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Effect of scour on the structural response of an offshore wind turbine supported on tripod foundation

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ABSTRACT

A simplified scour model for tripod foundation taking into account both local scour and global scour is proposed in this paper. The model is incorporated into a three-dimensional (3D) finite element model for analysis of a full-scale offshore wind turbine founded on a tripod structure using realistic structural properties. Applicability of the 3D finite element model is validated using full-scale load test data. Four different scour conditions under two wave situations are examined for the ultimate limit state (ULS), serviceability limit state (SLS) and fatigue limit state (FLS). The results show that scour has a minor effect on the natural frequency of the tripod-supported wind turbine but can significantly increase the maximum cross-sectional von Mises stress of piles under the ULS and increase the deflection of piles within nearly 20 m below the original seabed under the SLS. As for the fatigue life of the tripod structure, it can also be reduced by the effect of scour. These findings provide insights which are useful for development of safe and economic design of offshore wind turbines supported by tripod foundations.

1. Introduction

Engineers who plan and design wind turbines in offshore environment need to deal with scouring phenomena around the foundations for wind turbines [1,2]. Scour is the result of erosion of soil particles at and near a submerged foundation and is caused by waves and current. Scour can be regarded as a load effect and may have an impact on the capacity of the foundation and thereby on the response of the structure supported by it [3]. At present, most of the installed wind turbines in the world are supported by monopiles, and much work has been carried out to investigate the scour effect associated with monopile foundations [4–9]. Several methods have been proposed to estimate the maximum scour depth, the maximum scour extension and the development of scour depth over time [3,10]. These methods have been examined using full-scale measurements from nearly ten European offshore wind farms [4]. The examination showed that the maximum scour depth was less than the estimated for most wind farms [4,6]. The effect of scour on the natural frequency of a full-scale wind turbine with monopile foundation over a range of soil densities was studied using a numerical method [11], and it was found that the wind turbine in loose sand would exhibit the largest reduction in natural frequency resulting from scour.

For wind turbines with large capacity (>5 MW) and installed in deep waters (>30 m), monopile foundation is not considered economically viable or technically feasible [12]. Space-frame support structures such as tripod, tripile or jacket are feasible alternatives. Among these structures, a tripod structure is a three-legged steel structure which can provide good stability and stiffness to the entire system [13,14]. The tripod foundation has been used in three wind farm projects, namely Alpha Ventus, Trianel Windpark Borkum and Global Tech I Windfarm of Germany [12,15]. This type of foundation will also be used in Binhai and Dongtai offshore wind farms of Jiangshu province in China [16]. Due to the complexity of tripod structures, there are significant gaps in the knowledge of scour initiation and progression and their effects on stability of the structures. This knowledge is however important for the development of safe and cost-effective design of large offshore wind turbines [17]. Currently there is a rather limited number of studies concerning the effect of scour on tripod structures [2,17]. A recent notable one is that of Stahlmann [17], in which the possible influencing factors on scour progression for a tripod structure were investigated using physical model tests in wave flumes and using CFD based numerical simulations. A comparison with in-situ measured scour data [19] showed overall good agreement.

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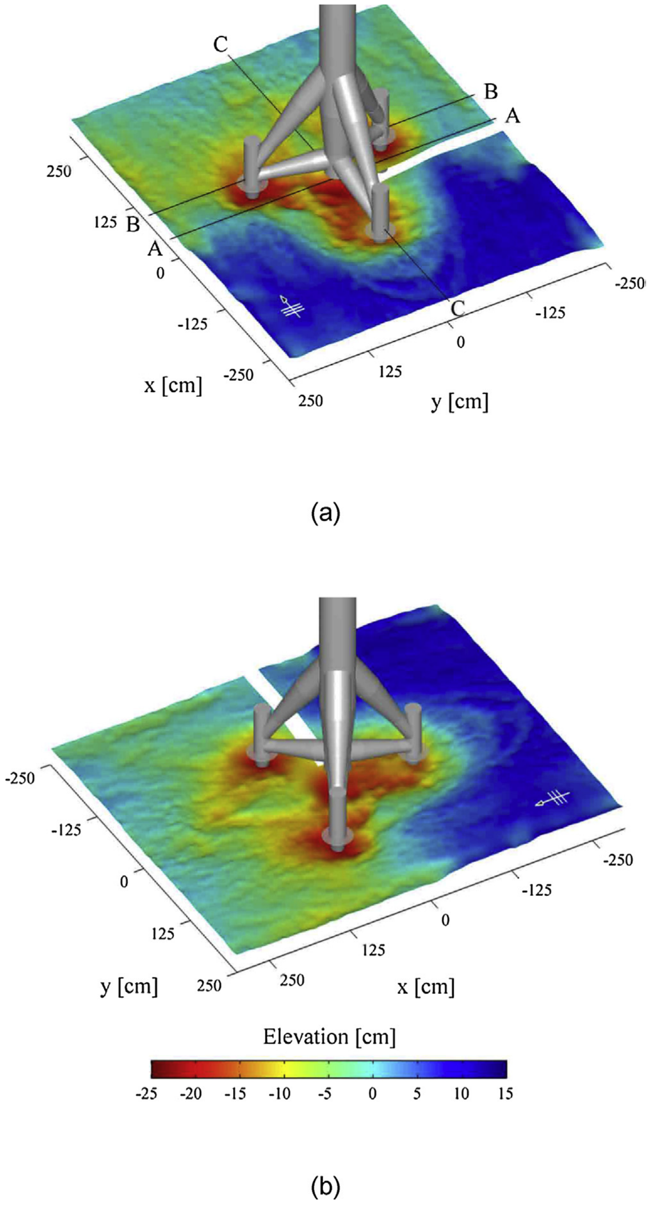
Nomenclature

