

EXAMPLES OF IMPORTANT ONGOING RESEARCH TOPICS FOR OFFSHORE WIND ENERGY

M.O.L.HANSEN^{*+#}, H. BREDMOSE^{*}, S. SCHLØER^{*}

^{*} TECHNICAL UNIVERSITY OF DENMARK
DTU MECHANICAL ENGINEERING
NILS KOPPELS ALLÉ, BUILD. 403
DK-2800 KGS. LYNGBY, DENMARK
e-mail: molh@mek.dtu.dk

⁺ Centre for Ships and Ocean Structures, CeSOS
Norwegian University of Science and Technology
N-7491 Trondheim
Norway

[#] Virtual Prototyping AS, Norway

Key words: Offshore wind energy, non-linear wave model, wave impacts, deck loads, FEM based servo aero-, hydrodynamic code VpOne.

Summary. The aim of the paper is to address some challenges related to offshore wind energy. A first example shows some results from an ongoing project on accurate computation of wave loads on monopole foundations. The effects of wave nonlinearity and bottom slope are examined and detailed CFD computations for an overturning wave impact are presented. Next the existing servo aero- hydrodynamic code VpOne used for estimating loads on offshore wind turbines is briefly described and an example of a fatigue analysis for a jacket foundation supporting the 5 MW NREL virtual wind turbine is shown.

1 INTRODUCTION

Even though demonstration plants for various concepts already exist for waves and tidal flow, the large scale development of offshore renewable energy is from wind farms, especially around UK, in the North Sea and the Baltic Sea. Presently approximately 3000 MW wind power is installed offshore; an equal number is under construction and a lot more is being planned. Several new technological challenges, however, arise when installing wind turbines offshore. The substructure for an offshore wind turbine adds significantly to the total cost. The majority of installed offshore wind turbines are placed on monopiles driven into the sea bed or gravity base foundations that rest on the bed. For depths in excess of 35-40m, alternative substructures such as jacket towers will be utilized, and at even larger depths (say 80m) floating substructures become feasible.

The presence of a substructure introduces dynamic wave loads that must be estimated and

taken into account when verifying the design against fatigue and ultimate loads. A realistic combined description of wind and wave climate is not trivial and thus measurement campaigns and research is taking place. Most often the waves are described from approximate wave theories and the famous Morison equation is used to derive time series of the wave loads. The effect of wave nonlinearity and bottom bathymetry on the wave kinematics and the accuracy of the Morison loads, however, is still an open question and thus an active research discipline. For example, wave nonlinearity may result in increased fatigue loads during storms, and impacts from breaking waves may affect the design for the ultimate limit state. In the first part of this paper an example from an ongoing research project on wave loads on monopile foundations is shown.

The second part describes a FEM based engineering servo aero- and hydrodynamic code running in the time domain that can be used to predict ultimate and fatigue loads for a given specification of the incoming wind and waves. Some examples of the loads in a jacket foundation are shown.

2 NONLINEAR WAVE LOADS ON MONOPILES

The frequent use of monopiles represents a potential for structural optimization by application of accurate wave models. The load is a result of the combined forcing from wind and waves. An accurate description of the wave loads is therefore required for a cost-effective design.

In general, water waves are three-dimensional, nonlinear, irregular and are affected by the sea bed topography. In standard design methods, several assumptions are made to allow a practical calculation of the associated loads: For the fatigue loads, a 2D linear wave field is assumed, and the kinematics of the irregular waves is obtained by spectral superposition. Wheeler stretching [1] is often applied to compensate for the over-prediction of the velocities above still water level by linear wave theory. For extreme waves, kinematics from the stream function wave theory is used (see e.g. Fenton [2]) which constitutes a fully nonlinear solution for regular waves.

Given the kinematics of the waves without the structure, the Morison equation [3] is next applied to derive a time series of force. The Morison equation is valid for slender structures, where the structural diameter is much smaller than the wave length. While this is often a good approximation for a monopile, the accuracy of the wave kinematics associated with standard design is affected by the lack of nonlinearity for the irregular waves and the lack of irregularity for the nonlinear waves. Further, in both cases, the effect of local bed slope is neglected. An improvement in the accuracy of the standard method for wave load prediction is therefore possible by application of more accurate wave kinematics.

