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Testing of Laterally Loaded Rigid Piles with Applied Overburden Pressure

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Small-scale tests have been conducted to investigate the quasi-static behaviour of laterally loaded, non-slender piles installed in cohesionless soil. For that purpose, a new and innovative test setup has been developed. The tests have been conducted in a pressure tank such that it was possible to apply an overburden pressure to the soil. As a result of that, the traditional uncertainties related to low effective stresses for small-scale tests have been avoided. A normalisation criterion for laterally loaded piles has been proposed based on dimensional analysis. The test results using the novel testing method have been compared with the use of the normalisation criterion.

INTRODUCTION

For offshore wind turbines, the monopile foundation concept is often employed. Typically, the monopile foundation concept consists of an open-ended steel tube, which is either drilled or driven into the seabed. The pile diameter, D, and the embedded pile length, L_p, are usually in the range of 4–6 m and 15–30 m, respectively. Hence, the slenderness ratio, L_p/D, is in the order of 4 to 7, and therefore the piles exhibit a rather rigid body motion.

The Winkler model approach is traditionally employed in the design of offshore monopiles. In this approach, the interaction between the soil and the pile is modelled by means of uncoupled nonlinear springs. The stiffness of the nonlinear springs is described by means of *p-y* curves. These curves describe the soil resistance acting on the pile wall as a function of the pile deflection. Design regulations of the American Petroleum Institute (API, 2000) and Det Norske Veritas (DNV, 2010) recommend the use of the *p-y* curve formulation proposed by O'Neill and Murchison (1983) for piles situated in cohesionless soils. The formulation has been validated by Murchison and O'Neill (1984) through tests on piles with diameters up to approximately 2 m and length-to-diameter ratios larger than 10. However, the formulation has not been validated for piles with $L_p/D \approx 5$ and $D = 4$–6 m.

The static and the cyclic behaviour of non-slender piles has in recent years been investigated by means of small-scale tests at 1 g and by means of centrifuge tests. LeBlanc et al. (2010a), LeBlanc et al. (2010b), Lombardi et al. (2013), and Peralta and Achmus (2010) investigated the accumulation of pile rotation for non-slender piles exposed to long-term cyclic loading by means of small-scale tests at 1 g. Klinkvort and Hededal (2010) and Haigh (2014) have carried out model tests of non-slender piles by means of centrifuge testing. Jardine et al. (2012) have carried out a literature review of cyclically loaded offshore piles.

Nowadays, the design of monopile foundations for offshore wind turbines is primarily driven by the dynamic behaviour. The natural frequency of the wind turbines is typically designed to be between the rotor frequency and the blade passing frequency (cf. Haigh, 2014). However, in order to understand the cyclic behaviour of non-slender piles, a better understanding of the static behaviour of non-slender piles is needed. An extensive test program has been carried out at Aalborg University in order to investigate the behaviour of non-slender piles in sand exposed to static lateral loading. Piles with diameters of 60 to 100 mm, embedded pile lengths of 240 to 500 mm, and slenderness ratios of 3 to 6 have been tested. Hence, the scale in comparison with real monopiles is between 1:40 and 1:100.

It is well known that when small-scale tests are conducted, the low effective stresses in the soil cause significant scale effects. The internal friction angle, φ, and the Young's modulus of elasticity for the soil, E_s, depend heavily on the effective stresses in the soil. Therefore, the average values of these parameters in traditional 1-g small-scale tests deviate from the average values of these parameters in the soil around full-scale foundations. To avoid this, it is necessary to increase the effective stresses in the soil. This can be accomplished by either testing in a centrifuge or by testing in a pressure tank. The tests presented in this paper have been conducted in a pressure tank, in which an overburden pressure of $P_0 = 0$–100 kPa has been applied to the soil. For $P_0 = 100$ kPa, the average vertical stress in the small-scale tests is slightly higher than 100 kPa and is similar to the average vertical effective stress in the soil around a foundation with $L_p \approx 20$–25 m. When the overburden pressure is applied to the soil, the effective stress distribution with the depth becomes trapezoidal instead of triangular. Therefore, the stress distribution in the small-scale tests with the applied overburden pressure is significantly different from the stress distribution around full-scale piles. However, this difference can be overcome by means of normalisation.

In the present paper, the pile behaviour of non-slender piles is assessed on the basis of small-scale tests in a pressure tank. The test setup is thoroughly described. A way to normalise the results is presented and tested against the test results.

TEST SETUP

Twenty-three static tests were conducted on laterally loaded piles. The test program is shown in Table 1. The tests were conducted in a pressure tank such that it was possible to apply an overburden pressure to the soil. Aluminium piles with diameters of 60 to 100 mm were tested. The majority of the test piles were closed-ended although nowadays monopile foundations for offshore wind turbines consist of open-ended driven pipe piles. The lateral behaviour of closed-ended and open-ended piles was compared in tests without the application of an overburden pressure to the soil. A wall thickness, wt, of 5 mm was used for all the test piles.

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