Guidance for use of the BSH standard „Design of Offshore Wind Turbines“

Verification of the geotechnical safety of foundation elements

Hierarchy of standards, cyclic loads, dynamic pile load testing

1 Background and purpose

Cyclic loads, either static or dynamic, acting on the foundations of offshore wind turbines are likely to cause major changes to the bearing capacity of the foundations. Generally accepted or sufficiently validated computation models for the design of cyclically loaded foundation elements are not yet available. Therefore, the codes of practice specified in the BSH's standard „Design of Offshore Wind Turbines“ (briefly „Design Standard“) do not contain uniform regulations in this respect. In the planning approval procedures conducted by the BSH so far, applicants have coped with this problem in different ways. Meanwhile, first scientific studies discussing offshore turbine foundation designs taking into account this load factor have been published.

European harmonisation has led to a revision of the technical standards for geotechnical safety verification. The DIN 1050:2005-01 standard on the Verification of Safety of Earthworks and Foundations used in construction supervision has been withdrawn on the national level by Deutsches Institut für Normung (DIN) at the end of 2010, in compliance with EU requirements. Nevetheless, DIN 1050:2005-01 will continue to be used in construction supervision on federal state level probably until 30 June 2012.

Almost all of the Eurocodes and National Annexes issued as of 2010-12 or earlier have meanwhile been published as DIN EN. In future, the relevant European and national standard for geotechnical design and calculations applicable in Germany will be DIN EN 1997-1:2009-09 (Eurocode EC 7-1) in connection with DIN 1054:2010-12 and DIN EN 1997-1/NA:2010-12. In DIN1054:2010-12, reference is made to the recommendations of the special working group on piles („EA-Pfähle“) specifying details of pile foundation design. The second edition of „EA-Pfähle“, whose Chapter 13 deals with the load properties and testing of piles under cyclic, dynamic and impact loads, thus also covers lateral pile resistance, which is particularly relevant for offshore wind turbine foundations and for the verification of safety under cyclic loading. Besides, a new revised and expanded edition of the guidance on soil dynamics („Baugrunddynamik“) of AK1.4 is being prepared which includes information on the calculation of cyclic loads acting on shallow foundations.

According to the above standards, the lateral pile resistance of foundation piles is verified by carrying out pile loading tests. Guidance and recommendations concerning the procedure are given in the following.

The following guidance integrates the above-referenced regulations into the verification procedure described in the Design Standard, for application in the EEZ. Effective immediately, they represent a state-of-the-art, future-oriented framework for preliminary planning, inspections, and testing carried out as part of the planning application procedure.

Based on the results of a workshop of BAM, BAW, and BSH on 29 April 2010 in Berlin, this guidance for the Design Standard has been developed by a national group of experts, as a working group of the BSH (see Appendix 1: members). The guidance will be updated by experience gained in the first application cases and by the results of ongoing research or will be integrated into a revised version of the Design Standard.

2 Guidance concerning hierarchy of requirements

2.1 General

In principle, the latest updated version of the Design Standard specifies the requirements concerning the design of foundation elements of offshore wind turbines to be built in the EEZ. The Design Standard specifies that primarily national and European construction standards shall be applied. The following guidance is based on this requirement.

2.2 Codes of practice for impacts

National DIN standards and codes of practice do not cover the full range of impacts on offshore wind turbines, so that they have to be supplemented with additional codes of practice. The Design Standard specifies the following standards and codes of practice to be used as a basis when determining load impacts:

- DIN EN 61400-3:2010-01
- DIN 1055-4:2005-03 and DIN EN 1991
- API RP 2A-LRFD / WSD
- GL-COWT
- DNV-OS-J101

2.3 Codes of practice for design and construction

The authors of the draft design and the geotechnical expert are required to apply the following basic standards with their corrections and references including relevant implementation standards, taking into account forthcoming amendments:

