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Comparison of Lateral Behavior of Rock-Socketed Large-Diameter Offshore Monopiles in Sands with Different Relative Densities

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Centrifuge tests were performed to investigate the effect of the relative density of the sandy layer on the lateral response of 6-m-diameter offshore monopiles. The end tips of the monopiles are socketed into rock-bearing layers. For the simulation of the rock-socketed monopiles in sands with different relative densities (dense and medium dense sand layers), centrifuge tests at an acceleration of 60 g were conducted using well-instrumented model monopiles under significant lateral loads and bending moments. Based on the centrifuge test results, the *p–y* relationship and the initial stiffness (initial gradient of a *p–y* curve) changed with an increasing depth for both dense and medium dense sand layers. As a result, the newly developed *p–y* curves for rock-socketed large-diameter monopiles in this study were quite different from the existing API (American Petroleum Institute) *p–y* curves, which were developed based on relatively small-diameter driven piles. It was found that the initial stiffness for the medium dense sand layer was significantly lower than that for the dense sand layer at a shallow depth; however, the ratio of initial stiffness of the medium dense sand layer to that of the dense sand layer decreases significantly as the depth increases and approaches the stiff rock-bearing layer.

INTRODUCTION

Renewable energy produced by wind turbines has now become one of the most promising clean energy resources. At the initial stage of wind turbine energy production, onshore or inland wind turbine construction was dominant. However, offshore wind turbines have been built recently for more steady energy production because the wind quality in terms of wind strength and duration is far better offshore than inland. In addition, the offshore wind turbines are freer from the problems caused by their noise and vibration than inland wind turbines. The number of offshore construction projects of wind farms keeps increasing worldwide, including off the shores of Northern Europe, the United States, China, and Korea. The sizes of generators and blades are increasing for more efficient energy production; therefore, larger offshore wind turbine foundations are also required for higher vertical and lateral capacities (resistances) against significant vertical and lateral loads and bending moments.

Because the diameters of constructed offshore monopiles are as large as 5 m and even larger diameters are required (Achmus et al., 2009), full-scale lateral load tests on the monopiles are practically impossible. A full-scale test to estimate the monopile's vertical and lateral capacities under offshore conditions is especially difficult because of the limitations of equipment settings in severe offshore environments. Therefore, centrifuge tests using well-instrumented monopiles are a good alternative and an effective method of evaluating monopiles' behavior.

The *p–y* method in sands recommended by the American Petroleum Institute (API) is widely used for the designs of offshore piles, including large-diameter offshore monopiles. The API *p–y* method (API, 1993) was developed after the work done by Reese et al. (1974) based on their experimental results from the lateral pile load tests of small-diameter piles (a pile diameter of up to 610 mm) and the simplification process of O'Neill and Murchison (1983). Significant diameter effect on *p–y* formulation has been experimentally identified in clays (Reese et al., 1975; Stevens and Audibert, 1979), although only limited literature notes its effect in sands. However, in the literature (Reese et al., 1975; Stevens and Audibert, 1979), there was no explanation of the disagreement between experimental results and *p–y* analysis results.

Theoretically, Terzaghi and Peck (1948) insisted that the low-strain elastic soil stiffness (in this paper, the initial gradient of a *p–y* curve is defined by the initial soil stiffness k_i) against the lateral movement of the pile should be independent of pile diameter. Ashford and Juirnarongrit (2003) also supported the results of Terzaghi and Peck (1948) based on the full-scale pile load test results.

The use of the API *p–y* method in sands on large-diameter offshore monopile designs without verification of its applicability would lead to unsafe or uneconomical designs. In this study, centrifuge tests on well-instrumented rock-socketed large-diameter monopiles in sands were conducted. The lateral behavior of monopiles from the centrifuge test results is compared with that

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