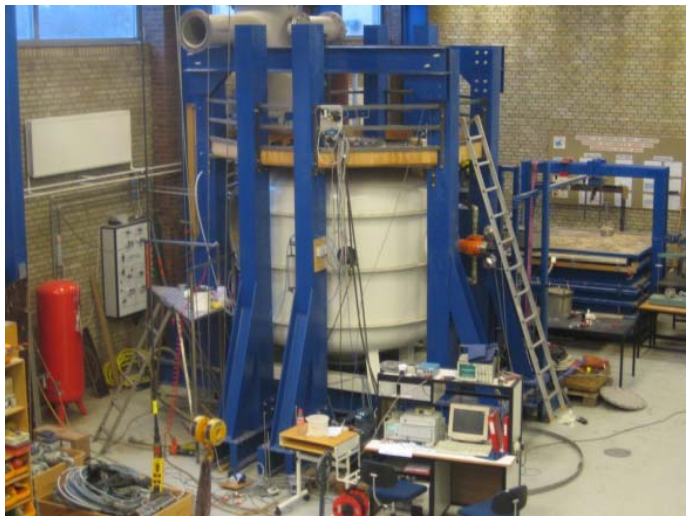
AALBORG UNIVERSITY

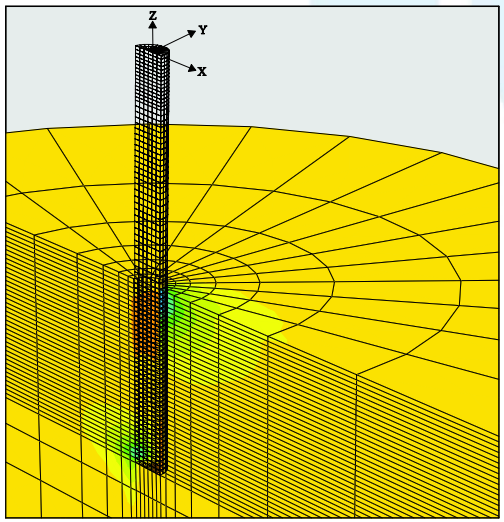
Evaluation of the Load-Displacement Relationships for Large-Diameter Piles in Sand

by
S. P. H. Sørensen, Aalborg University, Denmark
K. T. Brødbæk, COWI
M. Møller, COWI
A. H. Augustesen, COWI
L. B. Ibsen, Aalborg University, Denmark

Outline

- Introduction
- Objective
- Current design basis
- Laboratory tests
- Numerical simulations
- Conclusions and future research





Introduction

- Global warming ⇒ Interest in renewable energy sources
- Offshore wind energy
- Large-diameter pipe pile – "monopile"