Geotechnical:	from 1 January 2011 DIN EN 1997-1:2009-09 - Eurocode 7: Entwurf, Berechnung und Bemessung in der Geotechnik – Teil 1: Allgemeine Regeln DIN EN 1997-1/NA:2010-12: National Annex – National festgelegte Parameter – Eurocode 7: Entwurf, Berechnung und Bemessung in der Geotechnik – Allgemeine Regeln DIN 1054:2010-12: Baugrund – Sicherheitsnachweise im Erd- und Grundbau – Ergänzende Regelungen zu DIN EN 1997-1
Steel construction:	*presently*: DIN 18800-1:2008-11 and/or DIN EN 1993 (EC 3) *probably from 2011:* DIN EN 1993-1:2010-12 (EC 3)
Reinforced concrete construction:	*presently* DIN 1045 and/or DIN EN 1992-1-1:2005-10 (EC 2) probably from 2011: DIN EN 1992-1-1:2011-1 (EC 2) und DIN EN 1992-1-1/NA2011-01 National Annex
Concrete:	DIN EN 206-01:2001-07

Any interim regulations have to be agreed with the BSH on a case-by-case basis.

Reference is also made to the second edition of DGGT's recommendation „EA Pfähle", which contains additional specifications for the design of pile foundations. Information on cyclic load calculations is provided in Chapter 13 of „EA Pfähle" („Tragverhalten und Nachweis für Pfähle unter zyklischen, dynamischen und stoßartigen Einwirkungen", 2011 draft), as pointed under 1 above. Information on the computation of cyclic loads in the design of shallow foundations is also provided in Chapter E4: „Bleibende Verformungen und Standsicherheit" of the recommendation „Baugrunddynamik" issued by DGGT working group 1.4 (December 2010). The above recommendations are available on the homepages of DGGT (www.dggt.de) and BSH (www.bsh.de).

2.4 Deviations from and additions to the Design Standard

The standards and codes of practice referred to in Chapter 2.3 (design and construction) do not cover all aspects of the design of foundation elements for offshore wind turbines. Additional codes of practice, guidelines and recommendations have to be used, inter alia:

- GL-COWT
- API RP2A-LRFD
- API RP2A-WSD
- DNV-OS-J101
- DIBt-RiLi WEA

The following principles of the Design Standard apply to the use of codes of practice containing offshore-specific deviations from and additions to the German and European standards specified in 2.2 and 2.3 above:

Any planned deviations require a written application to the BSH, with full details and statement of reasons including information about the equivalence of the chosen method to the specifications of the Standard.

Any planned additions require a written application to the BSH, with full details and statement of reasons, and a feasibility analysis by an expert.

The BSH carries out a plausibility check and reserves the right to approve the application.

3 Guidance on the assessment of cyclic loads in the design of foundation elements

3.1 Preliminary remarks

With all foundation types presently considered, cyclic loads acting on the foundation elements and conducted into the foundation soil reduce the bearing capacity of the foundation and lead to accumulated deformation. Depending on local conditions, unfavourable changes of pore water pressure are possible which may lead up to soil liquefaction.

To assess possible changes of the bearing capacity of foundation elements, a geotechnical expert with special knowledge in this particular field has to be commissioned.

Within the framework of the first partial approval, the concept for incorporating cyclic loading in the design of foundation elements for the supporting structure and an explanation of the investigation programme planned to be carried out have to be provided. As part of the second partial approval, verification has to be provided that cyclical loading has been taken into account, which includes the documentation of laboratory and field tests conducted in that context.

3.2 Design event

The foundations of offshore wind turbines are continually subject to the impacts of wind, waves, and operating loads acting on the turbine support structure. Such cyclic loads have to be calculated in conformity with the Design Standard, section 3.2.3.2. Cyclic loading has to be included in the verification of bearing capacity by calculating a storm event as described in the following, also taking into account the other load cases. A special operating condition causing major cyclic loading of the foundation elements may also have to be included in the calculations.

