions

The stability function ψ depends on the non-dimensional stability measure $\zeta = z/L_{MO}$, where z is the height and L_{MO} is the Monin- Obukhov length.
for $\zeta \geq 0$
$\psi = -4.8$
for $\zeta < 0$

$$\begin{cases}\psi = 2\ln(1+x) + \ln(1+x^2) - 2\,\mathrm{tg}^{-1}(x)\\ \qquad x = (1 - 19{,}3\,\zeta)^{1/4}\end{cases}$$

The Monin- Obukhov length L_{MO} depends on the heat flux and on the frictional velocity u^*.
Its value reflects the relative influence of mechanical and thermal forcing on the turbulence as follows.

Atmospheric conditions	L_{MO} [m]
Strongly convective days	-10
Windy days with solar heating	-100
Windy days with little sunshine	-150
No vertical turbulence	0
Purely mechanical turbulence	∞

Nights where temperature stratification slightly dampens mechanical turbulence generation	> 0
Nights where temperature stratification severely suppresses mechanical turbulence generation	>> 0

If data for Richardson number R are available, the following relationships can be used to obtain the Monin- Obukhov length $\mathrm{L_{MO}}$.

$$\mathrm{L_{MO|unstable\ air}} = \frac{\mathrm{z}}{\mathrm{R}}$$

$$\mathrm{L_{MO|stable\ air}} = \mathrm{z}\frac{1-5\mathrm{R}}{\mathrm{R}}$$

The Richardson number can be computed from averaged conditions as follows.

$$\mathrm{R} = \frac{\frac{\mathrm{g}}{\mathrm{T}}(\gamma_{\mathrm{d}}-\gamma)}{\left(\frac{\partial\bar{\mathrm{u}}}{\partial\mathrm{z}}\right)^2+\left(\frac{\partial\bar{\mathrm{v}}}{\partial\mathrm{z}}\right)^2}\left(1+\frac{0{,}07}{\mathrm{B}}\right)$$

T	Temperature
$\gamma = -\partial\mathrm{T}/\partial\mathrm{z}$	Lapse rate
$\gamma_{\mathrm{d}} \cong 9{,}8\ \frac{°\mathrm{C}}{\mathrm{km}}$	Dry adiabatic lapse rate
g	Gravity acceleration

$\partial\bar{\mathrm{u}}/\partial\mathrm{z}$ and $\partial\bar{\mathrm{v}}/\partial\mathrm{z}$ are the vertical gradients of the two horizontal average wind speed components $\bar{\mathrm{u}}$ and $\bar{\mathrm{v}}$ and z denotes the vertical height.

Finally, the Bowen ratio B of sensible to latent heat flux at the surface near the ground can be approximated.

$$\mathrm{B} \approx \frac{\mathrm{c_p}}{\mathrm{L_{MO}}}\frac{(\bar{\mathrm{T}}_2-\bar{\mathrm{T}}_1)}{(\bar{\mathrm{q}}_2-\bar{\mathrm{q}}_1)}$$

$\mathrm{c_p}$ is the specific heat, $\bar{\mathrm{T}}_1$ and $\bar{\mathrm{T}}_2$ are the mean temperatures at two levels denoted 1 and 2, $\bar{\mathrm{q}}_1$ and $\bar{\mathrm{q}}_2$ are the average specific humidity at the same two levels and it is calculated as fraction of moisture by mass.

2.1.7 Wind direction

Transient wind conditions can occur when either the wind speed or the direction changes.

The following transient conditions are to be considered, if relevant, besides stationary wind conditions:

- Extreme of wind speed gradient, i.e. extreme of rise time of gust;
- Strong wind shear;
- Simultaneous change in wind direction and wind speed;
- Extreme changes in wind direction;

2.1.8 Other environmental conditions

(ref. IEC 61400-3, Subclause 6.5)

Other environmental conditions such as:

- Air temperature;
- Humidity;
- Air density;
- Solar radiation;
- Rain, hail, snow and ice;
- Corrosion;
- Lighting (ref. IEC 61400-24),

are to be taken into account if relevant for specific design topics.

The normal other environmental condition values to be taken into account are listed in IEC 61400-3, Subclause 6.5.1).
The extreme other environmental conditions that are to be considered for design of an offshore wind turbine are temperature, lightning, ice and earthquake (ref. IEC 61400-3, Subclause 6.5.2).

2.1.9 Electrical power network conditions

The normal conditions at the offshore wind turbine terminals to be considered are reported in IEC 61400-3, Subclause 6.6.

3. Support structure environmental conditions

The support structure is used to transfer the loads from the wind turbine and its tower to the foundation soil at the seabed.
In addition to the gravity loads, the structure is subject to relevant environmental loads such as wave loads, current loads and ice loads, if applicable.

3.1.1 Marine conditions

(ref. IEC 61400-3, Subclause 6.4)

The marine conditions to be considered for the design of the support structure are classified, according to IEC 61400-3, subclause 6.4) in:

- Normal marine conditions which will occur more frequently than once per year.
- Extreme marine conditions which are defined as having 1-year or 50-year recurrence period.

A design sea state is described by:

- The wave spectrum S_η
- The significant wave height H_s
- The peak period T_p

The wave climate at a location can be considered stationary within periods of typically 3 hours.

3.1.2 Significant wave height

H_s is a measure of the intensity of the wave climate and is statistically defined as the average of the highest one-third of the wave heights recorded during a sea state.
In deep waters, the sea elevation process η is a Gaussian process and the individual wave height H follows a Rayleigh distribution where H_s is given and ν is the spectral width parameter.

$$F_H(h) = 1 - e^{-\frac{2\,h^2}{(1-\nu^2)H_S^2}}$$

The distribution of H_{max} can then be approximated using N that denotes the number of zero-up crossing of the sea elevation process in this period.

$$F_{H_{max}}(h) \approx e^{-N\,e^{\frac{2\,h^2}{(1-\nu^2)H_S^2}}}$$

The expected value of the maximum wave height $E[H_{max}]$ can be expressed as follows.

$$E[H_{max}] \approx H_S\sqrt{\frac{(1-\nu^2)\ln N}{2}}$$

A first order approximation yields the following value for the spectral width parameter $\nu = 0{,}43$.
With this value of ν, the following relationship between the significant wave height H_s and the maximum wave height $H_{max} \approx 1{,}8\,H_s$ can be obtained.
Note that in shallow water, the wave heights will be limited by the water depth d. The maximum possible wave height at a water depth d is approximately equal to 0.8d.

3.1.3 Peak period

The peak period T_p is the period of the wave with the highest energy. The peak wave period is extracted from the spectra of the power density and it is correlated to the zero-up crossing period T_z.
Once the significant wave height H_S is given, the zero-up crossing period T_z is usually represented by a shifted lognormal distribution and it is defined as the mean time interval between upward or downward zero crossings on a wave record.

$$F_{T_z}(t) = \Phi\left(\frac{\ln(t-\delta)-a_1}{a_2}\right) \quad t \geq \delta$$

Φ denotes the Gaussian distribution function. a_1 and a_2 are function of H_S and the shift parameter δ can be approximated in seconds by $\delta \approx 2.2\sqrt{H_s}$.

The peak period T_p is related to the mean zero-crossing period T_z of the sea elevation process:

$$T_z = T_p\sqrt{\frac{5+\gamma}{11+\gamma}}$$

$$\gamma = \begin{cases} 5 & \text{for} \quad \frac{T_p}{\sqrt{H_s}} < 3{,}6 \\ e^{\left(5{,}75 - 1{,}15\frac{T_p}{\sqrt{H_s}}\right)} & \text{for} \quad \frac{T_p}{\sqrt{H_s}} = 3{,}6 \div 5{,}0 \\ 1 & \text{for} \quad \frac{T_p}{\sqrt{H_s}} > 5 \end{cases}$$

3.1.4 Power spectral density

(ref. IEC 61400-3, Annex B)

The analysis of the distribution of the wave energy as a function of wave frequency for a time-series of individual waves is referred to as a spectral analysis.
The frequency content of the sea elevation process characterized by an angular acceleration of ω can be represented by the power spectral density through the Jonswap spectrum.
The most frequently used spectra for wind generated seas are the Pierson-Moskowitz spectrum for a fully developed sea, and the Jonswap spectrum for a developing sea.
The two spectra are related:

$$S_{JS}(f) = C(\gamma) \cdot S_{PM}(f)\gamma^{\alpha}$$

where γ is the peak-shape parameter and $C(\gamma)$ is the normalising factor.
The first factor increases the peak and narrows the spectrum; the second reduces the spectral density to ensure that both spectral forms have the same H_s. the formulation has been chosen so that $\gamma = 1$ recovers the PM spectrum.
The Jonswap spectrum is formulated as follows.

$$S_\eta(\omega) = \frac{5}{32\,\pi} \cdot H_s^2\, T_p \cdot \left(\frac{\omega T_p}{2\pi}\right)^{-5} \cdot e^{-\frac{5}{4}\left(\frac{\omega T_p}{2\pi}\right)^{-4}} \cdot C(\gamma) \cdot \gamma^{-\frac{1}{2\sigma^2}\left(\frac{\omega T_p}{2\pi}-1\right)^2}$$

$$C(\gamma) = 1 - 0{,}287 \ln \gamma$$

$$\sigma = \begin{cases} 0.07 \text{ for } \omega \le \frac{2\pi}{T_P} \\ 0.09 \text{ for } \omega > \frac{2\pi}{T_P} \end{cases}$$

3.1.5 Sea states

The sea state characterization is done by the reference norm IEC 61400-3 that identified the different sea states and the relevant wave height H_s as follows:

- Normal Sea State (NSS) and Normal Wave Height $H_{s,NSS}$
  (ref. IEC 61400, Subclauses 6.4.1.1-2)
- Extreme Sea State (ESS) and Extreme Wave Height $H_{s,ESS}$
  (ref. IEC 61400, Subclauses 6.4.1.5-6)
- Severe Sea State (SSS) and Severe Wave Height $H_{s,SSS}$
  (ref. IEC 61400, Subclauses 6.4.1.3-4)

The wave models may be defined in terms of stochastic sea state or regular waves representation.
The Reduced Wave Height (RWH) for the definition of the 50-year return event and the reduced wave height for the definition of the 1-year return period shall be determined, according to IEC 61400-3, Subclause 6.4.1.7.
The influence of breaking waves shall be assessed during an offshore wind turbine design (ref. IEC 61400-3, Subclause 6.4.1.8).

3.1.6 Sea current

(ref. IEC 61400-3, Subclause 6.4.2)

Sea currents may vary in space and time, they are generally considered as a horizontally uniform flow field of constant velocity and direction, varying only as a function of depth.
The following components of sea current velocity are to be taken into account (ref. IEC 61400-3, Subclause 6.4.2.1-3):

- Sub-surface currents;
- Wind generated, near surface currents;
- Near shore, wave induced surf currents (ref. IEC 61400-3 Annex C).

The total current velocity is the vector sum of these components.
The designer shall determine whether sea currents may be neglected for calculation of

fatigue loads by means of an appropriate assessment of site-specific data.
Information on frequency of occurrence of total current speed and directions at different depths for each months and/or each season is useful for planning operations.
The characteristics of the current profile over depth depend on the regional oceanographic climate, in particular the vertical density distribution and the flow of water into or out of the sea.
The current model can be defined as normal NCM (Normal Current Model) or extreme ECM (ref. IEC 61400-3, Subclause 6.4.2.4-5).

The power law current profile can be used where appropriate, e.g. in areas dominated by tidal currents in relatively shallow water (such as southern North Sea).

$$U_c(z) = U_{c0}\left(\frac{z+d}{d}\right)^{\alpha}$$

$U_c(z)$	Current speed elevation z (≤ 0)
U_{c0}	Surface current speed at $z = 0$
z	Vertical coordinate
d	Still water depth
α	Exponent typically equals 1/7

Waves stretch and compress the current profile under crests and troughs.
Stretching means that, in the presence of waves, the instantaneous current speed $U_c(z)$ of a water particle calculated at depth z (measured positively upwards from still water level for $-d \leq z \leq 0$) is effective at a stretch vertical coordinate z_s.
The $U_c(z)$ is specified over the full water column between the sea floor at $z = -d$ and the still water level at $z = 0$.
In the linear stretching, the relationship between z_s and z is proportional to the ratio of the instantaneous height of the water surface elevation and still water depth.

$$F_S = \frac{d+\eta}{d}$$

η is the water surface elevation directly above the water particle, measured upwards from still water level and d is the still water depth.

The stretched vertical coordinate z_s can be expressed as function of the current stretching F_s and the original elevation z.

$$z_s = F_s\,(d+z) - d$$

For current stretching, the stretching factor F_s is larger than 1.0 and consequently $z_s > z$.
In non-linear stretching, the elevation z_s and z are related through linear wave theory as follows, where k_{nl} is the non-linear wave number.

$$z_s = z + \eta\frac{\sinh(k_{nl}(z+d))}{\sinh(k_{nl}\,d)}$$

$$k_{nl} = \frac{2\pi}{\lambda_{nl}}$$

λ_{nl} is the wave length for the regular wave under consideration for water depth d and wave height H.
For offshore wind structures, usually the current is supposed to be in the same direction as the wave.
The methods discussed above can be used taking into account this hypothesis.

3.1.7 Water level

The water depth at the site, including variations of the water depth where significant, is to be determined for the determination of relevant actions on the submerged supporting structure of the wind turbine.
Other variations in water level can result from long-term climatic variations, sea floor subsidence or episodic events such as tsunamis.
Water level variations have a relatively minor impact in deep water, but can be considerably more important in shallow water.
The different water levels of interest are identified by IEC 61400-3 in Subclauses 6.4.3 as follows:

- Normal Water Level Range (NWLR).
  (ref. IEC 61400-3, Subclauses 6.4.3.1)
- Extreme Water Level Range (EWLR).
  (ref. IEC 61400-3, Subclauses 6.4.3.2)

3.1.8 Other marine environmental conditions

3.1.8.1 Sea ice

For sea ice characterization, when relevant, reference can be made to IEC 61400-3, Subclause 6.4.4; ref. IEC 61400-1, Annex E.

3.1.8.2 Marine growth

(ref. IEC 61400-3, Subclause 6.4.5)

The thickness and type of marine growth, which are dependent on location, age of the structure and maintenance regime, are to be duly considered in the determination of hydrodynamic loadings during the service life of the support structure, also considering increased mass effect in its dynamic response evaluation.
The influence of marine growth on hydrodynamic loadings is due to increased dimensions and increased drag coefficient due to the roughness.
Site-specific studies are to be carried out to establish the likely thickness and its profile as a function of the depth.
Due consideration in this evaluation is to be given to the seawater site biological and environmental factors, such as salinity, oxygen content, pH value, current and temperature.

3.1.8.3 Earthquakes

(ref. IEC 61400-1, Annex C)

If the area is seismically active, an evaluation is to be carried out with reference to the regional and local geology, in order to determine possible location relative to the alignment of faults, the epicentral and focal distances, the source mechanism for energy release and the source to site attenuation characteristics.
In general, the site-specific seismic hazard assessment can be carried out according to the provisions of Clause 8 of ISO 19901-2:2005, *Seismic Design Procedures and Criteria*.
The analysis of seismic characteristics of the location is to include an evaluation of the following aspects.

- Characteristics of the ground motions anticipated for the design life of a platform
- Allowable seismic risk in relation to the design operation
- Ground instability due to liquefaction
- Instability of the sea floor
- Proximity to faults

The wind turbine has to be designed to withstand the earthquake loads characterized for the site.
The most widely used input parameter for the seismic verification of fixed offshore platforms is the design response spectrum, e.g. the spectral response associated to given level of peak ground acceleration, velocity and displacement.
The wind turbine structure, under the earthquake-induced accelerations, is to be analysed in one vertical and two horizontal directions.
Still referring to ISO 19901, the input parameter characterization for seismic assessment is to be made for two levels of earthquake:

- Extreme Level Earthquake (ELE): the structure shall be designed such that an ELE event will cause little or no damage.
- Abnormal Level Earthquake (ALE): the structure shall be designed such that overall structural integrity is maintained.

3.2 Soil investigation

Soil investigations shall provide all necessary soil data for detailed design of a specific foundation structure at a specific location.

Soil investigations may be divided into the following parts:

- Geological studies (based on the geological history of the area where the WT is to be installed);
- Geophysical survey (understanding of the seabed topography within a given area);

- Geotechnical investigation (through soil sampling and in-situ testing of soil).

The field and laboratory investigations should provide the following types of geotechnical data for all soil layers:

- Data for classification and description of the soil (unit weight of sample and solid particle, water content, liquid and plastic limits, grain size distribution);
- Permeability and consolidation tests for a detailed and complete foundation design;
- Static tests for determination of shear strength parameters;
- Cyclic tests for determination of strength and stiffness parameters.

Part B Chapter 3: Loads

(ref. IEC 61400-3, Subclause 7.3)

3.1 Loads for WT design

Loads as described from 3.1.1 to 3.1.7 shall be taken into account for the load combinations to be considered for the WT design.
The design load cases are described in 7.1.

3.1.1 Gravitational and inertial loads

Gravitational and inertial loads can be static and dynamic and they result from gravity, vibration, rotation and seismic activity.

3.1.2 Aerodynamic loads

Aerodynamic loads can be static and dynamic and they are caused by the airflow and its interaction with the blades.
The aerodynamic load is determined as function of the average wind speed and turbulence across the rotor plane, the rotational speed of the rotor, the air density and the aerodynamic shapes of the wind turbine, including the aeroelastic effects (ref. to 3.1.2.1).

The wind velocity conditions at a blade cross section are illustrated in Figure 3.1.

