

REVISION OF DNV STANDARD FOR OFFSHORE WIND TURBINE STRUCTURES

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ABSTRACT

Det Norske Veritas (DNV) was the first institution in the world to issue a self contained standard for design of offshore wind turbine support structures in June 2004. The standard DNV-OS-J101 "Design of Offshore Wind Turbine Structures" represented a condensation of all requirements in DNV standards for the offshore oil and gas industry which were considered relevant also for offshore wind turbine structures. The requirements were in many cases supplemented by necessary adaptation to the wind turbine application.

DNV plans to issue the next revision of DNV-OS-J101 in 2007. The revised standard now implements the requirements of the coming IEC 61400-3 standard, which was presented as a committee draft in 2006. Numerous practical guidelines have been included to help designers of offshore wind turbine structures to develop cost optimal designs. The present paper summarises the proposed revisions of DNV-OS-J101.

The most important revisions cover new formulations for design load cases, modified partial safety factors, more information on wave loads in shallow water and a revised chapter for design of concrete structures.

INTRODUCTION

DNV is an independent foundation working to safeguard life, property and the environment. DNV was established in 1864 and the first services involved classification of ships. During the years DNV has also provided a long range of certification and consultancy services to the oil and gas industry and within renewable energy, information technology, transportation, food and beverages, defence and health care.

Among the most important competences shared among DNV's specialist are: structural design, materials, geotechnical engineering, wave and wind loads, machine design including bearings and gearboxes, electrotechnical engineering, control and safety systems, welding, corrosion engineering, non-destructive testing, quality management, environmental impact assessment,

risk assessment, maintenance planning and occupational safety.

DNV has a staff of about 7000 employees and is represented in a global network of more than 300 offices in 100 countries. More information about DNV is found on www.dnv.com

DNV has been a market leader in certification of offshore installations since the 1970'es where the first development of oil and gas exploration in the North Sea took place. Maintaining this position has been possible because the technical basis for certification in the form of standards has been carefully maintained through scientific collaboration with industry, research centres, and universities and through systematic experience feedback from certification of individual projects.

Based on the extensive range of standards for the offshore oil and gas industry, DNV compiled all the relevant requirements for offshore wind turbine structures in a standard DNV-OS-J101 "Design of Offshore Wind Turbine Structures" in 2004 [1]. The oil- and gas-related requirements were in many cases modified since offshore wind turbines are unmanned structures where collapse will have only a modest impact on the environment. The standard was readily acknowledged by the industry and is the basis for certification of more than 10 offshore wind farms.

Recently, the International Electrotechnical Commission (IEC) completed the committee draft for the IEC 61400-3 standard [11] with principles and requirements for design of offshore wind turbines. The IEC standards have world-wide recognition as the technical basis for design and certification of wind turbines. All major wind turbine manufacturers, research institutions and certifying bodies participate in the development and maintenance of the IEC standards relevant for wind turbines.

In order to facilitate the design and certification of offshore wind farms in the future, DNV-OS-J101 [2] has been subject to a revision which includes a synchronisation with the coming IEC 61400-3 standard [11]. In this paper, we describe the major elements of this revision and outline the numerous changes that have been made to improve the value and the implementation of the DNV-OS-J101.



Figure 1. The support structures for the wind turbines at Kentish Flats are designed and certified to DNV-OS-J101

LOAD CASES ACCORDING TO IEC 61400-3

The definition of design load cases for offshore wind turbines is much more complicated than for offshore oil and gas installations due to the significance of the wind loading, the large effect of control and safety system actions and the sophisticated aeroelastic response of the rotor.

For the common type of modern offshore wind turbines ultimate wind induced loads for design can occur at the rated wind speed which is the lowest wind

speed where the wind turbine delivers full power. The rated wind speed is typically about 14 m/s at hub height.

Important control and safety system functions protect the rotor speed of the turbine from exceeding a level, where the turbine is overloaded or operation and braking cannot be controlled. If the limit is exceeded, the safety system will bring the turbine to a stop and disconnect the grid. Such emergency stops can also be activated manually by service personnel in the turbine in case they observe a condition which is critical for their own safety. Emergency stops will typically lead to large turbine loads, in particular when the stops occur at the same time as a wind gust.

Modern offshore wind turbines pitch the blades during storm conditions to minimize the blade loads. In this mode the largest tower bottom moments are typically crosswise to the wind.

