Prediction of Long-Term Deformations of Offshore Wind Power Plant Foundations Using HCA-Based Engineer-Oriented Models

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INTRODUCTION

The cyclic loading of offshore wind power plant (OWPP) foundations due to wind and wave action leads to permanent deformations. They may endanger serviceability since the OWPP generators tolerate only a small tilting (0.5°–1°) of the tower. Therefore, an accurate prediction of these long-term deformations is indispensable. The high-cycle accumulation (HCA) model proposed by Niemunis et al. (2005) is a suitable tool for that purpose. It has been validated based on simulations of model tests and full-scale in situ tests (Hartwig, 2010; Zachert, 2015; Zachert et al., 2014, 2015, 2016). Up to now, the HCA model has been primarily applied in finite element (FE) simulations (e.g., Wichtmann et al., 2010b; Zachert et al., 2014, 2015, 2016). Such calculations usually demand a rather laborious 3-D model and experienced knowledge on the field of FE. To facilitate the practical application of the HCA model to OWPP foundations, several simplified engineer-oriented models for different types of foundation structures have recently been developed by the authors based on the HCA equations:

- A sublayering model for the subgrade of shallow foundations under cyclic vertical loading. For example, such loading conditions are relevant for OWPPs founded on three or four separate footings. The calculation procedure using this model is similar to that in a conventional settlement calculation for foundations subjected to static loading, but with the HCA equations predicting the additional cumulative portion of settlement. In comparison to simple settlement formulas of type \( s(N) = s(N-1) - f(N) \) (or similar) (Diyaljee and Raymond, 1982; Hettler, 1984; Mallwitz and Holzlöhner, 1996), sublayering models are advantageous since they can be calibrated based on element tests in the laboratory. They are also more flexible with respect to stratified ground. Furthermore, it can be demonstrated that the common settlement formulas for cyclically loaded foundations are inconsistent, since the prediction depends on which cycle is regarded as the first one (Nienunis and Wichtmann, 2014).

- A sublayering model for the soil surrounding monopile foundations under horizontal cyclic loading. The soil stiffness and the cumulative deformations are represented by springs and dashpots, respectively. The cumulative deformations are calculated with the HCA model.

- A stiffness-degradation model (SDM) for monopile foundations under horizontal cyclic loading, with the stiffness-degradation factor based on the HCA model.

The following sections present the basic ideas and equations of these engineer-oriented models, along with some exemplary calculations. The predictions of the simplified models are compared to the results from FE simulations using the full HCA model.

In the case of monopile foundations, the prediction is also compared to the prognosis of the following engineer-oriented models available in the literature:

- The procedure according to the API (American Petroleum Institute, 2000) utilizing \( p-y \) curves with a reduction of the bedding stiffness considering cyclic loading.

- A modification of the API approach proposed by Dürrkop (2010), based on small-scale model tests on monopiles under horizontal cyclic loading.

- The enhanced strain wedge model (ESWM) published by Taşan (2012), an extension of the strain wedge model of Norris (1986) and Ashour et al. (1998) for cyclic loading conditions.

- The SDM of Achmus et al. (2008). Using that model, a monotonic loading of the monopile is simulated with a 3-D FE model and a simple elastoplastic constitutive model. Young’s modulus is reduced, accounting for the increased deformations due to cyclic loading.

A critical assessment of these various models can be found in Westermann et al. (2014a, 2014b). Simple formulas of type...