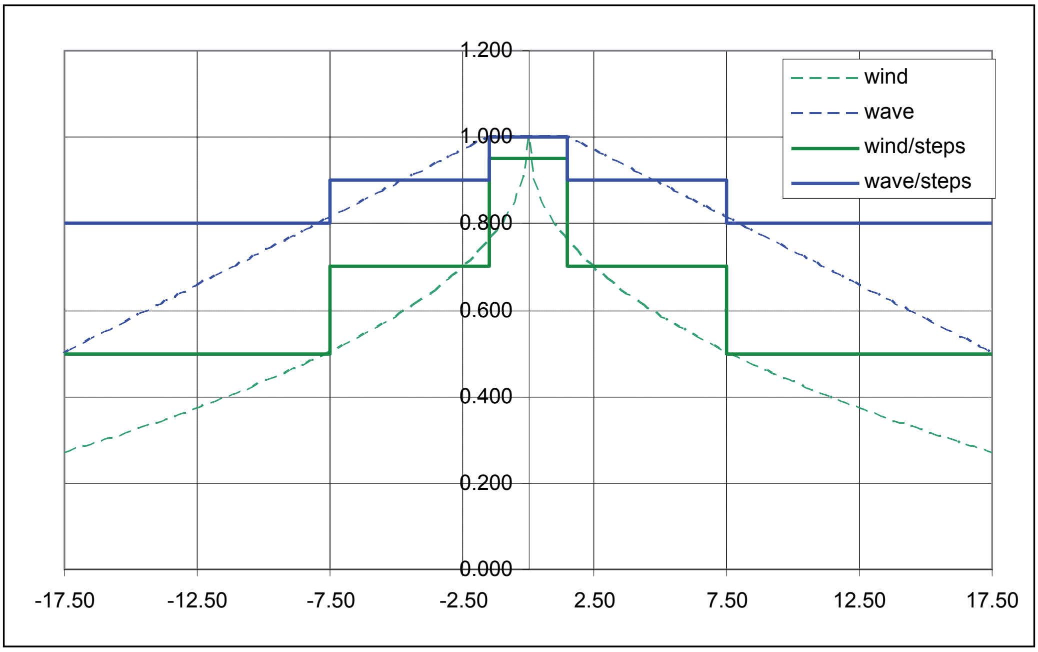
The potential bearing capacity reduction of a foundation which is subject to cyclic loading during a major storm event (Table 1 and Fig. 1) has to be analysed taking into account the complete load spectrum. The storm event must include the design extreme value acting on the foundation elements, and the number and distribution of extreme values used must be typical of the particular site. The loads thus computed shall be converted to the maximum design loads (see DIN EN 61400, part 1, Annex F).

The design event used to verify bearing stability under cyclic loading is described on the basis of the definition of design load case DLC 6.1 in Germanischer Lloyd [2005] and the boundary conditions in Table 1.

DLC 6.1: Parking – idling, EWM 50 & Hs50 yaw=±8°	
Wind model	EWM50 turbulent
Wind speed (m/s)	$V_{50,1h}$
Intensity of turbulence	12%
Wind direction	0 degrees
Yaw angle	-8, 0, 8 at the beginning of computation
Wave direction	0 degrees

Table 1: Load case definition

Y-axis: standardised wave height and wind speed



X-axis: time in h

Fig. 1: Development of wind speed and significant wave height during the design event

The standardised curves of wind speed and significant wave height are shown as dashed lines in Fig. 1. They are defined as follows:

- Wave height: max. Hs over a period of three hours
  linear decrease to 0.5 Hs after ±17.5h
- Wind speed (recommendation acc. to EU project RECOFF):
  v(t) = 1 – 0.09 (t/10)0.45 where t = time (min) {-1,050 min ≤ t ≤ +1,050 min}

For practical reasons, the curves have been discretised in steps on the time axis. An example curve is shown in Figure 1. Pending prior agreement with the BSH, the discretisation used for the storm development may differ from that in the Figure.

If pore water pressure development is likely to have a negative effect on the bearing capacity of the foundation structure due to its size and to the soil properties, relevant load/time curves taking into account such effects have to be established.

All impacts of the design event which may possibly affect the bearing capacity have to be included in the verification of bearing capacity. Computation of the unique design storm is currently considered adequate for the design because characteristic impacts with suitable safety margins are taken into account. Therefore, additional storm events need not be included in the verification of bearing capacity.

