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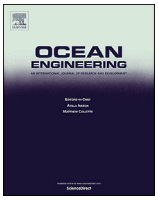

Impedance functions for rigid skirted caissons supporting offshore wind turbines

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ABSTRACT

Large diameter caissons are being considered as plausible foundations for supporting offshore wind turbines (OWTs) where reductions in overall cost and environmentally friendly installation methods are expected. The design calculations required for optimization of dimensions/sizing of such caissons are critically dependent on the foundation stiffness as it is necessary for SLS (Serviceability Limit State), FLS (Fatigue Limit State), and natural frequency predictions. This paper derives closed form expressions for the 3 stiffness terms (Lateral stiffness K_L, Rotational Stiffness K_R and Cross-Coupling term K_{LR}) for suction caissons having aspect ratio between 0.5 and 2 (i.e. $0.5 < L/D < 2$) which are based on extensive finite element analysis followed by non-linear regression. The derived stiffness terms are then validated and verified using studies available in literature. An example problem is taken to demonstrate the application of the methodology.

1. Introduction and background literature

With the growing interest and demand for renewable energy, larger wind turbines are used and installed in deeper waters. Fig. 1(a) shows a schematic diagram of the current and future wind turbine dimensions. Two important points may be noted:

(a) The hub height is increasing due to the large rotor diameter. This leads to the fact that not only does the dead load increase but more importantly the lateral loads and overturning moments will also increase. In fact, the governing load for foundation design is the large overturning moment.

(b) With increasing tower height and a heavier RNA (Rotor-Nacelle-Assembly) mass, the overall structure becomes more flexible and the target natural frequency for the so-called "*soft-stiff*" design shifts towards the wave frequency, see Fig. 1(b). For example, a typical 8 MW turbine will have a target frequency of 0.2 Hz which is very close to the predominant North Sea wave frequency of 0.1 Hz. This is even more challenging for Chinese Wind Farm developments as the predominant wave frequency for Bohai sea and the Yellow sea is 0.2 Hz, (Bhattacharya et al., 2017).

The above calls for optimized design and more importantly critical dynamic considerations. Monopiles are currently the most preferred foundations supporting 81% of Europe's OWTs (about 2900 turbines). However, there are multiple problems associated with monopiles of very large diameter (often known as XL piles) and the most obvious are the additional costs associated with material, manufacturing, transportation, and installation. Installation in particular poses numerous difficulties such as the risk of buckling of pile tip with very thin wall, large hammer requirements, and drilling requirement in the midst of driving (i.e. drill-drive-drill operation). These piles are hammered in dense sand or weathered bed rock, and several cases have been reported in the offshore oil and gas industry where large steel piles have collapsed during driving due to the progression of lateral deformations (Bhattacharya et al., 2005; Aldridge et al., 2005). Furthermore, there is a scarcity of installation barges required for driving piles of such large sizes which not only increases project costs but also construction delays. Apart from the engineering challenges, there are environmental issues: noise pollution caused by pile driving harms the marine life. German authorities impose regulations on pile driving noise (160 dB at 750 m distance) and it is expected to be adopted by other European nations in the near future (Müller and Zerbs, 2011). While measures may be adopted to limit noise pollution (such as the use of bubble curtains or sleeves), the success is limited (Golightly, 2014). In this context, it is important to state that foundations constitute about 34% of the overall cost of a wind farm mainly due to the stiffness requirements (Bhattacharya, 2013), and any innovation in this field can yield significant advantages.

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Nomenclature

L:	Foundation Depth
D	Foundation Diameter
R	Foundation Radius
Pile:	Foundation with $L/D > 2$
Caisson	Foundation with $0.5 < L/D < 2$
E_{SO}	initial soil Young's modulus at 1D depth
E_S	Vertical distribution of soil's Young's modulus
G_{SO}	initial soil shear modulus at 1R depth
υ_s	Soil Poisson's ratio
K_L:	Lateral stiffness of the foundation
K_{LR}	Cross-coupling stiffness of the foundation
K_R	Rotational Stiffness of the foundation
E_p:	Foundation Young's modulus
M	Applied moment at foundation head
H	Applied lateral load at foundation head
t	Foundation thickness
ρ	Foundation head deflection
θ	Foundation head rotation
I_p:	Foundation second moment of area
I_T	Tower second moment of area
f_0	First natural frequency (flexible)
f_{FB}	Fixed base (cantilever) natural frequency
C_L,C_R	Lateral and rotational flexibility co-efficient
m_{RNA}	Mass of Rotor Nacelle assembly
m_T	Mass of tower
C_{MP}	Substructure flexibility co-efficient
D_b	Tower bottom diameter
D_t	Tower top diameter
D_T	Average tower diameter
t_T	Tower wall thickness
Ψ	Length ratio
χ	Bending stiffness ratio

