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Small-Scale Testing of Laterally Loaded Bucket Foundations in Dense Sand

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Abstract

Monopod bucket foundations promise to become a reliable and cost-effective concept for offshore wind turbine. Physical models are essential to understand the behavior of soil-structure systems. When conducting small-scale experiments on soil, scale effects can considerably affect the tests outcome. In a bid for overcoming this issue, a novel testing system based on the application of suction between the soil surface and a membrane is employed. The comparison between the tests conducted at stress levels of 0 kPa, and the tests with increased stress level, shows remarkable differences. In particular the moment rotation curve of tests with pressure applied show more similar trend to large-scale tests. Further cyclic loading studies may be carried out adopting this testing system to investigate the accumulated rotation of bucket and monopile foundations.

The monopod bucket foundation

The monopod bucket foundation is a skirted foundation installed by means of a suction which allows the penetration of the foundation into the seabed. As reported in LeBlanc (2009) such foundation can be installed without using heavy vessels. The cost of installation is thereby considerably lowered.

In 2002 a 3.0 MW offshore wind turbine was installed on a prototype bucket foundation in Frederikshavn, Denmark (Ibsen 2008). More recently a meteorological mast has been installed at Horns Rev 2 Offshore Wind Farm, Denmark. At present, research on long-term capacity is needed.

Figure 1: 12 m diameter, 6 m skirt bucket foundation installed in Frederikshavn (DK)

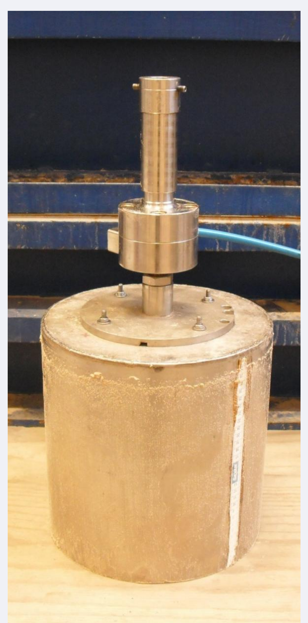

Figure 2: 30 cm diameter, 30 cm skirt, small-scale bucket

Results

The moment-rotation curves evidently depend on the overburden pressure applied. Furthermore, the failure of test without suction, occurs at a lower rotation than that shown by tests with overburden pressure (see Fig.6 and Fig. 7). The residual plastic deformation seems to be independent of the overburden pressure. Its value falls within the range 80-90 % of the deformation reached at the end of the loading phase.

Dimensionless moment-rotation curves of tests with increased effective stress show a distinct similar slope which contrasts with that of test without suction (see Fig. 8). Focusing on the first 0.01 rad of rotation (see Figure 9) test data can be represented by a power law:

$$\vartheta = \left(\frac{M}{\gamma d^4}\right)^u C$$

Where γ is the soil unit weight, d the skirt length and C a parameter depending on the overburden pressure. The exponent u does not change for tests with overburden pressure. This suggests that u might be a constant of the soil in real-scale.