Some of the most advanced wind turbines include tower vibration control by pitching the blades. Such advanced control systems reduce not only wind induced fatigue response, but also wave induced fatigue response.

The IEC 61400-1 [10] standard defines loads using stochastic wind input and transient deterministic wind input that define worst case scenarios such as extreme wind gusts, extreme wind shear and extreme direction change. Load cases refer to not only normal operation but also to fault conditions such as loss of grid and controller errors. Wind turbine response used as basis for design is computed as time simulation by means of aeroelastic software codes.

In the 2004 edition of DNV-OS-J101 [1] each of the wind load cases from IEC 61400-1 [10] were modified to include relevant companion marine loads from waves, current and ice. Stochastic wind loads were combined with stochastic marine loads and deterministic transient events were combined with deterministic marine loads.

Some of the experiences gained after the implementation of the 2004 edition of DNV-OS-J101 [1] imply that the water level variation due to tide and storm surge has a very significant effect on support structure loads and that a refined description of the relative direction of wind and wave loads can lead to a more rational basis for design in particular in storms.

The IEC 61400-3 standard [11] has been developed with significant input from the DNV-OS-J101 standard [1]. The wind and wave directionality and water level issues have been explained in more detail for the individual load cases and some load cases have also been modified.

The load case definitions in the 2007 edition of DNV-OS-J101 [2] will become completely synchronised with those of IEC 61400-3 [11].

In the 2004 edition of DNV-OS-J101 [1], the emergency shut down was combined with a 10-year deterministic extreme wave. Based on further discussions in the industry, this combination has been accepted as too conservative. In the 2007 revision of DNV-OS-J101 [2] it is accepted that the wave load during emergency

stopping is derived with a stochastic wave environment which corresponds to the expected significant wave height for the actual wind speed.

For a stop that occurs when the grid has an error, the 2004 edition of DNV-OS-J101 [1] prescribed that the design load case shall combine this scenario with the same critical wind gust which is used on land as well as with stochastic waves in a sea state with a 10-year return period. This load case was also considered too conservative after it had been discussed with the designers and the operators of offshore wind turbines. For onshore wind turbines installed where the electrical distribution system is carried on masts, grid errors are likely in storms because the storm also can damage the distribution system. In contrast offshore wind farms are connected to the grid on land by a cable buried in the sea bed. The wind speed in storms at the offshore wind farm will typically not reach its maximum at the same time as the wind speed reaches its maximum in the area of the masts that carry the distribution system. Further, grid error occurrences for offshore wind farms are not considered so frequent that they need to be combined with waves in a sea state with a 10-year return period.

In addition to the two load cases explained above, several other load cases which include a transient condition on the rotor side can, according to the 2007 revision of DNV-OS-J101 [2], be combined with a less severe stochastic wave condition than the deterministic extreme wave prescribed in the 2004 edition of DNV-OS-J101 [1]. Further details of the revision are described by Wedel-Heinen et al. [19].

SAFETY FACTORS

When the June 2004 version of DNV-OS-J101 [1] was developed, its requirements to partial safety factors for use in design of offshore wind turbine structures were laid down based on the conclusions from two different approaches to calibration of partial safety factors:

(1) A relative calibration based on safety factors required by DNV-OS-C101 [3]. This approach implied adjustments of the partial safety factor requirements of DNV-OS-C101, warranted by differences in type of loading, differences in definitions of characteristic values and differences in failure consequences between structures designed by DNV-OS-C101 and structures designed by DNV-OS-J101 [1]. DNV-OS-C101 [3] was developed for design of offshore steel structures for the oil and gas industry and aims for design to high safety class as defined in NKB [17] and Risø and DNV [14]. Wind turbine structures are unmanned and imply much less risk to human life, and they can therefore be designed to a lower safety class. Essentially, to obtain safety factor requirements for DNV-OS-J101 [1], the safety factor requirements in DNV-OS-C101 were lowered to reflect the lower safety class allowed for wind turbine structures. At the same time as it was kept in mind that DNV-OS-J101 defines characteristic loads as 50-year values, whereas DNV-OS-C101 uses 100-year

values, and that wind turbine structures are expected to be dominated by wind turbine loads which are of a different nature than the wave loads which are assumed to be dominating for structures designed according to DNV-OS-C101.