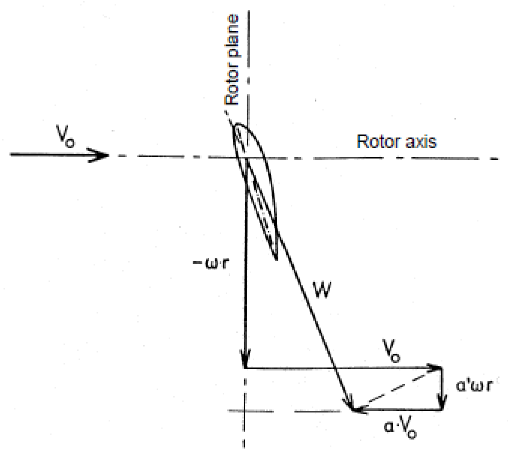

Figure 3.1: "Wind velocity at a blade cross section"

V_0 is the wind velocity perpendicular to the rotor plane.
When the wind passes through the rotor plane, this wind speed becomes reduced by an amount of aV_0 due to the axial interference.
Thus, a blade element at a distance r from the rotor axis will be moving at a speed ωr in the rotor plane.
When the wind passes through the rotor plane and interacts with the moving rotor, a tangential slipstream wind velocity $a'\omega r$ is introduced.
The resulting relative inflow wind velocity that the rotor blade will experience comes out and is denoted W.
This resulting relative wind velocity gives rise to aerodynamic forces on the blade, respectively lift and drag force, F_L and F_D.

3.1.3 Aeroelastic loads calculation

The purpose of an aeroelastic analysis is to solve the equations of motion for a given arbitrary set of forces acting on the structure and for forces generated by the structure itself.

The general formulation of the differential equations of motion contains the vector x and its derivatives, the mass matrix M, the damping matrix C, the stiffness matrix K and the force vector F acting on the structure varying with time.

$$M\ddot{x} + C\dot{x} + Kx = F$$

The necessary model elements for the aeroelastic load calculation are:

1. Wind field modelling
2. Aerodynamic model
3. Blade element momentum method
4. Beam theory
5. Control system modelling

3.1.3.1 Wind field modelling

The wind field contains the longitudinal, transversal and vertical wind velocity components and it is divided into a mean wind field and a fluctuating wind field.

For wind turbines, spatial variations in the turbulence must be considered, and three-dimensional wind simulation is required.
The first purpose is to predict time series of the wind speed in a number of points in space across the rotor disc of a wind turbine.
In order to predict the wind field in a number of points in space, the spatial coherence of the wind field must be properly accounted for.
There are two models available for generating a synthetic wind field over a rotor disc.

- Veers model by Sandia

It uses a circular grid in the rotor plane and it is based on a single point spectral representation of the turbulence and a coherence function.
A Kaimal formulation is chosen as the spectral model and an exponential Davenport coherence model is used.

$$S_i(f) = \sigma_i^2 \frac{6{,}8\,\frac{L_i}{U}}{\left(1 + 10.2\,\frac{fL_i}{U}\right)^{\frac{5}{3}}}$$

$$\mathrm{coh}_i(r,f) = e^{-c_i f \frac{r}{U}}$$

i: velocity components (u, v, w)
f: frequency
r: distance or spatial separation
L: integral length scale of the turbulence component
σ: standard deviation of wind speed component
c: coherence decay factor

- Mann model by Risø

It applies a quadratic grid and it is based on a spectral tensor formulation of the atmospheric surface layer turbulence.
The model has been developed with reference to onshore wind turbines and specifically for homogeneous terrain and the parameters used are: mean wind speed U, height above terrain z and roughness length z_0. Relevant considerations for offshore site are to be applied.
The turbulence intensity I_T, defined from the standard deviation of the longitudinal wind velocity σ_u, is usually measured by means of a anemometer.

$$I_T = \frac{\sigma_u}{U}$$

This measurement corresponds to vectorial summation of the longitudinal and transversal wind velocity components.

3.1.3.2 Aerodynamic model

Aerodynamic theory performs quantitative predictions of the forces set up by the airflow on the rotor.
The overall 3D-flow on a rotor is a very complex, unsteady flow depending on many variables such as wind speed, wind shear, atmospheric turbulence, yaw angle, rotational speed, rotor radius, overall layout of the rotor blade and the airflow properties.
For calculation of aerodynamic forces on a rotor blade, it is used the so-called “blade element momentum”.
The resultant force F is decomposed into two components F_L perpendicular to the direction of the resulting relative wind velocity W and F_D parallel to this direction.

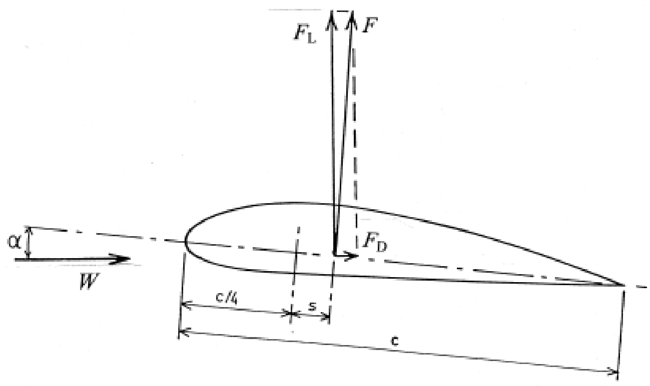

Figure 3.2: “Wind resulting force”

$$F_L = \frac{1}{2} C_L\, \rho\, c\, W^2$$

$$F_D = \frac{1}{2} C_D\, \rho\, c\, W^2$$

The aerodynamic drag force F_D on the tower and the nacelle can be calculated based on the projected area A perpendicular to the flow as follows:

$$F_D = 0{,}5\ \rho\ A\ V_0^2 C_D$$

The lift and drag coefficients C_L and C_D are defined using the chord length c of the airfoil.
The lift and drag forces are functions of the:

- Inflow angle α (between the wind direction and the blade axis);
- Airfoil shape;
- Reynolds number $Re = cW/\nu$, in which ν is the kinematic viscosity.

To describe the physics in a mathematical way, the wind turbine rotor can be considered as a disc, which is able to absorb energy from the wind by reduction of the wind speed as shown below.

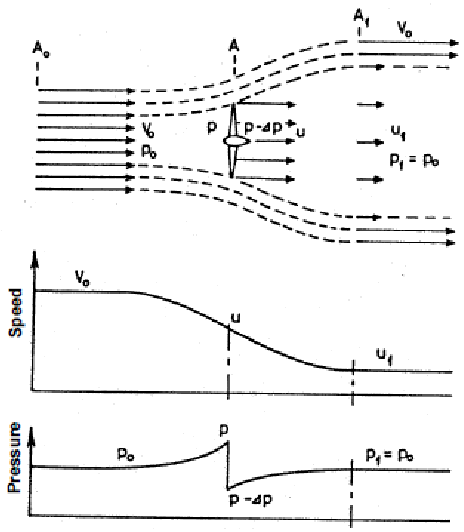

Figure 3.3: "Wind speed reduction"

C_L increases linearly with α up to α_{stall} after which the profile stalls.
For greater value of α, C_L reaches a maximum value followed by a decrease for further increases in α.
α_{stall} characterizes the stall phenomenon, a nonlinear phenomenon that results in a dramatic loss of flow attachment and airflow lift when a limiting inflow angle has been reached.
Two-dimensional wind tunnel calculations are used to obtain the coefficient values in the pre-stall region.

- Computational Fluid Dynamics (CFD)
- 2D wind field model
- Measurments and estimations

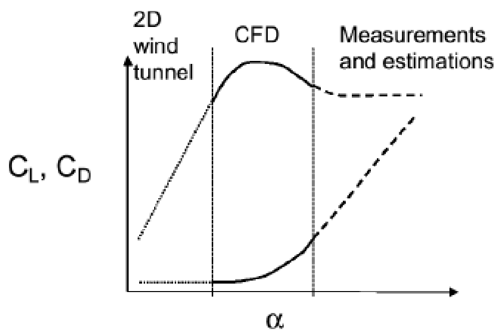

Figure 3.4: "Lift and drag curves"

Note that proper selection of values for the aerodynamic coefficients is a very important step in the design analyses of a wind turbine.
The norm IEC 61400-3 requires that the load model used to predict loads for design verification of wind turbines be validated for each design load case.
This validation of the load prediction is to be based on a representative comparison between measured and predicted loads on a similar wind turbine.

3.1.3.3 Blade element momentum method

Using this method the flow area swept by the rotor is divided into a number of concentric ring elements and there is no radial dependency between them.
Each ring is divided into a number of tubes, which are independent.
The wind speed is assumed uniformly distributed over each ring element.
The forces from the blades on the flow through each ring element are assumed constant and it is equal to assuming that the rotor has an infinite number of blades.
The thrust on the ring element T of radius r and thickness dr from the disc defined by the rotor is:

$$dT = 2\pi\rho u(V_0 - u_1)dr$$

V_0 is the wind speed before the rotor.
u_1 is the wind speed in the wake behind the rotor.
$u = \frac{1}{2}(V_0 - u_1)$ is the wind speed through the rotor plane.

When the tangential wind speed at radius r is zero upstream of the rotor and $\mathrm{u_w}$ in the wake, the torque Q on the ring element is defined.

$$dQ = 2\pi r^2 \rho u C_\theta dr$$

By introducing the axial induction factor a and the tangential induction factor a', where ω denotes the angular velocity of the rotor, the expressions for the thrust and the torque can be rewritten.

$$a = 1 - \frac{u}{V_0} \qquad a' = \frac{1}{2}\frac{u_w}{\omega r}$$

$$dT = 4\pi r \rho V_0^2 a\,(1-a)dr$$

$$dQ = 4\pi r^3 \rho V_0 \omega\,(1-a)a'dr$$

At this point, it is necessary to make an initial choice for a and a', for example $a = a' = 0$.

The flow angle $\emptyset$ is the angle between the rotor plane and the direction of the relative wind velocity V_{rel} on the rotating blade, shown in Figure 3.5.

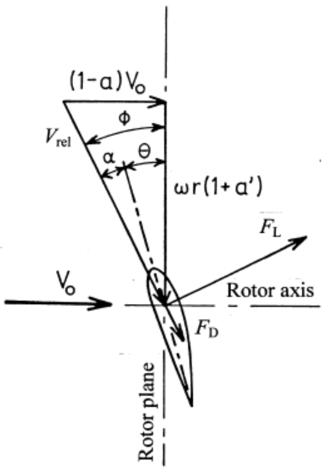

Figure 3.5: "Pitch angle"

$$\tan\emptyset = \frac{(1-a)V_0}{(1+a')\omega r}$$

The local inflow angle is $\alpha = \emptyset - \theta$, where the pitch angle θ is the local pitch of the blade relative to the rotor plane. It is possible to transform C_D and C_L coefficient to normal and tangential ones.

$$C_N = C_L \cos\emptyset + C_D \sin\emptyset$$

$$C_T = C_L \sin\emptyset + C_D \cos\emptyset$$

The solidity σ is defined as the fraction of the cross-sectional area of the annular element that is covered by the blades. It depends on the radius and on the number of blades B.

$$\sigma(r) = \frac{c(r)B}{2\pi r}$$

$$a = \frac{1}{\left(\frac{4\,F\sin^2\emptyset}{\sigma C_N} + 1\right)}$$

$$a' = \frac{1}{\left(\frac{4\,F\sin\emptyset\cos\emptyset}{\sigma C_T} - 1\right)}$$

$$F = \frac{2}{\pi}\arccos\left(e^{-\frac{B}{2}\cdot\frac{R-r}{r\sin\emptyset}}\right)$$

F is known as Prandl't tip loss factor.

If a and a' deviate significantly from the values assumed for the calculations go back to where the values were initially assumed and use the new value to calculate the flow angle $\emptyset$.

This iterative procedure needs to be repeated until a convergent set of values for a and a' results.

Note that the momentum theory breaks down when a becomes greater than 0,3.

Whenever $a > a_c$ and $a_c \approx 0.2$ Glauert's correction can be applied and a is replaced with the following value:

$$a = \frac{1}{2}\left(2 + K(1-2a_c) + \right.$$
$$\left. - \sqrt{((K(1-2a_c)+2)^2 + 4(Ka_c^2 - 1))}\right)$$

$$K = \frac{4 \cdot F\sin^2\emptyset}{\sigma C_N}$$

When a convergent set of a and a' is determined the Glauert's correction can be used to calculate the local forces on a rotor blade at distance r from the axis of rotation.

The normal and tangential forces per unit of length are expressed below.

$$F_N = \frac{1}{2}\rho\frac{V_0^2(1-a)^2}{\sin^2\emptyset}c\,C_N$$

$$F_T = \frac{1}{2}\rho \frac{V_0^2(1-a)\omega r(1+a')}{\sin\emptyset\cos\emptyset} c\, C_T$$

The procedure is repeated for all ring elements modelled and the result consists of distributions along the rotor blade of the normal and tangential forces per unit of length.

3.1.3.4 Beam theory

Since rotor blades are slender, they, from a structural point of view, can be considered beams and the "beam theory" can be thus applied.
For analysis of a rotor blade by means of beam theory, the following definitions relating to the blade profile are needed:

- The **elastic axis** is perpendicular to the section and intersects the section in a point where a normal force will not give rise to bending;
- The **shear centre** is the point where an in-plane force will not rotate the profile in the plane of section.

The two in-plane principal axes are mutually perpendicular and both cross the elastic axis.
The principal axes are defined by the phenomenon that if a bending moment is applied about one of them, the beam will only bend about this axis.
Applying a bending moment about any other axis will induce bending, also about another axis than the one corresponding to the applied moment.

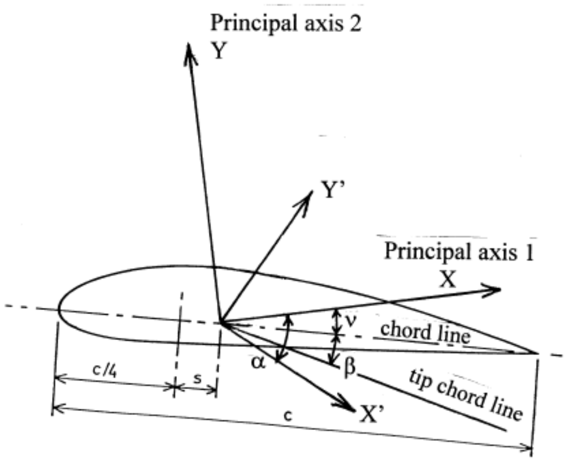

Figure 3.6: "Beam theory axes"

The angle α between the reference axis X' and the principal axis X can be calculated with the following formula where $[ED_{X'Y'}]$ is the deviation moment of inertia and $[EI_{X'}]$ and $[EI_{Y'}]$ are the bending stiffness properties about the X' and Y' reference axes, respectively.

$$\alpha = \frac{1}{2}\arctan\frac{2\,[ED_{X'Y'}]}{[EI_{Y'}]-[EI_{X'}]}$$

$$[ED_{X'Y'}] = \int_A EX'Y'dA$$

$$[EI_{X'}] = \int_A EX'^2dA$$

$$[EI_{Y'}] = \int_A EY'^2dA$$

The bending stiffness about the principal axes can be now computed as follows.

$$[EI_X] = [EI_{X'}] - [ED_{X'Y'}]\tan\alpha$$

$$[EI_Y] = [EI_{Y,}] - [ED_{X'Y'}]\tan\alpha$$

Since present wind turbine blades are usually relatively stiff in torsion, the torsional stiffness is usually neglected.
In structural modelling and analysis, it is important to be aware of the flutter phenomenon, which may result from coupled torsional and flapping motion.
Low ratios of torsional and flapwise frequencies and high tip speeds indicate rise of flutter.

3.1.3.5 Control system

A control system is usually provided to keep the operating parameters of the wind turbine within specified limits.
The operating parameters are usually controlled by monitoring their current values and/or their first or second derivatives; a regulation algorithm can be set up and coded for use together with an aeroelastic code for load prediction.
The mechanical power of the wind turbine can be expressed as a dependent on C_p which is a function of the pitch angle β and of the tip speed ratio $\lambda = \omega_R R/u$, where, ω_R is the angular frequency of the rotor and R is the rotor radius.

$$P = \frac{1}{2}\rho A u^3 C_p\,(\beta, \lambda)$$

The pitch angle β and the rotor speed $\omega_R$are the two parameters that can be used for the control of the turbine.
The control of the turbine can be based on one of the following two approaches:

- Optimize the power below the nominal power by choosing β equal to its nominal value β_{opt} and keeping λ constant at its optimal value λ_{opt}. λ cannot be controlled directly, since u is hard to measure, therefore ω_R is used as parameter to control the turbine.
- Limit the power by keeping it as close as possible to the nominal power.

By means of the pitch and speed regulation of the turbine, changes in the aerodynamic power are absorbed as changes in the angular velocity of the rotor instead inducing changes in the torque which is transferred to the gearbox.

3.1.4 Actuation loads

On a wind turbine, functional load occurs when the turbine is subject to transient operational conditions such as braking and yawing.

The most important functional loads to be considered are:

- Brake loads from mechanical and aerodynamic brakes;
- Transient loads in the transmission system;
- Yawing loads;
- Loads caused by pitching the blades or engaging the air brakes by the control system.

3.1.5 Hydrodynamic loads

(ref. IEC 61400-3, Subclause 7.3)

The hydrodynamic loads are caused by the water flow and its interaction with the support structure of an offshore wind turbine. They depend on the kinematics of the water flow, the water density, the water depth, the shape of the support structure.