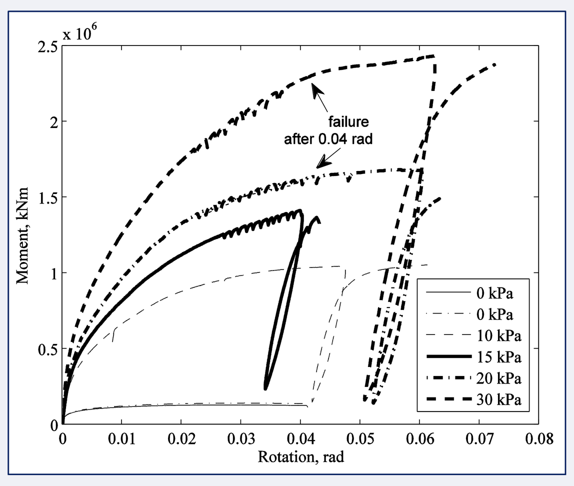

Figure 6: Moment-rotation curves of all tests

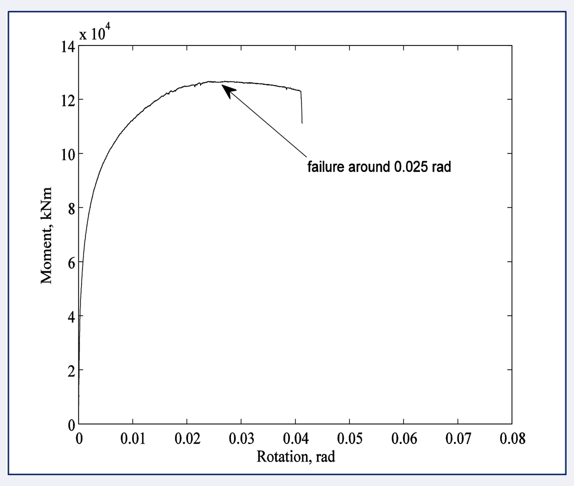

Figure 7: Moment-rotation curve of a test without suction

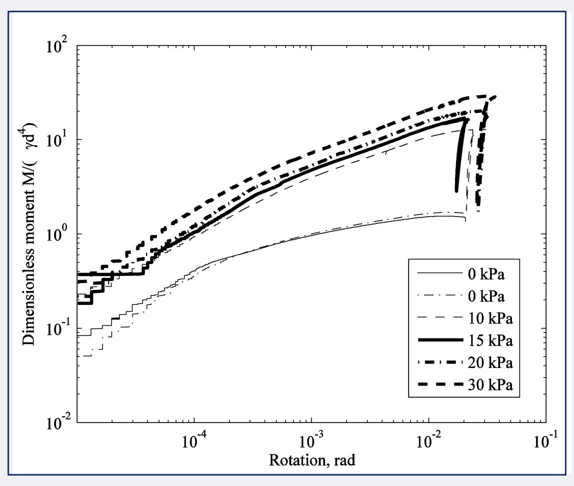

Figure 8: Dimensionless moment-rotation curves in log-log plane

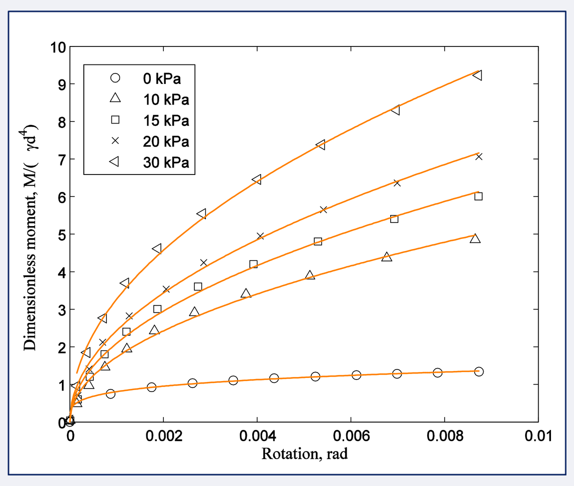

Figure 9: Dimensionless moment-rotation curves, until 0.01 rad

Displacements analysis

By computing the LVDTs measurement, the instantaneous centers of rotation position during all tests could be evaluated. Figure 10 and 11 show typical instantaneous centers of rotation distribution for test conducted with, and without overburden pressure.

In spite a general similarity, a little difference between the two distribution can be noted. This indicates that, the failure mode of the two cases is, to some extend, different. This is plausible, and can be attributed to the different stress states distribution in case of suction applied.