(2) An absolute calibration based on a probabilistic model in conjunction with a requirement to the target failure probability. A first-order reliability method as described in Madsen et al. [15] was used for this purpose, and it was assumed that a reasonable target safety level would be between low safety class and normal safety class as defined in NKB [17] and DNV and Risø [14] for structures whose failures are ductile with no reserve capacity.

Since DNV-OS-J101 [1] was first issued in June 2004, significant experience has been gained both with design of offshore wind turbine structures and with use of DNV-OS-J101. During the same period of time, work has been going on to develop an international standard for design of offshore wind turbines, IEC61400-3 [11]. Based on the accumulated experience and based on the implications of IEC61400-3, it has become clear that a revision of DNV-OS-J101 [1] would have to include a revision of its safety factor requirements. It has been concluded with consensus in the wind industry that the minimum requirements to structural safety are identical on land and offshore. Accordingly, it suffices to design wind turbine structures to normal safety class as defined in NKB [17] and Risø and DNV [14] for structures whose failures are ductile with reserve capacity. This implies a somewhat relaxed prescribed target safety level, i.e. an increased acceptable probability of failure. To reflect this and to bring DNV-OS-J101 in line with IEC61400-3, the load factor requirements of DNV-OS-J101 have been kept unchanged, such that they remain equal to those proposed in the committee draft of IEC61400-3, whereas the material factor requirements of DNV-OS-J101 overall have been reduced by approximately 4-5% in the 2007 revision of DNV-OS-J101 [2].

WAVES IN SHALLOW WATER

The 2007 revision of DNV-OS-J101 [2] includes a number of improvements and amendments with respect to modelling of waves and wave loads, in particular in shallow waters.

The 2004 issue of DNV-OS-J101 [1] provides guidance for representation of the short-term distribution of wave heights in deep waters by means of a Rayleigh distribution and only states that this Rayleigh distribution model may be conservative if applied to wave heights in shallow waters. The new revision of the standard [2] includes guidance for use of the composite Weibull distribution proposed by Battjes and Groenendijk [13] for representation of wave heights in shallow waters. Guidance is included for when the model can be used, and for its limitations.

A new subsection about wave theories and wave kinematics is included. Three wave parameters determine which wave theory to apply in a specific problem. These are the wave height H , the wave period T and the water depth d . These parameters are used to define three non-dimensional parameters that determine the ranges of validity of different wave theories,

- Wave steepness parameter:

$$S = 2\pi \frac{H}{gT^2} = \frac{H}{\lambda_0}$$

- Shallow water parameter:

$$\mu = 2\pi \frac{d}{gT^2} = \frac{d}{\lambda_0}$$

- Ursell parameter:

$$U_r = \frac{H}{k_0^2 d^3} = \frac{1}{4\pi^2} \frac{S}{\mu^3}$$

where λ_0 and k_0 are the linear deepwater wavelength and wave number corresponding to wave period T . The ranges of application of the different wave theories are given with reference to these three parameters. This is followed by presentations with descriptions of the following wave theories,

- Linear wave theory
- Stokes wave theory
- Cnoidal wave theory
- Stream function wave theory

Various orders of Stokes wave theory are dealt with. The presentations include expressions for the sea surface elevation for the different wave theories, except for the stream function theory.

The recommendations for the hydrodynamic inertia and drag coefficients C_M and C_D for calculation of wave loads, given in the 2004 version of DNV-OS-J101 [1], have been adjusted to bring them in line with the recommendations given in ISO 19902 [12] and in DNV-RP-C205 [18], see Nestegård et al. [16].

For evaluation of load effects from wave loads, the new revision of DNV-OS-J101 [2] includes a requirement to include possible higher order effects. Various types of higher order, interrelated high frequency wave actions may occur and cause extreme or repetitive action effects if the action frequencies coincide with natural frequencies of the structure. Such high frequency actions occur, among other things, due to slamming and due to the non-sinusoidal behaviour of large waves in shallow waters.

Since the theoretical knowledge of these phenomena is limited, it is important to assess them

jointly. The use of a slamming coefficient in Morison's equation is just to be considered as a first approximation and may in critical cases be followed up by more detailed analysis combined with experimental testing.

The term "ringing" is used in the literature for higher order transient action effects that may occur when steep, high waves encounter vertical components of structures with eigenperiods in the range from about 2 up to 8 seconds. See also DNV-RP-C205 [18].

