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Transient behaviour of grouted connections of offshore wind turbines subject to ship impact

Renjie Mo[a,c], Miao Li[b,*], Haigui Kang[a]

[a] State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology, Dalian 116024, China
[b] Engineering, Faculty of Business, Justice and Behavioural Sciences, Charles Sturt University, Panorama Avenue, Bathurst, NSW, 2795, Australia
[c] COOEC Subsea Technology Co. Ltd, Technology building, No. 1067, Nanhai Road, Shekou, Shenzhen, China

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ABSTRACT

Grouted connections are a critical structural element of monopile-supported offshore wind turbines (OWTs), connecting turbine towers with foundation piles. Due to engineering requirements, they are normally installed at the mean water level (MWL), leading to high risk of ship collisions. In this study, transient response and damage analysis were performed on the grouted connections of monopile OWT when subjected to ship impacts. Taking into account the sandwich construction of the grouted connection of the OWT and the non-linear behaviour of the structure materials, a finite element model of a vessel of 2000-ton displacement collision with a 5 MW monopile OWT was developed using explicit finite element code LS-DYNA. The ship was assumed to strike head-on and at the middle of the grouted connection. Characteristics of the collision system in terms of energy, velocity, impact force and the response of the ship and the grouted connection were analysed. Internal contact forces, stress and effective plastic strain distribution of the grouted connection were discussed. Four phases of the collision process were identified: initial collision, motion towards maximum OWT deflection, towards vessel-OWT separation, and after separation. The ship collision response and damage of the grouted connection were considerably influenced by the strain rate effect of the structure materials. Collided by a ship, even at a low velocity of 2 m/s, the grouted connection for monopile OWT could suffer heavy or major damage. The current analysis sheds light on the dynamic response of grouted connections of monopile OWTs to ship impact. It lays a solid foundation for future analysis on the design of grouted connections of OWTs.

1. Introduction

Offshore wind power as a renewable green resource attracts significant interest for its potential to protect the ecological environment. Taking advantage of vast available offshore areas and strong wind resources, the offshore wind market has grown exponentially worldwide over the last decade. According to the European Wind Energy Association (EWEA), Europe's cumulative offshore wind power capacity reached 12,631 MW at the end of 2016, across a total of 3589 offshore wind turbines (OWTs) [1]. Statistics compiled by the Chinese Wind Energy Association show the country had installed a total of 1630 MW of offshore wind capacity by the end of 2016, and more than twenty offshore wind farms are under construction or in planning [2]. However, as the development of offshore wind industry grows, more wind farms will be built and located closer to traffic areas for commercial and passenger ships. In addition, the use of offshore supply vessels within wind farms is required to perform a regular inspection and maintenance. As a result, the probability of OWT stricken by ships will increase. On 6th October 2006, a jack-up barge collided with an offshore wind turbine in the Scroby sands wind farm. About 20 cm off the tip of the 40 m blade was broken and vital maintenance works on wind turbines were interrupted [3]. On 21st September 2003, a float dock broke loose from the tug and threatened the wind farm in Lolland, Denmark [4]. For this reason, analysis should be conducted to evaluate the risk of ship collision events and ship collision safety of OWT structures.

In monopile OWT, grouted connection is usually used to connect the turbine tower to the monopile foundation, as illustrated in Fig. 1. However, grouted connections are usually installed at the mean water level (MWL) due to engineering requirements. In ship collision scenarios, ship collision greatly impacts on the large diameter grouted connections within a very short period of time. This short impact time by ships may lead to deformation of the wind turbine and local damage of the grouted connection. More specifically, the yield or crushing of the grout, which are concrete yet fragile material with a high compression strength but a low tension strength, will occur. Accordingly,

* Corresponding author.
E-mail address: mli@csu.edu.au (M. Li).

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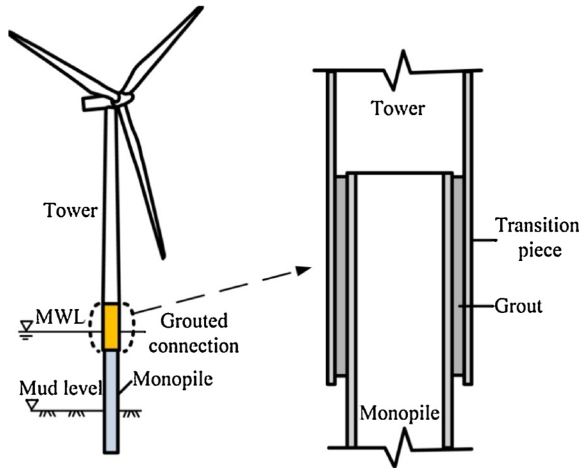

Fig. 1. Monopile OWT and its grouted connection.

for safe design and reliable utilization of OWTs, transient behaviour of grouted connections subject to ship impact requires to be better understood.

