Design and fatigue analysis of monopile foundations to support the DTU 10 MW offshore wind turbine

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INTRODUCTION

This study focuses on FLS analysis of large monopile foundations. Preliminary monopile designs for four water depths are established to support the DTU 10 MW reference wind turbine [1]. Pile-soil interaction is accounted for by deriving nonlinear P-Y curves using a finite element (FE) method. A method for predicting fatigue damage using fewer sea states is introduced and shown to be promising for the given designs and location.

MODELING AND SIMULATION

Pile-soil interaction for large-diameter piles is modeled in Plaxis 3D [2] using the methodology proposed by Hanssen [3]. For a 30,000 kN applied load, the resulting interface stresses and pile displacement are illustrated in **Fig. 1**. Nonlinear P-Y curves representing the lateral stiffness of the soil were extracted and used as main input in the aero-hydro-servo-elastic tool, RIFLEX [4].

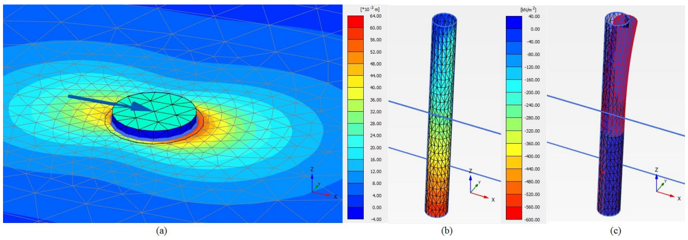

Figure 1: Graphical stress and displacement calculation showing (a) Load application, (b) Stress at the interface and (c) pile defection

RIFLEX is a modeling tool capable of static, dynamic and eigenvalue analysis based on FE analysis with beam (or bar) elements. The DTU 10 MW RWT model is shown in **Fig. 2**. Unidirectional loads due to wind, wave and current are applied for all simulations. Preliminary pile dimensions (see **Table 1**) were designed to achieve an overall natural frequency within the soft-stiff region (0.25 Hz) while satisfying ULS and stability requirements [5,6].

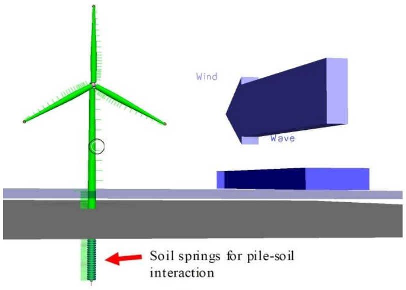

Figure 2: DTU 10 MW model in RIFLEX

Hydrodynamic loads on the monopile are modelled using Morison's equation and linear wave kinematics (with constant potential up to the instantaneous free surface), while aerodynamic loads are computed using the blade element/momentum theory.Fatigue damage is calculated for a reduced set of 29 operational conditions from the long-term wind and wave distribution (Site 15) of the MARINA platform project [7].

Table 1: Preliminary monopile design

Water depth [m]	Pile diameter [m]	Pile thickness [mm]	Tower D scale [-]	Tower thickness scale [-]	Penetration Depth [-]	Natural Frequency [Hz]
20	9	110	1.125	1.25	35	0.251
30	9	110	1.125	1.75	45	0.251
40	10	125	1.25	1	35	0.249
50	10	125	1.25	1.5	45	0.251

FATIGUE DAMAGE PARAMETER (FDP)

FDP is established to correlate fatigue damage with the parameters thrust, H_s, and T_p. The formulation assumes that wind and wave interaction is insignificant and fatigue damage is not directly correlated with mean thrust. **Fig.3** outlines the procedure for estimating fatigue damage.