STEEL STRUCTURES

Most European designers of steel structures are familiar with EN 1993, Eurocode 3 [8]. The Eurocode is to a large extent similar to the standards which traditionally have been used in the offshore industry such as DNV-OS-C101 [3] and DNV-RP-C203 [5] but includes also very detailed requirements to advance finite element based buckling analysis such as the analysis of a tower door opening illustrated in Figure 2. To ease the implementation of DNV-OS-J101 [2], it has been decided to refer more extensively to EN 1993 [8].

Eurocode 3 [8] is considered a recognised design code according to IEC 61400-1 [10] and IEC 61400-3 [11]. This implies that Eurocode 3 [8] can be used for design according to DNV-OS-J101 [2] when the total safety factor product exceeds the minimum required level specified in IEC 61400-1 [10]. Accordingly, Eurocode 3 [8] design procedures can be used for offshore wind turbine substructures when the following material factors are applied together with load factors and consequence of failure factors from IEC-61400-3 [11] and DNV-OS-J101 [2]:

Yielding: 1.1

Buckling: 1.2

Fatigue: 1.0 (above the splash zone and accessible for inspection and repair)

For several years, there has been a discussion among designers of offshore structures about the best set of parametric expressions for stress concentrations in tubular joints. Consensus has now been reached to generally recommend the use of the expressions originally proposed by Efthymiou [12]. All parametric stress concentration factors for tubular joints in jacket structures for support of wind turbines, given in the 2007 revision of DNV-OS-J101 [2], are now in line with those recommended for jacket structures for the oil and gas platforms in DNV-RP-C203 [5] and ISO 19902 [12].

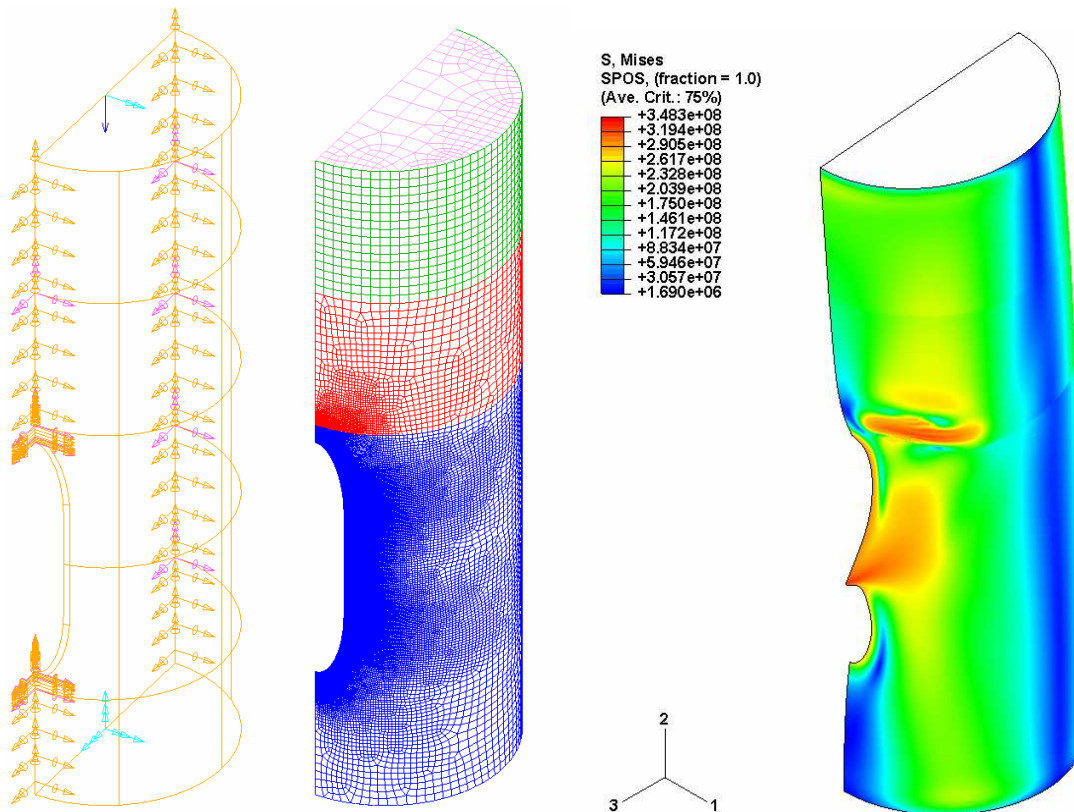


Figure 2. Buckling analysis of tower door opening.