3.1.5.1 Morison equation

Wave forces on slender structural members submerged in water, such as tubular members whose external diameter D dimension is lower than L/5 (where L is the length of the passing wave), can be predicted by Morison equation.
(ref. IEC 61400-3, Annex D)

The horizontal force acting on a vertical element dz of the structure at level z is expressed as follows.

$$dF = dF_M + dF_D$$

$$dF = C_M \rho \pi \frac{D^2}{4} \ddot{x} dz + C_D \rho \frac{D}{2} |\dot{x}| \dot{x} dz$$

C_M	inertia coefficients (inertia force)
C_D	drag coefficients (drag force)
D	diameter of the cylinder
ρ	water density
$\dot{x}$	horizontal wave-induced velocity of water
$\ddot{x}$	horizontal wave-induced acceleration of water
A_w	wave amplitude

Wave loads are strongly dependent on the water depth and it is important to consider effects of local variations in the water depth.
In particular, the appropriate wave theory to be used for deriving the velocity $\dot{x}$ and the acceleration $\ddot{x}$ for the boundary conditions (H_s, T_p) of a given wave is determined in relation to the water depth.
According to the first-order (or Airy) wave theory, the horizontal wave velocity and acceleration are calculated as follows.

$$\dot{x} = A_w \omega \frac{\cosh\,[k(z+d)]}{\sinh[kd]} \sin \omega t$$

$$\ddot{x} = A_w \omega^2 \frac{\cosh[k(z+d)]}{\sinh[kd]} \cos \omega t$$

$$\omega^2 = g\,k\,\tanh[kd]$$

k wave number
d water depth

The velocity and the acceleration in Morison's equation need to be taken as the resulting combined current and wave velocity $\dot{x}$ and acceleration $\ddot{x}$.
The resulting horizontal force F on the cylinder can be found by integration of Morison's equation for value of x from $-d$ (seabed) to 0.

$$F = F_M + F_D$$

$$F = \int_{-d}^{0} C_M \rho \pi \frac{D^2}{4}\frac{H}{2}\omega^2 \cos\omega t \frac{\cos h[k(z+d)]}{\sin h[kd]} dz + \int_{-d}^{0} C_D \rho \frac{D}{2}\frac{H^2}{4}\omega^2 \sin\omega t\,|\sin\omega t| \frac{\cos h^2[k(z+d)]}{\sin h^2[kd]} dz$$

As mentioned above, Morison's equation is valid when the dimension of the structure is small relative to the wave length $D < 0{,}2\,L$ and it is valid for nonbreaking waves $H/L < 0{,}14$.
The inertia force and the drag force can be expressed as follows.

$$F_M = A_M \cos\omega t$$

$$F_D = A_D \sin\omega t\,|\sin\omega t|$$

A_M amplitudes of inertia force
A_D amplitude of drag force

$$A = \frac{A_M}{A_D}$$

$$\frac{H}{D} = \pi \frac{C_M}{C_D} \frac{\sinh^2[kd]}{\left(\frac{\sinh[2kd]}{4} + \frac{kd}{2}\right) A}$$

By calculating H/D and d/L it is possible to establish whether the inertia force or the drag force is the dominating force.

3.1.5.2 Diffraction theory

When the dimension of the structure is large compared to the wavelength, typically when $D < 0{,}2\,L$, Morison's equation is no longer valid and the diffraction theory is to be applied.

For a cylinder of $R = D/2$ installed in water of depth d and subjected to a wave of amplitude A, this theory gives the following maximum horizontal wave force $F_{x,max}$.

$$F_{x,max} = \frac{4\rho g A}{k^2}\frac{\sinh\ [k(d + A\sin\alpha)]}{\tanh[kd]}\xi$$

ξ and α are parameters tabulated in literature and A is the wave amplitude.
The vertical arm of the wave force $F_{x,max}$ measured from the sea floor h_F is calculated.

$$h_F = d\,\frac{kd\sinh[kd] - \cosh[kd] + 1}{kd\sinh[kd]}$$

Wave loads are strongly dependent on the water depth and it is important to consider effects of local and tidal variations in the water depth.
The foundation structure of an offshore wind turbine will be subject to the combined action from wind and wave loads, and the resulting structural response from this action governs the design.
Often high wave intensity will imply high wind intensity and vice versa.
This dependency can be taken into account modelling one of the climate variables as an independent variables by means of its marginal cumulative distribution function, and then model the other variable as a dependent variable by means of a distribution conditioned on the independent variable.
For the considered case, the significant wave height H_s is represented by its marginal long-term distribution that is typically a Weibull distribution and the other is the 10-minute mean wind speed U_{10}.

3.1.6 Sea ice loads

(ref. IEC 61400-3, Annex E)

The sea ice loads acting on an offshore wind turbine can be static or dynamic.
Static loads are caused by temperature fluctuations or changes in water level in a fast ice cover.
Dynamic loads are caused by wind and current induced by motion of ice floes.

3.1.7 Other loads

They are induced by the tower shadow, the vortex shedding by the tower, the damping and instabilities like stall-induced blade flapwise and edgewise vibrations.
Where relevant, earthquake loads shall be considered according to IEC 61400-1.

3.2 Simulation requirements

Dynamic simulations utilizing a structural dynamics model are usually used to calculate wind turbine effects (ref. IEC 61400-3, Subclause 7.5.4).

3.3 Additional requirements

(ref. IEC 61400-3, Subclause 7.5.5)

Other topics relevant to loads determination shall be taken into account if relevant, such as the structural damping, the related stall-induced vibrations and the flutter.
These specific topics are discussed in the following.

3.3.1.1 Structural damping

The structural damping is to be included in the equation of motion in order to assure dissipation of energy from the structural system.
Experience shows that the structural damping in terms of damping ratio is usually of the order of 3% for the blades and of 5% for the shaft and the tower.
In order to ensure dissipation of energy, it is required that the part of the damping matrix C in the equations of motion that originates from structural damping is positive definite or at least semi-positive definite.
A commonly used model for representation of damping is the Rayleigh damping model whose major advantage is a decoupling of the equations of motion.

$$x^{T} C\, x \geq 0$$

$$C = \alpha\, M + \beta\, K$$

C	damping matrix
M	mass matrix
K	stiffness matrix

α, β are the model constants determined from two damping ratios that correspond to unequal frequencies of vibration.
A disadvantage of the use of the Rayleigh model is that it over predicts the damping at high frequencies of vibration.
In general, it is assumed that p damping ratios have been determined.
Based on this, the damping matrix is represented by Caughey series.

$$C = M \sum_{k=0}^{p-1} a_k [M^{-1} K]^k$$

The modelling constants a_k are determined from the $i = 1, \ldots, p$ simultaneous equations.

$$\xi_i = \frac{1}{2}\left[\frac{a_0}{\omega_i} + a_1\omega_i + a_2\omega_i^3 + \cdots + a_{p-1}\omega_i^{2p-3}\right]$$

ξ_i is the ith damping ratio and ω_i is the angular frequency for the vibration model that ξ_i was obtained for.
For $p = 2$ this model is reduced to a Rayleigh damping model.
For appreciation of the results presented herein, recall that ith-damping ratio is defined in function of mass, damping and stiffness:

$$\xi_i = \frac{c_i}{2\sqrt{m_i k_i}}$$

The corresponding logarithmic decrement is expressed in the following formula.

$$\delta_i = \frac{2\pi\xi_i}{\sqrt{1 - \xi_i^2}} \approx 2\pi\xi_i$$

Once the initial damping coefficients have been chosen, it must be verified that the model leads to a correct representation of the damping.
This is done by fixing all degree of freedom of the turbine, except the one for which the damping model is to be checked.
An external periodic force is applied to the structural component in question using the natural frequency of that component as the

excitation frequency. The structure is only excited for a few seconds.
The induced vibration is measured, and the damping coefficient is determined from a curve fit of the equation expressed in function of time t, excitation frequency f_n, logarithmic decrement δ and calibration constant from fit C.

$$f(x) = C \cdot e^{-\delta f_n t}$$

Upon application of a Rayleigh damping model, it is only possible to fit the correct damping properties at two frequencies. It is important to be aware of the over prediction of the damping by the Rayleigh model at high frequencies.

3.3.1.2 Stall-induced vibration

Stall induced vibrations, such as the edgewise vibrations, occur whenever the negative aerodynamic damping exceeds the structural damping and the aerodynamic forces supply more energy to the vibrations than the structural damping can absorb.
Examples exist of wind turbine which have developed significant stall-induced vibrations of the blades, even during moderate wind situations such as those characterized by 10-minute mean wind speeds of about 15 m/s.
For a new turbine design, where a great deal of freedom is at hand, the following procedure are recommended:

- Base the airfoil on well documented airfoil data;
- Choose airfoils, blade planform (chord and aerodynamic twist) and blade structural properties considering not only the rotor performance, but also the aerodynamic damping characteristics. Especially, the blade twist should be considered, not only in relation to the power performance, but also in relation to the vibration direction;
- Use a quasi-state approach to calculate the basic aerodynamic damping characteristics for a single blade, considering the flapwise and edgewise mode shapes;
- Extend the quasi-steady analysis and include verified models for dynamic stall on both the airfoil lift and drag considering a single blade;
- Continue the analysis using the full aeroelastic model, including verified models for stall hysteresis on both lift and drag, when the single blade analysis results in appropriate aerodynamic damping;
- Carry out full aeroelastic calculations for the wind speeds of interest through a single blade analysis;
- Investigate the damping characteristics by looking at the responses at the flapwise and edgewise natural frequencies of the blade;
- Repeat from Step 2 if the results are unsatisfactory.

When problems with flapwise and edgewise have been recorded on a particular turbine, the turbine must be redesigned:

- The scheme above should be applied to the existing design;
- The aerodynamic properties of the blades may be modified by using different aerodynamic devices;
- The structural properties of the turbine may be changed by adding local masses or increasing local stiffness properties;
- Mechanical damping devices may be used on the blades or on the supporting structure.

3.3.1.3 Flutter

Furthermore, the flutter is considered an important aspect to take into account.
The flutter is an aeroelastic instability that results in large amplitude vibrations of a blade and possibly in its failure.
Flutter vibrations consist of a coupling of flapwise and torsional blade vibrations, which are sustained by the airflow around the blade.
The most two critical conditions occur when the frequencies of a flapwise bending mode and the first torsional mode are not sufficiently separated, and when the centre of mass for the blade cross-sections is positioned aft of the aerodynamic

centre, which is approximately at the quarter chord point from the leading edge.
In the blades design it is important to ensure a high torsional stiffness and the centre of mass for the blade cross-sections is located between the leading edge and the quarter chord point.
Stall strips can be used on the outer section of a rotor blade to increase the damping on local sections of the blade by increasing the drag after the onset of stall.
Vortex generators are often used to increase the lift and thus to improve the aerodynamic properties of the blade.
The onset of stall becomes delayed when the inflow angle is varying periodically according to the following equation:

$$\alpha(t) = \alpha_0 + \beta \sin \omega t$$

α_0	mean inflow angle
β	amplitude
ω	angular frequency

The phenomenon of delayed onset of stall is denoted dynamic stall, and it influences the lift and drag coefficients.
It is important to account for dynamic stall when it occurs, since lift and drag coefficients are usually derived from wind tunnel tests with constant inflow angle.

Part B Chapter 4: Wind Turbine Components

4.1 Blades characterization

The typical configuration of the rotor blades described in the following is relevant to optimal design, but different configuration that provides same reliability in terms of safety and efficiency can be adopted.
The blade design is based on aerodynamic calculations and it is to be appropriate to withstand the acting loads.
The cross section of the blade has a streamlined asymmetrical shape, with the flattest side facing the wind.
The blade profile near the root is thicker and wider to fit the hub and it becomes thinner along the blade in order to obtain acceptable aerodynamic properties.
The blade is twisted along its axis to enable it to follow the variation in the direction of the resulting wind that the blade will experience when it rotates.
The blade has a hollow profile formed by two shell structures glued together, one upper shell on the suction side and one lower shell on the pressure side.
To make the blade strong and stiff, webs are glued onto the shells in the interior part of the blade.

4.1.1 Blade materials

Wind turbine blades are made of lightweight materials to minimize the loads from rotating mass.
A rotor blade is typically built up of the following elements:

- External panels, which form the aerodynamic shape and carry a part of the bending load;
- Internal longitudinal webs, to provide the cross section with adequate stiffness against deformation;
- Inserts like bushings, which transfer the loads from the panels into the steel hub;
- Lighting protection;
- Aerodynamic brake, typically the tip turning on a shaft.

The most important mechanical properties of the used materials are the shear modulus, the shear strength and the ductility.
Fibre Reinforced Plastics (FRP) is typically the material for external panels, internal webs and shaft for aerodynamic brake.
Fibres are used for transferring the global loads and a polymeric resin is used to distribute the load between the fibres and to restrain the fibres against local relative displacements.
Polyester, vinyl ester and epoxy are the most commonly used resins in wind turbine blades.
Gelcoats and topcoats are used to protect the FRP against abrasion, UV radiation and moisture and to give the white colour.
The most common core materials are structural foams and wood products.
Core/sandwich adhesive are used to bond the pieces together and to fill the voids between sheets of core.
Adhesives are used for joining blades that are manufactured in parts and to bond metallic insert like steel bushings at the root.
The mechanical properties, modulus and tensile strength, may vary significantly between different types of fibres and can vary within each type of fibre.
They depend also on the properties of the matrix, the structural interaction between fibres and matrix and the volume fraction of the fibres.
The blade manufacturer controls the final properties of the laminates, considering the qualification of FRP materials.
Full-scale tests of a sample blade are used to verify the strength of the blade statically and in fatigue as per IEC 61400-23 requirements.

4.1.2 Full-scale blade testing

For a given blade type, relevant wind turbine blade test is typically available as carried out to demonstrate to a certain level that the blade type

has the prescribed reliability with reference to specific limit states (i.e. that blade design has the load carrying capability for the required service life).
The basis for establishing the test loads is the entire envelope of blade design loads, derived according to IEC 61400-1.
The documentation and the procedures related to the test blade are to be reported in accordance with IEC 61400-23, Subclause 6.
The test program for a blade type shall include at least the following tests (ref. IEC 61400-23, Subclauses 7.2):

- Mass, centre of gravity and natural frequencies knowledge;
- Static tests;
- Fatigue load tests;
- Post fatigue load tests.

For the tests, the design load is compiled into a target load and the determination of the target loads shall be based on IEC 61400-23, Subclause 8.4 requirements.
Potential critical areas shall be considered according to IEC 61400-23, Annex B.
The static load testing, ultimate load testing and the fatigue load testing procedures are reported by IEC 61400-23, Subclause 9.
All the tests shall follow the test requirements reported in IEC 61400-23, Subclause 10.
The tests results shall be evaluated and reported according to IEC 61400-23, Subclause 12.
The test program shall include blade inspection.
The evaluation can be conducted through infrared, ultrasonic, visual inspection and recording of sound emission.

4.1.3 Blade natural frequency

The two lowest eigenfrequencies of the rotor blade, both in flapwise and edgewise oscillation, should be calculated and compared to the rotational frequencies of the wind turbine. A sufficient margin to these frequencies must be available to avoid resonance of the blade.
It is recommended to keep the eigenfrequencies outside a range defined as the rotational frequency ±12%.

4.1.4 Blade tip deflection

In the blade tip deflection analysis it must be proven that ultimate tip deflection is acceptable. Knowing the initial distance from the blade tip to the tower, in the no-load condition, this allows the determination of the clearance between the rotor blade and the tower.
The clearance shall be determined by using the most unfavourable combination of the geometrical tolerances and characteristic stiffness properties of the rotor blade and its support.
The clearance shall be calculated for the characteristic extreme load on the blade times a safety factor between 1,3 and 1,5.
The effect of damping may be important and shall be considered, furthermore allowing rotor creep, shrinkage, temperature, deformations or degradation with time.
In order to increase the distance between the blade tip and the tower during operation, the rotor can be coned, the blade can be produced with a pre-deflection and the rotor plane can be tilted of about 5°.

4.1.5 Lightning protection

Relevant information for understanding the lightning phenomenon and the processes involved when lightning interact with wind turbine are provided by IEC 61400-24, Annex A.
Lighting Protection Levels from I to IV are considered with reference to IEC 62305-1.
For each LPL a set of maximum and minimum lighting current parameters is fixed (ref. IEC 61400-24, Table 1 and Table 2).
The goal of any lighting protection system is to reduce the hazards to a tolerable level, which is based on an acceptable risk if human safety is involved.
The lightning protection is furthermore a precaution against economical losses due to damage and loss of revenue.

Guidance on how to make a simple lightning exposure assessment for individual wind turbines, and how to extend it to groups of WT and wind farms is given by IEC 61400-24, Subclause 7.
Lightning protection and verification shall be applied to:

- Blades, which are the most exposed parts of the turbine;
- Nacelle;
- Tower;
- Mechanical drive train;
- Yaw system;
- Electrical and control systems.

An efficient earthing system for the machine essential to disperse lightning currents and prevent damage to a wind turbine (ref. IEC 61400-24, Subclause 9).

4.2 WT hub

The hub is the fixture for attaching the blades to the rotor shaft.
It consists of nodular cast iron components for distribution of the blade loads to the wind support structure. It must be highly resistant to metal fatigue.
Three types of hub are common:

- Hingeless rigid hub (transmitting all moments to the tower);
- Teetering rotor (transmitting in-plane moments to the hub);
- Articulated hub (no mechanical restraint moment on the blades).

The blades are usually bolted to the hub.
There are two techniques for mounting the bolts:

- A flange is established at the blade root by moulding the glass fibre reinforced plastics to form a ring, in which steel bushes for the bolts are embedded;
- Treated steel bushes are mounted directly into the blade root and fixed to the blade by glue.