During the past two decades a number of accurate wave models have been developed, allowing the computation of three-dimensional nonlinear irregular waves on varying depth. Boussinesq wave models (e.g. [4]) is one such class of models where computational

efficiency is obtained by elimination of the vertical coordinate. Alternatively, one may directly solve the 3D Laplace equation for the velocity potential with nonlinear boundary conditions at the free surface and an impermeability condition at the sea bed. Li and Fleming [5] presented such a model with utilization of the multi-grid technique for the solution of the discretized Laplace equation. Engsig-Karup et al [6] developed a similar model and improved the numerical efficiency further by application of higher-order finite difference operators. The combination of a stretched numerical grid in the vertical direction and higher-order finite difference operators allowed accurate solutions for water wave problems with just 7 points in the vertical direction.

For wave loads on an offshore wind turbine, Schlører et al [7] examined the effect of bottom slope and wave nonlinearity by application of the Engsig-Karup et al [6] model. Unidirectional incident waves were propagated over a sloping bed from a depth of 50m to a depth of 20m. The wave climate at 50m was described from a JONSWAP spectrum [8] with a peak period of 6.8s and a significant wave height of 2.8m. This sea state is mild enough that wave breaking will not occur at the depth of 20m. The wave propagation is therefore well described by a potential flow model. A time series of 8000s was computed for two variations of the depth: one had a mean slope of 1:25 and the other a mean slope of 1:100. For both slopes, the results associated with full wave nonlinearity were compared to results of a computation, where all the nonlinear terms were switched off.

Figure 1 shows a probability plot of the inline force in the direction of wave propagation for the average slope of 1:100. All positive peaks in the computed time series of inline force has been detected and sorted after increasing magnitude. Next, a probability $P=i/N$ has been assigned to each event, where N is the total number of peaks and i is a running counter, where $i=1$ is associated with the smallest event and $i=N$ is associated with the largest event. The plot shows that for this relatively mild sea state, the bulk of the inline force peaks are not affected much by nonlinearity. The nonlinearity, however, strongly enhances the extreme values. For example the largest non-linear peak force is about 32% larger than the largest linear peak force and the largest linear peak force is exceeded 9 times by the nonlinear results.

Given that the wave nonlinearity affects the largest events of inline force to a large degree, a comparison between the force from the largest event of the above computation to the force from a stream function wave of same height and period is motivated. While both theories are fully nonlinear, the stream function solution is a regular wave solution at constant depth. For the stream function theory wave, the maximum inline force is found to be 12% smaller than for the irregular wave at sloping sea bed. Further, profiles of the force distribution in the vertical direction at the instant of maximum force are compared in Figure 2. For the irregular wave, the force is concentrated in the region close to the free surface, while the stream function wave gives rise to a much more uniform force distribution. This may be associated with the symmetric wave profile of the stream function theory wave opposed to the irregular wave on a sloping bed, that is likely to be asymmetric. The difference in force distribution leads to a larger overturning moment for the irregular wave of 10.0 MN compared to 8.1 MN for the stream function theory wave. Similar results to the above, but with even more

pronounced differences from nonlinearity and bed slope was found for the 1:25 mean slope. The full study is reported in Schlør et al [7].

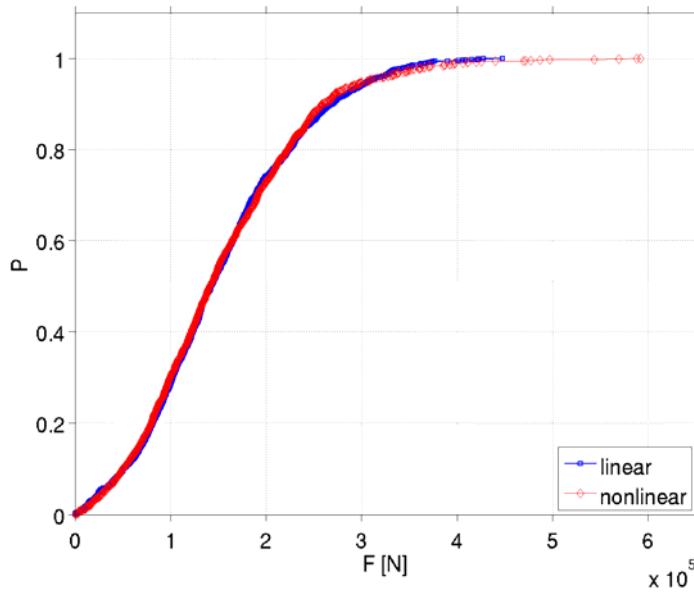


Figure 1: Probability map for inline force in the direction of wave propagation for a monopile at 20m depth, placed on a slope of average slope of 1:100. Comparison of linear and nonlinear results.