DESIGN IN THE SPLASH ZONE

There is a significant difference between design of steel structures for traditional offshore oil and gas installations and design of support structures for wind turbines with regard to design of structural details in the splash zone. For traditional oil and gas installations, the fatigue loads from the topside are modest and the fatigue load effects from wave loading in the splash zone are normally small. For offshore wind turbines this is not the case. The fatigue loads from the rotor on the tower and support structure are normally more important than the wave loads. Fatigue design of steel in the splash zone is therefore a very critical part of the design of support structures for offshore wind turbines. Due to the effects of tide, the splash zone for some of the offshore wind turbines in UK waters extends over a significant part of the support structure.

It is well known that fatigue in steel is sensitive to the environment. Normally reference SN curves for steel fatigue design are developed for the following environments:

1. In air
2. Submerged in sea water with cathodic protection

3. With free corrosion

The SN curves in air can also be used for steel with an intact coating for corrosion protection.

For steel jackets for the oil and gas industry the splash zone is protected by paint. Due to the harsh environment in the splash zone a significant breakdown of coating during the service life must be taken into account. As an approximation to the average fatigue condition between “in air” and “with free corrosion”, the fatigue curve “Submerged in seawater with cathodic protection” is used in the splash zone in the oil and gas industry, see DNV-RP-C203 [5].

For offshore support structures for wind turbines it has been found relevant to draw the attention of the designer more closely to the selection, application, inspection and necessary repair of the coating for the splash zone. To provide a rational basis for this, it is now specified in the new revision of DNV-OS-J101 [2] that the basic fatigue curve for unprotected steel in the splash zone is “free corrosion” and the basic fatigue curve for coated steel is “in air”. It is acceptable to carry out fatigue life calculations in the splash zone based on accumulated damage for steel considering the probable coating conditions throughout the design life – intact,

damaged and repaired. The coating conditions used for design shall refer to an inspection and repair plan. If the designer considers the steel surface accessible for inspection and repair of initial fatigue damage and coating, this must be documented through qualified procedures for these activities.

Due to the relatively large splash zones expected for wind turbine support structures, also the corrosion allowance in ultimate and fatigue analysis is an important parameter in design. In the 2004 edition of DNV-OS-J101 [1] a corrosion rate of 0.3-0.5 mm was generally recommended as has been the practice in the offshore oil and gas industry based on experience from the North Sea. It was also recommended not to reduce the corrosion allowance when a corrosion protection system is installed.

The corrosion rates for steel in sea water depend to a large extent on the chloride content which is different in the various waters around the world. It has also to be recognised that advanced corrosion protection systems can reduce the corrosion rate for design provided that inspection and repair is feasible.

In order to provide the best possible basis for rational design in various waters it is now specified that the corrosion allowance in the splash zone shall be taken according to the corrosion rate for the structural steel in the relevant sea water and the planned inspection and repair strategy. It is now made clear that the corrosion rates recommended in DNV-OS-J101 [2] apply specifically to North Sea conditions.

CONCRETE STRUCTURES

The text about concrete design in DNV-OS-J101 [2] has been revised such that this part of DNV-OS-J101 now serves as an application document for the more extensive DNV concrete design standard DNV-OS-C502 [4] and such that it facilitates use of EN 1992 [7].

The construction of concrete gravity foundations for offshore wind turbines is illustrated in Figure 3.

For offshore wind turbine concrete foundations the crack width requirement is an important design criterion. The crack width criterion covers degradation of the concrete and corrosion of the steel reinforcement due to opening of cracks. An unambiguous reference load has to be defined. In DNV-OS-C502 [4] the criterion refers to the load effect that is exceeded no more than 100 times during the service life. For wind turbine foundations this definition shall be detailed further. In the 2004 edition of DNV-OS-J101 [1] it was conservatively specified that the load used for the crack width criterion should not be exceeded more than 100 times during the service life. It has been found difficult to interpret this definition and the interpretation could be somewhat conservative. In the revision proposal for DNV-OS-J101 [2] the definition is based on the fatigue load simulations and specifies that

1. For each considered applicable combination of wind and wave climate, at least six 10-minute time

series of load effect in relevant cross sections shall be calculated by simulation with random seeds.

