Dynamic Model Test of Monopile Foundation for Offshore Wind Turbines

Stian Baardsgaard Hanssen, PhD Candidate

Norwegian University of Science and Technology, Department of Civil and Transport Engineering

stian.b.hanssen@ntnu.no

Background

Measurements on full scale operating offshore wind turbines have shown that the horizontal foundation stiffness for monopiles appears to be under-predicted by current design methods (Hald et al., 2009; Kallehave et al., 2012). The horizontal foundation stiffness is of particular interest for offshore wind turbines due to the dynamic nature of the excitation forces and strict deformation criteria. Environmental loads such as wind and wave, rotational effects from the rotor and blade passing drag-effects may all be categorized inside limited frequency bands as shown in Figure 1 (Lombardi et al., 2013). The eigen-frequency of offshore wind structures are commonly targeted to fall within the narrow frequency band denoted soft-stiff in the same figure. Precise prediction of the horizontal foundation stiffness is required in design to keep the system eigen-frequency outside the excitation frequency bands in order to avoid system resonance.

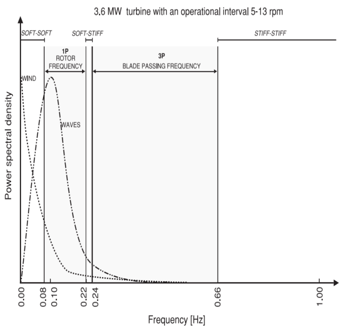


Figure 1. Simplified power spectral density of the forcing frequencies applied to typical three bladed 3.6 MW offshore wind turbine with an operational interval in the range of 0.14 - 0.31 Hz. Figure from Lombardi et al. (2013).

One of the key components in the horizontal pile-soil interaction stiffness is the soil-stiffness. Soil stiffness is known to vary among soil types and to be dependent on both stress- and strain magnitude. Figure 2, based on Atkinson and Sallfors (1991), shows the principle trend for the variation of soil's shear stiffness G based on variation in shear strain γ. The variation in soil stiffness is typically more than one magnitude and is highly non-linear. Our hypothesis is that the apparent under-prediction described from full scale measurements are based on inaccurate interpretations of the soil strain level, resulting in an under-prediction of the soil stiffness.

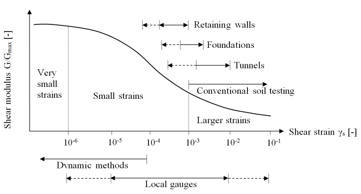


Figure 2. Characteristic stiffness-strain behavior of soil with typical strain ranges for laboratory tests and structures After Atkinson and Sallfors (1991)

Test Setup

The basic idea behind the test setup is to provide a bench-mark test for evaluation of calculation methods for laterally loaded monopile foundations. In this context is the system eigenfrequency an indirect measure of the pile-soil interaction stiffness. The current scale test provides results for system eigenfrequency and small strain soil stiffness along with known structural stiffness and mass.

The test setup is sketched in Figure 3. An impact load at the top end of the pile generates an initial velocity to the pile and excites it over a wide range of frequencies. The impact load is modeled by a 15.9 kg, soft-tipped hammer. The hammer acceleration and duration of the impact are measured by one accelerometer mounted at the rear end of the hammer.

The sand-bin is filled with dry Hokksund sand to a depth of 2.0 m and sealed with an airtight tarpaulin at the sand surface. A vacuum pump is connected to perforations in the tank floor, creating a pressure chamber. Simulating overburden pressures trough a pressure chamber makes it possible to overcome near surface scale effects by increasing soil effective stresses, and for the current test setup, an underpressure of 56 kPa has been achieved.

The embedded part of the pile is instrumented with 5 sets of strain gauges, arranged in line at 280 mm center-to-center spacing.

