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RESEARCH AT ALPHA VENTUS
Eine Forschungsinitiative des Bundesumweltministeriums

Behavior and capacity of pile foundations for offshore wind energy converters – Part I

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PtJ
Projektträger Jülich
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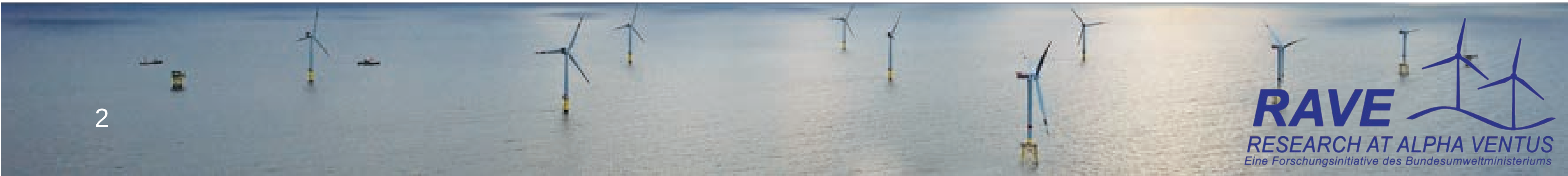
Coordination

Fraunhofer
IWES

Behavior and capacity of pile foundations for offshore wind energy converters – Part I

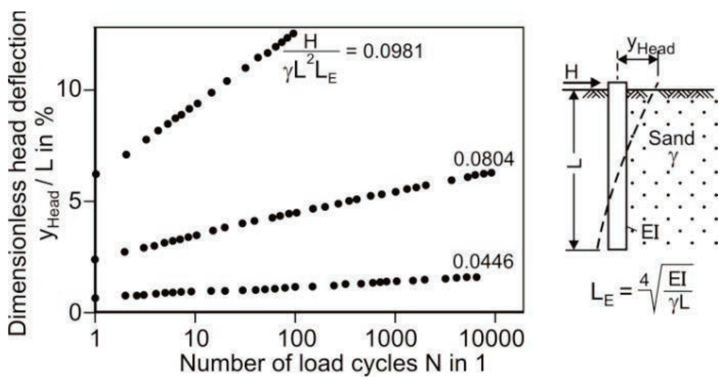
- Cyclic accumulation of monopile rotations
  * SDM method
  * Consideration of lifetime load spectra

- Prediction of axial pile capacity
  * Comparison of ß-method and CPT-based methods
  * Recommendations

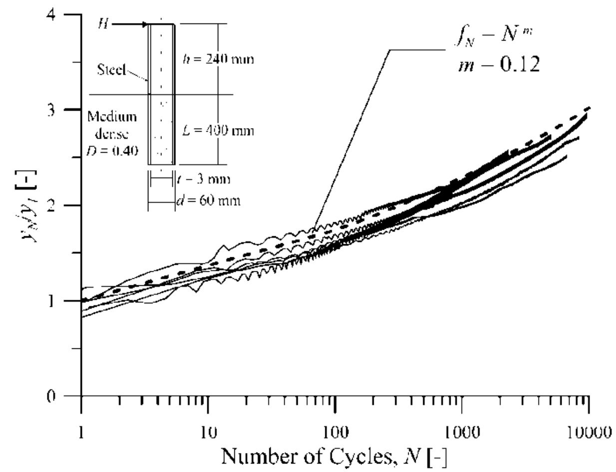


Behavior of piles under cyclic horizontal loading

Results of Hettler (1981)



Results of Peralta & Achmus (2010)



Accumulation of displacements:

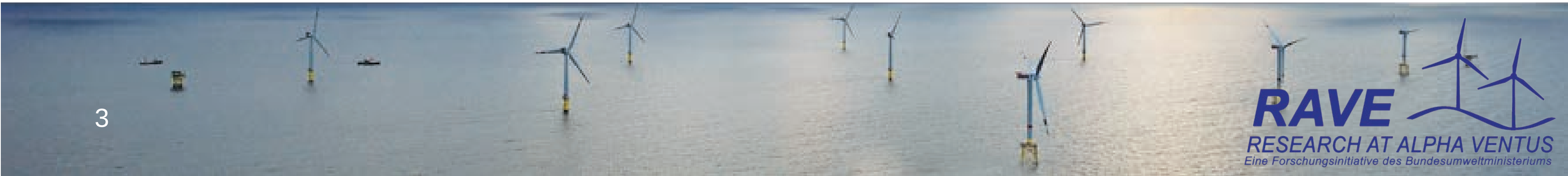
$$y_N = y_1 \, f_N(N)$$

$$f_N = N^{m}$$

$$f_N = 1 + t \times \ln N$$

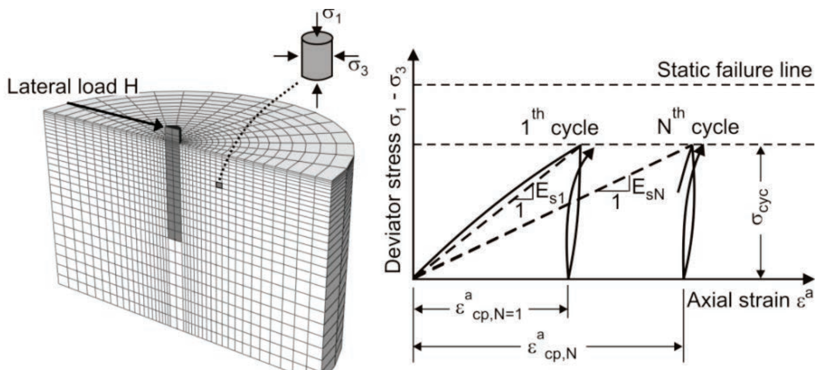
m / t are dependent on soil conditions and pile geometry (stiffness); in general also on loading conditions

→ No general empirical approach is available



Stiffness Degradation Method

Idea: Accumulation of strains is interpreted as decrease of (secant) stiffness



$$\frac{E_{sN}}{E_{s1}} \cong \frac{\varepsilon^{a}_{cp,N=1}}{\varepsilon^{a}_{cp,N}}$$

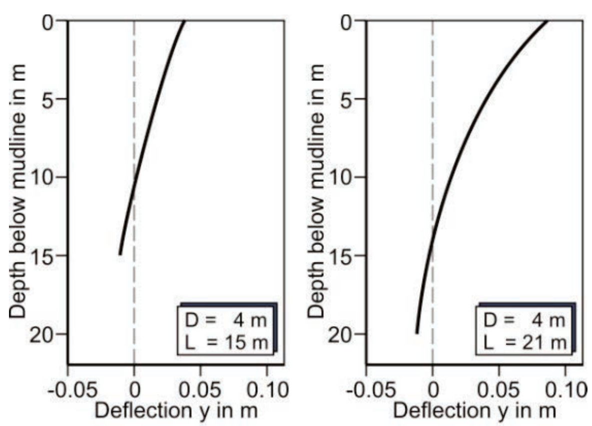
$$\frac{E_{sN}}{E_{s1}} = \frac{\varepsilon^{a}_{cp,N=1}}{\varepsilon^{a}_{cp,N}} = N^{-b_1 (X)^{b_2}}$$

$$X = \frac{\sigma_{1,cyc}}{\sigma_{1,sf}}$$

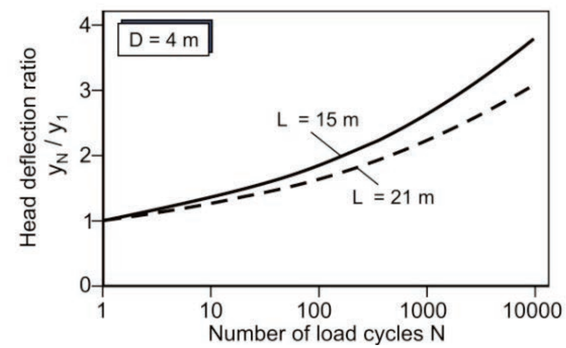
Results (example):

Loads:
Moment arm 37.9m
H = 40% H_{ult}

Static deflection lines:

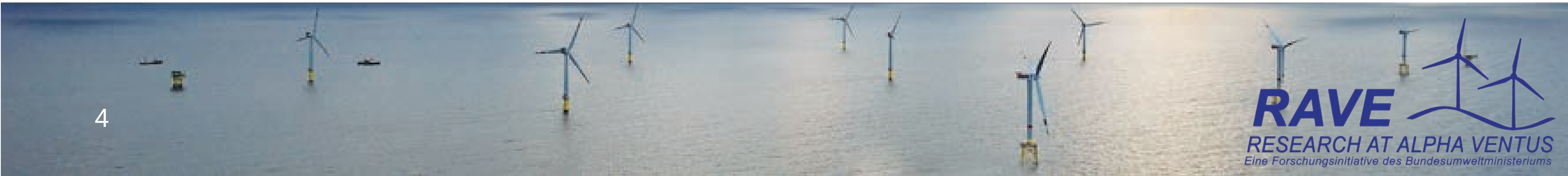


Cyclic performances:



$$f_N = N^{m}$$

with m=0.145 (L=15m)
and m=0.123 (L=21m)

