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Dynamic soil–structure interaction of monopile supported wind turbines in cohesive soil

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ABSTRACT

Offshore wind turbines supported on monopile foundations are dynamically sensitive because the overall natural frequencies of these structures are close to the different forcing frequencies imposed upon them. The structures are designed for an intended life of 25 to 30 years, but little is known about their long term behaviour. To study their long term behaviour, a series of laboratory tests were conducted in which a scaled model wind turbine supported on a monopile in kaolin clay was subjected to between 32,000 and 172,000 cycles of horizontal loading and the changes in natural frequency and damping of the model were monitored. The experimental results are presented using a non-dimensional framework based on an interpretation of the governing mechanics. The change in natural frequency was found to be strongly dependent on the shear strain level in the soil next to the pile. Practical guidance for choosing the diameter of monopile is suggested based on element test results using the concept of volumetric threshold shear strain.

1. Introduction

Offshore wind turbines are providing an increasing proportion of wind energy generation capacity because these sites are characterised by stronger and more stable wind conditions than comparable onshore sites. Offshore sites also have a higher capacity factor (the ratio of the actual amount of power produced over a period of time to the rated turbine power) when compared to equivalent onshore sites.

The design and construction of foundations for offshore turbines are challenging because of the harsh environmental conditions and as a result provide a focus of major research in Europe, see for example Achmus et al. [1], Kuhn [29], Kuo et al. [30], Bhattacharya et al. [5]. Different types of foundations have been proposed: including monopile, gravity base, jacket, suction caisson and floating systems. However, most of the offshore turbines currently in operation (UK Round 1 development) are supported on driven monopiles. The choice of monopiles results from their simplicity of installation and the proven success of driven piles in supporting offshore oil and gas infrastructures. The available methods for designing monopiles for offshore wind turbines (e.g. the approach suggested by DNV-OS-J101 [15] or IEC61400-1 [21]) are based on the methods originally developed for the offshore oil and gas industry [4]. Fig. 1 shows a typical monopile supported wind turbine and a pile supported fixed offshore jacket structure. There are, however, obvious differences between those two types of foundations.

Piles for offshore structures are typically 60–110 m long and 1.8–2.7 m diameter. By contrast, monopiles for offshore wind turbines are commonly 30–40 m long and 3.5–6 m diameter. Degradation in the upper soil layers resulting from cyclic loading is less severe for offshore jacket piles which are significantly restrained from pile head rotation causing lower pile head deflections. However, the overturning moments generated in the jacket superstructure are resisted by pairs of equal and opposite axial resultants in the piles. Such cyclic axial loads can produce a loss of shaft capacity because of the development of ‘friction fatigue’ down the piles. Monopiles are free-headed which encourages more pile head deflection. A design method using a beam on non-linear Winkler springs (‘*p–y*’ method in API code [4] or DNV code) may be used to obtain pile head deflection under cyclic loading, but its use is limited for wind turbines because:

(a) the widely used API model is calibrated against response of a few small diameter piles (length to diameter ratio of 30 to 50) subjected to small numbers of cycles (maximum 200 cycles) suited for offshore fixed platform applications, e.g. Matlock [38],

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Nomenclature

a	parameter in the rational function fitting
CSR	cyclic stress ratio
D	pile diameter
E	Young's modulus of pile
f_f	forcing frequency
f_n	natural frequency
G	shear modulus of soil
G_{max}	shear modulus of soil at small strains
G_{sec}	secant shear modulus of soil
I	second moment of area of pile
k_h	horizontal coefficient of soil permeability
K_L	stiffness of transverse spring
K_R	stiffness of rotational spring
K_V	stiffness of vertical spring
L	penetration depth of pile
M	external moment acting at the pile head
M_N	secant modulus of the p–y curve after Nth
M_1	secant modulus of the p–y curve after 1st cycle
N	number of load cycles
P	net horizontal load
t	time
t_w	wall thickness of pile
V	vertical load
y	distance between foundation level and application of P
α	parameter in the logarithm fitting
Δ	parameter in the rational function fitting
γ_a	average shear strain in the soil
γ_{tl}	linear shear strain threshold
γ_{tv}	volumetric shear strain threshold
δ	lateral deflection of pile head
e_p	strain in pile wall thickness
e_s	average strain in soil
λ	parameter in the rational function fitting
ξ	damping ratio of model
σ'_v	effective vertical on the soil at the same depth as above
σ_y	pile yield stress