In both cases, the bolts from the blade pass through a flange on the cast hub and a bolt tension procedure is usually required.
The hub enclosure is usually made of glass fibre reinforced polyester.
Spheroidal graphite cast iron is the preferred material for the hub and it is classified according to its mechanical properties in EN 1563.
Cast hubs are to be tested by non-destructive testing for verification of the mechanical properties and for detection of possible defects and internal discontinuities, such as ultrasonic inspection, magnetic particle inspection, visual inspection and hardness measurement.
Using ultrasonic inspection, a strict acceptance criterion should be assigned to an area with high stresses.
The stricter the acceptance criterion is in a particular area, the more deep is the ultrasonic inspection in that area and the stricter are the requirements to the allowable size of detected discontinuities.
Appropriate consideration of ductility requirements is to be carried out for the chosen structural material.
Low temperature can be critical for cast hubs and the choice of hub material should be made with due consideration to the expected operating temperatures.
The loads at the blade-hub interfaces to be considered at the blade root for the design of the hub are the following:

- Full flapping moment;
- Flapping shear, resulting thrust on one blade;
- Lead-lag moment, power torque of one blade, and gravity loads;
- Lead-lag shear, in-plane force that produces power torque;
- Centrifugal forces;
- Pitching moments of one blade.

It is beneficial for the hub structure to reduce the loads at the blade-hub interfaces, in particular, the large blade-flapping moment.
The blade-root flapping moment can be traded off against tip deflection.
Flexible blades have the advantage of relieving some of the load into centrifugal terms.
Yaw stability and fatigue life are both significantly affected by blade flexibility.

The structural assessment of the hub is to be carried out for both the ultimate limit state and the fatigue limit state.
The structural resistance in the ultimate limit state is to be determined by elastic theory.
The maximum allowable stress shall be taken as the characteristic resistance divided by a safety factor.
The allowable fatigue stress range is to be taken as the characteristic resistance divided by a safety factor as well.
The characteristic resistance for a given number cycles to failure is defined as the stress range that correspond to 95% survival probability.
The characteristic resistance should be modified to account for size effects, surface conditions and mean stress.
The layout of a wind turbine hub often makes it difficult to determine which section is the structurally most critical section of the hub.
The FEM forms a suitable tool for strength analysis of the hub: it can be used in conjunction with the state-of-art fatigue life optimizing the design with respect to strength and cost.

4.3 Rotor-nacelle assembly components

4.3.1 Main shaft

The main shaft transmits the rotational energy from the rotor hub to the gearbox or directly to the generator.
The purpose of the main shaft is to transfer the aerodynamic loads, the gravitational loads and reactions from bearings and gear from the rotor to the fixed system of the nacelle.
The main shaft is also subjected to torsional vibrations in the drive train.
Structural analysis of the main shaft shall be carried out for all relevant load cases in order to verify that the strength of the shaft is sufficient to withstand the loads to which it is subjected.
The material shall exhibit a high fracture toughness and low brittle transition temperature: steel within this category is standardised in EN 10083-2.

4.3.2 Main bearing

(ref. IEC 61400-1, Subclause 9.8)

The main bearing of a wind turbine supports the main shaft and transmits the reactions from the rotor loads to the machine frame.
The spherical roller bearing type is often used.
The bearings have a high radial load capacity and they can accommodate axial loads in both directions.
The main bearing is mounted in bearing housing bolted to the main frame.
The quantity of bearings varies among the different types of wind turbines.
The shaft is supported by a bearing placed adjacent to the rotor; another bearing at the opposite end of the rotor shaft is integrated in the main gearbox.
The loads are usually specified in terms of a load spectrum or distribution of loads, which on discretised form gives the number of hours of operation within each defined load interval in the discretisation.
For each interval, the associated operational and environmental conditions have to be taken into account. All relevant load cases are to be included in this load spectrum.
The main bearing must be able to accommodate axial and radial forces from the rotor.
The bearing must allow misalignment from deflection of the shaft and the support.
These requirements are fulfilled by means of spherical roller bearings.
Temperature, salinity, chemically active substances and abrasive particles have to be considered.
Bearing seals are needed to hold back bearing lubrication and to keep out contaminants.
Non-rubbing seals are appropriate since they have no friction and no wear.
To reduce the risk of scratches in the shaft the rubbing usage should be aimed to mount the seal on the shaft and to let the bearing housing form the sealing surface.
Lubrication is used to avoid wear and premature rolling bearing fatigue, to reduce the development

of noise and friction to improve the operating characteristics of bearing.
When selecting lubrication viscosity, consistency, operating temperature range and the resistance against corrosion are to be considered.
The most commonly used lubrication in the mean bearings is grease. It is easily retained and it contributes to sealing the bearing arrangement from contamination.
The following grease types are distinguished: mineral oil with metal soaps as thickener, mineral oil with non-soap thickener and synthetic oils with non-soap thickener.
In general, for a design life of 20 years, the required basic rating life should be equal or exceeded 300.000 hours.

4.3.3 Main gearbox

(ref. IEC 61400-1, Subclause 9.4)

The purpose of the main gear is to act as speed increaser and to transmit energy between the rotor and the generator.
The most common gear types used in main gears for wind turbines can be:

- Spur and helical gears consist of a pair of gear wheels with parallel axes;
- Epicyclical or planetary gears consist of epicyclical trains of gear wheels, i.e. gear where one or more parts travel around the circumference of another fixed or revolving parts.

Procedures for calculation of loads and prediction of load capacities for gears include prediction of surface durability, tooth root strength and scuffing load capacity.
Wear, micro pitting and fractures starting from flanks may also limit the gear capacity.
For these last aspects, ISO 6336-1 to ISO 6336-5 can be used as reference.

4.3.3.1 Gearbox lubrication

(ref. IEC 61400-4, Subclause 7.6)

The principal function of the oil lubrication is the protection of the rubbing surfaces of the gear teeth.
The choice of a lubricant and a lubrication system should be joint responsibility of the gearbox manufacturer and the gearbox purchaser.
Wind turbine gears have a relatively low pitchline velocity and high gear tooth loads.
These conditions require both synthetic or mineral gear oil with anti-scuff additives and the highest viscosity that is practical.
Oil level indication by means of a sight glass or dipstick or equivalent is to be provided. The lubrication oil temperature is to be monitored.
In case of forced lubrication system, the pressure is to be monitored.
The monitoring system should be arranged to imply shutdown in case of malfunction. During the installation of gearing the design of the oil systems and maintenance methods with respect to changing the oil should be developed to minimise oil leaks and spills.
The contact pattern has to be verified under real or simulated conditions for some gears in a series.

4.3.3.2 Other requirements

The quality requirements for materials and heat treatments are to be designed according to ISO 6336-5 or other applicable standard.
Specific requirements for quality control and material requirements and testing are given for each material type and quality level.
The strength values for both pitting and bending fatigue are dependent on the quality level.
Requirements to testing and inspection of gearing depend on which type of heat treatment is applied.
The following types of heat treatment are dealt with in separate subsections:

- Case-hardened gears;
- Alloyed through-hardened (quenched and tempered);
- Nitrided gears.

The complete surface crack detection by means of wet fluorescent magnetic particle method is required for the toothed area, including the ends of teeth.

The tooth accuracy of pinions and wheels is to be documented with reference to ISO 1328-1 or to corresponding National Standard.
Visual inspection is to be carried out considering:

- Surface roughness of flanks;
- Surface roughness of roots fillets;
- Rooth fillet radius;
- Possible grinding notches of root fillet.

4.3.4 Coupling

The major types of couplings are listed in the following along with issues of importance for their design:

- Flange couplings
  The level of safety is to be demonstrated in both the ultimate limit state and the fatigue limit state.
  If the torque transmission is based only on friction between the mating surfaces of flange couplings, the friction torque (including the influence of axial forces and bending moments) is not to be less than 1.5 times the characteristic peak torque.
- Shrink fit couplings
  The friction connection is to be able to transmit at least 1.5 times the characteristic peak torque without slipping. Bending moment influence is to be considered.
  The permissible material stress depends on the relative wall thickness, material type, and whether the coupling is demountable or not, and the usual range of permissible equivalent stress (von Mises) is 70% to 110% of the yield strength of the hub.
- Key connection
  The connection is to be able to transmit the characteristic peak torque.
  The shear stress in the key is not to exceed 50% of the yield strength in shear. The pressure on the side of the keyway is not to exceed 85% of the yield strength of the key.
  The yield strength to be applied in checks according to these two criteria is not to exceed 2/3 of the tensile strength of the key, and it is not to exceed twice the yield strength of the shaft or the hub, whichever is involved.
  In principle, there is to be no clearance between the hub and the shaft, however, a certain amount of minimum interference fit is required, e.g. approximately 0.02% of the shaft diameter.
- Torsionally elastic couplings
  Rubber couplings are to be designed such that a failure of a rubber element does not cause loss of the connection between the rotor and the brake.
- Tooth couplings
  Tooth couplings are to have a reasonable degree of safety with respect to surface durability and tooth strength. This is subject to special consideration.

4.3.5 Mechanical brake

Mechanical brakes are usually used as a backup system for the aerodynamic braking of the wind turbine and/or as a parking brake, once the turbine is stopped.
Mechanical brakes are sometimes also used as part of the yaw system.
A hydraulic system is usually used for the actuation and release of the brake.
Mechanical brake can be active or passive, depending on how the hydraulic system of the brake is applied:

- In the active brake, the pressure of the hydraulic system actively pushes the brake pads against the brake disc.
- In the passive brake, the pressure of the hydraulic system keeps a spring tight.

The hydraulic pressure is usually provided by means of an accumulator.
For active systems, it is important to make sure that the pressure in the accumulator is always available.
It is important to maintain an approximately constant spring pressure over a considerable range of the deflection.
Brake discs and brake pads must be able to withstand temperature loading, since the friction during braking leads to dissipation of energy in

terms of heat and causes high temperatures to develop locally.

4.3.6 Hydraulic systems

In a hydraulic system, power is transmitted and controlled through a liquid under pressure within an enclosed circuit.
A hydraulic system shall be protected against exceeding the maximum admissible pressure, by using a release valve.
Pressure shocks should be kept to a minimum and pressure drop must be avoided.
A safe condition shall be guaranteed in the event of power supply failure and in the subsequent event of restoration of the power supply.
The following external factors shall be considered in order to verify that they do not affect the operation of a hydraulic system: salt and other corrosive substances, sand and dust, moisture, external electromagnetic field, sunlight and vibrations.
The hydraulic fluid is not to have a flash point lower than 150 °C.
When a hydraulic system forms part of the protection system, grid failures and extreme temperatures must not compromise the operation of the system.
Hydraulic systems, which form parts of protection systems, can be divided into three categories as follows:

- Systems in which the brake is actively released by a hydraulic or pneumatic pressure medium;
- Systems in which the brake is actively released but actuated hydraulically and pneumatically;
- Systems in which the brake is released in the neutral state and is actuated hydraulically or pneumatically.

For the last two categories, an actively operated hydraulic or pneumatic installation shall not be used to keep a wind turbine in a safe state for a long period after a protection system has been actuated.
It is recommended to take the necessary steps to ensure that failure of redundant system can be detected.
In the case of oil leaks in hydraulic systems, other wind turbine components or other systems shall not be affected.
ISO 4413 gives the general rules for the application of equipment to transmission and control systems.
For actively released brakes, which are being actuated hydraulically or pneumatically, the actuation shall be accomplished by means of a pressure accumulator.
The pressure in the accumulator shall be monitored at a level which is sufficiently high to guarantee independent braking action.
ISO 5596 is referred to gas-loads accumulators with separator and relevant range of pressure and volume.

4.3.7 Generator

(ref. IEC 61400-1, Subclause 10)

The generator is the unit of the wind turbine that transforms mechanical energy into electric power.
The synchronous rotational speed of the generator is dependent on the grid frequency f and the number of poles p.

$$\mathrm{n_s} = 60\,\frac{\mathrm{f}}{\mathrm{p}}$$

The produced alternating current, which is transmitted to the electrical grid, must match the frequency of the grid.
A synchronous generator operates at a constant speed, dictated by the frequency of the connected grid, regardless of the magnitude of the applied torque.
In an asynchronous generator, the rotational speed is allowed to vary somewhat with the applied torque.
This is the most common generator type used in wind turbines.
The pitch or stall control of the wind turbine is meant to ensure that the allowable slip of the generator is not exceeded (the slip is difference between the rotational speed of the generator and the rotational speed dictated by the grid).

When a wind gust hits the wind turbine rotor, the slip enables the generator speed to increase in response to the gust without causing a corresponding increase in the generated power output.
The slip ensures a smooth power output and at the same time contributes to keep the loads on blades, main shaft and gearbox down.
Generator is to be constructed in such a way that when running at any working speed, all revolving parts are well balanced.
The generator is to be designed such that it can produce a sufficiently large torque to keep the turbine within its defined range of operation, in compliance with the control system requirements (see 4.4.1).
The generator shall be designed to be fully functional at the temperatures that are likely to occur locally, when the external temperature is within the range -10 °C ÷ 30 °C for normal operations.
The electrical equipment shall be constructed in such a way that it will not be damaged by the impact from the saline and moist environment.
The generator forms one of several links in the transmission between rotating system and electrical system of a wind turbine.
This risk is absorbed by the protection system, which brings the wind turbine to a safe condition.
The probability of breakdown shall be less than 0,02% per machine year.
If the generator is disconnected one of the two fail-safe brake system shall begin working.
Usually, the fail-safe brakes are pitchable blade tips and/or mechanical brakes.
Components which form part of both control and protection functions are to be fail-safe designed, or their probability of failure is to be minimised.

4.3.8 Generator cooling system

The cooling system of the generator has to correspond to IC 41 category for water-jacket cooling according to EN 60034-6.
The generator, including its possible external encapsulation and its external cooling system with cooling agents such as air or water, has to be protected against external impacts corresponding to degree of sealing IP 54 in accordance with EN 60034-5.
The generator shall be balanced such that it as minimum fulfils the requirements to Class N according to IEC 60034-14.
The generator is to be constructed such that it fulfils the requirements to overspeed according to EN 60034-1 and EN 60034-3.
The generator shall be designed for the same lifetime as the rest of the wind turbine.
The design lifetime shall be at least 20 years.
The manufacturer test reports shall provide information about making, type, serial number, insulation class, all technical data necessary for the application of the generator.
The recommended tests are listed below:

- Temperature test at full load;
- Overload test;
- Overspeed test;
- High-voltage test;
- Measuremennt of insulation resistance;
- Measurement of resistance of windings;
- Measurement of air gap;
- Open-circuit voltage characteristics;
- Short-circuit current reistance;
- Measurement of excitation current at rated current, voltage and power factor;
- Short-circuit test.

4.3.9 Machine support frame and nacelle enclosure

The machine support frame is located on top of the tower and supports the machinery, including the gearbox. Usually, it also provides support for nacelle cover.
In contrast to the tower, the machine support frame is usually a very turbine-specific structure.
It can be welded, bolted or cast steel structure.
For design of the machine support frame, the following issues are to be considered:

- A sufficient stiffness of the frame must be ensured in order to meet the stiffness requirements for the machinery;
- Fine tolerances must be met during the manufacturing of the frame;
- The frame must be designed against fatigue due to its exposure to the rotor forces;
- Access to the nacelle through the tower and the machine support frame is provided (it must include a hole of convenient size for personnel to pass).

The machine support frame is exposed to rotor loads consisting of thrust, yaw moment and tilt moment.

The purpose of the nacelle enclosure is to protect the machinery and control system of the wind turbine against rain, moisture, salt, solid particles. It is also meant to protect against noise and is often covered with some noise reducing material.

The nacelle enclosure is to be designed for wind load as a walkway and needs to have sufficient dimensions for this purpose.

4.3.10 Yaw system

(ref. IEC 61400-1, Subclause 9.5)

Yaw denotes the rotation of the nacelle and rotor about the vertical tower axis.

By yawing the wind turbine, the rotor can be positioned such that the wind hits the rotor plane at a right angle.

The yaw system provides a mechanism to keep the rotor axis aligned with the direction of the wind.

The yaw system can be either passive or active.

- A passive yaw system implies that the rotor plane is kept perpendicular to the direction of the wind by utilisation of the surface pressure.
- An active yaw system employs a mechanism of hydraulic or electrically driven motors and gearboxes to rotate the turbine and keep it turned against the wind.

The extreme design yaw moment is likely to appear during operation at a maximum wind speed with a maximum yaw error.

Dynamically, the yaw moment will have a tendency to oscillate with a frequency three times the rotor frequency.

The yaw speed must therefore be small enough for gyroscopic effects to become negligible.

To achieve such a low yaw speed (equals to 1°/sec for large turbines with active yaw system) the yaw motors needs to be connected through a gearbox.

The yaw drives must have sufficient power to overcome the largest mean yaw moment occurring plus friction in the yaw bearing.

The wind turbine must be equipped with a cable twist sensor, which monitors the number of the revolutions and informs the controller when the cables become too twisted.

4.3.11 Pitch system

(ref. IEC 61400-1, Subclause 9.6)

Pitch control gearboxes serve the essential purpose of setting wind turbine blades at the best angle to the wind to turn the rotor.

4.4 Control and protection system

4.4.1 Control functions

(ref. IEC 61400-1, Subclause 8.2)

Controls are used for the following functions:

- To enable automatic operation;
- To keep the turbine in alignment with the wind;
- To engage and disengage the generator;
- To govern the rotor speed;
- To protect the turbine form overspeed;
- To sense malfunction as and warn operators of the need for maintenance or repair.

The control system is meant to control the operation of the wind turbine by active or passive means and to keep operating parameters within their normal limits.

Passive controls use their own sensing and are exercised by use of natural forces.

Active controls use electrical, mechanical, hydraulic or pneumatic means and require

transducers to sense the variables that will determine the control action needed.
Typical variables and features to be monitored in this respect include:

- Rotor speed;
- Wind speed;
- Vibration;
- External temperature;
- Generator temperature;
- Voltage and frequency at main connections;
- Connection of the electrical load;
- Power output;
- Cable twist;
- Yaw error;
- Brake wear.