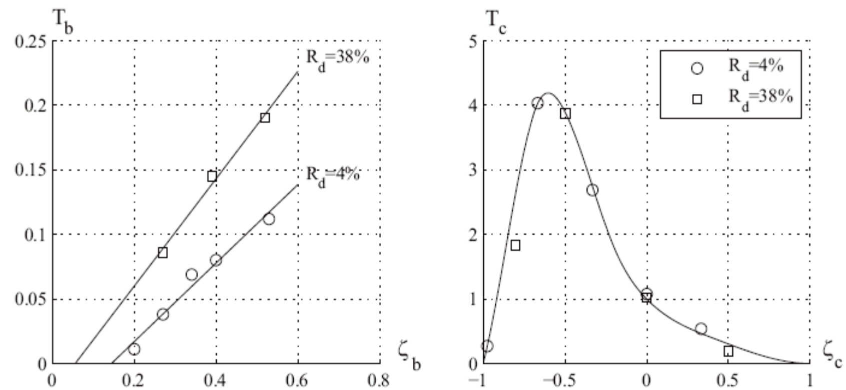


General load data

Application of an approach proposed by LeBlanc et al. (2010)

$$\Delta\theta_N = \theta_{stat}\, T_b\, T_c\, N^{\alpha}$$

$$\zeta_b = \frac{M_{max}}{M_{ult}} \qquad \zeta_c = \frac{M_{min}}{M_{max}}$$



- T_c is a function independent of soil conditions
- α and $T_b(\zeta_b)$ can be determined by SDM simulations ($\zeta_c = 0 \rightarrow T_c = 1$)

For each load data set: $\Delta N_{ref,equ} = \left(\frac{\theta_{stat}\, T_b\, T_c\, N^{\alpha}}{\theta_{stat,ref}\, T_{b,ref}\, T_{c,ref}}\right)^{1/\alpha}$ (with respect to a reference load)

→ $$N_{ref,total} = \sum \Delta N_{ref,equ}$$

$$\theta_N = \theta_{stat,ref}(1 + T_{b,ref} T_{c,ref} N^{\alpha}_{ref,total})$$

Accumulation of monopile rotations

Concept:

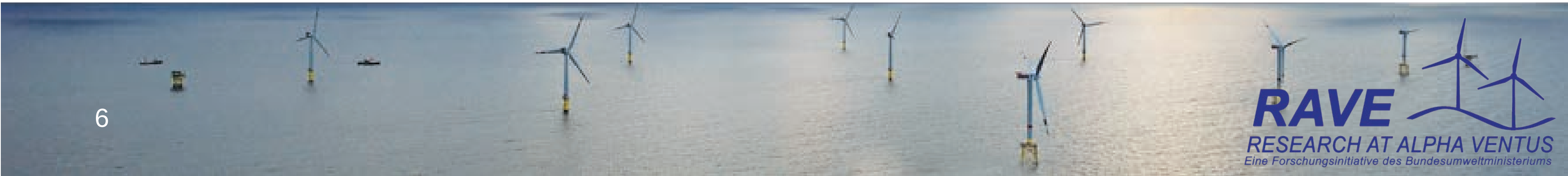
1) Calculate cyclic performance for characteristic extreme load by SDM

2) Determine accumulation parameter m and cyclic parameters $T_b(\zeta_b)$, α from SDM results

3) Define reference load and calculate equivalent load cycle number from LeBlanc approach
   ($H_{ult} = f(M/H)$ and $\theta_{stat} = f(H, M/H)$ must be known)

4) Determine permanent pile rotation

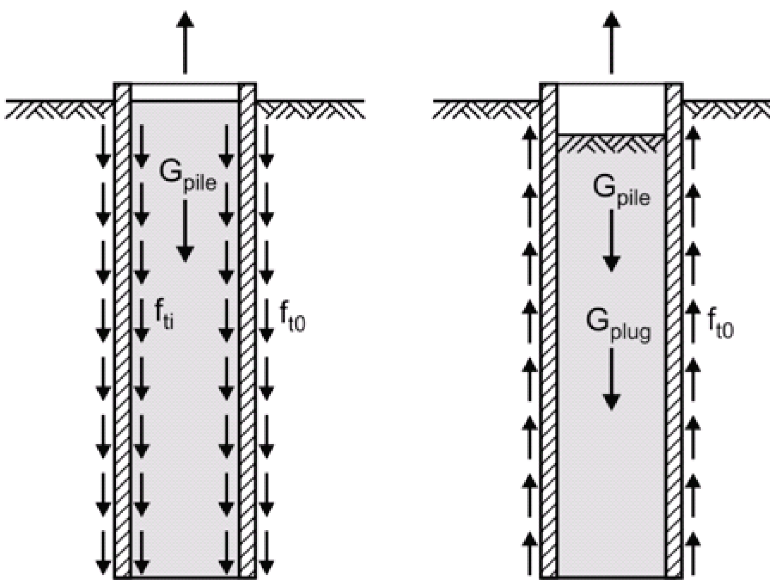
SDM calculations for a few representative locations might be sufficient to be able to estimate site-specific α and T_b–values with sufficient accuracy.



