Experimental Comparison of Non-Slender Piles under Static Loading and under Cyclic Loading in Sand

Søren Peder Hyldal Sørensen and Lars Bo Ibsen
Department of Civil Engineering, Aalborg University, Aalborg, Denmark

ABSTRACT

An experimental evaluation of the pile behavior of non-slender piles exposed to static and cyclic lateral loading is presented. The tests were conducted in a pressure tank at Aalborg University. This enabled the possibility of applying an overburden pressure to the soil. When conducting small-scale tests at 1-g the determination of the friction angle and the Young’s modulus of elasticity of the soil are difficult and further these soil parameters varies greatly with depth. These uncertainties were avoided by application of an overburden pressure.

KEY WORDS:
Piles; Experimental testing; Lateral loading; Offshore wind turbine; Pressure tank; Static loading; Cyclic loading.

INTRODUCTION

Wind energy is a competitive source of renewable energy. Presently, the majority of the wind turbines are located onshore due to lower construction costs onshore than offshore. However, the amount of suitable locations for wind turbines on land is limited due to dense populations, built-up areas, etc. As an alternative, wind turbines can be positioned offshore. The first large-scale offshore wind farm were installed at Horns Rev, Denmark, in 2002. Since then, several offshore wind farms have been built in, among others, Denmark, Germany, and Great Britain. Furthermore, several offshore wind farms are either under construction or under consideration.

The foundation costs of offshore wind farms account for up to 30 percent of the total costs. Hence, it is of great financial interest to optimize the foundation design. Several foundation concepts have been proposed for offshore wind turbines. Until now, mostly the gravitational foundation concept and the monopile foundation concept have been employed. However, foundation concepts such as jacket structures, tripods, and bucket foundations might be suitable for wind farms located on deeper water. The choice of foundation depends primarily on the soil conditions and the water depth. However, other factors such as the sea conditions and the size of the wind turbines also play a role in the choice of foundation concept. This paper deals with the monopile foundation concept.

Typically, monopiles are hollow steel tubes driven or drilled open-ended into the seabed. The pile diameter, $D$, the embedded pile length, $L$, and the pile wall thickness, $wt$, are often 4-6 m, 15-30 m, and 0.05-0.1 m, respectively. Hence, the slenderness ratio, $L/D$, is around 5, and the piles therefore exhibit a rather rigid behavior.

Foundations for offshore wind turbines are exposed to large lateral loads and overturning moments mainly due to loading from wind and waves. Ubilla et al. (2006) state that the design loading on a 3.5 MW wind turbine is approximately 6 MN in vertical loading, 4 MN in horizontal loading, and 120 MNm in overturning moment. The vertical loading primarily originates from the weight of the structure. Hence, the vertical loading can be considered as a static load. The horizontal load is in contrast a cyclic load. According to LeBlanc (2009), the wave frequency of extreme waves is typically 0.07-0.14 Hz while the energy rich wind turbulence typically is below 0.1 Hz.

When designing foundations for offshore wind turbines, especially the serviceability and the fatigue limit state is of high importance. The wind turbine supplier often requires the accumulated rotation of the foundation to be less than a specified value and further requires the natural frequency of the structure to be between the rotor and the blade passing frequency. To fulfill these requirements, it is important to model the stiffness of the foundation accurately.

Currently, design regulations by organizations such as the American Petroleum Institute and Det Norske Veritas (API 2000; DNV 2010) recommend the use of the Winkler Model Approach for the design of monopile foundations for offshore wind turbines. Hence, the pile is modeled as a beam on an elastic foundation, and the soil-pile interaction is modeled by means of a series of uncoupled, non-linear springs. These springs describe the relationship between the pile deflection, $y$, and the soil resistance acting against the pile wall, $p$. The $p-y$ curve formulation proposed by Murchison and O’Neill (1984) is currently advised in API (2000) and DNV (2010). This formulation is a slight modification of the formulation originally proposed by Reese et al. (1974). Both the formulation proposed by Reese et al. (1974) and Murchison and O’Neill (1984) are based on experimental tests on slender piles with length to diameter ratios larger than 10. Hence, these formulations have not been validated for the non-slender piles which...