2. The maximum load effect shall be interpreted from each of the time series for a particular cross section and a particular combination of wind and wave climate.
3. The mean value and standard deviation of the interpreted six or more maxima shall be calculated.
4. The characteristic load for the particular combination of wind and wave climate shall be calculated as the mean + 1.28 times the standard deviation.
5. For each cross section the maximum characteristic load for the different combinations of wind and wave climate shall be used in the crack width design criterion.

The format for material resistance in the crack width criterion follows DNV-OS-C502 [4]. However, some of the interpretations in EN 1992 [7] are found acceptable when this standard is applied to wind turbine support structures. The text in the revised DNV-OS-J101 [2] explains how the EN 1992 [7] requirements are modified to meet DNV-OS-C502 [4].

Based on a calibration study, the partial safety factor for concrete and reinforcement strength is reduced by approximately 5% in the revision proposal. This is in line with the above-mentioned reduction in the requirement to material factors for steel when implementing the safety level inherent in IEC 61400-3 [11].

In the revision it is now stressed that all metallic components in an offshore support structure including appurtenances shall have equipotential bonding and electrical earthing in order to protect against potential differences, stray currents and lightning. Documentation for this shall be included in the design documentation.

As guidance, it is mentioned that the transfer resistance for the reinforcement in an offshore concrete structure may often be low and could then be used for earthing. If used for earthing the reinforcement should as a minimum be tied with metallic wire at every second crossing and the vertical and horizontal connection shall be supplemented by separate electrical connections clamped to the reinforcement at a suitable distance.

It is normally required to protect rebars and prestressing tendons against corrosion wherever they can be subject to corrosion in sea water. This is recommended to be done by means of cathodic protection.

Care shall be taken to make sure that the corrosion protection system and the electrical earthing do not conflict.



Figure 3. Concrete gravity offshore foundations during construction.

FUTURE WORK

DNV-OS-J101 is intended as a “living document” which incorporates received feedback in a thorough and timely fashion with frequent new revisions. Since the first issue of DNV-OS-J101 in 2004 [1], DNV has received a significant amount of feedback from the industry with suggestions for topics to be included in a revision, either in terms of technical requirements or in terms of guidance for design. Many of the suggestions have been complied with in the new revision of the standard. However, a number of issues raised in the feedback received have not yet been implemented in the standard.

One such issue, which remain open and unresolved and which needs to be referred to future work, is the issue of detailed requirements and guidelines for assessment of the risk for extraordinary high wind speeds above the design limits for the potential wind turbine design in climates governed by tornados, hurricanes and typhoons. Data to support general requirements and guidelines for design of wind turbine structures for such climates are very limited, and designs will have to be carried out on a case-to-case basis until sufficient experience is gained to allow for generalised rules for design.

Another topic, which has not yet been incorporated in the standard and which thus also has to be referred to a future revision, is the issue of design requirements which are specific for floating wind turbine structures.

The steel grade conversion tables in DNV-OS-J101 [2] still only cover European steel grades and DNV’s own grading system. It is desirable to include other national steel grading systems in the conversion tables in a future revision of the standard.

A further improvement of the basis for design against ice loads is also referred to a future revision. DNV is currently hosting a JIP on ice loading of structures, which will eventually result in the publication of a DNV recommended practice for ice loading for arctic offshore structures and which will allow for the desired improvement of the basis for design against ice loads in DNV-OS-J101 [2].

Finally, it is noted that requirements to design of systems for occupational safety are not specified in DNV-OS-J101 [2], although inclusions of such requirements in a future revision of the standard certainly will be desirable. However, such mandatory requirements are currently not part of the IEC WT01 [9].

CONCLUSIONS

The DNV-OS-J101 standard for design of support structures for offshore wind turbines was first issued in 2004 [1] and has now been revised according to the latest knowledge. The revision has been concluded in a proposal for a revision [2].

The most important new item is a synchronisation of the definition of load cases and partial safety factors with those of the coming IEC 61400-3 standard [11]. The basis for describing design waves in shallow water, for designing concrete foundations and for designing against fatigue in steel support structures in the splash zone has also been improved.

At the time of writing, the proposal for a revision [2] has not yet been through the formal hearing process where specialists and stakeholders in the offshore wind industry are invited to review the details of the revision.

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