Axial capacity in sand: ß-method

Tensile capacity for open-ended steel pipe piles:

$$R_t = f_{to} \cdot A_o + G'_s + Min\left[G'_p;\ f_{ti} \cdot A_i\right]$$



β-method acc. to API and GL guidelines:

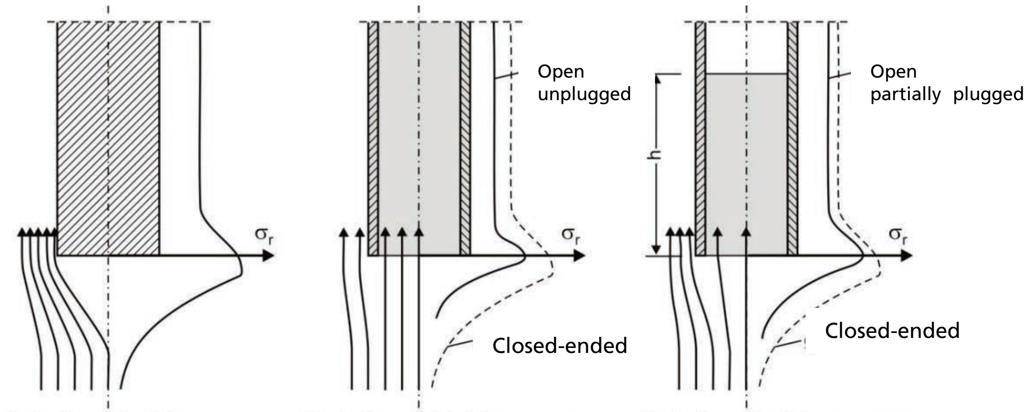
$$f_t(z) = \frac{2}{3} \cdot \beta \cdot \sigma'_v(z)$$

$$\beta \cdot \sigma_v(z) \leq f_{t,\max}$$

Table 1. Design parameters for predicting shaft friction in cohesionless soil (API 2007).

Relative density	soil	β [-]	$f_{t,max}$ [kPa]
Medium dense	Sand-Silt	0.29	67
Medium dense Dense	Sand Sand-Silt	0.37	81
Dense Very Dense	Sand Sand-Silt	0.46	96
Very Dense	Sand	0.56	115

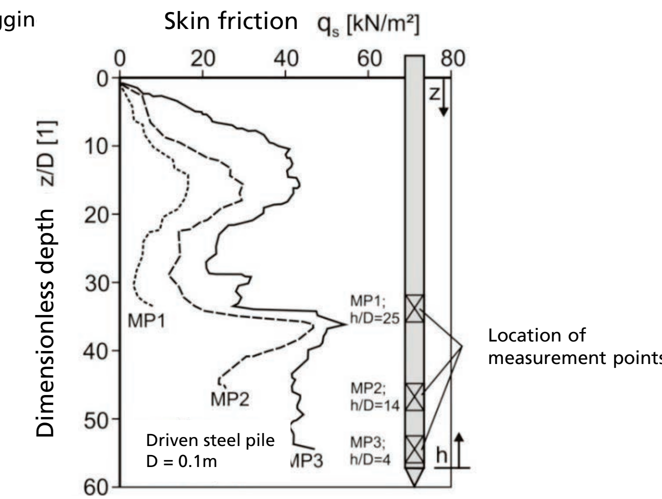
Effects due to installation



a) Closed-ended pile b) Open-ended pile without plugging c) open-ended pile with partial pluggin

<u>Plugging</u> affects the magnitude of soil displacement and thus the radial stresses acting on the pile shaft.

<u>Friction fatigue</u> occurs due to cyclic shearing during installation. The result is a decrease of radial stresses.



CPT-based methods acc. to API RP 2A (2007)

New methods for the calculation of skin friction in non-cohesive soils.

General equation for ICP-05, Fugro-05 und UWA-05 methods:

Initial stress state — Friction fatigue — Interaction between skin friction and base resistance

$$q_{s,k}(z) = u\, q_c(z) \left[\frac{\sigma'_{v0}(z)}{p_a}\right]^a A_r^b \left[\max\left(\frac{L-z}{D}, v\right)\right]^{-c} (\tan\delta_{cv})^d \left[\min\left(\frac{L-z}{D}\cdot\frac{1}{v}, 1\right)\right]^e$$

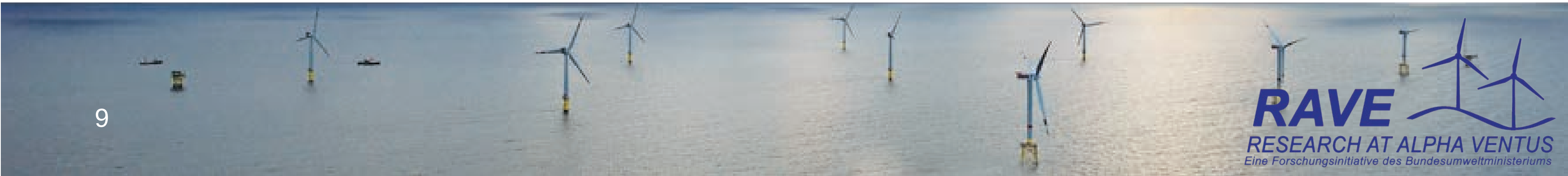
(DIN EN ISO 19902)

