Renewable Energy 131 (2019) 667–677

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

New detected uncertainties in the design of foundations for offshore Wind Turbines

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ARTICLE INFO

Article history:
Received 29 November 2017
Received in revised form
18 July 2018
Accepted 20 July 2018
Available online 23 July 2018

Keywords:
Offshore wind farms
Monopiles
Gravity based structures
Technical standards
Recommendations

ABSTRACT

In 2014, the Renewable Energy Journal published innovative research where the authors showed the results obtained in work where the design of support structures and foundations in marine based wind farms were questioned. The uncertainties in the design were then justified by the "limited" field experience and in the review of the standards and recommendations existing at that time. Fundamentally, an analysis was made of the ratio between useful life and the probability of failure, the wave theories to be used, the hydrodynamics of Morison, Froude-Krylov and diffraction domains, together with the scouring phenomena processes and consequent protection of structural items.

Using the knowledge gained during these three years, the research work herein presented covers further reflections such as the nonlinearity in wave mechanics, its effects on orbital seabed velocities, variation in the behaviour of the Keulegan-Carpenter number (KC), impact on scour in the KC-6 equation, the analysis of statistics of forces applied to load combinations in structures at depths in excess of fifty metres, taking giant steps in offshore engineering and leaving behind classical maritime engineering techniques.

1. Introduction

Offshore wind power has reached an outstanding position in the electricity market over the last few years [1]. During 2017, it did set a record of 3148 MW of new power capacity connected to the European grid. At the end of 2017, there were 15,780 MW of offshore wind power in operation, with a total of 4149 turbines. This system provides almost 1.5% (43 TWh) of electricity consumption in the European Union per annum (2906 TWh). The UK is the leading country in this field (6835 MW, i.e. 43% of the total power in Europe), followed by Germany (5355 MW, 28%), and Denmark (1266 MW, 12%) [2].

In view of this fact, more countries such as France, Denmark or Belgium, amongst others, are positioning their national electricity strategy for this source [2]. Demand and consumption have come to be a technical challenge [1]. The sea has been conquered as far as design, materials and machines are concerned and increasingly larger and more powerful farms are being built [3]. Nevertheless, from the maritime engineering perspective, uncertainties are still being found in all phases of design, construction, operation, repair and dismantling when the useful life has been reached.

The fundamental ideas expounded in 2014 are reviewed on a synthesis level and in connection with the new uncertainties raised here [1]:

- The useful life/return period ratio [4,5].
- The useful life/probability of failure ratio [5].
- The comparison between the Linear Wave Theory [6] and Stokes higher order schemes [7–10].
- The pile diameter/pile length ratio [11].
- The difference between the various wave heights considered (H_s, H_{max}) and the undulatory wave periods associated to them (T_{02}, T_m, T_s, T_p or $T_{0\text{-}2}$)

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https://doi.org/10.1016/j.renene.2018.07.103
0960-1481/

- The Keulegan-Carpenter number [12].

The Useful life commonly considered is 20 years, while the return period (T_r) of the design storm is 50 years. This implies that there is a 33% probability (Pr) of a design storm appearing [4,5] during the useful life (n) of the structure as shown in the equation below. This value should be unacceptable:

$$\Pr(T_{rn}) = \left(1 - \left(1 - \frac{1}{T_r}\right)^n\right) \bullet 100 = \left(1 - \left(1 - \frac{1}{50}\right)^{20}\right) \bullet 100 = 33\% \tag{1}$$

In addition, the ratio between the aforementioned useful life and the commonly used probabilities of failure (Pf = 0.10 for rigid elements and 0.20 for flexible elements), gives rise to return periods of [5]:

$$T_r = \frac{-n}{ln\left(1 - P_f\right)} = \frac{-20}{ln(1 - (0.10 \sim 0.20))} = \begin{matrix} 89\ years\ flexible \\ 189\ years\ rigid \end{matrix} \tag{2}$$

The Linear Wave Theory [6] is normally used for considering the climate's design forces instead of Stokes higher order (nonlinear) wave theories [7], as defined by Le Méhauté's [8], Dean and Dalrymple's [9] or Horikawa's nomogram [10].