3.3 Equivalent load spectrum

In order to assess the impacts of loads of different amplitudes and from different directions according to Chapter 3.2, EA-Pfähle [2011], it may be appropriate to derive a cyclic equivalent single-stage spectrum from the design event load; it should comprise a mean load level Fmitt, an equivalent load range Feq, and an equivalent number of load cycles Neq (see Fig. 2). It should be noted that a small number of large cyclic loads normally produces a greater reduction of the bearing capacity of soils than a large number of small loads, which is a behaviour unlike that of other materials. Depending on the verification method chosen, the equivalent load amplitude and appropriate equivalent number of load cycles can be determined using a method proposed by Lin Liao [1999]. More details are provided in Chapter 13, EA Pfähle [2011].

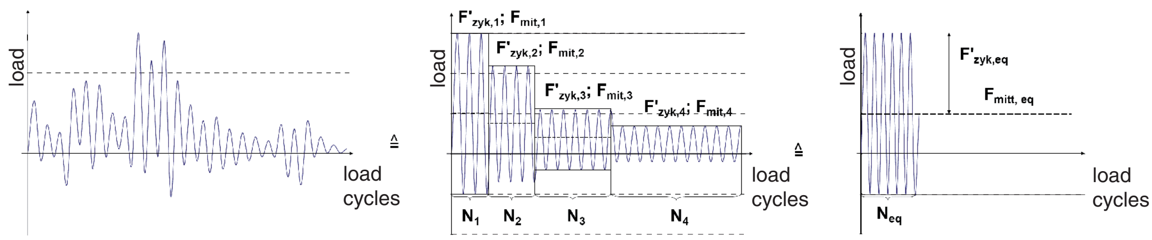


Fig. 2: Definition of quivalent number of load cycles and load amplitude

3.4 Design situations and partial safety factors

Impact combinations are attributed to design situations according to DIN 1054:2010. The design load values are determined in analogy to the DIBt-RiLi guideline for onshore wind turbines, with partial safety factors deviating from those in DIN 1054:2010. Partial safety factors for impacts can be derived from the standards and guidelines for offshore wind turbines referred to in 2.2 above. The BSH reserves the right to grant its consent. To assess the impacts of cyclic loads on the foundation elements, the characteristic impact loads normally have to be indicated.

4 Guidance on the verification of ultimate limit states for foundation elements taking into account cyclic loading

4.1 General

Ultimate limit states of bearing capacity and serviceability taking into account cyclic loading effects have to be calculated both for shallow and deep foundations of offshore wind turbines. Based on general experience gained so far and recent research, the following information is provided on the verification methods to be used.

According to the Design Standard, the observation method according to DIN EN 1997-1 (EC-7-1) and DIN 1054 shall be used in all cases where calculation results are not fully adequate and do not include sufficient safety margins for the particular aspect. The Design Standard requires a qualified description and presentation of the observation method to be used.

In case cyclic laboratory tests are planned to be carried out, they have to be planned and conducted in close co-operation with the geotechnical expert and the author of the draft foundation design. These tests have to be documented as part of the Basic Design.

4.2 Shallow foundations

Some preliminary information on shallow foundation design is provided in the following. The requirements for this type of foundation have only been coarsely sketched during the expert workshops and will have to be concretised as the knowledge base grows.

The load bearing capacity of shallow foundations can be analysed using conventional geotechnical methods, i.e. by carrying out cyclic shear tests on undrained soil samples and calculating the resulting reduction of bearing capacity (e.g. in cyclic triaxial tests; refer to Savidis & Schuppe, 1982).

The recommendations in Chapter E4 of the „Baugrunddynamik“ guideline of DGGT’s AK 1.4 can be used to verify the serviceability of shallow foundations. The examples given in the guideline can be translated to the shallow foundations of offshore wind farms.

In addition to the general design requirements set out in Eurocode EC 7-1:2009-09 and DIN 1054:2010-12, it has to be ensured that soil erosion below the foundation due to cyclic loading is prevented by the design. With respect to shallow foundations having no circumferential skirts of adequate penetration depth, this normally means that gap formation under all characteristic loads must be prevented.