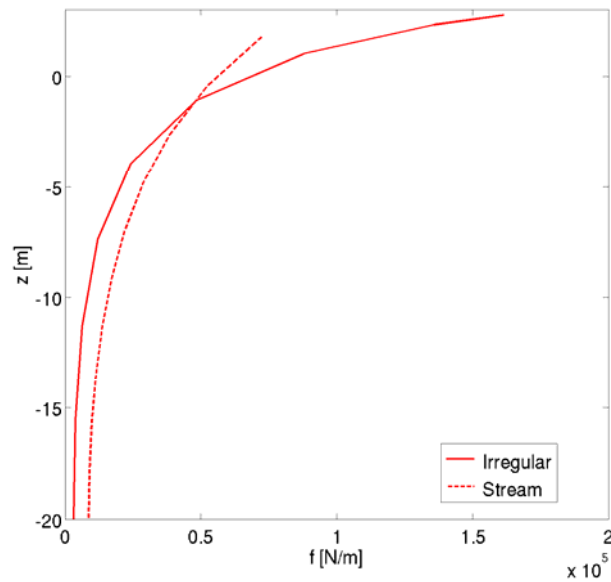


Figure 2: Profiles of distributed load for a selected wave at the 1:100 slope (solid line), and a stream function theory wave with same wave height and period (dashed line).

For cases where the interaction with the structure affects the wave kinematics significantly or where the structure is hit by a breaking wave, the undisturbed wave kinematics in combination with the Morison equation is not sufficient for an accurate load description. Examples of such situations are impacts from overturning breaking waves; diffraction by substructures that differ from the simple geometry of a vertical circular cylinder and wave impacts that include forces on secondary structures such as boat landings. Damsgaard et al [9] and Frigaard et al [10] reported on several incidents at the Danish Horns Reef 1 wind farm where strong wave impacts lead to a substantial run-up along the transition piece of the monopile and subsequently damaged the inspection platforms that were placed 9.0m above the mean sea level.

In such cases CFD methods can be applied for the detailed computation of the hydrodynamic loads. Here the Navier-Stokes equations are solved in a full three-dimensional domain that resolves the structure and the propagation of the incident waves. The presence of a free surface in the associated fluid problem can be treated by specialized numerical methods, where the VOF (Volume Of Fluid) method [11] and the Level Set method (e.g. [12]) are the most used.

Inspired from the platform damage at Horns Reef 1, Bredmose and Jacobsen [13] presented such VOF computations for overturning wave impacts at a monopile at 20m depth with subsequent run-up and impact on a horizontal inspection platform. The numerical solver is part of the OpenSource CFD toolbox OpenFOAM®, released by OpenCFD Ltd®, version 1.5. It solves the Navier-Stokes equations for the two-phase flow of incompressible water and air. The wave generation framework of Jacobsen [14] was utilized to propagate waves from the offshore boundary of the computational domain. A large-amplitude overturning wave was obtained by application of the focused wave group technique to a discretized JONSWAP spectrum. In the linear description, the free surface elevation η can be written as

$$\eta_{lin}(x, t) = \sum_{p=1}^N a_p e^{i(\omega_p t - k_p x)} \quad (1)$$

where x is the spatial horizontal coordinate, positive in the direction of wave propagation, N is the number of frequencies, (a_p, ω_p, k_p) is the wave amplitude, radian frequency and wave number at frequency p and (x_0, t_0) is the focus point and focus time. While the true large-amplitude wave will be nonlinear and thus differ from Eq. (1) at the focus time, the method is still useful to provide the boundary condition for the computation. To avoid problems with second-order spurious wave components, the second-order bound wave field as derived by e.g. Sharma and Dean [15] was further added to the boundary condition.