The following symbols are used in this paper

A^{z}_{tower}	Wind pressure area on the tower of height z
C_D	Drag coefficient
C_M	Mass coefficient
C_s	Shape coefficient
C_T	Thrust coefficient
d_w	Water depth
D_{bb}	Diameter of the base
D_{bt}	Diameter of the brace
D^{b}_{mc}	Diameter of bottom segment of the main column
D^{m}_{mc}	Diameter of middle segment of the main column;
D^{t}_{mc}	Diameter of top segment of the main column
D_p	Diameter of the pile
D_s	Diameter of the sleeve
E_p	Young's modulus of steel
E_s	Young's modulus of the soil
$F_{current}$	Horizontal current drag force per unit length
F_D	Drag force
F_M	Inertia force
F^{Z}_{tower}	Wind load acting on the tower of height z
F_{vh}	Wind load acting on the hub
g	Acceleration of gravitation
h_w	Wave height
k	Wave number
r_b	Base radius of the tripod foundation
r_c	Radius of the lowermost main column
r_p	Radius of the tripod piles
r_{sc}	Radius of the scour hole under the main column
r_{sp}	Radius of the scour hole of the tripod piles
R_T	Rotor radius
S_c	Equilibrium scour depth under the main column
S_G	Global scour depth
S_p	Equilibrium scour depth of tripod piles
t_{bb}	Base wall thickness
t_{bt}	Brace wall thickness
t^{b}_{mc}	Bottom segment wall thickness of the main column
t^{m}_{mc}	Middle segment wall thickness of the main column
t^{t}_{mc}	Top segment wall thickness of the main column
t_p	Pile wall thickness
t_s	Sleeve wall thickness
T_w	Wave period
$U_{current}$	Local current velocity
V_{hub}	Wind speed at the hub height
V_z	Wind profile
z	Height above the sea water level
z_2	Depth below sea surface
α	Power law exponent
c'	Cohesion
ϕ'	Friction angle
λ_p	Unit weight of steel
ρ	Mass density of the sea water
ρ_a	Air density
γ'	Density of the soil
ψ'	Dilation angle
ν_p	Poisson's ratio of steel
υ'	Poisson's ratio of the soil
$\dot{x}$	Wave induced velocity of water
$\ddot{x}$	Wave induced acceleration of water
$\eta(t)$	Surface wave profile
w_w	Wave frequency
$\Delta\sigma_{eq}$	Equivalent stress range due to wind and wave loads
$\Delta\sigma_{wind}$	Stress range due to wind load
$\Delta\sigma_{wave}$	Stress range due to wave load
FLS	Fatigue limit state
SLS	Serviceability limit state
ULS	Ultimate limit state

In this paper, a simplified scour model including both local and global scour for tripod foundation is proposed based on the test results of Stahlmann [17] and field scour measurements for a tripod foundation in the Alpha Ventus wind farm [18]. This scour model is then incorporated in a three-dimensional (3D) finite element model for a full-scale offshore wind turbine founded on a tripod structure in which realistic structural properties for a 6 MW wind turbine are adopted. The applicability of the finite element model is validated against experimental results. The effect of stiffness and capacity of the foundation and the natural frequencies of the wind turbine system are investigated. Design implications for tripod foundations against scour are suggested.



(a)

(b)

Fig. 1. Results of scour development from test series r7655-01 after 3000 wave cycles [17]: (a) front view; (b) rear view.