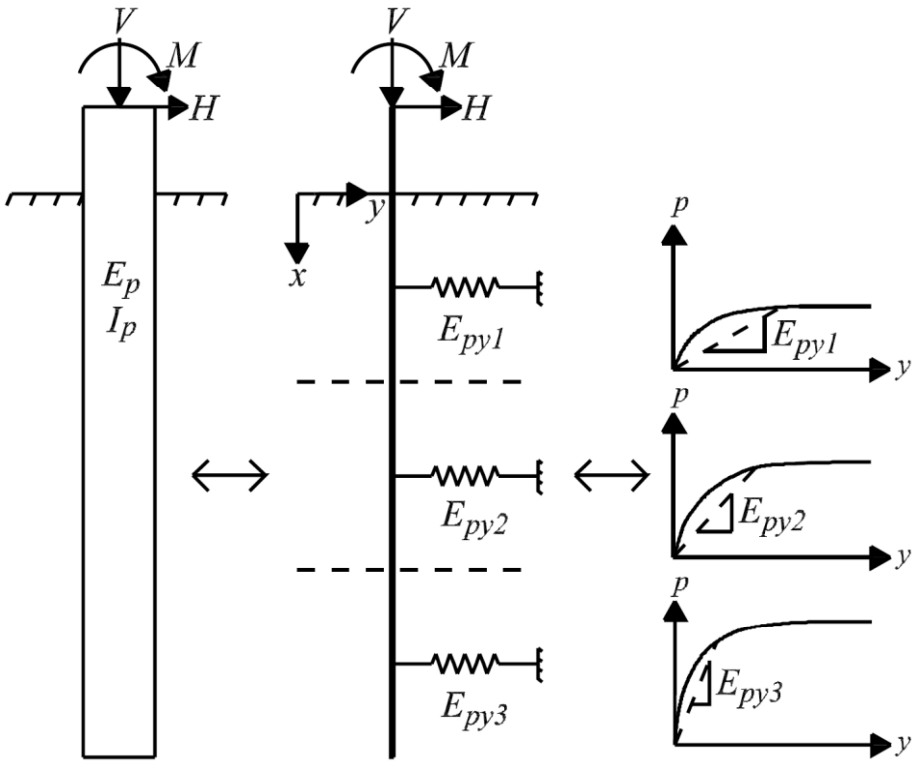
Objective

For laterally loaded piles in sand with diameters up to 6m, for example monopiles used as foundations of offshore wind turbines, there is no approved design procedure. The p − y curve method, given in offshore design regulations, is usually employed for the design of monopiles. However, this method was developed for slender piles with diameters much less than 6m and it is based on a limited number of tests.

The aim of the present work is to extend the p − y curve method to large-diameter non-slender piles by considering the effects of the pile diameter on the soil response!

Current design basis

- Winkler model approach
- Beam on an elastic foundation
- Series of uncoupled springs
- Soil response given by means of *p*-*y* curves



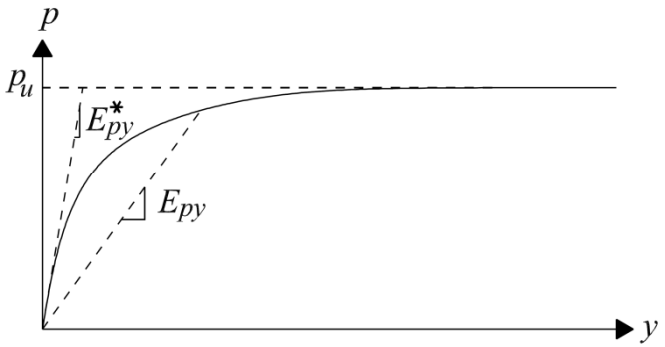
Current *p*-*y* curve formulation (API and DNV)

Full-scale tests at Mustang Island:

- D = 610 mm, L/D = 34.4
- 2 static and 5 cyclic tests

$$p(y) = Ap_u \tanh\left(\frac{E^*_{py}}{Ap_u} y\right)$$

$$E^*_{py} = kx$$



Monopiles for modern wind turbine foundations:

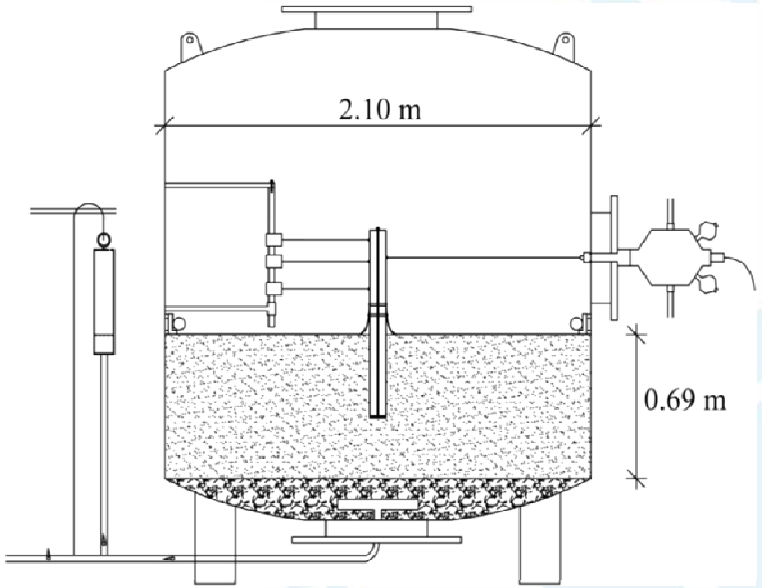
- D = 4-6 m, $L/D \approx 5$
- Strict requirements regarding pile-head rotation and total stiffness of the structure