For a fixed shape of the incident overturning wave, a parametric study for the impact forces

was conducted for the five platform levels of $z_p=(12.08, 10.0, 8.96, 7.08, 6.04)$ m, measured upwards from the still water level. Although the two lowest platform levels are smaller than one would expect for a real design, they were included as part of the parametric study. Figure 3(a) shows a snapshot from the computation for $z_p=7.08$ m at the computational time of $t=59.1$ s, which is 0.2s after the initial impact of the overturning wave at the monopile. At the instant of the snapshot, the run-up has reached the horizontal platform and pressures from the impact occur in the corner region between the monopile face and underside of the platform. At the base of the run-up sheet, a region of strong pressure can be seen on the monopile front. This pressure acts to accelerate the water from the incident wave upwards and sideways away from the impact zone. No significant pressure is seen between the impact pressure and the corner pressure. This indicates that this portion of the run-up water is in almost free fall.

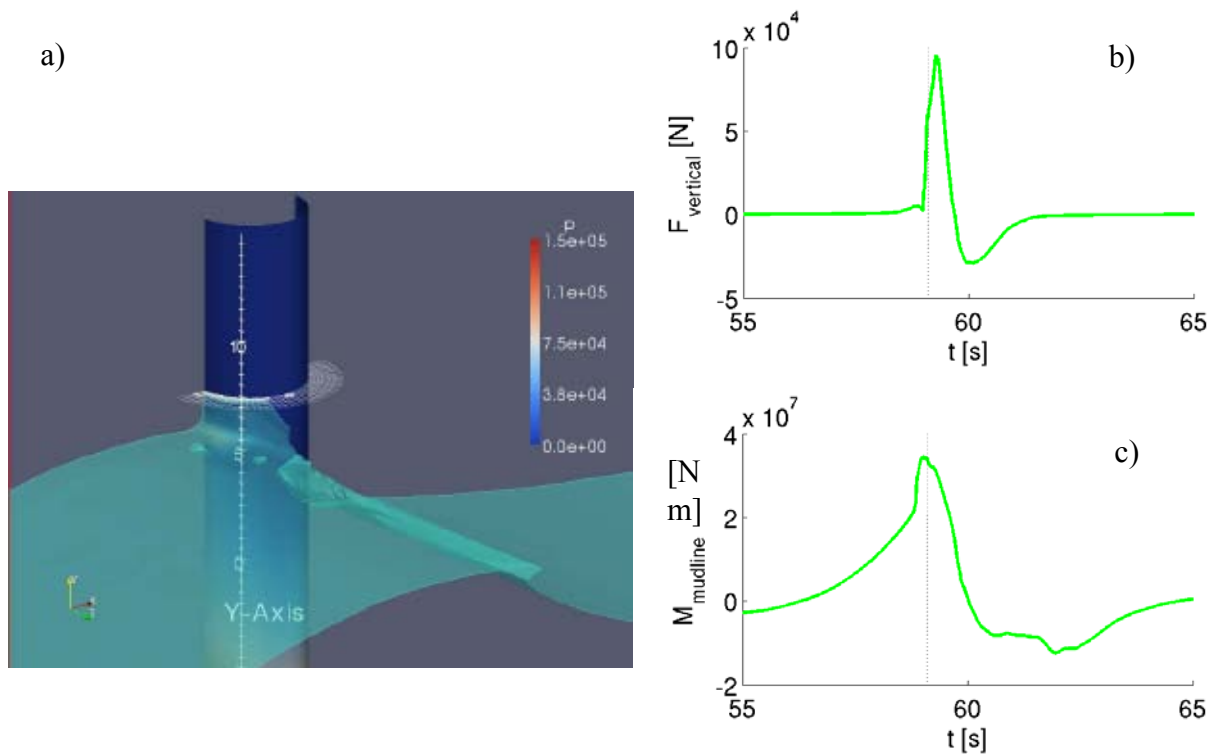


Figure 3: a) Snapshot of free surface during impact with the monopile and inspection platform. The colors show the total pressure. b) Time series of vertical force on the platform. c) Time series of global overturning moment, calculated with respect to the monopile center at the level of the sea bed. The dotted vertical lines in panel (b) and (c) marks the time for the snapshot of panel (a).

Time series of the vertical force on the platform and the global overturning moment around the sea bed are shown in panel (b) and (c) respectively, obtained by direct integration of the pressure. At the instant of the snapshot the vertical force is 59kN. The maximum force of 95kN occurs at $t=59.3$ s. After the positive upward force associated with the blockage of water

with an upward velocity, a negative suction force occurs. This force is well-known for wave-in-deck impacts (see e.g. Kendon et al [16]) and is associated with the escape-flow of the water from the corner region subsequent to the impact.