Max. radial stress — Degree of plugging — Wall friction pile / soil

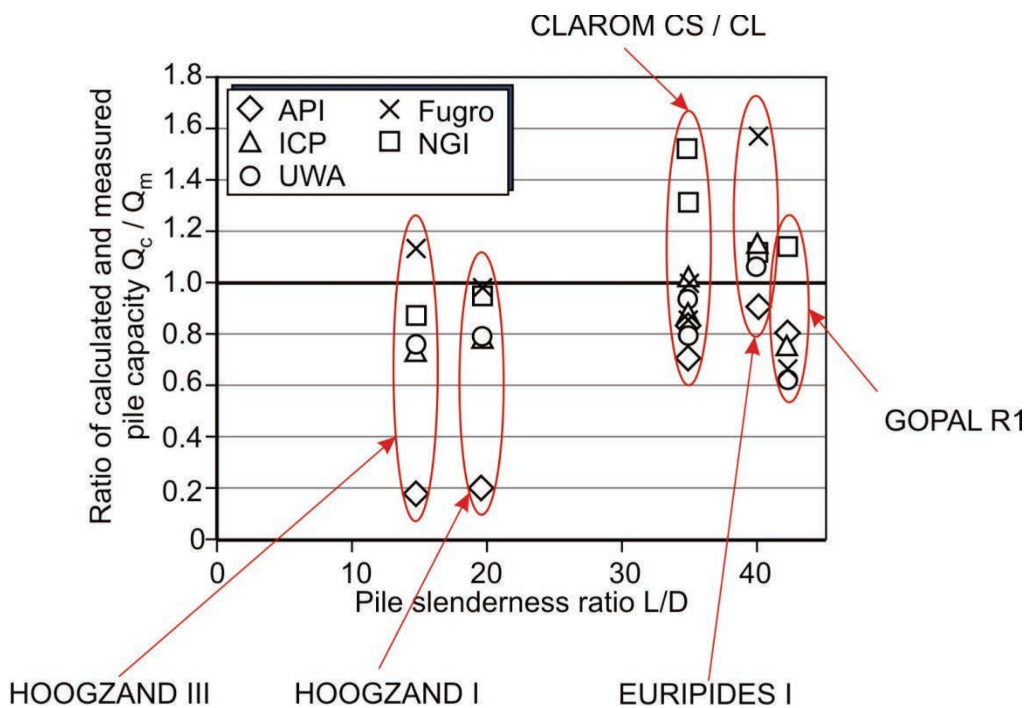
$A_r = 1 - (D_i / D)^2$ effective area ratio
D = pile diameter
D_i = inner pile diameter
L = embedded depth
P_a = atmospheric pressure
q_c = cone resistance from CPT
$q_s = f(z)$ = skin friction
σ'_{v0} = effective vertical stress
δ_{cv} = wall friction angle
a, b,c, d, e, u, v = empirical coefficients, dependent on method

Method	Type of loading	Parameter						
		a	b	c	d	e	u	ν
ICP-05	Compr.	0,1	0,2	0,4	1	0	0,023	
	Tension	0,1	0,2	0,4	1	0	0,016	
UWA-05	Compr.	0	0,3	0,5	1	0	0,030	2
	Tension	0	0,3	0,5	1	0	0,022	2
Fugro-05	Compr.	0,05	0,45	0,9	0	1	0,043	
	Tension	0,15	0,42	0,85	0	0	0,025	

Which method is best suited for open-ended steel pipe piles with L/D = 10 to 40 in dense sands?

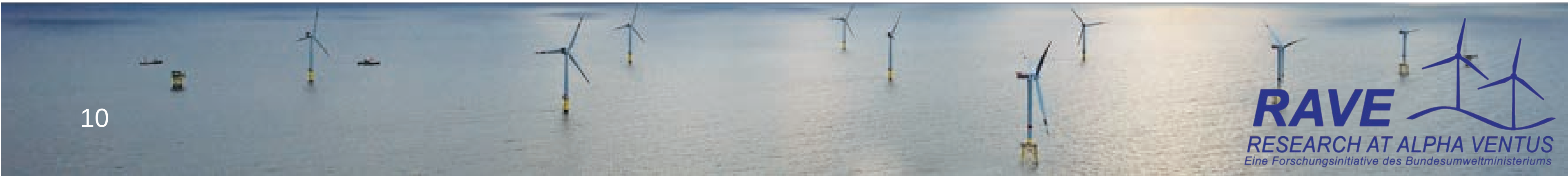


Back-calculation of (tensile) pile tests: Results



Mean value and standard deviation of Q_c/Q_m.