4.3 Pile foundations

4.3.1 Axial cyclic loading

Verifications of serviceability can be performed using methods described in the literature (see Chapter 13, EA Pfähle, Randolph [2009], Kirsch & Richter [2010], i.a.), provided that they are suitable for the intended application.

General information on bearing capacity verification is provided in Eurocode EC 7-1:2009-09 and DIN 1054:2010-12. Results should be documented using the formats shown in Chapter 13, EA Pfähle, 2nd Edition. The recommendations given in that guideline are based mainly on published studies and results by Schwarz [2002], Mittag & Richter [2005], and Kempfert [2009]. These results are also allowed to be used in the verifications when applying directly the pre-published draft of the 2nd Edition of EA Pfähle (Chapter 13) before the complete 2nd Edition of EA Pfähle is available (probably second half of 2011).

Other published „interaction graphs“ (e.g. by Jardine & Standing [2000]) may be used provided that they are suitable for the object to be assessed and the design event according to Chapter 3 is taken into account.

The suitability of published approaches and methods for the particular object to be assessed (pile system, soil properties and loading characteristics) shall be demonstrated.

4.3.2 Cyclic loading transverse to the pile axis

Lateral cyclic loading of pile foundations leads to a deflection of the pile head which, if large enough, places considerable stress on the soil close to the pile head, with pile deflection increasing with the number of load cycles. Besides, soil resistance may be reduced if cyclic loading causes an accumulation of pore water excess pressure.

Moreover, in cohesive soils under water, permanent soil deformation may cause gap formation between pile and soil, and a de-stabilisation of the near-surface area, which reduces the bearing capacity of laterally loaded piles.

The serviceability of predominantly laterally loaded pile foundations of offshore wind turbines can be assessed by applying, e.g., the methods proposed by Grabe & Dührkop [2008] and Achmus [2008]. Additional information on calculations for the assessment of permanent deformation of piles that are subject to cyclic lateral loading is available in Hettler [1981] and Long & Vanneste [1994].

In order to calculate the ultimate limit state for lateral bearing capacity of a pile, it is necessary to determine the expected reduction of mobilisable soil resistance taking into account the pile system used (type, diameter), type of soil, and number of load cycles. The assessment can be made either on the basis of experience or can be based on the results of suitable cyclic laboratory tests taking into account changes of pore water pressure. Bearing capacity can be verified on the basis of soil resistance, which may be diminished, applying the method described in Chapter 13, EA Pfähle, and using the p-y method described in API RP2A-LRFD. In verifying serviceability and load capacity, application areas and limits of the methods chosen must be taken into account.

The influence of pore water pressure changes on the bearing capacity must be analysed and taken into account.

4.4 Additional information

Besides the prediction of tilt, required to verify serviceability of the foundation design, it must be ensured that constraint stresses on the supporting structure resulting from potential differences in the displacement of foundation elements are borne with an adequate safety margin.

5 Dynamic pile loading tests

According to Eurocode EC 7-1:2009-09 and DIN 1054:2010-12, the axial bearing capacity of foundation piles is verified by means of pile loading tests. Therefore, dynamic pile loading tests are required to verify the bearing capacity of offshore wind turbine foundations, where piles are predominantly subject to axial loading.

Eurocode EC 7-1:2009-09 and DIN 1054:2010-12 describe the methods to be used in conducting dynamic pile loading tests and in evaluating and interpreting the results. The geotechnical expert determines the number and location of pile loading tests in accordance with EA-Pfähle. Generally, dynamic pile loading tests have to be carried out at 10 percent of turbine locations as a minimum, which should include at least two locations for each geotechnical type of soil found in the area of the wind farm.

The concept for the dynamic pile loading tests (number and location of tests) has to be developed by the geotechnical expert and has to be submitted complete with the application documents for the second partial approval. The concept should specify the type and scope of tests to be carried out and the way in which the test results are to be applied to the entire construction site.

