Probabilistic Assessment of Cyclic Behavior of Laterally Loaded Piles in Sand

Ivan Depina, Thi Minh Hue Le, Gudmund Eiksund and Thomas Benz
Department of Civil and Transport Engineering, Norwegian University of Science and Technology (NTNU) Trondheim, Norway

This article provides insight into the influence of soil variability on the performance of a monopile type of wind turbine foundation subjected to long-term lateral cyclic loading in sandy soil. The effects of soil variability are studied by coupling a numerical pile-soil model with the stochastic model of soil properties. The variability of soil properties is transformed by the numerical pile-soil model in the uncertainties of the resulting pile deflections, rotations, and bending moments. A statistical representation of the results of the stochastic simulations is used for the probabilistic assessment of the ultimate and the serviceability limit state. The cyclic soil behavior is taken into account by means of an elasto-plastic stiffness degradation model.

INTRODUCTION

The requirement that the European Union (EU) will reach a 20% share of energy from renewable sources by 2020 (EU, 2009) is powering the development of reliable and cost-effective renewable energy sources. One of the sources with great potential is wind energy, captured by wind turbines installed onshore and offshore. Due to the environmental impact and a lack of space onshore, the number of offshore wind turbines is steadily increasing (Breton and Moe, 2009). The offshore environment is introducing new challenges to wind turbine technology, and many of these challenges have not been solved properly from the technical-economic standpoint (Breton and Moe, 2009). Until now, the focus in wind turbine design was on the “upper” part of the wind turbine, and there has been a lack of adequate consideration of the foundation design, which is becoming an important issue. This is because of the intention to place wind turbines in greater sea depths, to prolong the operational period of the foundations, and to reduce the cost of production and installation of the foundations. All these requirements result in the need for a greater understanding of the processes and parameters that define the environment of the wind turbine. Special consideration is dedicated to the long-term behavior of the foundations, where accumulated displacements resulting from the cyclic loading can play an important role.

Since around two-thirds of the installed wind turbines as of the end of 2013 are based on monopile foundations (LORC, 2013), this study deals with the challenges related to the behavior of monopile foundations under long-term cyclic loading. The cyclic loading, caused by the interaction of the wind turbine with waves and winds, causes the accumulation of displacements on the foundations during the operational lifetime of a wind turbine. These displacements over time can accumulate in such quantity that they exceed the pile rotation limit defining the serviceability limit state or generate forces in the pile that exceed the values defining the ultimate limit state. It is important to have a reliable estimate of the long-term rotation of the pile in the design phase.

Current design codes (e.g., DNV, 2010 or API, 2005) for estimating the static and cyclic lateral resistance of monopile foundations rely on the API method (Matlock, 1970; Reese et al., 1974) due to its simplicity and ability to incorporate soil nonlinearity. The API method is a semi-empirical procedure developed from tests conducted on slender piles in soft soil. In the case of large diameter piles, where small deformations are a concern, the API method performs conservatively because it is not intended for use in the evaluation of the soil capacity (Augustesen et al., 2000; Hamre et al., 2010). Due to the absence of soil continuum effects and the fact that the accumulated deformations are not directly related to the number of cycles, advanced finite element (FE) models with nonlinear material models are preferably used in the analysis of the lateral cyclic resistance of monopiles (Achmus et al., 2009; Niemunis et al., 2004).

In order to understand the influence of the variability of soil properties on the lateral bearing capacity of piles, several studies have been conducted where soil properties are assumed to be random. The majority of these studies are conducted by using the API model. For example, Legian and Hadley (1977) investigated the uncertainties in estimated deflections and bending moments. Folse (1989) used the design point method to estimate the reliability of laterally loaded piles by including variability in soil, load, and pile parameters. Chan and Low (2009) investigated the reliability of piles by modeling point and spatial soil variability with random fields. Tandjiria et al. (2000) estimated the reliability of laterally loaded piles by implementing the response surface approach in the probabilistic analysis. Chan and Low (2012) combined the response surface and the neural network methodology to reduce the complexity of the probabilistic model. Andersen et al. (2012) implemented a random field model of soil properties in order to identify the first natural frequency of wind turbines. Fenton and Griffiths (2007) investigated the axial capacity of a pile by implementing random field theory to model variability in the soil and pile material properties. In Haldar and Babu (2008), a 2D random field has been created to study the capacity of a laterally loaded pile.

This study conducts a probabilistic assessment of the long-term cyclic behavior of a monopile type of wind turbine foundation in sandy soil by evaluating the effect of soil variability. The probabilistic assessment is conducted by coupling the stochastic model of soil variability with the 3D FE pile-soil model. The long-term cyclic behavior of sand is simulated by implementing the stiffness degradation material (SDM) model (Achmus et al., 2009). Uncertainties associated with the response of the monopile foundation are used to evaluate the ultimate and the serviceability limit states.