The overturning moment, as shown in panel (c), shows a maximum value of 34.5MNm. The maximum occur prior to the instant of maximum vertical force. For the present case of incident wave and platform elevation, the pressure associated with the platform does therefore not contribute substantially to the global overturning moment.

It should be noted that the computations were carried out on a numerical grid of 691.000 cells, with refinement towards the monopile and the vertical levels of the free surface. At the face of the monopile, the grid spacing was $dr \times rd\theta \times dz = (0.12 \times 0.18 \times 0.21) \text{ m}^3$. While Bredmose & Jacobsen [17] found that the in-line force was converged at slightly coarser resolution, a dependency to the grid resolution for the position of wave overturning was found in the present study. Grid-convergence for the shape of the impacting wave and the results for inline force, overturning moment and vertical deck loads is therefore a topic for further work.

Despite this limitation, the study of Bredmose and Jacobsen [13] and [17] illustrate the potential of CFD calculations of violent wave loads. An accurate prediction of such loads is important for practical design.

3 DESCRIPTION OF THE SERVO AERO- AND HYDRODYNAMIC CODE V_pO_{NE}

To validate an offshore design according to the standards [18] and [19] one must calculate the fatigue and ultimate loads for many different described combinations of wind and waves. Also one must assure the stability of the construction, especially for floating foundations where some stiffness may become very low. There exist several certified aeroelastic codes used for onshore sites such as FLEX [20], Bladed [21] and HAWC2 [22] that can calculate the elastic response of the wind turbine from gravitational, aerodynamical, centrifugal and inertia loads, but these codes are still in the developing phase when it comes to wave loads and calculating the buoyancy from integrating the hydrostatic pressure of the submerged part of the construction. Since there some years ago was a real need for design codes for floating wind turbines, it was decided in an existing and well proven FEM platform used in offshore industry to introduce the possibility of large rotations required to model the rotor and to include aerodynamic loads. The FEM model is a general 3D non-linear method based on the knowledge and technology behind the USFOS code, and is built on the SAM library [23]. The idea behind the code can be described as

The philosophy behind the development of V_pOne was to apply well proven and standard models for wind and wave loads in a highly verified FEM technology in order to produce a robust and reliable code to calculate the dynamics and internal material loads of a fixed or floating wind turbine.

The calculation of the aerodynamic loads is based on the classical BEM method as described in [24]. Using this standard BEM theory one assumes the inflow and thus the loads to be steady, which is not the case for a real wind turbine mainly due to atmospheric turbulence, yaw misalignment and influence of tower. To estimate unsteady loads it is necessary to include some so called engineering models. In [25] and [26] are described a time lag of the flow near the rotor plane when the loads are changed in time e.g. by pitching the blades and a redistribution of the flow in the rotor plane when the rotor is not perfectly aligned with the incoming wind. The first model is called dynamic inflow and the second a yaw model. Also a model for unsteady aerodynamics denoted dynamic stall is included as described in [27] introducing a time delay of the aerodynamic lift coefficient when changing the angle of attack. A BEM code including these engineering models is the aerodynamic model used in most commercial and verified aeroelastic codes. The standard Morison formula [3] is used to calculate the wave forces. Some validations VpOne can be found in [28]-[30]

According to [31] a monopile hammered into the seabed is an often used solution for shallow water (3-20 m depth) and a soft sea bottom. For deep water (in the order of 40 m) a three or four legged jacket foundation can be used and for even deeper seas floating foundations are needed. Many future offshore turbines may thus be mounted on jacket foundations that must be designed to withstand the ultimate and fatigue loads experienced during the design lifetime. The advantage of basing a servo aero- and hydrodynamic design code on an existing FEM platform is that also tools for calculating local fatigue and ultimate loads in the construction is already available. In the following an example of calculations done with VpOne on a jacket foundation on which is mounted the virtual NREL 5MW wind turbine [32]. Figure 4 shows the setup and some example output of the simulation.