4.4.2 Protection functions

(ref. IEC 61400-1, Subclause 8.3)

The protection system is sometimes referred to as the safety system, since it shall bring the wind turbine to a safe condition and maintain it in this condition when required.
In the IEC standard an additional requirement is that means shall be provided for bringing the rotor to a complete stop from a hazardous idling state in any wind speed less than the annual extreme wind speed.
Situations which call for activation of the protection system include, but are not necessarily limited to:

- Overspeed;
- Generator overload or fault;
- Excessive vibration;
- Failure to shut down following network loss;
- Abnormal cable twist owing to nacelle rotation by yawing.

Therefore, the protection system should as a minimum cover the monitoring of the following:

- Rotational speed or rotational frequency;
- Overload of a generator;
- Extreme vibrations in the nacelle;
- Safety- related functioning of the control system.

A protection system consists of:

- A registering unit;
- An activating unit;
- A brake unit.

In addition, the protection system shall:

- take precedence over the control system;
- be fail-safe in the event that power supply fails;
- be designed to high safety class;
- be able to register fault and to bring the wind turbine to a standstill situation;
- be tolerant towards a single fault in a sensor; ensure that situations caused by failures in the protection system can be neglected.

Part B Chapter 5: WT Structure Concept Selection

5.1 Support structure characterization

The support structure of a wind turbine is to be designed to carry the nacelle and the rotor as well as to provide the necessary elevation of the rotor, in order to bring it up to the level required for both adequate wind velocity and appropriate clearance for avoiding wave slamming occurrence.

Nowadays, most towers are tubular tower but also lattice tower can be considered.

The support structure is composed by the tower, which is connected to the substructure, and consequently to the foundations, by means of a bolted flange connection or a weld.

The support structure transfers the load from the bottom of the wind turbine tower through the water to the supporting soils.

Such a support structure will experience loads from current, waves and ice.

Different support structure concepts exist for wind turbine.

5.1.1 Support structure types

Three different types of support structure exist (see Fig. 5.1 for reference) and they are adopted depending on the water depth $\mathrm{W_d}$ of the site:

- Monopile
- Tripod
- Jacket

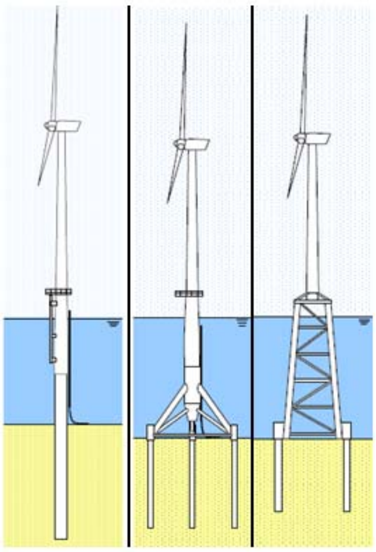

Fig. 5.1

5.1.1.1 Monopile ($\mathbf{W_d < 30\ m}$)

The monopile is in principle a vertical pipe, driven into the soil, onto which the wind turbine tower is mounted.
The advantages are the easy design and production procedures and the low unit price per ton.
The monopile is an attractive foundation solution for wind turbines to be placed in shallow waters and smooth seas.

5.1.1.2 Tripod ($\mathbf{30 < W_d < 40\ m}$)

The tripod supports a central tube that extends into the tower, with each corner of the tripod support piled into the seabed.
Each leg is supported by either a driven pile or a suction bucket for transfer of loads to the supporting soils.
The tripod is preferred in presence of harsher climates and less shallow waters.
The solution with suction buckets under the three legs is only feasible for foundations in clay; it does not work in sand or other permeable soils.

5.1.1.3 Jacket ($\mathbf{40 < W_d < 60\ m}$)

The jacket can be any of arrangements whereby a central tube is surrounded by numerous piled supports.
While the monopile transfers the loads by bending to the soil, both the tripod and jacket

dissolve the global moments to pairs of forces and transfer them as axial loads to the soil.

5.1.2 Solutions comparison

In the following table 5.1 it is highlighted which of the three concepts is the preferred solution and which is not preferable regarding the respective criterion indicated in the row.

	M	T	J
Transportability	green	yellow	red
Corrosion protection	green	yellow	red
Scour	red	yellow	green
Ship collision	green	red	yellow
Availability of installation equipment for large water depth	red	green	green
Design experience	green	yellow	red
Complexity of joint (fatigue design)	green	red	yellow
Structural Reliability (in terms of redundancy with respect to single fatigue failure and reserve strength to ultimate loads)	red	yellow	green
Serial production	green	yellow	red
Installation procedure (soil preparation, levelling)	green	yellow	red
Deconstruction after lifetime	green	yellow	red
Deflection at tower top	red	yellow	green
Dependency on soil conditions	red	green	green
Footprint	green	yellow	red
Foundation loads	red	yellow	green
Unit price of manufacturing (per ton of steel)	green	yellow	red
Overall weight to be expected	red	yellow	green

Table 5.1: “Solutions comparison”

The cost for structural steel is constant for all concepts.

As to manufacturing costs, it can be assumed that this will be cheapest for the monopile, while the jacket solution will be the most expensive.
The main peculkiarity of the monopile is the simplicity for fabrication and installation.

5.1.3 Water depth choice dependency

To be technically feasible, each concept has to provide the following aspects:

- The dynamic behaviour of the overall system has to be such that the first fundamental natural frequency is a relatively small band, typically between 0.25 Hz and 0.35 Hz, in order to avoid excessive dynamic excitation of the global system to the wave loads;
- The structure has to provide sufficient bearing capacity to survive the design lifetime. This includes the ultimate limit state (ULS) scenario as well as the fatigue limit state.

Deeper water influences the structural dynamic response; it can be seen in terms of moment of inertia I of the cross-sections, which is important for the dynamics and relevant section modulus for the load bearing capacity.
In case of monopile, the support structure can be represented as a SDOF (Single Degrre Of Freedom) system, where the rotor and the nacelle are represented by a single mass m and the distributed bending stiffness is idealized as a single spring:

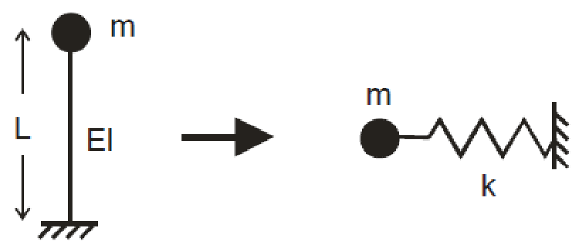

Fig. 5.2: “Support structure scheme”

The fundamental frequency of a SDOF system is:

$$\omega = \sqrt{\frac{k}{m}}$$

with m being the top mass and k the spring stiffness; this latter is obtained by the bending stiffness of the system:

$$\mathrm{k} = \frac{3\mathrm{EI}}{\mathrm{L}^3}$$

L is the length of the system or the height of the tower.

Going to deeper waters means increasing this length, i.e. reducing the stiffness, which, in turn, means reducing the fundamental frequency, i.e. increasing the natural period.

That means the structure becomes more flexible with possible amplification in its dynamic response, eventually more critical to the fatigue issue too.

In order to maintain the fundamental frequency low while increasing water depth, the moment of inertia has to be increased; given a limited ω the required moment of inertia is:

$$\mathrm{I}_{\mathrm{req}} = \frac{\mathrm{m}\,\omega^2}{3\mathrm{E}}\mathrm{L}^3$$

i.e. proportional to the length of the system to the power of 3.

The weight per unit of length depends on the section area.

$$\mathrm{A} = \frac{\pi}{4}(\mathrm{D}^2 - \mathrm{d}^2)$$

with D the outer diameter (OD) and d the inner diameter of the pile.

Increasing stiffness means to increase the sectional properties (i.e. OD or wall thickness of the pile) diameter, with possible negative effects on both the weight per unit length and acting hydrodynamic loads (proportional to the OD to the power of 2).

With tripod and jacket it is possible to come around this problem, since these provide the required stiffness by a sufficient height of construction without increasing the required weight per unit length significantly.

Increased water depth often means also increased foundation penetration depth due to the increased loads.

Part B Chapter 6: Structural Analysis

1 Load cases

The wind turbine is to be analysed for the various loads it will experience during its design life, in order to verify that relevant structures are able to withstand these loads with appropriate safety margin.

Load cases can be determined by combining the design situations relevant for the wind turbine with applicable external conditions.

For WT loads characterization reference is to be made to the standard IEC 61400-3, specifically Table 1 “Design load cases” (see Table 6.1 at the bottom).

The following combinations are relevant:

- Normal operation and normal external conditions;
- Normal operation and extreme external conditions;
- Fault situations and appropriate external conditions;
- Transportation, installation and maintenance situations and appropriate external conditions.

Table 6.1 serves as a basis.
It is the duty of the designer to apply it appropriately by taking into account the possible factors, which can influence the involved wind conditions and the magnitude of the loads (IEC 61400-1, Subclause 7.5), such as:

- Disturbance of the wind flow due to the presence of the tower;
- Wake effects wherever the wind turbine is to be located behind other turbines;
- Misalignment of wind flow with respect to the rotor axis.

For each design situation, both ultimate (U) and fatigue (F) loads analysis are to be carried out, according to the basic recommendations reported in Table 6.1.
According to the same table, for each design situation, a partial safety factor (PSF) is to be associated among normal (N), abnormal (A), transport and erection (T) and for fatigue partial safety factor (F) to evaluate the fatigue design resistances.
In general, the partial safety factor is introduced to account for:

- the variability in loads (ref. IEC 61400, Subclause 7.6.2.1) and materials (ref. IEC 61400, Subclause 7.6.2.2-3) characterization;
- the uncertainties in the analysis methods;
- the importance of structural components with respect to the consequences of failure (ref. IEC 61400-3, Subclause 7.6).

The partial safety factors for loads and materials and the ultimate strength analysis of the RNA of an offshore wind turbine shall meet the requirements of IEC 61400-1, Subclauses 7.6.1 and 7.6.2.
For the partial safety factor to be used for the ultimate strength analysis in normal (N), abnormal (A), transport and erection (T), reference can be done to IEC 61400-3, Subclauses 7.6.2, while specific safety factors for the fatigue failure (*) are provided in IEC 61400-3, Subclauses 7.6.3.
The system and components design resistances of the support structure is to be verified according to Tasneef Rules for Classification of Fixed Offshore Platforms (2015 Ed.) or, more in general, to the applicable requirements of ISO offshore structural design standard (ISO 19900 series).

1.1 Ultimate strength analysis

Extreme value distributions are of interest when extreme load responses are needed such as for design against failure in ultimate loading.
Reference is made to particular load cases:

- Normal operation at 10-minute mean wind speed near the cut-out wind speed;
- Standstill at a rare 10-minute mean wind speed such as the one with a 50-year recurrence period;
- Faulty operation at a high wind speed due to error in the protection system.

For the considered load cases, it is assumed that a total of n 10-minute time series of the load response X has been generated by aeroelastic simulations, as a result of the lift and drag forces in conjunction with the blade profile properties and damping, and with effects of the motion of the rotor structure included.
The maximum value X_m of the load response X in the 10-minutes will not be fixed but will have a natural variability represented by a probability distribution.
The mean value of the maximum load response in 10-minutes is denoted μ_m and the standard deviation is denoted σ_m.
There are two different approaches to predicting the maximum load response and particular quantiles of its distribution: the statistical model and the semi-analytical model.

- Statistical model

In the statistical model, the maximum load response X_m in 10-minutes can be assumed asymptotically to follow a Gumbel distribution F_{X_m}.

$$F_{X_m}(x_m) = e^{-e^{-\alpha(x_m-\beta)}}$$

In which α is a scale parameter and β is a local parameter.
From the n simulated time-series there are n observations of the maximum load response X_m.
For estimation of α and β, the n values of X_m are ranked in increasing order $x_{m,r}$, with $r = 1, \dots, n$.
Two coefficients b_0 and b_1 are calculated from the data and α and β are estimated as $\hat{\alpha}$ and $\hat{\beta}$.

$$b_0 = \frac{1}{n}\sum_{r=1}^{n} x_r$$

$$b_1 = \frac{1}{n}\sum_{r=1}^{n} \frac{r-1}{n-1} x_r$$

$$\hat{\alpha} = \frac{\ln 2}{2b_1 - b_0}$$

$$\hat{\beta} = b_0 - \frac{\gamma_E}{\hat{\alpha}}$$

$$\gamma_E = 0{,}5772$$

The mean value μ_m and standard deviation σ_m of X_m are estimated as $\hat{\mu}_m$ and $\hat{\sigma}_m$.

$$\hat{\mu}_m = \hat{\beta} + \frac{\gamma_E}{\hat{\alpha}}$$

$$\hat{\sigma}_m = \frac{\pi}{\hat{\alpha}\sqrt{6}}$$

The θ-quantile in the distribution of X_m and the standard error $se(\hat{x}_{m,\theta})$ can be estimated.

$$\hat{x}_{m,\theta} = \hat{\mu}_m + k_\theta \hat{\sigma}_m$$

$$k_\theta = \frac{\sqrt{6}}{\pi}\left(-\ln\left(\ln\left(\frac{1}{\theta}\right)\right) - \gamma_E\right)$$

$$se(\hat{x}_{m,\theta}) = \frac{\hat{\sigma}_m}{\sqrt{n}}\sqrt{1 + 1.14\,k_\theta + 1.1k_\theta^2}$$

This reduces to the following definition

$$se(\hat{\mu}_m) = \frac{\hat{\sigma}_m}{\sqrt{n}}$$

for the special case that θ-quantile is replaced by the mean value μ_m.

Assuming a normal distribution for the estimate of the θ-quantile, the two-sided confidence interval for the θ-quantile with confidence 1- α becomes:

$$\hat{x}_{m,\theta} \pm t_{1-\frac{\alpha}{2},n-1} \cdot se(\hat{x}_{m,\theta})$$

In which $t_{1-\frac{\alpha}{2},n-1}$ is the 1-α/2 quantile in the Student's *t* distribution with n-1 degree of freedom.
When a characteristic value with a specified confidence is aimed for, it is usually taken as the upper confidence limit.
Note that a high number of simulations n may be necessary to achieve a sufficiently accurate estimate of $x_{m,\theta}$ and μ_m.

- Semi-analytical model

The semi-analytical model utilizes more information about the n 10-minute time series of the load response than just the n maximum response value X_m.

The load response X can be viewed as a stochastic process during the 10-minute series.

The process X can be considered as a quadratic transformation of a parent standard Gaussian process U.

$X = \zeta + \eta(U + \varepsilon U^2) \qquad \varepsilon \ll 1$

A first-order approximation gives the following expressions for the coefficients

$$\varepsilon = \frac{\alpha_3}{6}$$

$$\eta = \sigma$$

$$\zeta = \mu - \varepsilon\sigma$$

From which it appears the mean value μ is used, as well as the standard deviation σ and the skewness α_3 of the load response process X.

The mean value and standard deviation of X_m are estimated.

$$\hat{\mu}_m = \eta + \zeta\sqrt{2\ln(\nu_\mu T)} + \varepsilon\, 2\ln(\nu_\mu T) + \frac{\gamma_E \zeta(1 + 2\varepsilon\sqrt{2\ln(\nu_\mu T)})}{\sqrt{2\ln(\nu_\mu T)}}$$

$$\hat{\sigma}_m = \frac{\pi\eta}{\sqrt{6}} \frac{1 + 2\varepsilon\sqrt{2\ln(\nu_\mu T)}}{\sqrt{2\ln(\nu_\mu T)}}$$

ν_μ is the crossing rate of level μ and T denotes duration and is usually the length of a simulated time series.

Corresponding estimates of the Gumbel distribution parameters α and β can be found as:

$$\hat{\alpha} = \frac{\pi}{\hat{\sigma}_m\sqrt{6}}$$

$$\hat{\beta} = \hat{\mu}_m - \frac{\gamma_E}{\hat{\alpha}}$$

The standard error in the mean value estimate $\hat{\mu}_m$ is:

$$se(\hat{\mu}_m) = \frac{\hat{\sigma}_m}{\sqrt{n}}$$

where n is the sample size (i.e. the number of 10-minute series available for the estimation of μ_m.

When σ_m can be considered well determined by the above formula for $\hat{\sigma}_m$, the two-sided confidence interval for μ_m with confidence $1 - \alpha$ becomes:

$$\hat{\mu}_m \pm u_{1-\frac{\alpha}{2}} \cdot \frac{\hat{\sigma}_m}{\sqrt{n}}$$

In which $u_{1-\alpha/2}$ is the 1-α/2 quantile of the standard normal distribution function.

The semi-analytical results provide a higher accuracy of the extreme value estimates than the statistical results.

It is recommended to predict extreme loads by means of the semi-analytical method, based on the statistics of the simulated load response process.

Selecting the average extreme load or the largest extreme load as the ultimate load without proper consideration of the stochastic nature of the extremes will not give reproducible results. The presented semi-analytical model provides good accuracy for prediction of extreme values for wind turbines, which are not in operation.

For the operating load cases, the periodic nature of the response mean and standard deviation for some loads must be accounted for.

A method, based on azimuthal binning can be used for this purpose. Applying this method, the rotor disc is divided into a number of sectors, each identified by its azimuth angle. When the rotor disc is discretized into M sectors of an equal angle of aperture, sector specific mean values and standard deviations of the load response process can be established.

1.2 Fatigue loads analysis

Cyclic loads can cause cumulative damage in the materials of the structural components, eventually leading to structural failure.

For fatigue analysis of the RNA, reference is to be made to IEC 61400-3, Subclause 7.6.3.

For fatigue analysis of the support structure, reference is to be made to to IEC 61400-1, Subclause 7.6.3.

