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Axial capacity degradation of single piles in soft clay under cyclic loading

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Abstract

A kinematic hardening constitutive model with von Mises failure criterion considering cyclic degradation was developed to analyze the cyclic axial response of single piles in saturated clay. After validation by comparison against published triaxial test results, this model was applied to a numerical simulation developed for computing the axial bearing capacity of a pile foundation subjected to a cyclic loading. The axial bearing capacity degradation of a single pile under different cyclic load levels and different cyclic load numbers was studied. It was found that the pile–soil system remains elastic at very low cyclic load levels, and the degradation of pile capacity happens when the cyclic load level increases. A higher cyclic load level after more cycles leads to faster degradation. In order to improve the computational efficiency, a simplified analysis method based on a simple nonlinear soil model is presented for the cyclic axial capacity degradation of single piles. The results calculated by this simplified analysis are consistent with those of the numerical simulation. Comparisons with laboratory test data suggest that both the finite element method and the simplified analysis method provide reasonable estimates of the axial pile capacity degradation of a single pile after cyclic loading.

Keywords: Kinematic hardening; Cyclic degradation; Axial pile capacity; Simplified analysis method

1. Introduction

Pile foundations are the predominant foundation concept for offshore wind turbines at present in moderate water depths up to 20–30 m (Lesny and Hinz, 2009). Although pile foundations are relatively simple and involve a straightforward design, their behavior is complex, subject to a variety of load conditions, all of which have to be considered. In a marine environment, besides the work load of wind turbine, environmental loads such as wind, waves and currents can cause long term axial and lateral cyclic loads to the pile foundation, which unavoidably have some detrimental effects. The degradation of pile stiffness and capacity, in particular, is potentially hazardous to the safety of the wind turbine structure. Although the lateral response of piles under cyclic loading is important for the design of offshore wind turbine foundations, the axial response still requires further attention.

Many researchers have investigated the axial response of piles in clay subjected to cyclic axial loads. A theoretical analysis published by Poulos (1979) was the first outline of an effective stress approach based on elastic theory, in which excess pore pressure is caused by cyclic loading in the soil adjacent to the pile, and soil stiffness and skin resistance are consequently reduced. An improved method later developed to consider the total stress (Poulos, 1981) can be applicable to a

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wide range of problems. A cyclic stability diagram was then suggested with the mean and cyclic axial loads on a pile plotted and the three regions identified: the stable zone, the metastable zone and the unstable zone (Poulos, 1988). Lee (1993) presented a simplified cycle-by-cycle total stress hybrid load-transfer approach for analyzing the behavior of pile groups in clay under cyclic axial loading. In their work, degradation factors, empirically expressed as functions of the number of loading cycles were introduced.

Based on experimental tests carried out at normal gravity, Poulos (1979) found failure during cyclic loading occurred in several tests at a cyclic load level, P_c/P_{us}, between 0.56 and 0.62, and the number of cycles to failure ranging between 13 and 64. The cyclic degradation of the toe resistance for piles was indicated to be less significant than the cyclic degradation of shaft resistance (Poulos, 1987). Jardine and Standing (2012) found that two-way conditions may promote more severe cyclic losses than a one-way condition to the axial capacity of piles at the same cyclic loading level in full-scale field tests. Different patterns of the development of effective stress were reported in the experiments involving a highly instrumented model displacement pile and an array of soil stress sensors (Tsuha et al., 2012). These observations of the stress–strain behavior of the soil made a good understanding of three styles (stable, metastable and unstable) of pile responses under different cyclic loading levels. Lombardi et al. (2013) conducted a series of 1 g model tests to investigate the external dynamic and cyclic loading acting on a typical offshore wind turbine in soft saturated clay. A zone of soil softening around the pile was found after cyclic loading, and the increased moisture content of nearby clay evidently implies a reduction in the undrained strength and a decrease in the stiffness of the clay. The results of these experimental studies can be used for comparisons with theoretical predictions.

To gain a better understanding of the interaction of structure and soil under cyclic loading, the behavior of clays under cyclic loading must be considered. According to previous experimental studies, the modulus of saturated soft clays is degraded during cyclic loading and the undrained shear strength is reduced after cyclic loading. Factors such as the overconsolidation ratio, the confining pressure and the cyclic stress level have been examined in detail, and many empirical formulas have been set up (Sangrey et al., 1969; Andersen et al., 1980; Hyodo et al., 1994; Zergoun and Vaid, 1994; Soroush and Soltani-Jigheh, 2009; Huang and Li, 2010). However, according to the literature, these empirical formulas are seldom applied in practice to analyze the interaction of the structure and soil under cyclic loading.

Elasto-plastic models for clays in terms of total stress are usually chosen for the analysis of the cyclic response of a single pile because of their simplicity. Because the dissipation of pore water pressure is not considered in these models, the analysis results are relatively conservative. The constitutive models can be broadly divided into two categories. The models in the first category describe the dynamic stress–strain curve for soils directly by mathematical formulas, and are represented by the Hardin and Drnevich (1972) hyperbolic model and Ramberg and Osgood (1943) model. Models in the second category are based on the elasto-plastic theory and calculate the stress and strain relationship by certain yield criteria and hardening rules; examples are the kinematic hardening models and bounding surface models (Prévost, 1977; Mróz et al., 1981; etc.). While the models in the second category are more rigorous in theory, a number of the parameters needed may be difficult to determine, leading to further complicated numerical requirements. To date, a simplified kinematic hardening constitutive model with the von Mises failure criterion developed in the commercial finite element software ABAQUS has been used for the analysis of the cyclic response of shallow and deep foundations (Anastasopoulos et al., 2011; Giannakos et al., 2012).

The objective of this paper is to investigate the axial capacity degradation of single piles under cyclic loading in clay. At first, the simple kinematic hardening constitutive model in ABAQUS is modified slightly to describe the degradation behavior of clay under cyclic loading. Then this model is applied for calculating the axial bearing capacity of the pile in the FE analysis. Since the cyclic loading may recur millions of times in the entire service life of the structure, the computational efficiency must be improved to make it possible to carry out long-term loading calculations for engineering applications. Hence, a simplified analysis procedure based on a simple nonlinear model which considers cyclic degradation for the axial capacity degradation of the single pile under cyclic loading is presented in the last part of this paper. The proposed simplified method is validated by comparing with the FE analysis of the simplified kinematic hardening model and the model test results in the literature.

2. A kinematic hardening constitutive model considering cyclic degradation

2.1. Basic model description

The model presented herein is modified from a kinematic hardening model with von Mises failure criterion, which is available in ABAQUS. The model was developed originally based on the work of Armstrong and Frederick (1966) and Lemaitre and Chaboche (1990). This model can be used for the total stress analysis of clayey soils under undrained conditions. In what follows, a brief introduction of the basic model available in ABAQUS is presented.

The total strain rate $\dot{\varepsilon}_{ij}$ is written in terms of the elastic and plastic strain rates $\dot{\varepsilon}^e_{ij}$ and $\dot{\varepsilon}^p_{ij}$ as

$$\dot{\varepsilon}_{ij} = \dot{\varepsilon}^e_{ij} + \dot{\varepsilon}^p_{ij} \tag{1}$$

The elastic behavior is modeled as linear elastic, and the yield surface is defined by the function

$$F = f(\sigma_{ij} - \alpha_{ij}) - A = 0 \tag{2}$$

where σ_{ij} is the stress tensor, A is the size of yield surface. α_{ij} is the backstress tensor, which determines the kinematic evolution of the yield surface in the stress space. $f(\sigma_{ij} - \alpha_{ij})$ is the