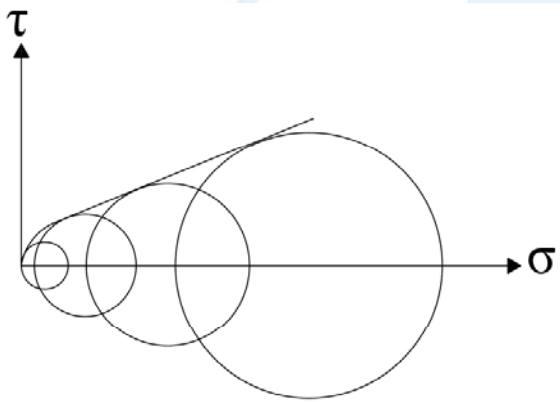
Verification of *p*-*y* curves for large-diameter piles is needed

Laboratory tests

- Effect of diameter
- Verification of numerical model
- Pressure tank (new test method)
- Piles instrumented with strain gauges

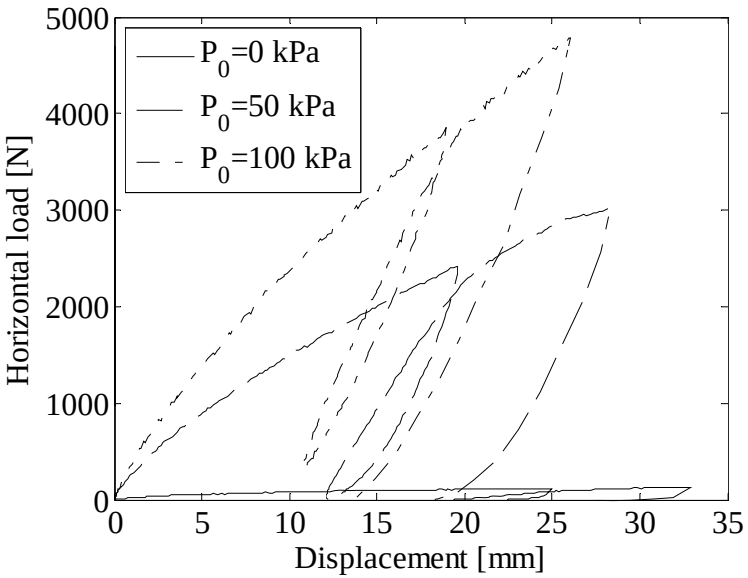
	D [mm]	*L* [mm]	[kPa]
Test 1	80	400	0
Test 2	80	400	100
Test 3	80	400	50
Test 4	60	300	0
Test 5	60	300	50
Test 6	60	300	100