Fatigue loads are usually below the load level that will cause static failure and many load cycles are required before a fatigue failure will take place, however, for materials with high S-N curve slopes,

such as epoxy materials, the loads of importance for fatigue are close to those that will cause static failure.
The S-N curve is established through numerous sample tests with different load ranges, resulting in pairs of stress range S and a number of stress cycles N to failure at this stress range.
The cumulative damage is commonly determined using the Palmgren-Miner rule and it requires knowledge of the distribution of the stress range or design spectrum extracted from an aeroelastic computer code (ref. IEC 61400-1, Annex G).
According to Palmgren-Miner's rule, the accumulated damage D can be predicted as follows.
Given a specified stress range S, the S-N curve gives the number of cycles N to failure. The accumulated damage D can be interpreted as a sum of partial damage owing to load cycles at various stress ranges, regardless of the sequence in which the load cycles occur.

$$D = \sum_{i=1}^{k} \frac{n(S_i)}{N(S_i)}$$

In which n denotes the number of stress cycles of stress range S in the lifetime of the structure, and N is the number of cycles to failure at this stress range.

The sum is overall damage D in a sufficiently fine discretization of the stress range distribution into K blocks of constant range stress cycles.

$$\log N = \log K - m \cdot \log S$$

K Empirical material constant determining the level of the S-N curve

m Slope of S-N curve

When the long-term stress range distribution is a Weibull distribution with scale parameter s_0 and shape parameter h, given by:

$$F_s(s) = 1 - e^{-\left(\frac{s}{s_0}\right)^h}$$

and the total number of stress cycles in the design life is n_{tot} then the cumulative damage D can be formulated as $D \leq 1$.

$$D = \frac{n_{tot}}{K} \Gamma\left(1 + \frac{m}{h}\right) s_0^m$$

Attention should be paid in cases where the sequence in which the load cycles arrive is important.

The cycle counting methods are used to establish distributions of stress ranges from a stress history. Several methods may be used, among them:

- Peak counting
- Range counting
- Rain-flow counting

These three counting methods give the same result for a pure sinusoidal stress history and for an ideal narrow-banded stress history.

1.3 Rain flow counting method

In the rain-flow counting method, the stress history is first converted into a series of peaks. This method is not restricted to high-cycle fatigue but can also be used for low-cycle fatigue where strain range is the important parameter.
The resulting stress range distribution from cycle counting by the rain-flow method is represented as a matrix with one row for each mean stress level and one column for each stress range.
Each element of the matrix will contain the number of stress cycles associated with a particular stress range and a particular mean stress.

When S-N curves are available for various ratios $R = \sigma_{min}/\sigma_{max}$ the total fatigue damage D can be determined by summing up the partial damage over all elements in the matrix.

$$D = \sum_{I} \sum_{j} \frac{n_{ij}(S_j)}{N_{ij}(S_j)}$$

n_{ij} denotes the number of stress cycles in the matrix element corresponding to the jth stress range S_j and the ith mean stress.

N_{ij} is the number of stress cycles to failure in this element.

1.4 Stress range distribution

To establish the stress range distributions for a structural component in a wind turbine, it is important to consider the various conditions that the turbine faces.

There are various operational conditions, including:

- Production
- Start at cut-in and at cut-out
- Stop at cut-in and stop at cut-out
- Idling and standstill
- Yaw misalignment

Start and stop are transient conditions, for which the stress distributions in the considered structural component are not easily determined.

During production, stationary conditions can be assumed to prevail in the short term.

For example, during 10-minute period, the wind climate parameters such as the 10- minute mean wind speed U_{10} and the turbulence intensity I_T at the hub height can be assumed to be constant.

Under stationary conditions, stress ranges are often seen to have distributions, which are equal to or close to a Weibull distribution.

$$F_s(s) = 1 - e^{\left(-\left(\frac{s}{S_A}\right)^B\right)}$$

Note that when $B = 1$ this distribution turns into an exponential distribution and when $B = 2$ it becomes a Rayleigh distribution.

For representation of stress range distributions, which are not Weibull distributions, it will be sufficient to apply a distorted Weibull distribution, for example a three parameters Weibull distribution, where a, B and S_A are functions of the wind climate $U_{10}$and I_T such as follows.

$$F_s(s) = 1 - e^{\left(-\left(\frac{s-a}{S_A}\right)^B\right)}$$

When the short-term stress range distributions, given U_{10} and I_T , are known, and when the total number of stress cycles during the production life of the turbine is assessed, then the compound distribution of all stress ranges during this production life can be established.

This compound distribution can itself often be represented by a Weibull distribution and it has to be supplemented by the stress ranges owing to start, stop, standstill, idling and yaw misalignment since these are considered to contribute to the cumulative fatigue damage.

Starting the wind turbine is considered critical with respect to fatigue. One reason for this is that connection of an electric generator to the grid can cause high loads in the drive train and the rotor blades.

When stopping the wind turbine, it is recommended to distinguish between stopping slightly below the cut-in wind speed and stopping at the cut-out wind speed, as the latter is associated with large aerodynamic loads.

For standstill and idling below the cut-in wind speed, loads are considered insignificant with respect to fatigue; furthermore, yaw misalignment can be critical with respect to fatigue.

Once the load spectrum has been established with contributions from all operational modes over the design life of the wind turbine, it is often convenient to define a so-called damage-equivalent load range S_0 to be used with an equivalent number of cycles n_{eq}.

S_0 in n_{eq} cycles will lead to the same accumulated damage as the true load spectrum that consists of many different load ranges S_I and their corresponding cycle numbers n_i.

When the equivalent number of cycles $n_{eq}$is chosen or specified, the equivalent load range S_0 can be found with the following formula in which m denotes the S-N curve slope of the material in question.

$$S_0 = \frac{(\sum_I n_i S_i^m)^{1/m}}{n_{eq}}$$

For a given wind climate, characterized by the two parameters U_{10} and I_T as specified in IEC 61400, the uncertainty in the estimated equivalent load range can be expressed in terms of the coefficient of variance (COV) of the estimate.

COV can be expected to be proportional to $1/\sqrt{NT}$, where N is the number of simulated

time series for the given wind climate, and T is the duration of the simulated time series (e.g. 10’).
A total of n simulated lifetime load spectra are established, and one equivalent load range S_{0i} is interpreted from each simulated lifetime load spectrum. The central estimate of the equivalent lifetime load range is taken as the arithmetic mean $\bar{S}_0$ and the standard deviation s of S_{0i} is estimated.

$$\bar{S}_0 = \frac{1}{n}\sum_{i=1}^{n} S_{0i}$$

$$s = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(S_{0i} - \bar{S}_0)^2}$$

A two-sided confidence interval for the estimated equivalent load range with confidence $1 - \alpha$ can be established.

$$\bar{S}_0 \pm \frac{s}{\sqrt{n}} t_{1-\frac{\alpha}{2},n-1}$$

In which $t_{1-\frac{\alpha}{2},n-1}$ is the $1 - \frac{\alpha}{2}$ quantile in the Student’s t distribution with n-1 degrees of freedom.

1.5 Stability analysis

For stability analysis reference is to be made to IEC 61400-1, Subclause 7.6.4.

1.6 Critical deflection analysis

Deflections affecting structural integrity shall be avoided in the design conditions of IEC 61400-3, Table 1.
The most important consideration is to verify that the blades do not interfere with the tower.
The maximum elastic deflection in to be calculate for all the load cases and it shall be multiplied by the combined partial safety factors for loads, material and consequence of failure (ref. IEC 61400-1, Subclause 7.6.5).

Design situation	*Wind cond.*	*Waves*	*Wind & Wave direction*	*Sea current*	*Water level*	*Other conditions*	*Type of analysis*	*PSF*
Power production	NTM	NSS	COD,UNI	NCM	MSL	For extrapolation of extreme loads on the RNA	U	N
	NTM	NSS jpd of H_s, T_p, V_{hub}	COD,MUL	No currents	NWLR or ≥ MSL		F	F
	ETM	NSS	COD,UNI	NCM	MSL		U	N
	ECD	NSS (or NWH)	MIS, wind direction change	NCM	MSL		U	N
	EWS	NSS (or NWH)	COD,UNI	NCM	MSL		U	N
	NTM	SSS	COD,UNI	NCM	NWLR		U	N
	NTM	SWH	COD,UNI	NCM	NWLR		U	N
Power production plus occurrence of fault	NTM	NSS	COD, UNI	NCM	MSL	Control system fault or loss of electrical power	U	N
	NTM	NSS	COD, UNI	NCM	MSL	Protection system or preceding internal electrical fault	U	A
	EOG	NSS (or NWH)	COD, UNI	NCM	MSL	External or internal electrical fault including loss of electrical network	U	A
	NTM	NSS	COD, UNI	No currents	NWLR or ≥ MSL	Control, protection or electrical system faults including loss of electrical network	F	F
Start-up	NWP	NSS (or NWH)	COD, UNI	No currents	NWLR or ≥ MSL		F	F
	EOG	NSS (or NWH)	COD, UNI	NCM	MSL		U	N
	EDC_1	NSS (or NWH)	MIS, wind direction change	NCM	MSL		U	N
Normal shutdown	NWP	NSS (or NWH)	COD, UNI	No currents	NWLR or ≥ MSL		F	F
	EOG	NSS (or NWH)	COD, UNI	NCM	MSL		U	N
Emergency shutdown	NTM	NSS	COD, UNI	NCM	MSL		U	A

Parked (standing still or idling)	EWM^T	ESS	MIS,MUL	ECM	EWLR		U	N
	EWM^S	RWH	MIS,MUL	ECM	EWLR		U	N
	RWM^S	EWH	MIS,MUL	ECM	EWLR		U	N
	EWM^T	ESS	MIS,MUL	ECM	EWLR	Loss of electrical network	U	A
	EWM^S	RWH	MIS,MUL	ECM	EWLR	Loss of electrical network	U	A
	EWM^T	ESS	MIS,MUL	ECM	NWLR	Extreme yaw misalignment	U	N
	EWM^S	RWH	MIS,MUL	ECM	NWLR	Extreme yaw misalignment	U	N
	NTM	NSS jpd of H_s, T_p, V_{hub}	COD,MUL	No currents	NWLR or ≥ MSL		F	F
Parked and fault conditions	EWM^T	ESS	MIS,MUL	ECM	NWLR		U	A
	EWM^S	RWH	MIS,MUL	ECM	NWLR		U	A
	RWM^S	EWH	MIS,MUL	ECM	NWLR		U	A
	NTM	NSS jpd of H_s, T_p, V_{hub}	COD,MUL	No currents	NWLR or ≥ MSL		F	F
Transport, assembly, maintenance and repair	To	be stated	by	manufacturer			U	T
	EWM^T	ESS	COD,UNI	ECM	NWLR		U	A
	EWM^S	RWH	COD,UNI	ECM	NWLR		U	A
	RWM^S	EWH	COD,UNI	ECM	NWLR		U	A
	NTM	NSS jpd of H_s, T_p, V_{hub}	COD,MUL	No currents	NWLR or ≥ MSL	No grid during installation period	F	F

Table 6.1:"Load cases"

COD	co-directional
ECD	extreme coherent gust with direction change
ECM	extreme current model
EDC	extreme direction change
EOG	extreme operating gust
ESS	extreme sea state
EWH	extreme water height
EWLR	extreme water level range
EWM	extreme wind speed model
EWS	extreme wind shear
MIS	misaligned
MSL	mean sea level
MUL	multi-directional
NCM	normal current model
NTM	normal turbulence model
NWH	normal water height
NWLR	normal water level range
NWP	normal wind profile model
NSS	normal sea state
RWH	reduced wave height
RWM	reduced wind speed model
SSS	severe sea state
SWH	severe wave height
UNI	uni-directional
JPD	Joint Probability Distribution

Table 6.2:"Table of abbreviations"

Chapter 7: WT Foundations

Overall considerations are defined in the Subclause 17.1 of ISO 19902:2007. General requirements for foundation design are listed also in Subclause 5.1, 5.2 and 5.3 of ISO 19901-4:2003.

1 General

1.1 Geotechnical investigation

(see Chapter 2, Subclause 3.2)

1.2 Design principles

The analysis of foundations is to aim to prevent their total failure and local overstressing of members of the base structure.

Any type of analysis is to take account of scour.

The calculations are to cover both the installation and operation phases.

The characteristic properties of each layer of soil are to be carefully evaluated (see Chapter 2, Subclause 3.2)

1.2.1 Effects of pulsating loads

Where deemed necessary, the influence of load fluctuations on the soil properties is to be evaluated.

The effects of wave induced forces are to be considered for:

- A design storm during the installation phase and the consolidation period;
- The 100-year storm;
- The cumulative effects of several storm, including the 100-year storm.

Realistic assumptions are to be made regarding the duration and intensity of such storms.

In case of seismically active geographical areas, the deterioration of soil properties due to the cyclic characteristic of the seismic actions is to be taken into consideration (such as the reduction of shear strength of soil).

1.2.2 Stability

The stability should be analysed for shallow foundations ensuring equilibrium between design actions and design resistance (ref. ISO 19901-4:2003, Subclauses 7.1 and 7.2).

The main requests for stability analysis are described below.

- An effective stress stability analysis based on effective strength parameters of the soil and realistic estimates of the pore water pressure in the soil;
- Total stress stability analysis based on total shear strength of the soil evaluated on representative soil samples which are to be subjected (as far as possible) to the same loading conditions as corresponding elements in the soil.

1.2.3 Settlement and displacement

In the evaluation of settlements and displacements, the following aspects are to be considered:

- Initial and secondary settlements;
- Differential settlements;
- Permanent horizontal displacements;
- Dynamic motions due to loads fluctuations.

The evaluation of settlements of structures is essential for design foundation piles.

The tilt of the structure consequent to differential settlements of the foundation system, due to variations in the soil characteristics and/or preferential direction of application of external loads, is not to exceed the tilt which can be allowed for the serviceability and safety of the platforms.

An alternative description for settlements and displacements for shallow foundations is reported in Subclause 7.8 of ISO 19901-4:2003.

1.2.4 Soil-structure interactions

The evaluation of sectional forces and moments, as well as of dynamic motions in the members of the foundation system, is to be based on an integrated analysis of the soil-structure interaction.

The analysis is to be based on realistic assumptions regarding the soil stiffness and the transfer to the soil of loads from structural members resting on the sea bed or penetrating into it.

1.3 Stability of sea bed

1.3.1 Slope stability

The analysis of slope stability is to consider the natural slope, those due to the installation or the presence of the platform, the possible future variations of existing slopes during the design life and the effects of wave loads on the sea bed.

The slope stability is to be carefully evaluated in the presence of layers of soft clays and loose deposits of silt or sands as well as seismically active geographic areas.

1.3.2 Hydraulic stability

In case of platform whose foundations are on soils subject to erosion and softening (reduction in the modulus of elasticity due to fluctuations loads), the following aspects are to be considered:

- The reduction of soil bearing capacity due to hydraulic gradients and seepage forces;
- The formation of piping channels and consequent erosion in the soil;
- The local surface erosion in areas under the foundation due to hydraulic pressure variations resulting from environmental loads.

1.3.3 Scour

The risk of scour around the foundation is always to be taken into account; unless it can be proved that the foundation soil is not subject to scour for the expected range of water particle velocities.

To prevent the effects of scour, one of the following measures is to be taken:

- Place materials around the platform as early as possible after the installation;
- Remove all materials which are not resistant to scour for the foundation design;
- Inspect the sea bed close to the platform foundations and provide suitable means to quickly stop the development of any scour detected.

Materials placed on the sea bed to prevent scour are to have adequate weight and dimensions, such that they are not removed by currents and that they prevent soil erosion though without impairing the draining of overpressure caused on the layers by the loads imposed.

1.4 Pile foundations design

1.4.1 General requirements

Deep foundations for fixed offshore steel platform are usually intended as piles. The type of pile foundation differs for the installation method:

- Driven piles
- Drilled and grouted piles
- Belled piles
- Vibro-driven piles

Detailed description of pile foundations is given in Subclause 17.2 of ISO 19901:2007.

General requirements are reported in Subclause 17.3 of the ISO 19002:2007.

The design strengths of coupled structure/soil design model are to be in accordance with the criteria defined below or according to an applicable international standard in accordance with Tasneef.

1.4.2 Analysis to be performed

1.4.2.1 General

The foundation pile is to be analysed on the basis of loads imposed by the platform and those due to its installation.

1.4.2.2 Loads from platform

As regards the loads imposed by the platform, the analysis is to consider the maximum values of axial and lateral loads and the actual restraint conditions of the soil.

The soil lateral reactions are to be represented by the (p, y) curves, considering the scour effects (see 7.2.6.2) and the deterioration of soil characteristics occurring for cyclic lateral loads.

The transfer of the axial load from piles to the soil may be assumed as proportional to the friction resistance between them, divided by the relevant safety factors and to the contribution of the bearing capacity of pile tip.

In general, the instability analysis of the pile is not required unless there are justified reasons for considering that the pile is without lateral support on account of considerable scour phenomena, the presence of particularly yielding soils, high calculated lateral deformation, etc.

1.4.2.3 Loads during installation

The structural analysis of the pile during the installation phase is to include realistic evaluation of stresses induced by the various systems used.

In particular, for driven piles it is necessary to consider the static loads due to driving equipment weight and dynamic loads induced during driving operations, due attention being paid to bending moment caused by axial load eccentricity and to lateral deformation of the pile, magnified when high resistance layers are encountered or when the blow frequency of the hammer approaches the natural frequency of the pile-hammer elastic system.

1.4.3 Pile design criteria

In the design of piles for foundations it is necessary to take into account the method used for their installation.

Where the transfer of loads from one pile to another or from a pile to the foundation soil is achieved by grouting, the surfaces are to be free from rust scales or other imperfections which may reduce the capacity to withstand the design compressive and tensile loads.

The foundation capacity is to be verified by the following two strength assessments, depending on the steps of the load transfer path generated from the structure to the soil.

- Pile strength

  It shall be carried out according to Part B, Chapter 4, Section 4 of Tasneef "Rules for steel fixed offshore platform".