Ship collisions were traditional concerns for bridge structures over navigable waterways, offshore oil and gas platforms and ship collision with other ships. Efforts have been made to investigate ship impact forces and damage to structures. By analysing ship-ship collision, Minorsky [5] proposed an empirical relationship between the resistance of penetration and the energy absorbed in the collision process. Based on the test results of high energy ship collisions, Woisin [6] modified Minorsky's method and proposed a new empirical formula for ship-bridge collision. Based on the idealised structural unit method, Paik and Pedersen [7] presented a mathematical method to evaluate structural damage due to ship collisions. Zeinoddini et al. [8] studied the effects of axial pre-loading on a cylindrical member of an offshore structure struck by a supply vessel. It was found that the axial pre-loading has a remarkable effect on the lateral collapse load and the energy the cylindrical member can absorb prior to collapse. Jin et al. [9] proposed a comprehensive procedure to evaluate the damage to an offshore jacket platform that collided with a large barge. Wang et al. [10] presented a flexible energy-dissipating crashworthy device, consisting of hundreds of steel-wire-rope coil connected in parallel and series. Travanca and Hao [11] studied the dynamic behaviour of steel offshore platforms that were subjected to ship impact.

As the development of offshore wind energy industry grows, attentions are attracted to ship collision safety of OWTs. Analysis have been conducted to investigate collision risk [12], impact damage [13,14] and crashworthy device [15] of OWTs. Dai et al. [3] investigated the magnitude of the collision risk and risk-influencing factors of vessel collisions with OWTs, and concluded that collisions between turbines and service vessels with a low speed can cause damage to the turbines. Biehl and Lehmann [16] studied the anti-impact performances of monopile, jacket and tripod OWTs subject to side impacts of tankers, container and bulk carries. Results showed that monopile and jacket OWT were safer than tripod OWT. In order to minimise the damage to tripod substructures caused by collisions with service boats, Lee [17] numerically analysed the influences of boat speed and material of the rubber fender on strain energy, total deformation, plastic strain, internal energy, and deformation of the supporting foundation. Based on the simulation results, minimum thickness of rubber fenders was suggested relative to different barge speeds to relieve the impact damage for the structure. Ren and Ou [18] proposed a crashworthy device for OWT using steel sphere shell, circular ring aluminum and form pad. Graczykowski and Szulc [19] numerically simulated ship collision with wind turbine towers protected by pneumatic structures. Results showed that inflatable structures can effectively protect the wind turbine towers and the ship against serious damage. Liu and Hao [20,21] analysed anti-impact performance of monopile, tripod and jacket OWT foundation and proposed a cylindrical crashworthy device for monopile OWTs, which contains a rubber blanket and an outer steel shell. Bela et al. [22] analysed offshore supply vessel of 3000 tons displacement collision with monopile OWT. The results showed that the monopile OWT can withstand collisions without collapsing with an impact velocity of up to 6 m/s. However, the grouted connection was not considered in the simulation. Moulas et al. [23] analysed the damage of monopile and jacket wind turbine foundations subjected to ship collision. The study showed that the collision energy, the height of the vessel and the area of the impact are all critical factors for ship collision with monopile foundation. It was stated that ship with low profile hit on the transition piece resulting in less extensive damage. However, the striking ship was assumed to be rigid, and the sandwich construction of the grouted connection was not considered in the analysis.

In published papers, little attention has been paid to the dynamic response and the damage of the grouted connection of OWTs in the previous studies of ship collision-safety of OWTs. Nevertheless, ship hitting the grouted connection could lead to local deformation and crushing of the grout layer, and thus result in failure of the grouted connection. Further research is needed to better understand the responses and safety of the grouted connection when subjected to ship impact. The purpose of this study is to investigate the dynamic response and damage of the grouted connection of monopile OWT when subjected to ship collision. The study case is a 5 MW monopile wind turbine with a conical grouted connection standing in a wind farm in the East China Sea. The ship-OWT collision model is developed using the explicit finite element code LS-DYNA. The grouted connection is modeled as cone shape concentric tubes with different materials, and the nonlinear and failure of the grout material is accounted for. The pile-seabed soil interaction was model using p-y curve method [24]. A deformable ship of 2200 tons displacement navigating at different initial velocities head-on strikes on the middle of the grouted connection were simulated. The dynamic responses of the grouted connection and the OWT, and damage of the grout layer were analysed.

The remainder of this paper is arranged as follows: Section 2 describes the characteristics of the 5 MW monopile OWT and the grouted connection adopted in this study, and outlines the vessel-OWT collision system. The finite element model of the vessel-OWT collision system is developed and validated in Sections 3 and 4, respectively. In Section 5, modal analysis is conducted to investigate the modal characteristics of the monopile OWT. The behaviour of the vessel-OWT collision system and the responses of the grouted connection are thoroughly analysed in Section 6. Finally, conclusions are made in Section 7.

2. Problem description

2.1. Physical description of the OWT and the grouted connection

In this study, the National Renewable Energy Laboratory (NREL) 5 MW baseline wind turbine [25] is used as a reference wind turbine, with main parameters listed in Table 1. The wind turbine is to be installed with a monopile

Table 1
NREL 5-MW baseline wind turbine [25].

Rating	5 MW
Rotor orientation, configuration	Upwind, 3 blades
Rotor, hub diameter	126 m, 3 m
Hub height (relative to basic flange)	80 m
Cut-in, rated, cut-out wind speed	3 m/s, 11.4 m/s, 25 m/s
Cut-in, rated rotor speed	6.9 rpm, 12.1 rpm
Rotor, Nacelle, Tower mass	110,000 kg, 240,000 kg, 347,460 kg
Coordinate location of overall CM	(−0.2 m,0.0 m,64.0 m)