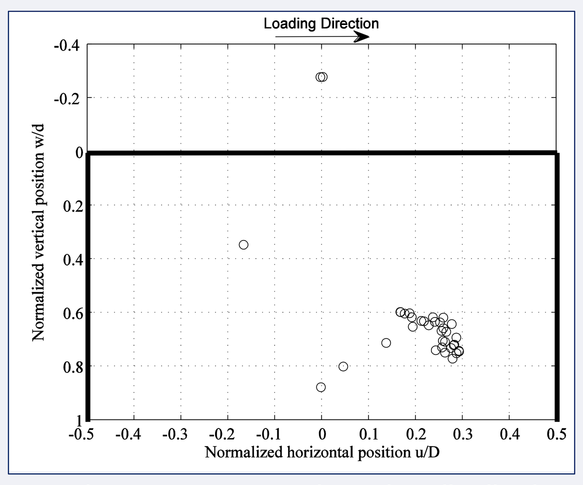

Figure 10: Centre of rotation distribution for test with no suction

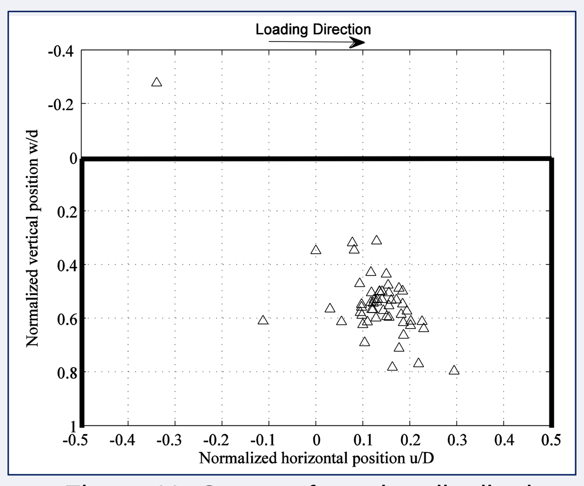

Figure 11: Centre of rotation distribution for test with 20 kPa pressure

Comparison with large-scale test

Within a research led by Aalborg University and MBD-Offshore-power A/S seven large-scale tests of bucket foundation were performed. The foundation adopted was a 2 m diameter, 2 m skirt length and 12 mm thickness steel bucket (Larsen 2008)

The soil failure of the large scale test occurs after 0.04 rad. Further, the trend seems to be distributed similarly to the small-scale tests with overburden pressure. Proper scaling laws must be nevertheless derived to compare large-scale tests with small-scale tests.

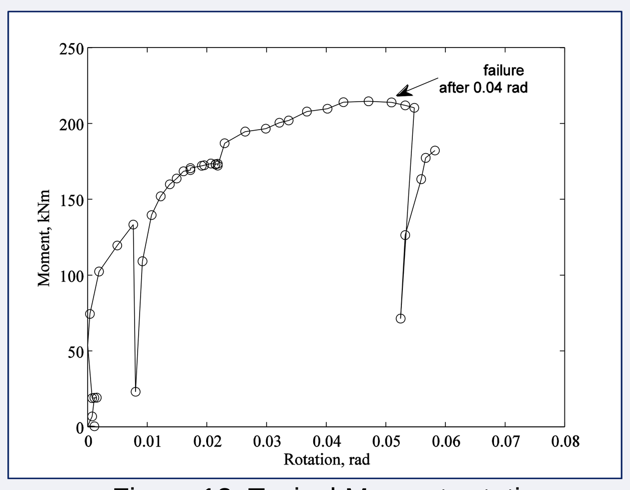

Figure 12: Typical Moment-rotation points for large-scale test

Figure 13: Large-scale test facility in Frederikshavn (DK)

Traditional physical model

Load-controlled monotonic tests on dense saturated sand were conducted. The soil was prepared prior to every test to guarantee proper soil density and homogeneity of the sand. Soil properties and soil homogeneity were evaluated by performing cone penetration test. A 30 cm diameter, 30 cm skirt bucket was tested (see Figure 2). By using an electric motor the bucket was carefully driven in the middle of a sand box.

The loading phase consisted of a horizontal load (arm 0.6 m) applied to the bucket foundation by means of an electric motor. During the loading phase the displacement of the foundation was monitored with three LVDTs (linear variable differential transducer).