  Internal pile forces to be checked are the ones due to the design actions according to the Part B, Chapter 3 of Tasneef "Rules for steel fixed offshore platform" using a coupled structure/soil non-linear foundation model. Take care to consider the column buckling effect on the pile in which case the lateral restrains of the soil is inadequate.
- Pile axial resistance

  The axial pile capacity is to be defined, in accordance with ISO 19902:2007, Equations 17.3-1 and 17.3-2, as:

$$Q_{d,e} = \frac{Q_r}{\gamma_{R,Pe}}$$
$$Q_{d,p} = \frac{Q_r}{\gamma_{R,Pp}}$$

$Q_{d,e}$ is the extreme design axial pile capacity.

$Q_{d,p}$ is the design axial pile capacity for permanent and variable actions or operating situation.

Q_r is the representative value of the axial pile capacity as determined in the following paragraph.

$\gamma_{R,Pe}$ is the pile partial resistance factor for extreme conditions ($\gamma_{R,Pe} = 1.25$).

$\gamma_{R,Pp}$ is the pile partial resistance factor for permanent and variable action or operating conditions ($\gamma_{R,Pe} = 1.50$).

The design axial pile capacity $P_{d,e}$ and extreme axial pile capacity $P_{d,p}$ shall satisfy the following conditions, as per Equations 17.3-1 and 17.3-2 of ISO 19902:2007.

$$P_{d,e} \le Q_{d,e}$$
$$P_{d,p} \le Q_{d,p}$$

1.4.4 Pile capacity for axial compression

1.4.4.1 Ultimate bearing capacity

The characteristic ultimate bearing capacity of pile Q [kN] is given by:

$$Q = Q_s + Q_p$$

Q_s is the characteristic total skin friction resistance of pile due to external and/or internal friction contribution.

$$Q_s = \sum f_i A'_{si}$$

Q_p is the characteristic total end bearing capacity of pile.

$$Q_p = qA_p$$

f_i is the unit skin friction capacity measured in kN/m^2 in i-layer.

A_{si} [m^2] is the external side surface area of pile in the i-layer.

A_p gross end area of pile or annulus area of pile (it depends on the presence or not of the plug).

q is the unit end bearing capacity of pile [kN/m^2].

D_e is the pile end external diameter [m].

D_i is the pile end internal diameter [m].

In determining the ultimate bearing capacity of piles, consideration is to be given, when appropriate, to the in-water weight of pile-soil plug.
The contribution of the total end bearing capacity Q_p and the internal friction Q'_s shall not be considered both together.
If the pile is driven up to the target penetration depth, the axial force shall not exceed the sum of the external friction contribution Q_s and the internal friction contribution Q'_s and the total end bearing capacity acting only on the pile wall annulus, or the sum of the external friction contribution Q_s and the bearing capacity Q_p acting on the total end bearing area, whichever is lesser.
For open-ended pipe piles plugged, the total bearing capacity Q_p shall not exceed the sum of the end bearing capacity of the internal plug and the end bearing on the pile wall annulus.
In computing the design actions in compression on the pile, the weight of the pile is to be considered.
Where a pilot hole is drilled, its end bearing area is to be discounted in computing the area A_p.
For pile-bell systems the skin friction resistance of a portion of pile above the bell-shaped area having length of 3 pile diameters is to be neglected.
If the pile-bell system is driven with a pilot hole, the area of the hole should also be discounted in computing the total bearing area of the bell.
If the pile is laterally loaded by cyclic loads and deformations imposed on the soil are rather high (higher than the quantity γ_c defined in 7.2.6.2), the friction resistance relevant to those layers of soil affected by such deformations is to be reduced or annulled.

1.4.4.2 Skin friction and end bearing capacity of piles in clay soils (cohesive soil)

For piles driven through clay, the unit skin friction capacity $f\left[\frac{kN}{m^2}\right]$ is generally not to exceed the values given in the Table 7.1 as a function of the undrained shear strength of the clay soil $c\left[\frac{kN}{m^2}\right]$.
For piles driven in undersized drilled holes or jetted (drilled by fluid under pressure) holes and for drilled and grouted piles in normally consolidated clay soils, f values are to be determined by reliable methods based on the evaluation of soil disturbance resulting from installation.
In any case, the values given in Table 7.1 are not to be exceeded.
For drilled and grouted piles in over-consolidated clay soils, f values may exceed the Table 7.1 values.
In this case, careful consideration is to be given to the strength of the soil-grout and grout-pile skin interfaces (see 7.2.7) also in relation to the amount and quality of drilling mud used.
The unit end bearing capacity of piles in clay soils q may be determined, in general, by the equation.

$$q = 9c$$

Special consideration is to be given where the value of the shear strength of the soil in layers under the end of piles changes in an uneven way.

c	f
$c \leq 24$	$f = c$
$24 < c < 72$	$f = \left(1{,}25 - \frac{c}{96}\right) \cdot c$
$c \geq 72$	$f = 0{,}5\ c$

Table 7.1: “f and c values”

The pile capacities computed above represent the long-term capacities. The axial capacity immediately after installation of piles is usually lower.
The set-up of piles passes through the initial change of undisturbed soil condition due to the driven phase which generates pore overpressures. After that pure overpressures drift to dissipate and the soil drift is dependent on the development of pore pressures during installation phases and its consequent dissipation.
The shortly application of design actions are important design consideration to be done in light

of the lower axial capacity of pile immediately after installation.

1.4.4.3 Skin friction and end bearing capacity of piles in sandy and silty soils (cohesionless soil)

The unit skin friction capacity f of piles driven in sandy and silty soils, except carbonate sands and gravels, may be determined by:

$$\mathrm{f} = \mathrm{K}\,\mathrm{p_0} \tan \delta$$

K is the coefficient of lateral soil pressure (ratio of horizontal to vertical normal effective stress).

It varies between 0,5 and 1 with the increase of the grade of sand density (the growth is not linear).

In particular for open-ended piles driven unplugged, it is appropriate to assume K as 0,8 for both tension and compression loadings.

When piles are plugged or close-ended the K coefficients may be assumed as 1.

$\mathrm{p_0}$ is the effective overburden pressure of soil around pile at the depth in question.

δ is the friction angle between the soil and pile wall.

The values of friction angle depend on the angle of internal friction of soil Ø [degrees] and if other data are not available Table 7.2 may be used.

For close-ended or fully plugged open-ended piles values of $\mathrm{K} \tan \delta$ may be increased by 25%.

For long piles f may not indefinitely increase linearly with the overburden pressure $\mathrm{p_0}$.

In such case it is appropriate to limit f to the limiting skin friction values $\mathrm{f_{lim}}\,[\mathrm{kN/m^2}]$ given in Table 6.2, dependent on the angle of internal friction of soil Ø.

Alternative method, based on cone penetration test results, could be used to evaluate the skin friction and end bearing capacity as defined in the Annex A.17 of ISO 19902:2007.

f values from the above equation may be adopted even for open-ended piles driven unplugged in drilled and grouted holes.

For piles driven in undersized drilled holes or jetted holes, f values are to be determined by reliable methods based on the evaluation of soil disturbance resulting from installation and are not to exceed those for driven piles.

The unit end bearing capacity of piles $\mathrm{q}\ [\mathrm{kN/m^2}]$ in sand and silt soils, except carbonate sands and gravels, may be determined by the following equation.

$$\mathrm{q} = \mathrm{p_0 N_q}$$

$\mathrm{N_q}$ is the bearing capacity factor and its values depend on the angle of internal friction of soil Ø, in accordance with Table 7.2.

$\mathrm{p_0}$ is the effective overburden pressure of soil around pile at the depth in question.

For deep foundations q values may be lower than those given above.

For layered soils, $\mathrm{N_q}$ may be limited to values lower than those given in Table 7.2 and are to be determined on the basis of considerations regarding the local soil conditions.

Soil type	Ø	δ	$\mathrm{N_q}$	$\mathrm{f_{lim}}$
Clean sand	35	30	40	114.8
Silty sand	30	25	20	95.7
Sandy silt	25	20	12	81.3
Silt	20	15	8	67.0

Table 7.2: ”Foundations characteristics of soil type”

1.4.4.4 Skin friction and end bearing capacity of piles grouted in rock

The unit skin friction capacity of grouted piles in rock may theoretically have an upper limit equal to the shear strength of the rock or of the grout.

Actually, the f e value may be considerable reduced in relation to the installation procedure and to the type of rock or of drilling fluid used.

An upper limit of this value may be given by the allowable bond stress between the pile wall and the grout.

The end bearing capacity of the rock is to be determined from the shear strength of the rock itself and an appropriate bearing capacity factor, but in any case it is not to exceed $10000\left[\frac{\mathrm{kN}}{m^2}\right]$.

1.4.5 Pile capacity for axial pull-out loads

The ultimate axial pull-out capacity of pile is not to exceed the total skin friction of pile Q_s.

The effective weight of the pile, including the in-water soil plug weight, is to be considered.

For clay soils, the unit skin friction capacity f is to have the same values give in 6.2.4.2.

For sandy and silty soils, the same considerations given in 7.2.4.3 are applicable, except that $k = 0{,}5$ is to be used. For rock, see 6.2.4.4.

The safety factors applicable to the ultimate axial pull-out capacity of pile of pile are to be the same as those 7.2.3.

1.4.6 Soil-pile interaction modelling

The capacity of the pile as defined in the previous paragraph represents the resistance parameter of this foundation.

The behaviour of soil around piles is dependent upon many variables (e.g. type of soil, pile characteristic, installation method and applied actions).

The occurrence of these variables should be considered in soil-pile interaction modelling.

1.4.6.1 Axial performance

The axial resistance of the soil for pile compression is provided by a combination of axial soil-pile adhesion and associated shear transfer along the sides of the pile and end bearing resistance at the pile tip.

The relationship between mobilized soil-pile shear transfer and local pile displacement at any depth is described using a (t, z) curve.

Various empirical and theoretical methods are available for developing curves for axial shear transfer and pile displacement as referenced in the Annex A.17.7.2 of the ISO 19902:2007.

Curves developed from pile load tests in representative soil profiles or based on laboratory soil tests that model pile installation can also be justified.

In the absence of more definitive criteria, the (t, z) curves recommended in in Subclause 17.7.2 of the ISO 19902:2007.

Similarly, the relationship between mobilized end bearing resistance and axial tip displacement is described using a (Q, z) curve.

The characteristic end bearing capacity is to be determined as described in 6.2.4.

In the absence of more definitive criteria, the prescriptions described in Subclause 17.7.3 of the ISO 19902:2007 are recommended for both sands and clays.

The pile foundation is to be designed to resist the static and cyclic axial actions.

1.4.6.2 Lateral performance

The behaviour of the soil-pile system subjected to lateral loads is to be analysed on the basis of realistic relationships which relate the deformations to the soil reactions.

Such relationships, generally represented by (p, y) (soil reaction lateral deflection) curves, are characteristic of the type of soil, pile dimensions and loading application conditions (static, cyclic or impact loads).

The (p, y) curves may be constructed using the results of laboratory tests on soil samples; the influence of scour in proximity to the sea bottom and the disturbance caused by pile installation on the soil characteristics are to be taken into account.

In the absence of criteria which are more appropriate to the individual practical cases, the (p, y) curves may be constructed according to indications given in 7.2.6.2 and 7.2.6.3.

- (p, y) curves for clay soils

a) For soft clay soils, the (p, y) curve for the layer of soil located at a depth z from the sea bottom may be represented by the broken line shown in Figure 6.1, generated by the values specified in Table 6.3 (see also Table 17.8-1 of ISO 19902:2007).

b) For stiff clay soils (i.e. when c > 96 kPa according to ISO 19902:2007 Subclause 17.8.4) and for static loads, the same considerations in item a) above are applicable.

   Instead, for cyclic loads a sharp deterioration of soil characteristics occurs due to high deformations, which result in considerable reduction of representative lateral capacity p_r.

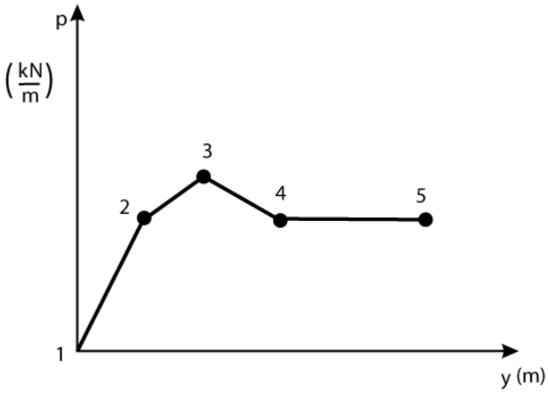

Figure 6.1: "(p,y) curve for soft clay soils"

Point	$\mathbf{p/p_u}$	$\mathbf{y/y_c}$
Static load or short term action		
1	0	0
2	0,5	1,0
3	0,72	3,0
4	1,00	8,0
5	1,00	∞
Cyclic load for $z \geq z_R$		
1	0	0
2	0,5	1,0
3	0,72	3,0
4	0,72	∞
5	0,72	∞
Cyclic load for $z \leq z_R$		
1	0	0
2	0,5	1,0
3	0,72	3,0
4	$0{,}72\ z/z_R$	15,0
5	$0{,}72\ z/z_R$	∞

Table 7.3:"(p,y) points for soft clay soils"

$$y_c = 2{,}5\ \varepsilon_c D\ [\mathrm{m}]$$

D is the pile diameter; ε_c is the strain which occurs at one half the maximum stress on laboratory undrained compression tests of undisturbed soil samples;

$$z_R = \frac{6D}{\frac{\gamma D}{c} + J}\ [\mathrm{m}]$$

z_R is the depth of reduced strength zone; γ is the effective specific gravity of soil [kN/m^2]; c is the undrained shear strength of soil [kN/m^2]; J is the empirical coefficient, whose values are between 0,5 and 0,25.

p_u is the ultimate soil resistance [kN/m], given by the following formulae.

$$p_u = \left(\frac{6c}{z_R} z + 3c\right) D \qquad \text{for } z \leq z_R$$

$$p_u = 9\ D\ c \qquad \text{for } z > z_R$$

- (p, y) curves for sand soils

The (p, y) curve of the layer located at depth z is as shown in Figure 7.2, generated by the abscissa and ordinates of the points u, m and k, which may be computed as follows:

$$\begin{cases} y_u = \dfrac{3}{80} D \\ p_u = A \cdot p_c \end{cases}$$

Where A is the empirical coefficient according to Figure 6.3.

p_c is to be taken equal to p_{cs} if $z \leq z_t$ or equal to p_{cd} if $z > z_t$.

$$p_{cd} = \gamma \left[\begin{array}{c} \dfrac{k_0 z \tan \varnothing \sin \beta}{\tan(\beta - \varnothing) \cos \alpha} + \dfrac{\tan \beta}{\tan(\beta - \varnothing)} (D \\ + z \tan \beta \tan \alpha) \\ + k_0 z \tan \beta (\tan \varnothing \sin \beta - \tan \alpha) \\ - k_a D \end{array} \right]$$

$$p_{cs} = D\ \gamma\ z\ [k_a(\tan^8(\beta - 1) + k_0 \tan \varnothing \tan^4 \beta]$$

In any case, it could be useful consider the p_c as the minor value between p_{cd} and p_{cs} in order to avoid the overestimate of the lateral resistance as defined in Subclause 17.8.6 ISO 19902:2007.

z_t is the depth below the soil surface to bottom, obtained when p_{cs} is equal to p_{cd}.

$\varnothing$ is the angle of internal friction of sand [°].

$$\alpha = \frac{\varnothing}{2}$$

$$\beta = \frac{\varnothing}{2} + 45°$$

$$k_0 = 0{,}4$$

$$k_a = \tan^2\left(45 - \frac{\varnothing}{2}\right) = \frac{1 - \sin \varnothing}{1 + \sin \varnothing}$$

point m:

$$\begin{cases} y_m = \dfrac{1}{60} D \\ p_m = B \cdot p_c \end{cases}$$

Being B an empirical coefficient according to Figure 7.4.
Point k is determined by the intersection of the lines given by the following equations.

$$p = K\,z\,y$$
$$p = C\,y^{1/n}$$

Where the initial modulus of subgrade reaction depending on the grade of sand density K is given in Table 7.4.

$$C = \frac{p_m}{y_m^{1/n}}$$
$$n = \frac{p_m}{m \cdot y_m}$$
$$m = \frac{p_u - p_m}{y_u - y}$$

Therefore, the abscissa and ordinated of point k are:

$$\begin{cases} y_k = \left(\dfrac{C}{K\,z}\right)^{\frac{n}{n-1}} \\ p_k = K\,z\,y_k \end{cases}$$

For some combinations of the parameters involved, the K value may result in a deflection y_k greater than y_m, in which case the parabolic portion of (p, y) curve is to be omitted.

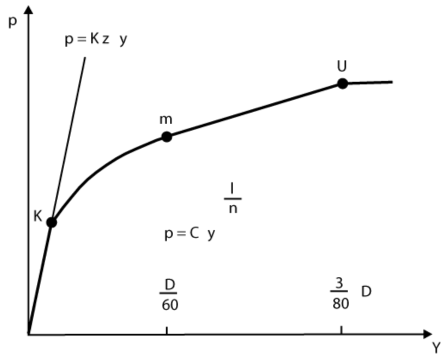

Fig. 7.2: "(p-y) curve for sand soil"

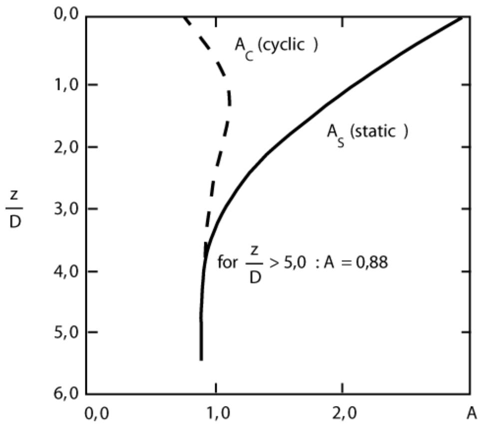

Fig. 7.3: "Empirical coefficient A as a function of z/D"

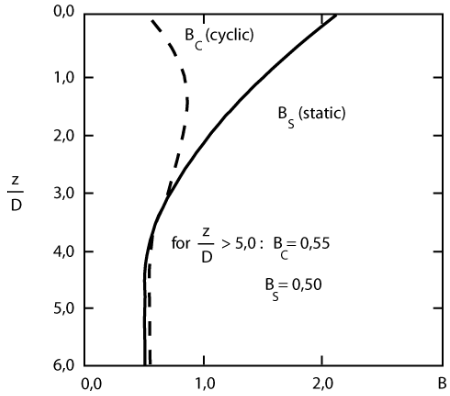

Fig. 7.4: "Empirical coefficient B as a function of z/D"

The initial modulus of subgrade reaction represents the soil in the Winkler method. It considers the soil as equivalent spring and K represents the stiffness of the spring.