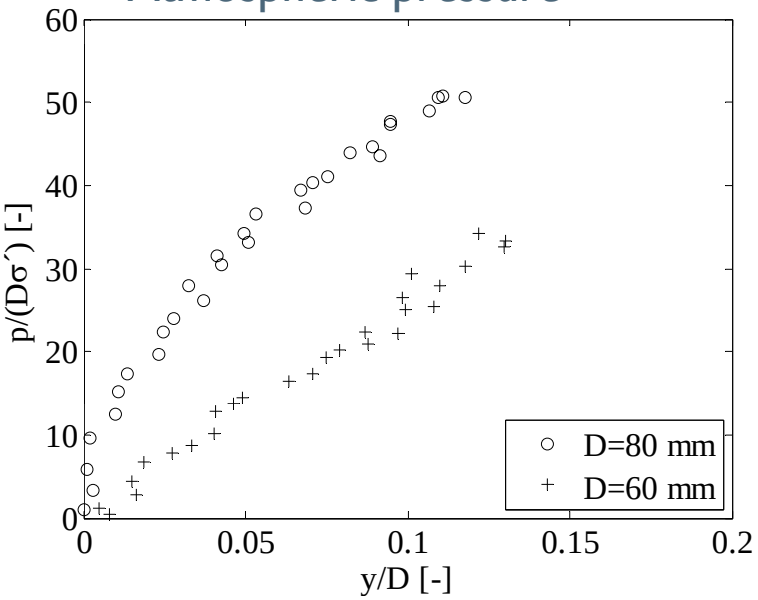
Results from laboratory tests

Effect of overburden pressure



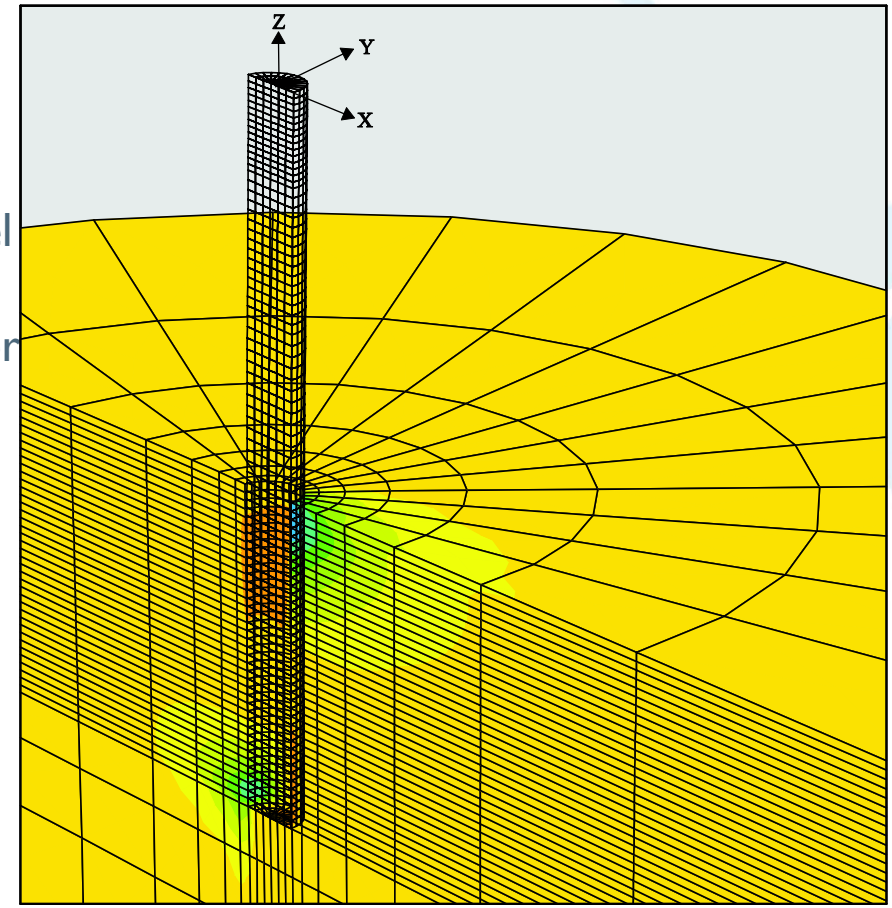
Increase in E^*_{py} for increasing D

Atmospheric pressure



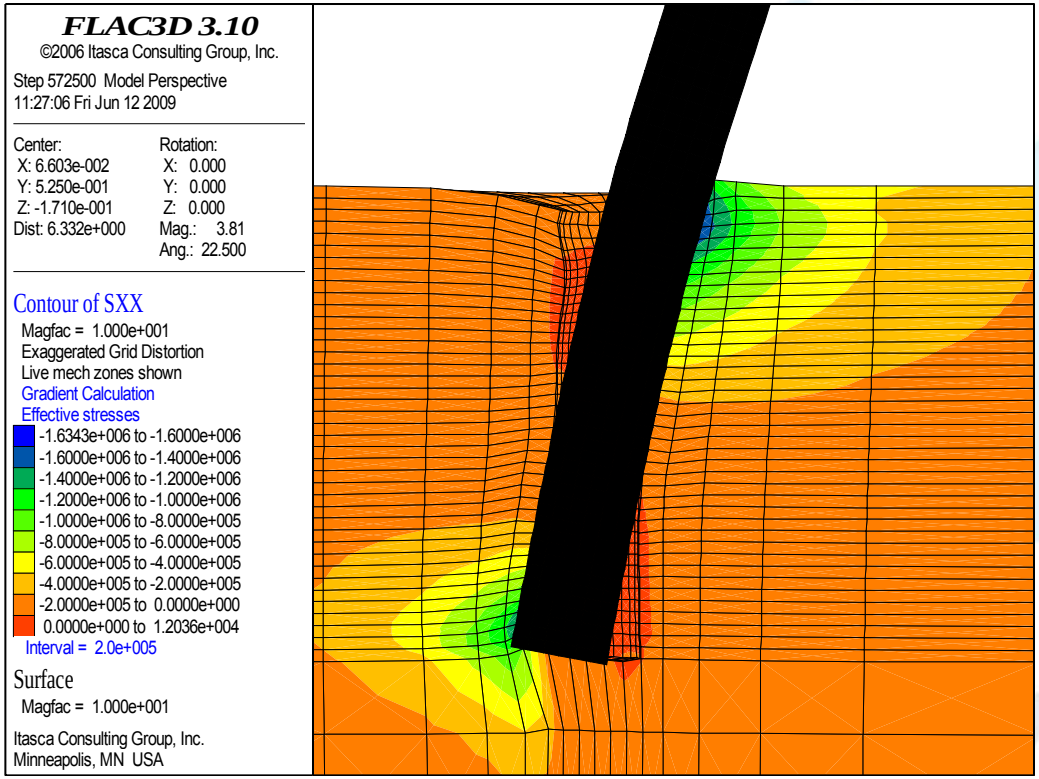
Numerical simulations in *FLAC*^{3D}

- Commercial program
- Finite difference method
- Dynamic solver
- Mohr-Coulomb material model
