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A method to predict the cyclic loading profiles (one-way or two-way) for monopile supported offshore wind turbines

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A B S T R A C T

Monopiles are currently the preferred option for supporting offshore wind turbines (OWTs) in water depths up to about 40 m. Whilst there have been significant advancements in the understanding of the behaviour of monopiles, the guidelines on the prediction of long term tilt (Serviceability Limit State, SLS) under millions of cycles of loads are still limited. Observations and analysis of scaled model tests identify two main parameters that governs the progressive tilt of monopiles: (a) Loading type (one-way or two-way) which can be quantified by the ratio of the minimum to maximum mudline bending moments (M_{min}/M_{max}); (b) factor of safety against overturning i.e. the ratio of the maximum applied moment (M_{max}) to the moment carrying capacity of the pile or *Moment of Resistance* (M_R) and therefore the ratio M_{max}/M_R. Due to the nature of the environmental loads (wind and wave) and the operating conditions of the turbine, the ratio M_{min}/M_{max} changes. The aim of this paper is to develop a practical method that can predict the nature of loading for the following governing load cases: Normal Operating Conditions, Extreme Wave Load scenario, and Extreme Wind Load scenario. The proposed method is applied to 15 existing wind farms in Europe where (M_{min}/M_{max}) and (M_{max}/M_R) are evaluated. The results show that the loading ratio is sensitive to the water depth and turbine size. Furthermore, under normal operating conditions, most of the wind turbine foundations in shallow waters are subjected to one-way loading and in deeper waters and under extreme conditions the loading is marginally two-way. Predictions for the nature of loading for large wind turbines (8 MW and 10 MW) in deeper waters are also presented. The results from this paper can be used for planning scaled model tests and element tests of the soil.

1. Introduction

Offshore wind turbines are currently implemented as practical sources of energy with a low carbon footprint. Foundations are considered to be an expensive item in the overall cost breakdown of an offshore windfarm, with the foundation, substructure, assembly, and installation covering a staggering 25–34% of the total cost [6,39]. This was one of the main drivers for extensive research and industrial efforts to reduce the Levelized Cost of Energy (LCOE). Based on the 2017 auction price, the cost of megawatt hour of energy produced from offshore wind farms was cheaper than that produced by a nuclear power plant and set to compete with other sources of energy such as natural gas in the near future [22]. Monopiles are currently the preferred option for supporting OWTs in water depths up to about 40 m and are even considered for deeper waters. These foundations are to be designed to resist certain levels of deformations and long-term tilt and are summarized below:

1. The initial tilt of the monopile due to installation has to be within the allowed limit (current limit set in DNV code is 0.25°).
2. The accumulated tilt due to millions of load cycles during the lifetime of the turbine has to be within the allowed limit (current limit is 0.25°). Alternatively, the total tilt i.e. initial + accumulated at the nacelle level is limited (current limit is 0.5°).

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Nomenclature

A_R	Rotor swept area
C_D	Drag coefficient
C_I	Inertia coefficient
C_T	Thrust coefficient
c_u	Soil undrained shear strength
d	Point of rotation for rigid piles
D_P	Pile diameter
H_m	Extreme wave height
H_S	Significant wave height
I_{ref}	Reference turbulence intensity
k	Wave number
K_P	Soil passive earth pressure coefficient
L_K	Integral length scale
L_p	Length of pile
M_{min}	Minimum mudline bending moment
M_{max}	Maximum mudline bending moment
S	Average water depth
T_M	Period for extreme wave height
T_S	Period for significant wave height
M_R	Ultimate moment resistance
U_R	Rated wind speed
U_{hub}	Wind speed at hub height
$\overline{U}$	Mean wind speed
w	Velocity of wave particle
z_{hub}	Hub height
η	Wave surface elevation
γ′	Buoyant unit weight of the soil
φ′	Angle of internal friction
σ'_v	Vertical effective stress
σ_u	Standard deviation
ρ_a	Density of air
ρ_w	Density of water
ω	Frequency of wave

3. The initial deflection at the monopile head (mudline/seabed level) has to be within the allowed limit (e.g. 0.1 m).
4. The accumulated deflection at the monopile head (mudline/seabed level) has to be within the allowed limit (e.g. 0.1 m). Alternatively, the total pile deflection at mudline (initial + accumulated) is limited (e.g. 0.2 m).

The readers are referred to Bhattacharya [7] and Arany et al. [5] for further details. If these limits are exceeded, the warranty from turbine manufacturers might be lost leading to possible financial implications for windfarm developers. Therefore, reliable methods to estimate long term tilt are essential for cost effective solutions. Design standards such as the API [2] and DNV [18] do not have a comprehensive method to predict rotation accumulation due to cyclic loading. Instead they present methods to adjust p-y curves by reducing the soil stiffness in order to incorporate the effect of cyclic loading. Furthermore, the API method is calibrated against slender-small diameter piles for low number of loading cycles, which does not present an accurate idealization of current monopiles supporting OWTs. Fig. 1 shows a simple schematic representation of the mudline bending moment acting on a monopile which is effectively a superposition of wind and the wave loading. The work of Arany et al. [4] showed that moment due to 1P and 3P are orders of magnitude lower than the wind and wave and can be ignored for tilt calculations.

Scaled model tests have been carried out in the last decade, see for example Refs. [15,24,35,36] for establishing methodologies for the assessment of the long-term performance (deflection and tilting) for monopiles. The main parameters affecting tilt are the ratio of M_{min}/M_{max} and M_{max}/M_R. The definition of M_{min} and M_{max} are provided in Fig. 1 and is also explained later in the paper. M_R is the ultimate moment capacity of the pile considering soil failure and strictly not the failure of the pile through local buckling or yielding. The load cases (i.e. M_{min}/M_{max} and M_{max}/M_R) used in most of these scaled tests show a wide range from extreme one-way loading to extreme two-way loading and is often an unrealistic loading range.

Therefore, the aim and scope of this paper is to provide general recommendations on the loading profiles (one-way vs two-way

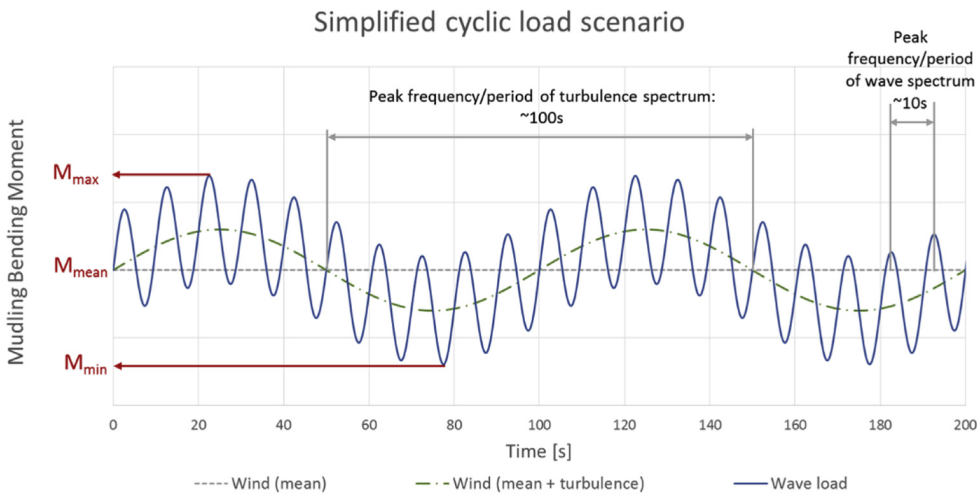

Fig. 1. Simplified time history of the mudline bending moments.