O'Neill and Murchison [42], Poulos and Hull [44], Reese et al. [47,48]. In contrast, for a real offshore wind turbine, the length to diameter ratio of piles is of the order of 4 to 8 and 10^7–10^8 cycles of lateral and moment loading are expected over a lifetime of 20–25 years.

(b) It can be shown that the calibrated p–y curves used in the API and DNV codes are based on flexible pile behaviour where the pile is expected to fail by formation of plastic hinges (structural failure of piles). On the other hand, the squat nature of monopiles makes them sufficiently rigid that the formation of plastic hinges is not expected. Rather, a monopile will rotate like a rigid body (potentially including some reverse toe-kick) and the soil next to the pile may fail.

(c) under cyclic loading, the API or DNV model always predicts degradation of foundation stiffness in sandy soil. However, recent work by Bhattacharya and Adhikari [7], Cuéllar et al. [13], LeBlanc [32] suggested that the foundation stiffness for a monopile in sandy soil will actually increase as a result of densification of the soil next to the pile.

(d) The ratio of horizontal load (P) to vertical load (V) is very high in offshore wind turbines when compared with fixed jacket structures. Therefore, the monopiles experience disproportionately higher moment loading in comparison to a jacket pile. This more extreme loading condition was not taking into account during the calibration of the API and DNV p–y curves.

A similar problem of cyclic degradation of the soil surrounding a relatively short pile (20–30 m) was encountered in designing the floating offshore platforms for the North Sea Alvheim field [8]: Mechanisms included post-holing and possible jetting action due to the one-way cyclic loading on the anchoring piles. These near-surface effects, Bhattacharya et al. [8] are much more significant for the shorter monopiles, affecting a greater proportion of their length.

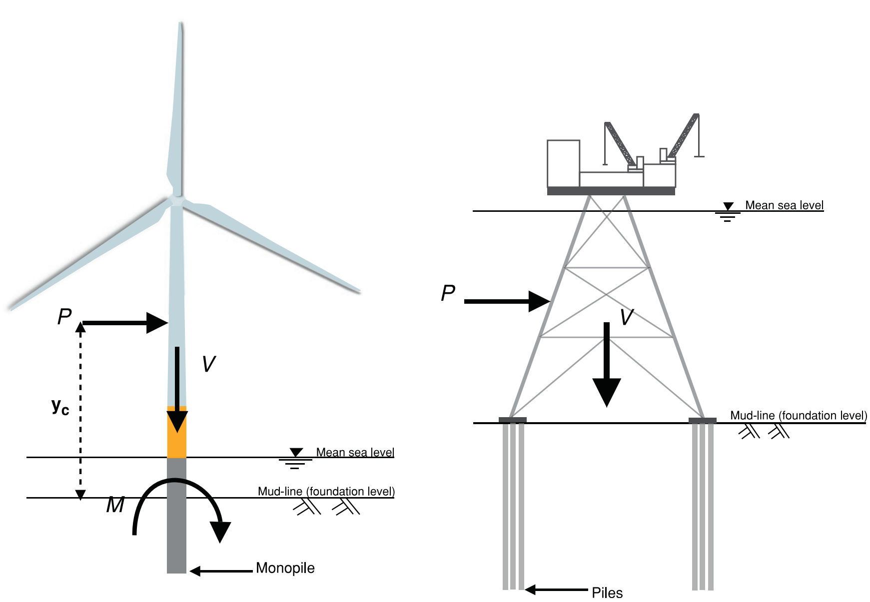

Fig. 1. Typical monopile supported wind turbine and a fixed offshore jacket structure supported on piles.