Cyclic lateral loading of monopile foundations in sand

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Abstract

Monopiles are large open ended steel piles of 3.5-8 m in diameter which are often used as foundations for offshore wind turbines. Due to the action of wind, waves and rotation of the turbine blades, monopile foundations must withstand large lateral loads while meeting serviceability conditions on pile head rotation and natural frequency. The pile head rotation must not exceed 0.5^{o} and the natural frequency of the structure must not interact with the frequencies of cyclic lateral loading. In order to ensure this, engineers must be able to predict the response of monopile foundations to monotonic and cyclic lateral loading.

Monopile foundations are currently designed using the p-y method which is based on the assumption that the soil may be treated as a series of non-linear Winkler springs. The stiffness of the p-y springs is based on empirical relationships from full scale tests on laterally loaded piles (Reese et al., 1974). Research into the lateral response of monopiles suggests that these empirical relationships overestimate the stiffness of stiff piles. This may result in interaction between the blade passing frequency and the natural frequency of the turbine.

In this thesis, the response of a monopile in sand for a 3.5 MW offshore wind turbine is investigated via a series of lateral load tests conducted at prototype stress in a centrifuge. A pushover test was performed to identify the monotonic response of the pile. This serves as a backbone curve for a study into the response of the pile cyclic lateral loading. Further, the monotonic test confirms that existing design guidance over estimates the lateral stiffness of monopile foundations in sand. A modification to p-y curves proposed by Klinkvort (2012) is found to give an accurate prediction of the monotonic response.

Existing design guidance (API, 2011 and DNV, 2014) does not offer advice on how the stiffness of a pile changes during cyclic lateral loading. This study shows that during cyclic lateral loading at constant amplitude the stiffness increases logarithmically with cycle number for both loose and dense sand. The rate at which the response stiffens depends on the characteristics of the applied load, the effect of previous loading at different magnitudes and the density of the sand. Results from cyclic lateral load tests conducted in the centrifuge show that one-way loading results in the stiffest response of the pile and the greatest accumulation of displacement at the pile head. It is therefore, the critical case for changes in natural frequency and displacement of the pile. Based on the results of quasi-static loading over 4000 lateral load cycles, relationships are developed to predict the stiffness and displacement of the pile. These are shown to predict the response of the monopile in the centrifuge for up to 30,000 lateral load cycles at prototype frequency.

In order to understand the reasons for changes in the pile stiffness and displacement the bending moment in the pile and soil pressures acting on the pile were measured using strain gauges and Tekscan pressure sensors respectively. During cyclic lateral loading at constant amplitude strain energy was locked into the pile and soil. The locked in stresses were partially dissipated by loading in the reverse direction thus explaining why the lateral pile stiffness is greatest for one-way loading. Critical state soil mechanics is used to explain the measured changes in soil pressure around the pile during cyclic lateral loading at constant amplitude and for increases in the loading magnitude.