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Probabilistic examination of the change in eigenfrequencies of an offshore wind turbine under progressive scour incorporating soil spatial variability

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ABSTRACT

The trend for development in the offshore wind sector is towards larger turbines in deeper water. This results in higher wind and wave loads on these dynamically sensitive structures. Monopiles are the preferred foundation solution for offshore wind structures and have a typical expected design life of 20 years. These foundations have strict serviceability tolerances (e.g. mudline rotation of less than 0.25° during operation). Accurate determination of the system frequency is critical in order to ensure satisfactory performance over the design life, yet determination of the system stiffness and in particular the operational soil stiffness remains a significant challenge. Offshore site investigations typically focus on the determination of the soil conditions using Cone Penetration Test (CPT) data. This test gives large volumes of high quality data on the soil conditions at the test location, which can be correlated to soil strength and stiffness parameters and used directly in pile capacity models. However, a combination of factors including; parameter transformation, natural variability, the relatively small volume of the overall sea bed tested and operational effects such as the potential for scour development during turbine operation lead to large uncertainties in the soil stiffness values used in design. In this paper, the effects of scour erosion around unprotected foundations on the design system frequencies of an offshore wind turbine is investigated numerically. To account for the uncertainty in soil-structure interaction stiffness for a given offshore site, a stochastic ground model is developed using the data resulting from CPTs as inputs. Results indicate that the greater the depth of scour, the less certain a frequency-based SHM technique would be in accurately assessing scour magnitude based solely on first natural frequency measurements. However, using Receiver Operating Characteristic (ROC) curve analysis, the chance of detecting the *presence* of scour from the output frequencies is improved significantly and even modest scour depths of 0.25 pile diameters can be detected.

1. Introduction

In order to meet increasing energy demands, reduce reliance on non-renewable sources and increase energy security, alternative and renewable energies are in high demand. In Europe, offshore wind turbines provided over 11,000 MW of grid-connected capacity at the end of 2015 [1], supplying 1.5% of the electricity consumption demand of the European Union (EU) [2]. The offshore wind industry is continually undergoing rapid development, tending towards larger capacity turbines, ever-increasing hub heights and

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locations further offshore in deeper waters. This rapid development is a challenge for foundation design, and design methods are constantly evolving [3,4].

To date, over 80% of offshore turbines are founded on monopiles, followed by 9% founded on Gravity Base Foundations (GBFs) and approximately 5% on jacket structures [1]. Other solutions include Tripods, Tripiles, floating solutions as well as experimental foundation concepts. Monopiles are by far the preferred foundation solution with typical diameters (D) ranging from 4 to 6 m and larger with typical penetrations (L) of 20–30 m [5,6]. As turbines grow larger and water depths increase monopiles with diameters of up to 10 m are being planned, leading to increased foundation costs. Foundations typically account for 30% of the cost of the entire system [7]. Larger monopiles will lead to increased lateral hydrodynamic loads, impacting the monopile in the horizontal direction, resulting in significant shear forces and overturning moments. Foundations typically resists this loading through flexural action and rigid rotation and the ultimate capacity is governed by soil strength properties or the structural properties of the pile. Rigid monopiles with slenderness ratios, length normalised by diameter (L/D), of 5 and below have more uncertain lateral load-resistance characteristics as the design methods for offshore piles were originally developed for long, slender piles [8–11] which flex under an applied lateral load.

Scour erosion around monopiles reduces the lateral load bearing capacity as well as the soil-structure interface stiffness [12] and can result in significant changes to load effects at the mudline level. Scour occurs when the near bed shear stresses applied by hydraulic action exceed the threshold shear stress at which sediment commences movement and occurs as a result of the obstruction caused by the monopile changing the waterflow characteristics locally [13]. It is a complicated mechanism and is environment dependent. In rivers, scour generally occurs under steady current conditions whereas in the marine environment, it occurs due to current, tides and waves [14]. The combined action of current and waves typically gives rise to lower ultimate scour depths than under current only conditions [10,15], however the interaction is complex and uncertain.

Scour alters the dynamic characteristics of structures, a phenomena that has led to significant research interest related to the performance of river bridges [16–23]. From this research there is consensus that scour reduces the foundation stiffness for bridges. In the offshore environment however, there is uncertainty about the effects of scour on the strength and stiffness properties of soil and the combined effects of load cycling and pore pressure accumulation [6]. In marine conditions, combined effects from currents and waves lead to variations in the equilibrium scour depth, with erosion and backfilling both occurring. Unlike in rivers under live-bed erosion conditions [24], where the deposited material typically has lower strength and stiffness properties, the wave action can densify this material potentially restoring stiffness to pre-scour levels or higher [25]. The uncertainty associated with the effects of scour on the strain dependant stiffness behaviour of the remaining soil, cyclic load response, bearing capacity and other factors potentially makes scour occurrence a critical safety issue.

The analysis in this paper builds on the study presented by Prendergast et al. [26], which examined the effect of scour on the natural system frequency of an offshore turbine under three idealised soil profiles. The model is expanded in the present work to investigate the effect of spatial variability in soil properties derived from measured Cone Penetration Test (CPT) data on the system frequencies of a typical turbine under scoured conditions. A sample of twenty deep CPT profiles measured in a reclaimed area of Rotterdam Harbour were used to generate 50,000 hypothetical spatially-correlated CPT profiles for the statistical analyses. A Monte-Carlo analysis was performed to derive the likely system frequencies for a typical offshore turbine considering a range of scour depths. The variation in frequency from the spatial uncertainty of the ground conditions and with scour is investigated, with a view to understanding whether the magnitude of the changes could be detected within a SHM framework.

2. Test site

The ground model developed in this paper is based on data from the Port of Rotterdam, Netherlands. The site was originally located offshore in the North sea, but was reclaimed by the Dutch Authorities in the 1970s [27]. The site consists of predominately Holocene era sands to a depth of approximately 25 m below existing ground level (egl) with bulk unit weights ranging from 18.5 to 20.5 kN m^{-3}. The relative density (D_r) is approximately 50%. Some modest clay to clayey silt lenses of varying thickness are found in between primarily close to ground level, with a maximum thickness of approximately 1 m–1.5 m. The bulk unit weight of the clay layers is in the range of 15–18 kN m^{-3}. Some medium coarse Pleistocene sands are found at a depth of 24–25 m below egl [27], with a bulk unit weight between 19 and 20 kN m^{-3}, a D_r of 80% and ϕ' between 35° and 37°. The perched water table elevation ranges from a minimum of 3.5 m below egl to a maximum of 1 m below egl. Twenty CPT q_c profiles were measured at the site and corrected to the ordnance datum (NAP). The relative locations of these CPT profiles are shown in Fig. 1. Fig. 2 shows the CPT q_c profiles measured, with the average and maximum/minimum envelopes also shown. As is evident, there are two distinct layers present in the profiles, transitioning at approximately 23–25 m below ground level.

3. Stochastic ground model

Soil is a naturally heterogeneous material, understanding how it varies is essential to the development of accurate mechanics based ground models, which can encapsulate and subsequently represent soil physical properties. Traditionally, variability within soil was accounted for by subdividing the soil into a number of discrete layers, with each layer having a different set of deterministic soil parameters to describe the soil properties within that layer [28,29]. Naturally, given the significant uncertainty present in such an approach, conservative values have to be chosen.

In an effort to eradicate such gross oversimplifications, probabilistic techniques have come to the fore for geotechnical applications [30–34]. Such approaches utilise all of the available data from a soil layer in the form of a probability distribution. While the

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