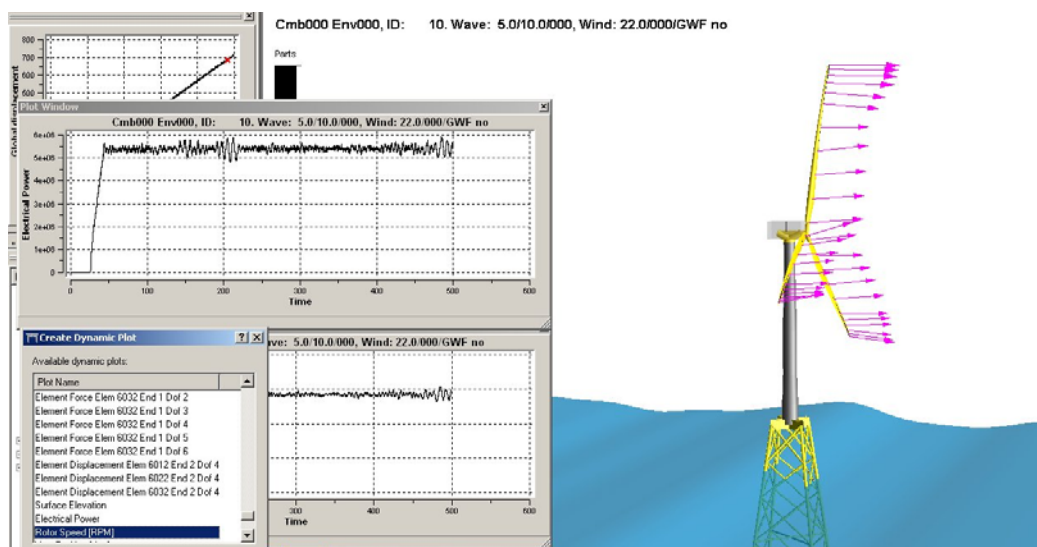


Figure 4: NREL 5MW mounted on a jacket foundation modelled in VpOne. Water depth 35 m.

Figure 5 shows an example of combined fatigue loads in the welding between the tubes in the jacket based on a limited set of the load cases described in [19]. These cases involves:

- Waves with H_s ranging from 1 to 5m and T_p from 6 to 10 seconds
- Wave directions 0, 45 and 90° relative to the wind.
- Wind Speed from 4 m/s to 22 m/s, 16% turbulence intensity

And the complete system is run as one integrated system. Stress time series are computed for every hotspot in the actual joints and the part-damages are computed using conventional Rainflow counting / SN curves. Each case is weighted with its relative probability and accumulated to damage per year.

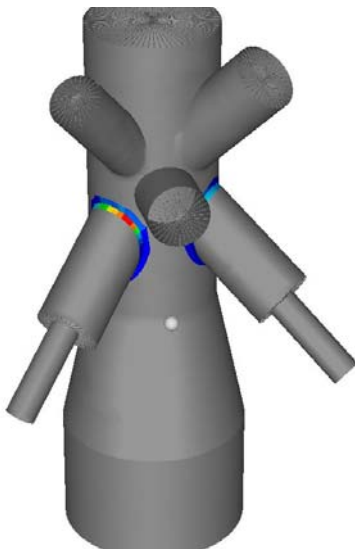


Figure 5: Fatigue loads in the welding between the tubes in the jacket foundation. The loads is a combination of 10 design load cases as described in [11].

4 CONCLUSIONS

The paper give examples of some important projects related to offshore wind energy. Two examples concerning wave loads on a monopile is described. The first compares the wave loads from a fully nonlinear wave model on a sloping seabed to those obtained by a linear model. The waves propagate from a depth of 50m to a depth of 20m on an average slope of 1:100. While, for the relatively mild sea state considered, the bulk of the force peaks were not affected much by nonlinearity, the extreme force peaks were quite different. The largest nonlinear peak force was 32% larger than the largest linear peak force and nine force peaks from the nonlinear results exceeded the largest linear event.

Next a case where the presence of the monopile alters the shape of the waves is discussed. When an overturning wave hits the monopile, the subsequent run-up of water at the face of the structure may lead to a subsequent vertical impact on the horizontal inspection platforms. This highly non-linear feedback process can only be solved using full 3D CFD. Further investigations and refinements of the needed grid resolution will be pursued in the future.

Finally, an engineering code VpOne for load predictions of offshore wind turbine construction is described. This code is based on a FEM model including the integration of the hydrodynamic pressure of the wetted part and is thus well suited for estimating the stability of floating wind turbines. The code can also be used for calculating fixed foundations and an example of a jacket foundation is shown with emphasis on fatigue loads.

ACKNOWLEDGEMENT

Two of the authors (H. Bredmose and S. Schlør) were supported by the Statkraft Ocean Energy Research Program (www.statkraft.no). This support is gratefully acknowledged.

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