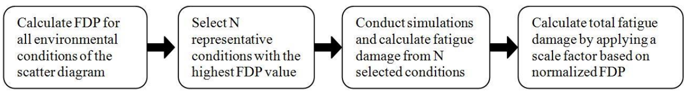

Figure 3: FDP procedure for calculating fatigue damage

The formulations for the FDP and the scale factor (S_F) are given below. M is the total number of environmental conditions, while N is the number of conditions for which simulations are carried out.

$$FDP = H_s^5\, T_p^{-11} P \quad (1)$$

$$(FDP_{norm})_i = \frac{FDP_i}{\sum_{i=1}^{M}(FDP_i)} \quad (2)$$

$$S_F = \frac{\sum_{i=1}^{M}(FDP_{norm})_i}{\sum_{i=1}^{N}(FDP_{norm})_i}, \text{ where } \sum_{i=1}^{M}(FDP_{norm})_i = 1 \quad (3)$$

RESULTS

The calculated 20-year fatigue damage is shown in the outer envelope of **Fig. 4**. The relative contribution of each sea state (arranged in increasing H_s) implies that hydrodynamic loads become more significant with higher depths.

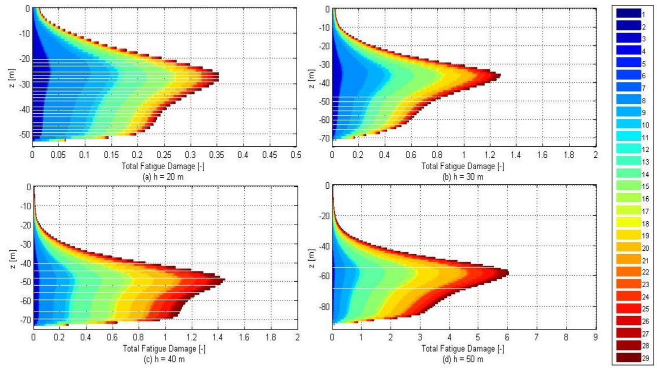

Figure 4: Total fatigue damage, showing contributions from each environmental condition.

The calculated fatigue damage for different numbers of representative conditions (N = 3, 9, 15, 20, 26) out of 29 sea states is shown in **Fig. 5**. The accuracy of damage prediction at the section where maximum fatigue damage occurs is shown in **Fig. 6**.

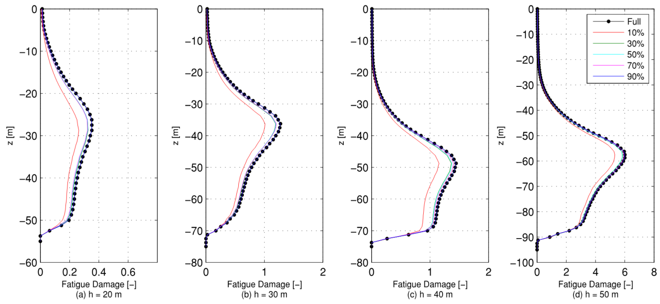

Figure 5: Fatigue damage prediction (along the monopile, where 0 is the mean still water level) for different values of N

Using a larger number of sea states generally increased the accuracy of prediction. The method is also observed to be more accurate for higher water depths. Using at least 30% of the total number of conditions resulted in at least 90% accuracy.

Further work includes accounting for wave diffraction, investigation of the applicability of the FDP procedure with other types of support structures and other (more extensive) site-specific environmental conditions, including misalignment.

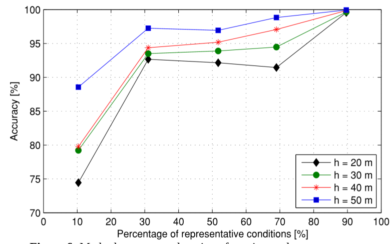

Figure 6: Method accuracy at location of maximum damage

ACKNOWLEDGEMENT

The author acknowledges the support from the European Commission through the Erasmus Mundus European Wind Energy Master (EWEM) Program. The authors also wish to acknowledge the financial support from Research Council of Norway through Center for Ships and Ocean Structures (CeSOS) and Centre for Autonomous Marine Operations and Systems (AMOS, RCN Project number 223254). Thanks are extended to Dr. Stian Baardsgaard Hanssen, Prof. Gudmund Reidar Eiksund, Asst. Prof. Eliz-Mari Lourens and Prof. Andrei Metrikine for stimulating discussions.

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