Density	K [kN/m^3]
Loose	5400
Medium	16300
Dense	33900

Table 7.4: "Initial modulus as a function of grade of sand density"

1.4.7 Group effects

The axial and lateral bearing capacity of a group of piles depends on several factors such as pile characteristics, type and strength of soil, sequence of soil layers, pile installation method, etc.
The knowledge on this subject is rather limited and therefore the strength calculation of the group is to be carried out on the basis of

conservative assumptions, due consideration being given to the possibility that the actual spacing of piles is less than that assumed for the design due to a non-perfect installation.
First of all the group effects have to be considered where piles spacing are less than eight diameters.
Where more reliable data are not available, the following considerations are applicable.

- The end bearing capacity of the group in homogeneous soils may be taken equal to the sum of the single pile contributions;
- The skin friction capacity of the pile group is to be taken equal to the sum of the single pile contributions multiplied by a reduction factor R, given by the following formula.

$$R = \frac{p}{\sum_{i=1}^{N} \pi D_i}$$

p is the external perimeter of the group; D_i is the diameter of the i-pile; N is the number of the piles.
Such a reduction is required in any case for sandy soils, while it may be neglected for clay soils when the ratio of the minimum spacing of piles to the pile diameter exceeds the value $0{,}785\ (N^{0{,}5} + 1)$.
If $R > 1$, is to be assumed $R = 1$.

1.4.8 Pipe wall thickness

The D/t ratio of pile diameter to thickness is to be such as to preclude the possibility of occurrence of local buckling during the installation operations and the operation life of the foundation.
For guidance, it can be specified that the D/t ratio for piles driven in high strength soils is to comply with the following formula:

$$t \geq 6.35 + \frac{D}{100}$$

In general, the pile wall thickness is not constant for the entire length of the pile, but varies with the anticipated stress level, which is normally highest in the portion close to the sea bed.
It is recommended that the heavy wall thickness of the pile is extended for a reasonable length to take account of the two possibilities of not achieving the foreseen penetration or of being compelled to exceed it in order to reach a layer with high bearing capacity.
It is recommended that the end of the pile is provided with a driving shoe having a thickness increased by 50% in respect of that mentioned above.
Other detailed information on pipe wall requirements is described in the Subclause 17.10 of ISO 19902:2007.

1.4.9 Bonding between pile and structure

Platform loads are generally transferred to foundation piles by filling the annulus between the pile and relevant housing in the structure by cement grout in such a way that the axial load transferred by the structure to the pile is transferred through the bond action between the pile surface and the cement grout.
Instead, the lateral force results in a compression of the cement grout annulus whose effect is generally negligible.
The bonding action between pile and cement grout (and between cement grout and pile housing) is affected by several factors, such as:

- Type of cement grout (cement, water, additives, etc.);
- Temperature;
- Method of installation;
- Movements of platform while the cement grout is setting.

For general provisions relevant to the strength and the fatigue resistance of grouted connections reference can be made to Clause 15 of ISO 19902:2007.
Where mechanical devices are provided to avoid the pile axial load being transferred by friction between steel and cement grout only, for instance by fitting welded circumferential rings between the outer surface of pile and the inner surface of its housing, it will be necessary to verify the connection taking into account the geometry realised and the compressive strength of the portion of the grout close to the rings.

1.5 Gravity type foundations

1.5.1 General requirement

Gravity type foundations are characterised by a low ratio of the maximum penetration depth to the horizontal extent of the foundation base. General consideration on the design of shallow foundations is contained in the Subclause 17.12.1 of ISO 19902:2007.

1.5.2 Design criteria

The acceptance criteria for all the design condition to be checked for the shallow foundations are described in the Subclause 7.3 of ISO 19901-4:2003.

Also reference can be made to Annex A of ISO 19901-4:2003.

1.5.3 Soil resistance

1.5.3.1 Unit bearing capacity

The bearing capacity of the foundation system is influenced by the following main aspects:

- The shape of the foundation base;
- Loads acting on the foundations and their variation over time;
- Characteristics of sea bottom;
- Geophysical characteristics of the soil layers concerned;
- Possible rupture surfaces in the soil in relation to measures adopted against sliding (see Figure 6.5);
- Possible softening phenomena in the soil due to alternating loads;
- Pore pressure variation corresponding to the actual stress level of the soil.

Where conditions given in 7.3.5 do not occur, the unit bearing capacity may be performed by the bearing capacity formulas given in 7.3.3.2 and 7.3.3.3.

The soil develops its resistance depending on the following conditions:

- Undrained conditions;
- Drained conditions.

The first one above applies when loading and its variation occur so rapidly that no drainage and hence no dissipation of excess pore pressure occurs.

Such type constitutes the also called "short-term analysis"; it considers the angle of internal friction of the soil $\text{Ø} = 0$ and the undrained shear strength of the soil c as essentially involved.

Where, on the contrary, the rate of loading is sufficiently slow, complete drainage occurs and excess pore pressures are not developed, the "long-term" condition is developed. The behaviour of the soil is controlled by its friction angle $\text{Ø}'$ and by the cohesion intercept c' of the Mohr-Coulomb effective stress failure envelope.

1.5.3.2 Undrained conditions

Detailed practise in order to define the unit bearing capacity of the soil is given in the Subclause 7.4 and the Subclause 7.5 of ISO 19901-4:2003.

In the quite frequently encountered cases of:

- Vertical centric load;
- Horizontal foundation base;
- Horizontal sea bed;

Formulas defined in the mentioned ISO 19901-4:2003 references may be reduced as follows:

- For infinitely long rectangular footing, the unit bearing capacity may be given by the simplified formula:

$$q_{d,v} = 5{,}14\ c_u$$

- For circular or square footing, the unit bearing capacity may be given by the simplified formula:

$$q_{d,v} = 6{,}17\ c_u$$

Where c_u is the undrained shear strength.

In order to evaluate the shear strength the Subclause 7.7 of ISO 19901-4:2003 can be used as reference.

1.5.3.3 Drained conditions

Detailed practise in order to define the unit bearing capacity of the soil is given in the Subclause 7.6 of ISO 19901-4:2003.

Also in this case, in the presence of soil having $c_u = 0$ (sand) and of applied centric load, simplified formulae may be used, as follows:

- For infinitely long rectangular footing, the unit bearing capacity may be expressed by the formula:

$$q_{d,v} = 0.5\ \gamma' B\ N_\gamma$$

- For circular or square footing, the unit bearing capacity may be expressed by the formula:

$$q_{d,v} = 0.3\,\gamma' B\, N_\gamma$$

Where the parameters γ', B, N_γ are to be selected in accordance with the Subclause 7.6 of ISO 19901-4:2003.

1.5.3.4 Filling of voids

To ensure sufficient platform stability, filling of voids between the platform structure and the sea bed may be necessary. In such case the stresses induced by filling pressures are to be kept within acceptable limits.

The materials used for filling are to be capable of maintaining sufficient strength during the whole design life of the platform under the deteriorating effects of repeated loads, chemical action and possible defects in the placement of filling materials themselves.

1.5.4 Settlement and displacements

The evaluation of possible short-term and long-term deformations is to be performed by recognised methods deemed appropriate by Tasneef.

It is very important to determine such deformations for the safety both of the structural members of the platform and of the components which pass through the contact surface between the foundation base and ground (risers, etc.) or which join the sea bed to the platform itself (pipelines, etc.).

The evaluation of possible short-term and long-term deformations shall include:

- Immediate settlements;
- Consolidation settlements of the soil (long-term soil deformation);
- Soil settlements induced by cyclic actions;
- Differential settlements induced by moments, torque and eccentricity;
- Creep.

For the condition where the structure base is circular, rigid, subject to static loads or to loads which may be considered as static, and rests on isotropic and homogeneous soil, the short-term (undrained) deformations may be evaluated by the following formulae:

$$u_v = \frac{1-\nu}{4\,G \cdot R} Q$$

$$u_h = \frac{7-8\,\nu}{32\,(1-\nu) \cdot G \cdot R} H$$

$$\vartheta_f = \frac{3(1-\nu)}{8\,G \cdot R^3} M$$

$$\vartheta_t = \frac{3}{16\,G \cdot R^3} M_t$$

u_v Vertical deformation $[m]$
ν Poisson ratio of the soil
Q Vertical loads $[kN]$
G Elastic shear modulus of the soil $[kN/m^3]$
R Radius of the base
H Horizontal loads
ϑ_f Overturning rotations $[rad]$
M Bending moments $[kN \cdot m]$
ϑ_t Torsional rotations
M_t Torsional moments

These formulae may also be used for square base of equal area.

1.5.5 Limits of application of the formulae for the determination of the bearing capacity

The application of the formulae for the determination of the unit bearing capacity is subject to the following limiting conditions:

- Homogeneous, isotropic and fully plastic soil;
- Low ratios of horizontal to vertical loads;
- Low torsional stress levels;
- Regular foundation geometry;
- Presence of suitably spaced skirts so that, if lateral instability occurs, a horizontal failure plane in the soil is ensured rather than a failure at the base structure-soil interface.

Where the above conditions are not satisfied, more conservative methods of analysis and increased safety factors are to be used or more refined techniques are to be adopted, such as:

- Limit analysis to determine bounds on collapse loads and relative sensitivity of collapse loads to parameters of interest;
- Numerical analysis such as finite differences or finite elements;
- Properly scaled model tests such as centrifuge tests.

Special consideration is also to be given to the effects of cyclic loading on pore pressures and to the possibility that soil softening may occur.

1.5.6 Hydraulic instability

This type of foundation failure may occur in the presence of soils which are easily subject to erosion and softening.

The risks of reduction of bearing capacity due to hydraulic gradients, with consequent seepage (i.e. constant flow of water through pores), of formation of piping channels, with consequent erosion of soil beneath the foundation, and of scour are to be considered.

To prevent erosion beneath the foundation, scour skirts may be provided penetrating through erodible layers and extending their influence up to those layers which are not subject to erosion.

In order to assess the hydraulic stability the prescriptions given in the Subclause 7.10 of ISO 19901-4:2003 shall be followed.

1.5.7 Dynamic behaviour

The construction of a model which satisfactorily represents the dynamic behaviour of gravity foundations, when the stress level is quite low, is generally performed by the continuous "half space" approach, which is based on the assumption of linear elastic behaviour of the soil considered as homogeneous.

In real cases of anisotropy, of layered soil with energy radiated from the footing reflected by the interfaces between the layers and, especially, of non-linearity of stiffness and damping characteristics of soil and their frequency dependence, more appropriate analyses are required.

Dynamic actions are imposed on a structure-foundation system by current, waves, ice, wind and earthquakes. The influence of the foundation on the dynamic forces and the integrity of the foundation itself are to be considered.

1.5.8 Installation feasibility

The gravity foundations are frequently provided with scour skirts to improve stability and prevent scour and with dowels (hollow pipes of large diameter) to facilitate orienting and positioning operations.

The estimate of resistance to penetration of these devices is of great interest for the purpose of scantlings of the ballasting system, so that proper installation of the structure base on the sea bed can be ensured.

For its determination it is necessary to identify the soil layers by means of soil samples and laboratory tests and to measure by a cone penetrometer the average resistance to penetration among the values obtained by tests carried out on various soil layers.

The resistance to penetration $\mathrm{R}\ [\mathrm{kN}]$ of scour skirts is given by their end resistance and skin friction resistance, and is calculated by the following formula:

$$\mathrm{R} = \mathrm{k_p(d)} \cdot \mathrm{A_p} \cdot \mathrm{q_c(d)} + \mathrm{A_s} \int_0^{\mathrm{q}} \mathrm{k_f(z)}\, \mathrm{q_c(z)dz}$$

- z Depth of the soil layer under consideration;
- d Penetration depth;
- $\mathrm{k_p}$ Empirical coefficient relating to end resistance;
- $\mathrm{k_f}$ Empirical coefficient relating to skin friction;
- $\mathrm{q_c}$ Resistance to penetration measured by cone penetration $[\mathrm{kN/m^2}]$;
- $\mathrm{A_p}$ End area of scour skirt;
- $\mathrm{A_s}$ Skin area of scour skirt per unit penetration depth $[\mathrm{m^2/m}]$.

The empirical coefficients $\mathrm{K_p}$ and $\mathrm{K_f}$ may be selected in Table 7.6, which are the highest expected values of the resistance to penetration.

For penetration depth lower than 1 to 1.5 m, the values shown in Table 6.6 should be reduced by 25 to 50 % due to local piping or lateral movements of the platform.

For situations with negligible environmental actions seeing as the Subclause 7.14 of ISO 19901-4:2003, the following criterion shall be satisfied:

$$\mathrm{E_v} \geq \mathrm{R}$$

Where E_v are the vertical actions due to the installation phase.
Usually the vertical action can be evaluated as the percentage of weight in water of the gravity foundation interesting the scour skirt.
The installation criteria given in the Subclause 7.14 of ISO 19901-4:2003 are to be considered.

Type of soil	k_p	k_f
Clay	0,6	0,05
Sand	0,6	0,003

Table7.6: ”Empirical coefficients”

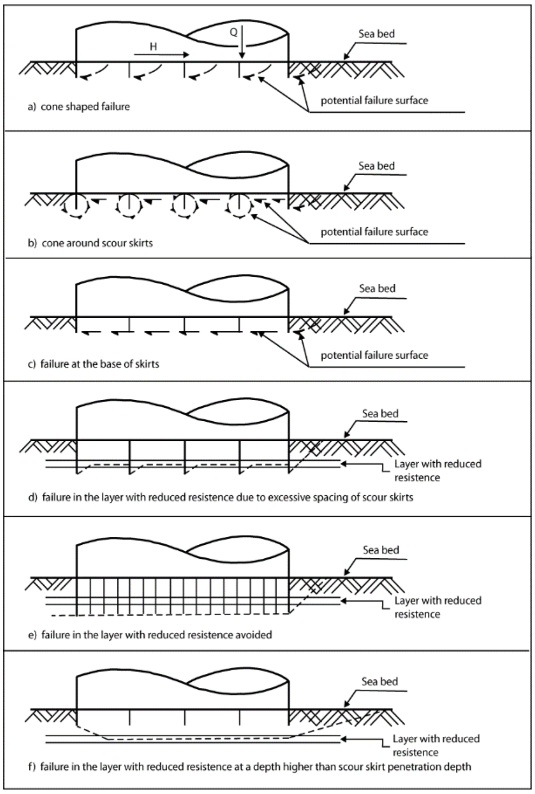

Fig. 7.5:”Representation of possible soil failure mechanism due to lateral displacement”

Part C Chapter 1:
Fabrication and Installation

1. Materials for structures

1.1 Type of materials

Type of materials deemed appropriate for the realization of the components of the wind turbine structures are those provided in Tasneef Rules for Steel Fixed Offshore Platforms, Part D, Chapter 1, Section 1.

1.2 Requirements for structural steel

The applicable requirements for weldable structural steels for:

a) Manufacturing;
b) Chemical composition;
c) Mechanical properties;
d) Additional properties for plates and hot rolled sections;
e) Testing,

are to be satisfied in accordance with the Tasneef Rules for Steel Fixed Offshore Platforms, Part D, Chapter 1, Section 2, para. 2.1, 2.2, 2.3, 2.4 and 2.5 respectively.

2. Fabrication

For structures fabrication reference is to be made to Tasneef Rules for Steel Fixed Offshore Platforms, Part D, Chapter 3, where the applicable provisons for:

a) Fabrication;
b) Material preparation;
c) Dimensional tolerances;
d) Grouted connections;
e) Welded connections;
f) As built documentation,

are to be satisfied according to para. 1, 2, 3, 4 and 5 respectively.

3. Quality Assurance and Quality Control

Quality assurance and quality control procedures able to cover the overall fabrication, inspection, testing, transportation and installation of the wind turbine structure are to be implemented according to the general requirements reported in Tasneef Rules for Steel Fixed Offshore Platforms, Part D, Chapter 5, para 1.

The overall project execution as well as each single phase is to be covered by a Quality Management System designed and implemented in accordance with Tasneef Rules for Steel Fixed Offshore Platforms, Part D, Chapter 5, para 2 and documented according to the requirements reported in the same Rules, Part D, Chapter 5, para 3.

4. Protection against Corrosion

The components of the wind turbine structures are to be protected against corrosion in relation to adopted materials, service conditions and expected operating life, according to general requirements and methods stated in Tasneef Rules for Steel Fixed Offshore Platforms, Part D, Chapter 6.

5. Offshore Installation

All marine operations necessary for the load out, transportation, installation and eventually removal of the wind turbine structure, limited to those aspects of such operations which may influence the safety of the whole structure or of some of its components, in the offshore site location are to be carried out according to the requirements of Tasneef Rules for Steel Fixed Offshore Platforms, Part E, Chapter 1.