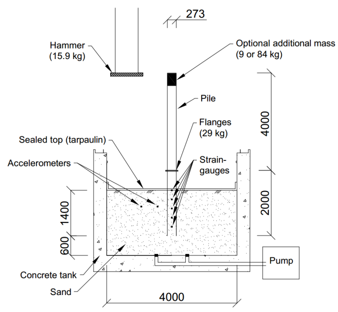


Figure 3. Model test set up

Buried Accelerometers for Shear Wave Velocity Measures

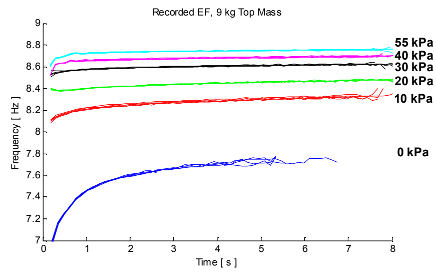
The small-strain soil stiffness is measured through wave-speed measurements in the sand. The small-strain shear modulus is the theory of elasticity related to the shear wave velocity and the density of the sand as described by Eq.(1).

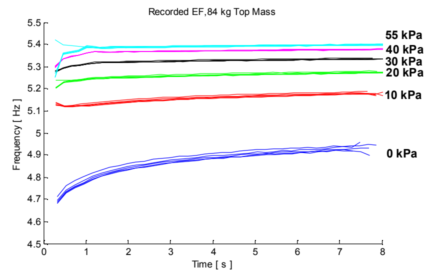
$$G = V_s^2 \rho \qquad (1)$$

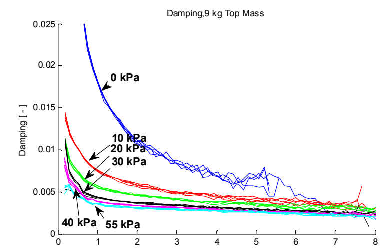
Two three-way accelerometers are installed 0.5 m below the sand surface for recording shear wave velocities at different overburden pressures. The shear waves are induced by hitting the pile vertically at the connection flange, resulting in shear waves spreading radially out from the pile. Differences in arrival time and a known distance of 0.50 m between the two accelerometers are used to calculate shear wave velocities based on vertical particle motion.. Setup and testing for wave-speed measurements are performed separate from the lateral pile testing to avoid interfering waves

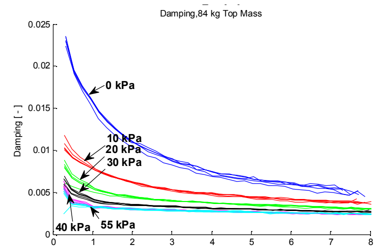
Experimental Results

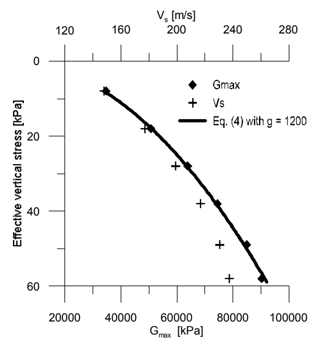
The experimental results are presented in terms of eigen-frequency and damping of the pile-soil system. The presented results will serve as benchmark-results for a study of different approaches to soil stiffness in Winkler-beam analyses, and in 3D-FEM soil models. This study is planned for spring 2015.











References

Atkinson, J.H., Sallfors, G., 1991. Experimental determination of stress-strain-time characteristic in laboratory and in situ tests, in: Italiana, A.G. (Ed.), X ECSMFE. A.A. Balkema, Firenze, pp. 915-956.

Kallehave, D., LeBlanc, C., Liingaard, M.A., 2012. Modification of the API P-y Formulation of Initial Stiffness of Sand,. Society for Underwater Technology, London, UK, pp. 465-472.

Hald, T., Mørch, C., Jensen, L., Bakmar, C.L., Ahle, K., 2009. Revisiting monopile design using p-y curves –Results from full scale measurements on Horns Rev, European Offshore Wind Conference & Exhibition 2009, Stockholm, Sweden, pp. 1926-1935.

Lombardi, D., Bhattacharya, S., Muir Wood, D., 2013. Dynamic soil–structure interaction of monopile supported wind turbines in cohesive soil. Soil Dynamics and Earthquake Engineering 89, 165-180.

NTNU
Kunnskap for en bedre verden