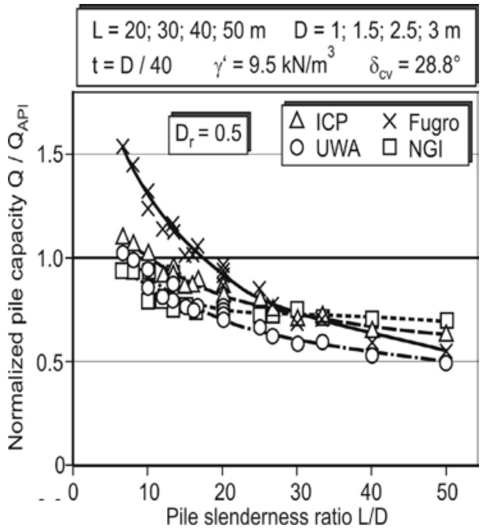
	API	ICP	UWA	FUGRO	NGI
Q_c/Q_m mean	0.60	0.88	0.82	1.03	1.15
COV	0.29	0.15	0.14	0.28	0.21



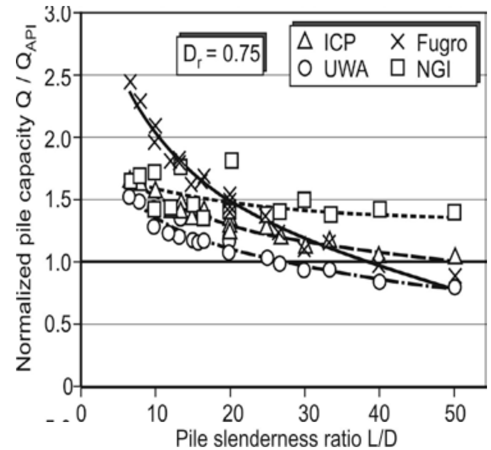
Parametric study for Q/Q_{API}

Effects of relative density and pile slenderness

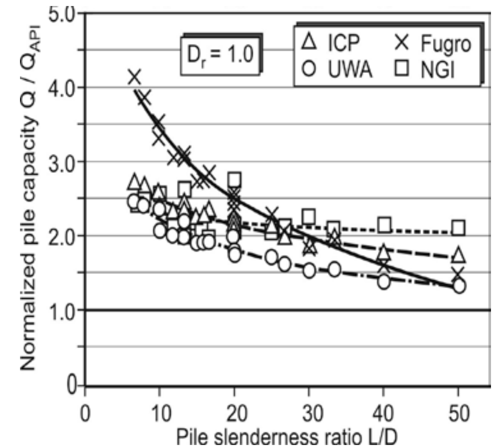
Medium dense to dense



Dense



Very dense

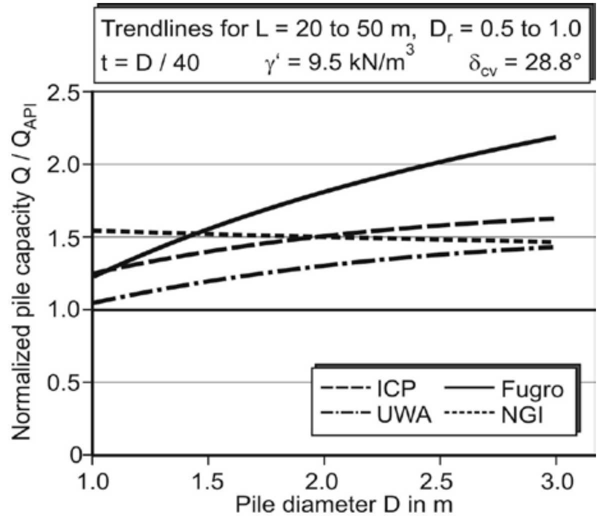


- **For piles in dense sand with L/D<30 (North Sea conditions), the ß-method seems to be conservative**

- **For long, slender piles in medium dense sands the ß-method is non-conservative**