Dynamic pile loading tests are carried out in the first construction phase. The institutions commissioned to conduct the tests must have proven experience in the field of dynamic pile loading testing and test evaluation.

If the temporal development of bearing capacity following installation of the piles is to be taken into account in the verification of bearing capacity, a sufficient number of additional dynamic pile loading tests have to be carried out subsequently .

To derive characteristic pile resistance data Rk from the measurements of dynamic pile loading tests Rm, scatter factors have to be applied in accordance with DIN EN 1997-1:2009-09 (Eurocode EC 7-1) and DIN 1054:2010-12. Where the supporting ground consists mainly of cohesionless soils, use of the scatter factors $\xi_{5,6}$ und $\Delta\xi$ in the case „calibration of dynamic pile loading tests against static pile loading tests in similar construction measures“ is allowed even if static pile loading tests have not been carried out at the particular wind farm site. This is due to the fact that ample experience with static and dynamic pile loading tests in cohesionless soils is available from other construction projects in the entire area of northern Germany, and proven calibration factors thus are available for such soils. Besides, the pile foundations for offshore wind turbines normally use steel piling, where scatter due to manufacturing is of lesser importance and where piling reports are prepared which allow a quantitative evaluation of each individual pile.

The dynamic pile loading tests have to be supervised and evaluated by the responsible geotechnical expert. The complete documentation of the dynamic pile loading tests conducted and of their evaluation and interpretation, as well as the geotechnical expert's translation of the results to the piles which have not been tested, must be submitted to the BSH immediately after completion of the dynamic pile loading tests and their interpretation.

The BSH, supported by expert advice, holds the view that dynamic pile loading tests to determine axial bearing capacity currently are not required for the verification of monopile bearing capacity. Generally, measurements may be useful during piling operations in order to check pile drivability and driving stresses and to calculate the driving stresses exerted on the pile during pile driving. The BSH reserves the right to require monopiles to be subjected to dynamic pile testing for technical reasons or on the basis of recent findings.

6 Technical Regulations and Literature

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API RP 2A – WSD	Recommended practice for planning, designing and constructing fixed offshore platforms – Working stress design, Twenty first edition, December 2000, Errata and supplement 3, October 2007.
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DIN EN 1997-1/NA:2010-12:	Nationaler Anhang – National festgelegte Parameter – Eurocode 7: Entwurf, Berechnung und Bemessung in der Geotechnik – Allgemeine Regeln.
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Appendix 2

The expert committee for structural engineering (Fachkommission Bautechnik), which is responsible for the implementation of Eurocodes according to section 3, clause 3, sentence 1 of the German national building code (Musterbauordnung, MBO), and the building ministries of the German federal states, are currently planning to declare the use of certain Eurocodes mandatory from 1 July 2012 as per „key date regulation“. From that date, the Eurocode building regulations will be exclusively applicable. This declaration affects Eurocodes 0 (basis of structural design), 1 (actions on structures), 2 (design of concrete structures), 3 (design of steel structures), 4 (design of composite steel and concrete structures), 5 (design of timber structures), 6 (design of masonry structures), 7 (geotechnical design) and 9 (design of aluminium structures).

Given that chapter 13 of the German standard “EA-Pfähle”, which addresses the consideration of cyclic loads for the pile bearing behaviour of foundations for offshore wind turbines, follows strictly the verification formats of Eurocode EC 7-1 / DIN1054:2010-12 / NA, and considering the fact that certain partial safety factors and verification formats of DIN 1054:2010-12 have been changed substantially as compared to DIN 1054:2005-01, the Federal Maritime and Hydrographic Agency (BSH) decided to implement mandatory use of DIN EN 1997-1:2009-09 (Eurocode EC 7-1) in connection with DIN 1054:2010-12 and DIN EN 1997-1/NA: 2010-12 from an earlier data, i.e. from 1 January 2011. As from that date, all official applications for preliminary design approval and for design approval and certification of current projects must be in compliance with the geotechnical regulations laid down in these codes (see also Section 1). This is in conformity with the opinion of the expert committee for structural engineering, as documented in writing on 25 August 2010.