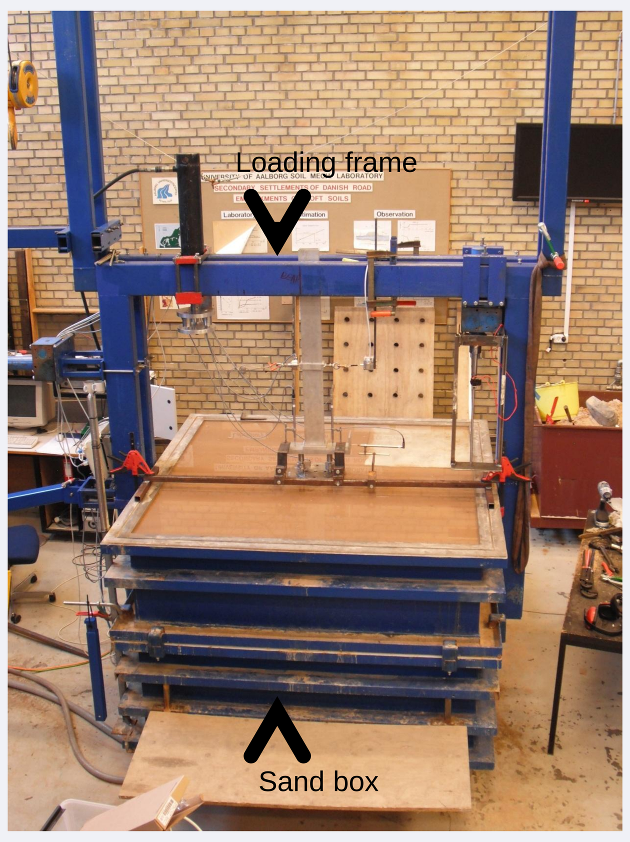

Figure 3: Sand box, with bucket foundation installed

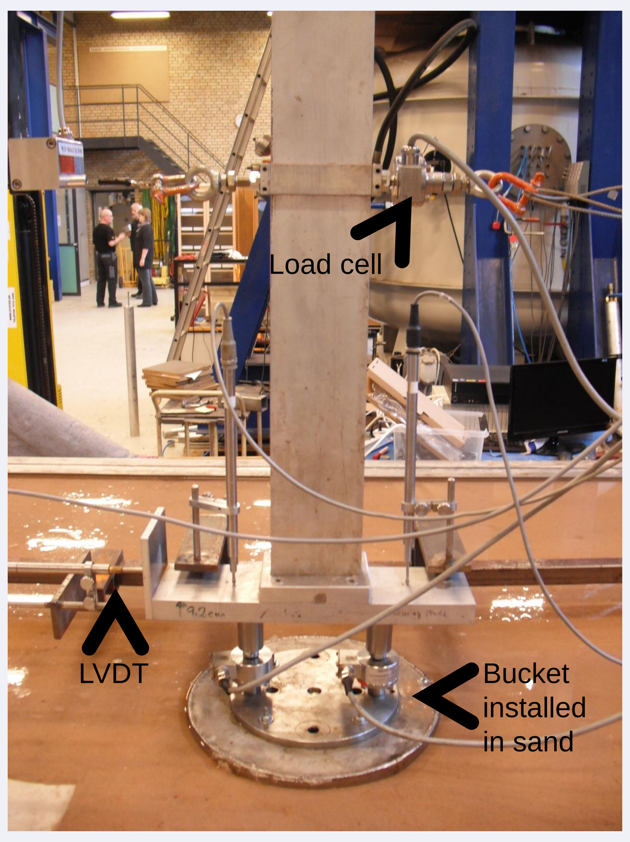

Figure 4: Bucket foundation instrumented with LVTDs and lad cells

New physical model

In a bid for minimizing the scale effect, suction was applied between the soil surface and a membrane. As a result of that the effective stresses of the soil were increased, leading to more reliable values of the friction angle of the sand.

The suction system consisted of a membrane with four suction spots, each of them connected to a vacuum pump through a suction hose. An additional spot was placed on the membrane and connected to the data acquisition device by means of a pressure transducer. The pressure was regulated with a control valve and kept steady during each test.