Large diameter suction caissons are currently being considered as an alternative to monopiles for water depths of 30 m and less. These foundations consist of a rigid circular lid with thin skirts (Fig. 2) and have been primarily used as anchors in the oil and gas industry. Extensive research has been conducted on the use of skirted suction caissons to support OWTs in sand and clays under different loading conditions where Houlsby et al. (2005) and Cox and Bhattacharya (2016) presented scaled model tests, numerical modelling and general comprehensive findings for feasibility. The installation of such foundation consists of allowing the caisson to sink under its own weight and then achieving full depth of penetration by pumping the trapped water out and also by creating a pressure difference. This method can arguably reduce noise pollution

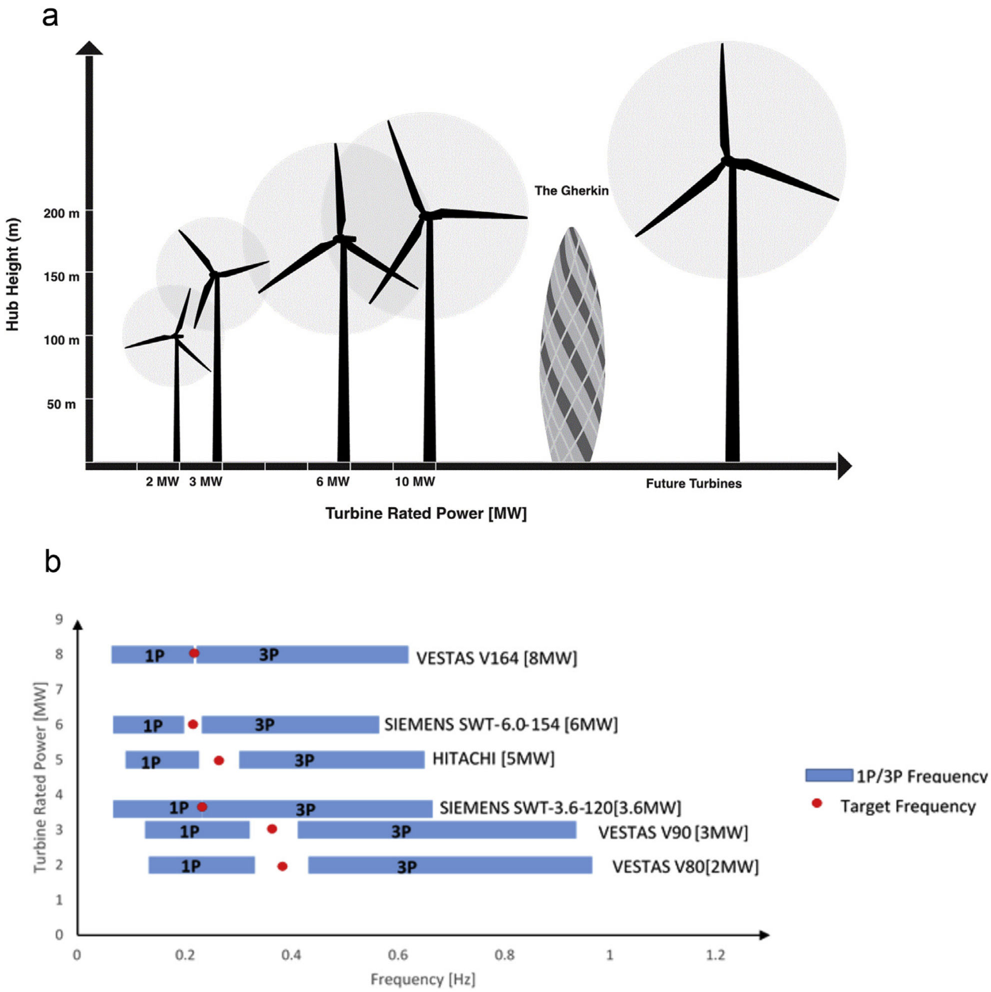

Fig. 1. (a): Current and Future OWTs. (b) Shift in target frequency.