The slenderness of piles is a determining factor in order to consider linear or nonlinear hydrodynamic behaviour for their design. So, for D/L ratios less than 0.05, Morison's formulation is usually employed and for ratios of D/L higher than 0.20, diffraction controls the structural response to the hydrodynamic actions, with the range between both figures (0.05–0.20) acting as a transition region [11].

Scour depends on the KC number [12] and not on the sea bed geotechnical parameters (friction angle, ϕ, cohesion, c, and soil density, γ). The seabed-structure interaction and the geotechnical parameters of the foundation's substrate must also be included in the design.

Following a review of these ideas, this research paper will develop another series of reflections related to the monopile type of structures typically used in the construction of offshore wind farms (Fig. 1).

The investigation work carried out has led to innovative results in this field of study, which will be dealt with in this paper in order to provide answers to different physical phenomena occurring in the offshore wind farms:

- What would happen if nonlinear phenomena were added to the calculation of orbital wave velocities? This directly impacts the prevalence of drag forces, inertia forces, or diffraction, according to different domains of hydrodynamic behaviour:

$$U = \frac{H}{2}\frac{gT}{L}\frac{cosh\left(\frac{2\pi}{L}(h+z)\right)}{cosh\left(\frac{2\pi h}{L}\right)}cos\theta[Linear\ Wave\ Theory][6] \tag{3}$$

$$U = \frac{H}{2}\frac{gT}{L}\frac{cosh\left(\frac{2\pi}{L}(h+z)\right)}{cosh\left(\frac{2\pi h}{L}\right)}cos\theta + \frac{3}{4}H^2\omega\frac{2\pi}{L}\frac{cosh\left(\frac{4\pi}{L}(h+z)\right)}{sinh^4\left(\frac{2\pi h}{L}\right)}cos2\theta[Stokes\ 3rd\ order][7] \tag{4}$$

- What would happen if the celerity field was altered, taking into consideration a nonlinear theory instead of linear calculation schemes? This directly affects scouring occurring in the seabed-foundation interaction region, and in the forces and the stress-strain suffered by the piles:

$$C = \sqrt{gh}\ \ [Linear\ Wave\ Theory] \tag{5}$$

$$C = \left(1 - \frac{1}{2}\frac{H}{h}\right)\sqrt{gh} \tag{6}$$

$$C = \left(1 - \frac{1}{2}\frac{H}{h} + \frac{1}{m}\frac{H}{h}I_{el}\right)\sqrt{gh} \tag{7}$$

- From the foregoing, how would the KC number be altered [12] (KC=(U·T)/D) depending on whether Linear Wave Theory [6] or Stokes Wave Theory [7] were used, as well as depending on the wave statistics (T_{02}, T_p, T_s …)? As scouring (either local or global effects) depends directly on the value of the KC number, the estimation of this scouring (scour depth, scour extension, etc) might vary considerably when considering linear or nonlinear wave theories to compute the KC number.
- The maximum scour the structure may potentially suffer due to hydrodynamic effects without taking into consideration the geotechnical characterisation of the seabed on which it has its foundations, may be obtained from Sumer and Fredsoe formulation [13,14], drawn up for D/L < 0.2, L < 30 m, T < 4 s or from DNV formulation. S_{max} might also attain different values depending on the wave theory considered. Using Sumer and Fredsoe formulation:

$$\frac{S_{máx}}{D} = \frac{S_c}{D} = (1 - exp(-A(KC - B))) \tag{8}$$

where

Fig. 1. Fabrication and on-site setting up of monopile type support structures for an offshore wind farm (source: Heavylift news, OffshoreWIND.biz, Groundsure Location Intelligence).