- Symmetric model
- Pile modelled as a solid cylinder with equivalented *EI*



Soil-pile interaction

- Linear Coulomb shear-strength criterion
- Tension cut-off



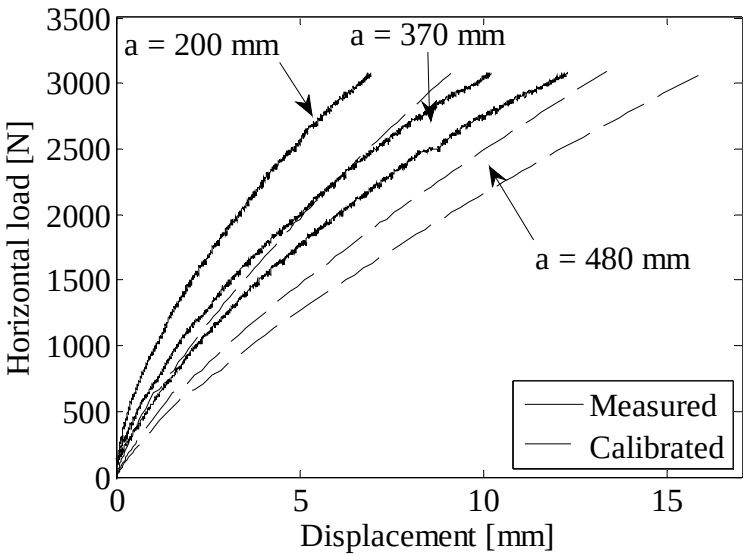
Simulation of large-scale monopiles

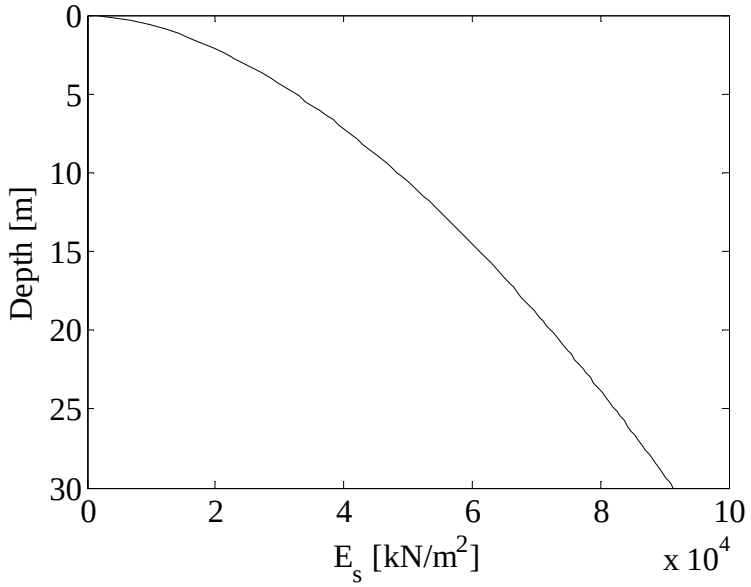
Comparison with laboratory tests:

- Soil parameters determined by CPT

Large scale piles:

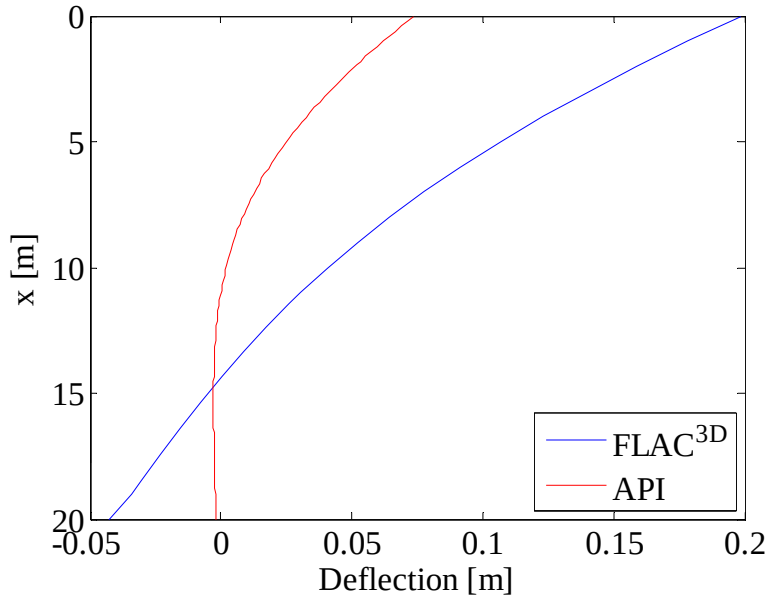
- D = 2-7 m, L = 20 m, t = 50 mm
- f = 40°, y = 10°, c = 0.1 kPa
- Varying E_s

