Response of Monopile Foundations Under Cyclic Lateral Loading in Normally Consolidated Clay

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The behavior of monopile subject to repeated lateral loads in normally consolidated clay is investigated using centrifuge modeling technique. A strain-softening model of clay is characterized by T-bar cyclic tests. A comparison between the results with the strain-softening model and the test results on monopiles under displacement-controlled repeated loading reveals that the accumulation of plastic strain leads to a reduction in the soil undrained shear strength and lateral stiffness. Further tests are conducted under load control. By interpreting the gradual changes in the progressive pile deflection with the strain-softening model, the mechanism for the lateral stiffness degradation of monopiles subject to repeated lateral loads is discussed.

INTRODUCTION

Monopiles comprising single open-ended steel pipes are often employed as the foundation for offshore wind farm structures in waters up to 30 m deep. The diameter $D$ of a monopile typically ranges from 2 to 8 m with a length/diameter $L/D$ ratio ranging from 4 to 12. The bending rigidity $EI$ for a typical pile shaft ranges from 30 GNm$^2$ for a 2-m diameter pile to 4,000 GNm$^2$ for an 8-m diameter pile subject to extreme environmental loading (Hokmabad et al., 2012). Monopiles often experience repeated lateral loads due to wind, waves, currents, and tides. Owing to difficulties in conducting load tests offshore, full-scale tests were conducted onshore to investigate the degradation of soil stiffness and lateral stiffness of piles subject to repeated lateral loadings (Ting, 1987; Werasak and Meng, 2013).

Bienen et al. (2012) conducted centrifuge model tests to examine the behavior of monopiles under lateral cyclic loadings, focusing on the long-term bearing characteristics of monopiles in sand. They established an approach to estimate the lateral stiffness degradation with loading cycle and amplitude. On the other hand, Zhang et al. (2011) investigated the undrained soil strength and stiffness degradation around a rigid pile under lateral cyclic loadings in soft clay. They found that the soil strength and pile lateral stiffness could recover gradually after a period of soil reconsolidation. In their centrifuge model study, the model pile head was rigidly fixed, thus not permitting any rotation. However, this approximation could not simulate the permanent cumulative pile rotation that is crucial in design practice. Furthermore, as the wind turbine–pile–soil system is rotation-controlled, free pile head is more appropriate to model the actual situation compared with fixed pile head, which does not allow rotation at the pile head.

Most of the existing studies mainly focus on the influence of cycle number and amplitudes of loads on a monopile. Zhang et al. (2011) reported that the degradation behavior of a monopile is the result of cumulative plastic soil displacement due to progressive pile deflection. In addition, Einav and Randolph (2005) reported that the rate-dependent and strain-softening soil model can be determined by means of T-bar cyclic penetration and extraction tests. As this soil model reflects, the undrained shear strength of every soil element reduces with cumulative absolute plastic shear strain. As such, the soil stiffness degradation around a monopile denotes the macro performance of the accumulated plastic shear strain in the soil around the pile, not the additive effects of load cycle and amplitude.

As the review of existing studies clearly merits further evaluations, a series of centrifuge model tests is conducted in the present study to examine the behavior of free-head monopiles subject to repeated lateral loads in normally consolidated (NC) soft clay. NC clay with soil strength varying linearly with depth is examined, as such a soil strength profile is not uncommon in the offshore seabed. The change in the soil shear strain around the pile during each loading and unloading stage is compared with the findings from existing studies on T-bar cyclic tests. Based on the centrifuge test results, the relationship between lateral stiffness degradation and the soil-softening model revealing the mechanism of monopiles subject to repeated lateral loads is presented.

EXPERIMENTAL SETUP AND PROCEDURE

Centrifuge Model Setup

All the tests were carried out at 50 g in the National University of Singapore geotechnical centrifuge. Figure 1 shows the