Tests were conducted at 0 kPa, 10 kPa, 15 kPa, 20 kPa and 30 kPa, respectively.

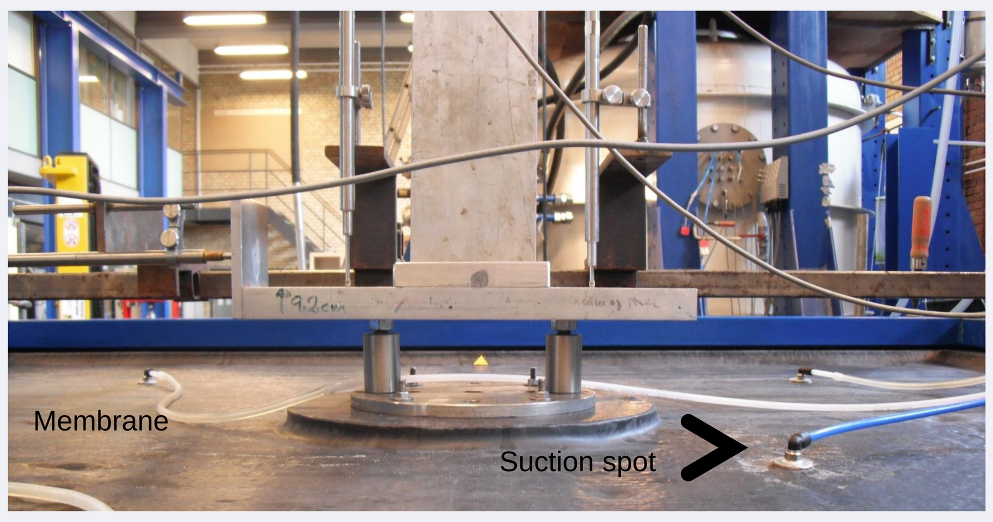

Figure 5: New method to minimize the scale effects by applying a suction between sand surface and a latex membrane

Conclusions and upcoming challenge

The upcoming challenge is addressing the behaviour of the bucket foundation under repetitive horizontal loading.

The method presented in this study, in combination with proper scaling laws, may be used for a testing program of bucket foundation under long-term cyclic lateral loading.

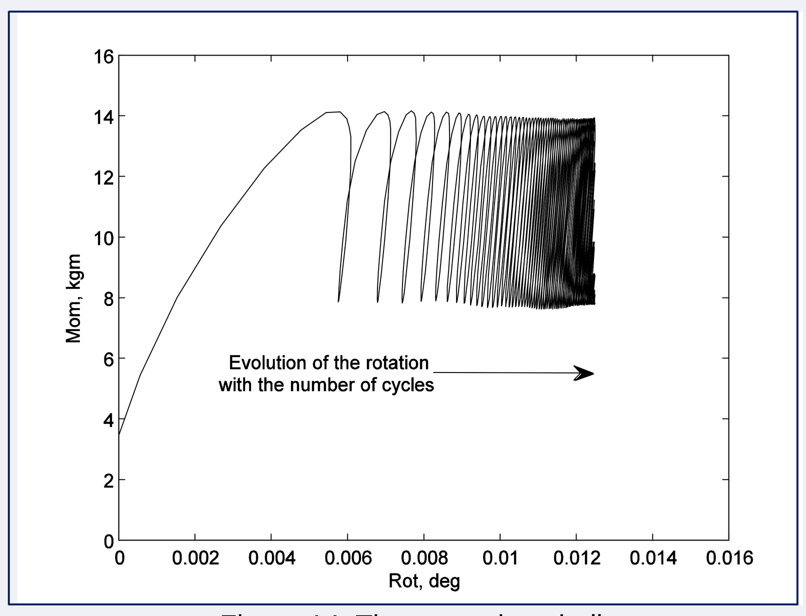

Figure 14: The upcoming challenge, cyclic loading investigations

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