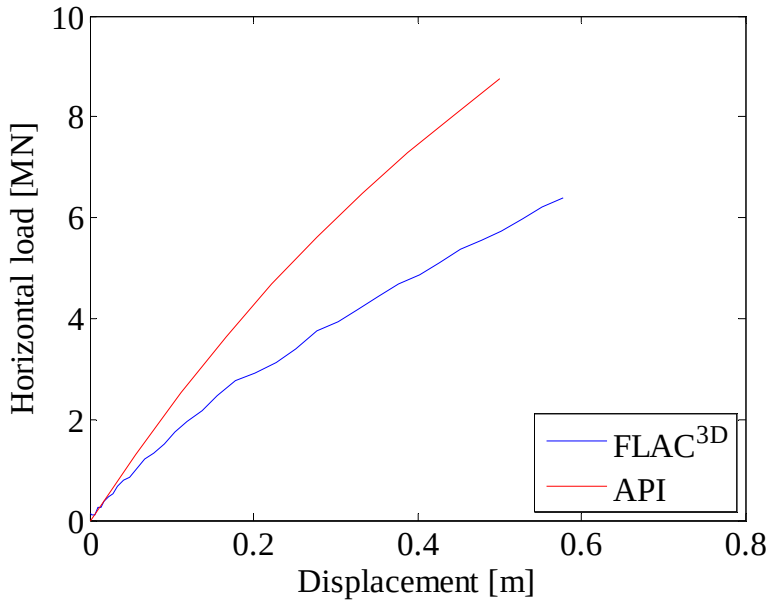




Comparison of numerical simulations with the Winkler model approach

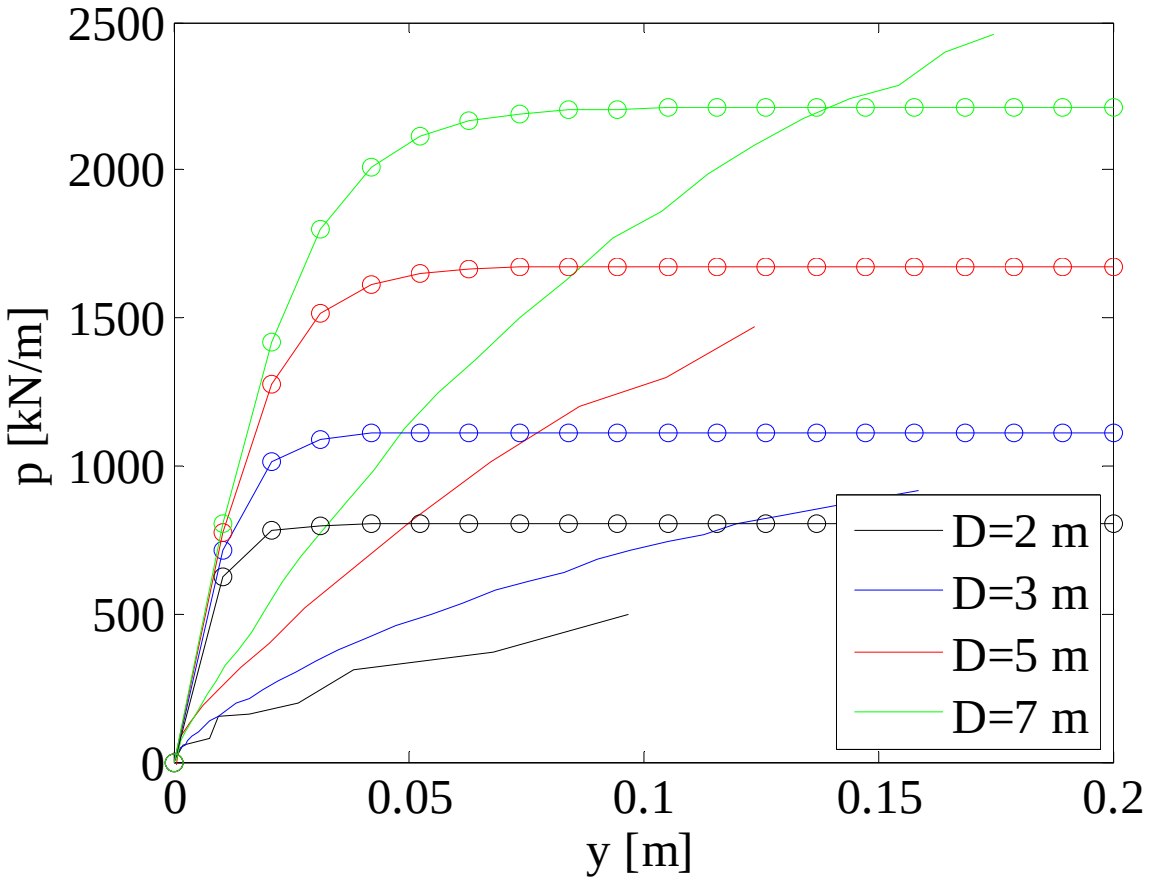
D = 3 m





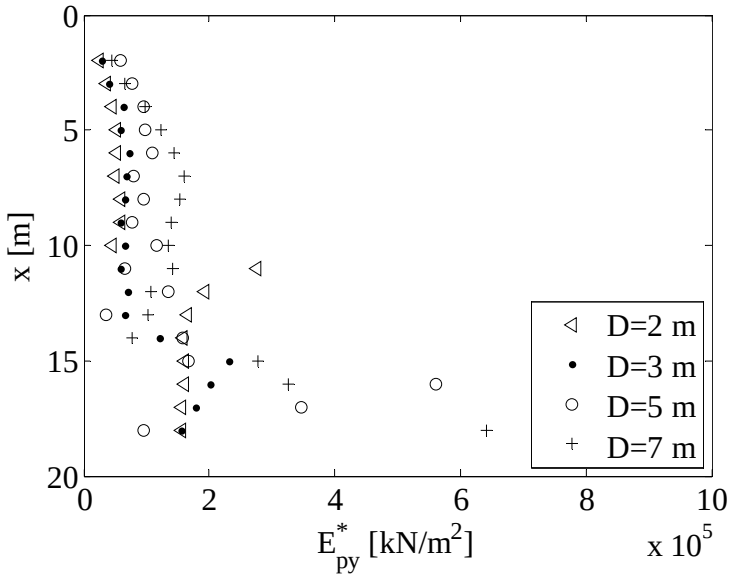
Validation of *p*-*y* curves

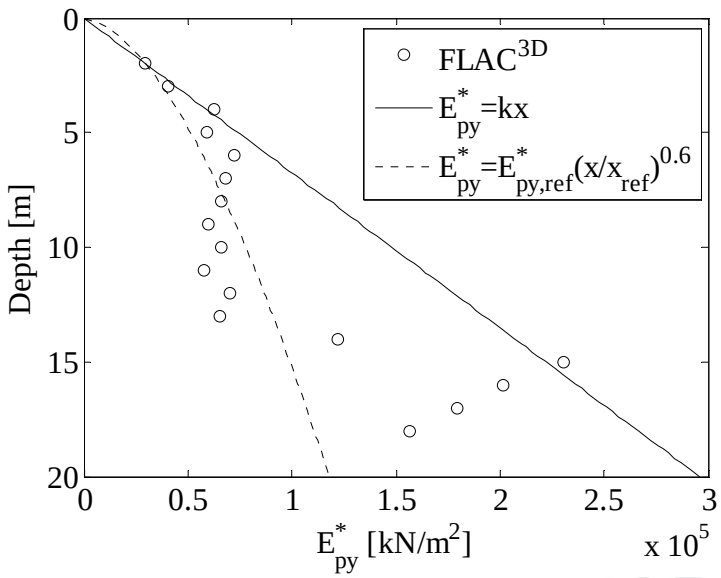
Depth, *x*=2 m



Initial stiffness

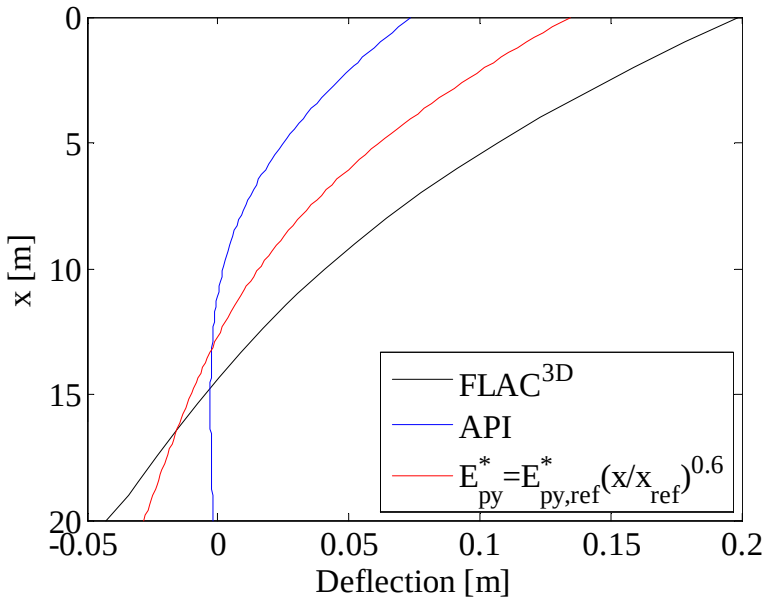
- E^*_{py} increase with increasing *D*
- Non-linear variation of $E^*_{py} \neq kx$
- Lesny and Wiemann (2006)

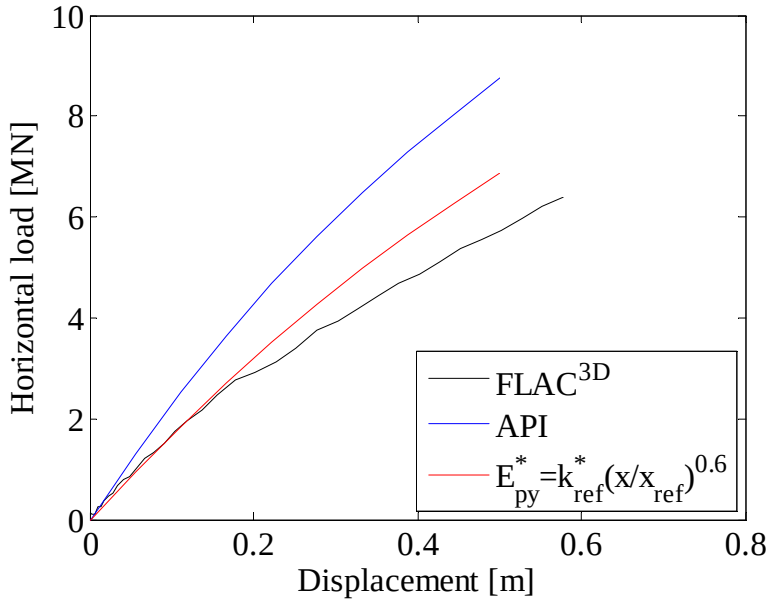




Improved *p*-*y* curves

$$E_{py}^{*} = \left(\frac{x}{x_{ref}} \right)^{0.6} \cdot k_{ref}$$





Conclusions

Increase in E_{py}^{*} for increasing *D*

- Numerical analyses and laboratory tests

Non-linear variation of E_{py}^{*} with depth

- Power function, numerical analyses

Updated *p*-*y* curves for large-diameter piles is needed

Future research

- Cyclic loading has to be considered
- Assessment of a wider range of soil and pile properties
- Full-scale measurements are needed

AALBORG UNIVERSITY

Thank you for your attention!

S. P. H. Sørensen (sphs@civil.aau.dk)