Small-scale testing of laterally loaded non-slender piles in a pressure tank

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Outline

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  o Test setup
  o Preparation of soil
  o Results

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Introduction

Types of foundation for offshore wind turbines:
• Gravitational foundation
• Bucket foundation
• Monopile foundation
• Tripod/multipod foundation
• Jacket structure
• Floating foundation

After Liingaard (2006)
Monopile foundations for offshore wind turbines

Loads:
- Large horizontal loads and overturning moments
- Small vertical loading
- Long-term cyclic loading

Design issues:
- Resonance with the frequency of the loading, the frequency of the rotor and the blade passing frequency should be avoided
- Fatigue failure in the steel material needs to be prevented
- The accumulated rotation should be minimized (rotation from installation and from the loading should not exceed 0.5°)

Accurate estimation of the stiffness of the soil-pile interaction is important
Winkler model approach

- Beam on an elastic foundation.
- Soil pile interaction governed by means of non-linear springs.
- Uncoupled springs
- Spring stiffness governed by $p$-$y$ curves
$p-y$ curves for piles in sand (API, DNV)

Cox et al. (1974), Reese et al. (1974):
- $D = 0.61$ m
- $L_p/D = 34$
- 2 static and 5 cyclic tests

Murchison and O’Neill (1984):
- Modified the $p-y$ curves proposed by Reese et al. (1974) based on a database of field tests.
- $D \leq 2$ m
- Flexible piles

Monopile foundations for offshore wind turbines:
- $D \geq 4$ m
- $L_p/D \approx 5$
Testing of laterally loaded rigid piles with applied overburden pressure

Traditional small-scale tests at normal stress level:
- Very high friction angle
- Low soil stiffness
- Large variation of soil properties with depth
- Large uncertainties when determining the soil properties

Small-scale tests with applied overburden pressure:
- Effective stresses in small-scale tests are similar to effective stresses around a full-scale pile
- Soil stiffness and friction angle is comparable to full-scale parameters
- Accurate determination of soil properties is possible
- Trapezoidal distribution of effective stresses with depth instead of triangular
- Scaling is needed
Test programme

29 static tests on laterally loaded rigid piles:
- Closed/open-ended piles
- Diameters of:
  \(0.04 \, \text{m} \leq D \leq 0.10 \, \text{m}\)
- Slenderness ratios of:
  \(3 \leq \frac{L_p}{D} \leq 6\)
- Overburden pressures of:
  \(0 \, \text{kPa} \leq P_0 \leq 100 \, \text{kPa}\)
- Loading eccentricity of:
  \(0.37 \, \text{m}: \qquad 0.74 \leq \frac{e}{L_p} \leq 1.54\)

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Pressure tank and test setup

1. Ascension pipe
2. Displacement transducers
3. Monopile
4. Wire
5. Membrane
6. Force transducer
7. Hydraulic piston
8. Saturated sand
9. Saturated gravel
10. Drain pipe/water inlet
Test piles

- 5 closed-ended aluminium piles of which 3 had strain gauges attached
- 1 open-ended aluminium pile
- Strain gauges placed in milled grooves. Size of milled grooves: 6 mm wide, 10 mm long and 2 mm deep
Test procedure

- Vibration/upward gradient
- CPT
- Installation of pile
- Vibration/upward gradient
- CPT
- Position of membrane, transducers, etc.
- Pressure tank is closed
- Pressure is applied
- Loading is applied
Preparation of sand and determination of soil properties

\[ d_s = 2.64 \]
\[ e_{min} = 0.549 \]
\[ e_{max} = 0.858 \]
\[ d_{50} = 0.14 \text{ mm} \]
\[ U = \frac{d_{60}}{d_{10}} = 1.78 \]
\[ I_D = c_2 \left( \frac{\sigma'_1}{q_c c_1} \right)^{c_3} \]
\[ \varphi_{tr} = 0.152 \ I_D + 27.38 \sigma'_3^{-0.2807} + 23.21 \]
Results

Comparison of open- and closed-ended piles:

\[ D = 80 \text{ mm}, \ P_0 = 0 \text{ kPa} \]
Results

Effect of overburden pressure on the load-displacement relationship:
• Overburden pressure causes an increase in pile stiffness and capacity
• The increase is bigger for the pile stiffness than for the pile capacity
• Pile displacement at failure is larger for tests with overburden pressure than tests without overburden pressure – analogous to conventional triaxial tests where the strain at failure increases with increasing confining pressure.

\[ D = 80 \text{ mm}, \frac{L_p}{D} = 5 \]
Results

Effect of applied overburden pressure on the pile flexibility:

Criterion for flexible/rigid pile behaviour, Poulos and Hull (1989)

Rigid pile behaviour:
\[ L_p < 1.48 \left( \frac{E_p I_p}{E_s} \right)^{0.25} \Rightarrow \frac{E_s}{E_p} < 1.48^4 \frac{I_p}{L_p^4} \]

Flexible pile behaviour:
\[ L_p > 4.44 \left( \frac{E_p I_p}{E_s} \right)^{0.25} \Rightarrow \frac{E_s}{E_p} > 4.44^4 \frac{I_p}{L_p^4} \]

\( I_p \) is proportional to \( D^4 \):

Rigid behaviour: \( \frac{E_s}{E_p} < 1.48^4 \frac{C D^4}{L_p^4} \)

Flexible behaviour: \( \frac{E_s}{E_p} > 4.44^4 \frac{C D^4}{L_p^4} \)

Hence, the pile flexibility for the test with overburden pressure applied is similar to the pile flexibility for full-scale foundations.
Conclusions

- A new and innovative test setup for small-scale tests on laterally loaded piles have been presented. The test setup enables the application of overburden pressure.
- Traditional small-scale tests at normal stress level leads to very high friction angles and low soil stiffness.
- By application of overburden pressure, it can be ensured that the soil friction angle and the soil stiffness are comparable to the properties for a full-scale foundation.
- By application of overburden pressure the increase in pile capacity is greater than the increase in the stiffness of the load-displacement relationship.
- The pile displacement at failure increases when applying an overburden pressure – Analogous to conventional drained triaxial tests.
- The pile flexibility for piles in small-scale tests with overburden pressure applied is comparable to the flexibility of full-scale piles.
- Testing laterally loaded piles with applied overburden pressure is a useful testing method, however further research is needed regarding the scalability of small-scale tests with overburden pressure applied to the soil.
Contact information

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