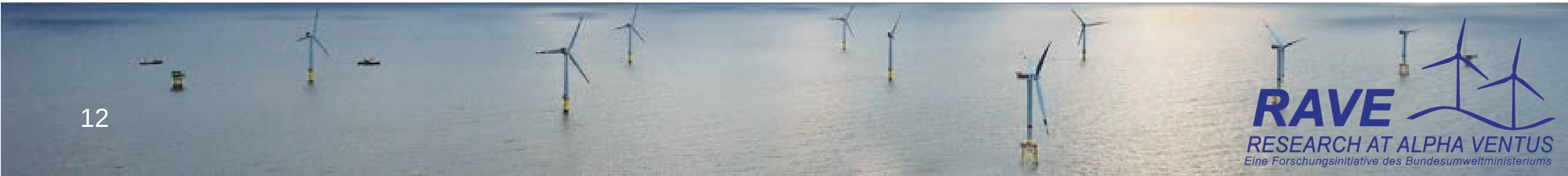
Parametric study for Q/Q_{API}

Effect of the absolute pile diameter



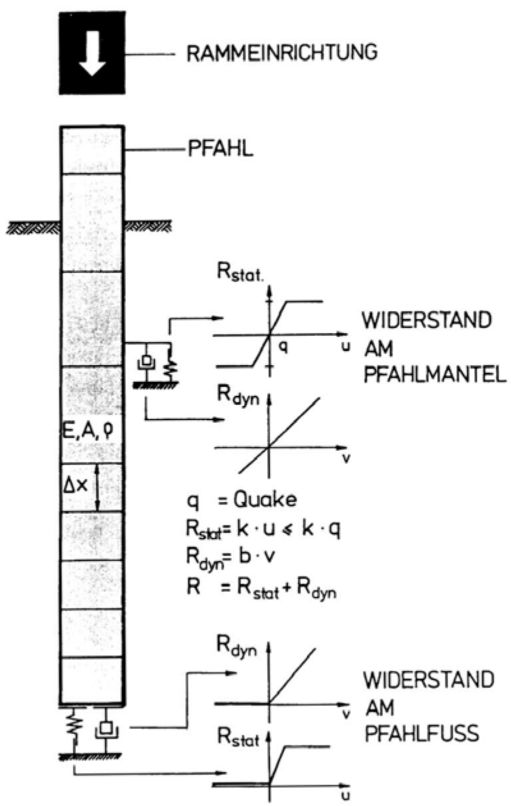
- **CPT-based methods (Fugro, ICP, UWA) predict a greater relative capacity increase with increasing diameter than the ß-method. But: For D>1m no experimental evidence exists!**

- **CPT-based methods should be applied with great caution. More experience is urgently needed.**



Dynamic pile tests

Dynamic pile tests are compulsory acc. to BSH guidelines
→ The predicted capacities are checked
→ The prediction must lie on the safe side!



$$R_k = \frac{R_{m,min}}{\xi_6} \qquad \xi_6 = \left(\xi_{0,6} + \Delta\xi\right)\eta_D$$

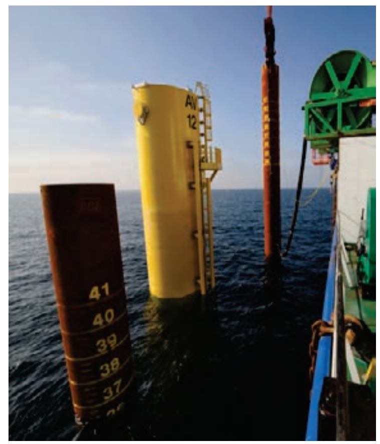
$$R_k = \frac{R_{m,av}}{\xi_5} \qquad \xi_5 = \left(\xi_{0,5} + \Delta\xi\right)\eta_D$$

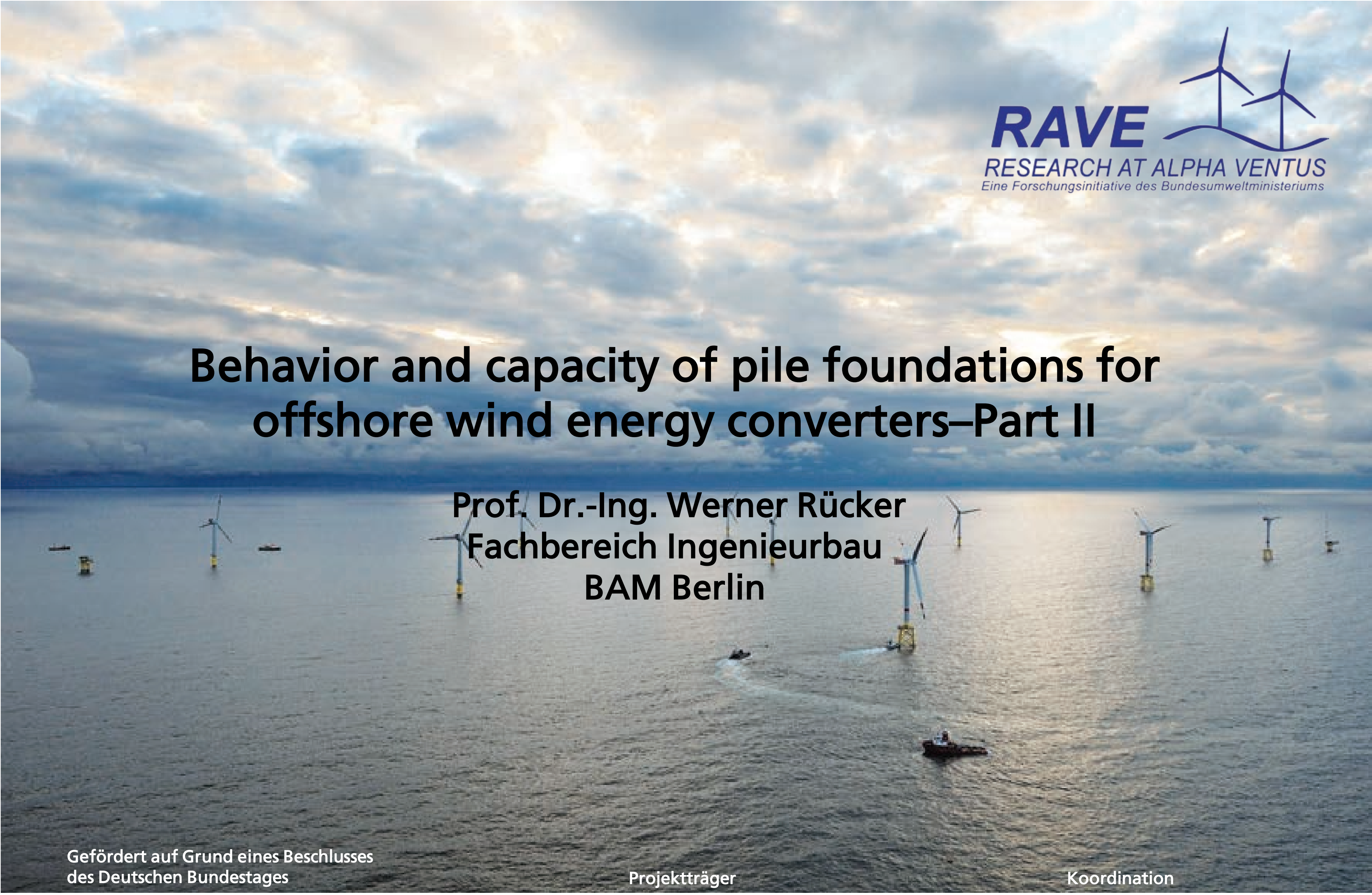
Recommendation:

- Application of API ß-method
- Comparison with CPT-based methods
- Use of conservative approach

→ More experience needed!

Thanks for your attention !





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Behavior and capacity of pile foundations for offshore wind energy converters–Part II

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BAM Berlin

Gefördert auf Grund eines Beschlusses des Deutschen Bundestages

Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit

Projektträger

PtJ Projektträger Jülich Forschungszentrum Jülich

Koordination

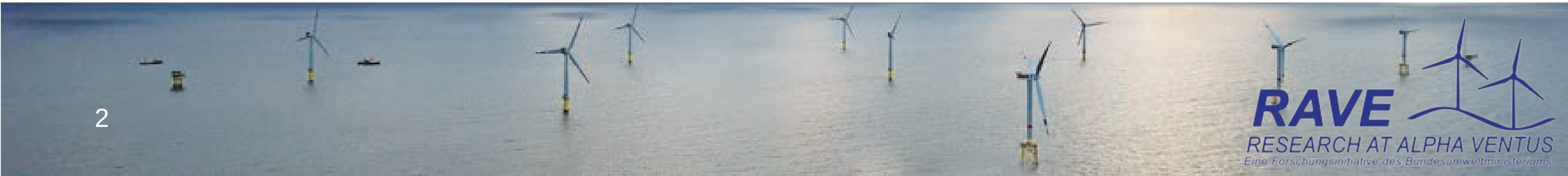
Fraunhofer IWES

Based on the research project

Practical Design and observations model for pile foundations under cyclic loading
Project Nr.: 0327618A

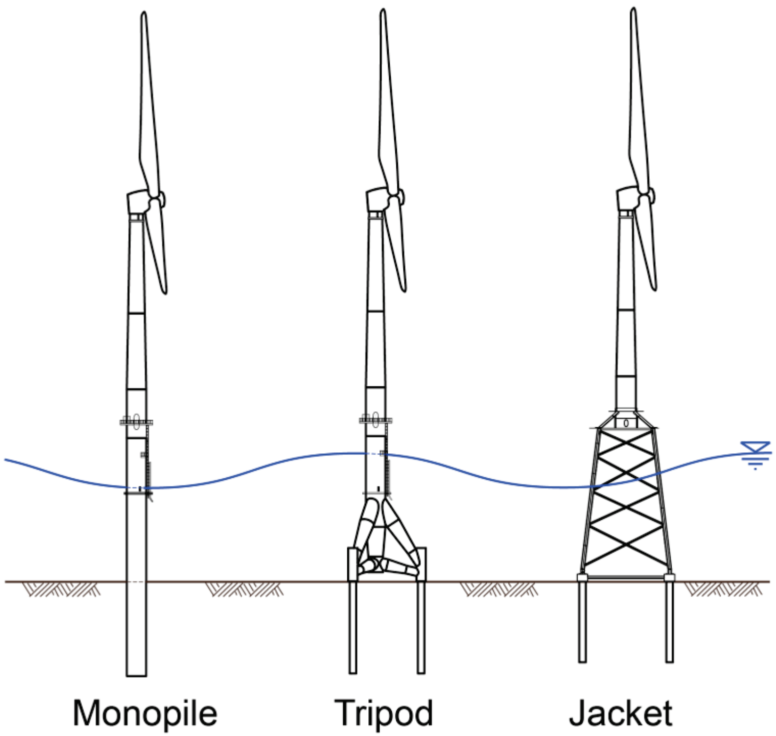
Main Partners

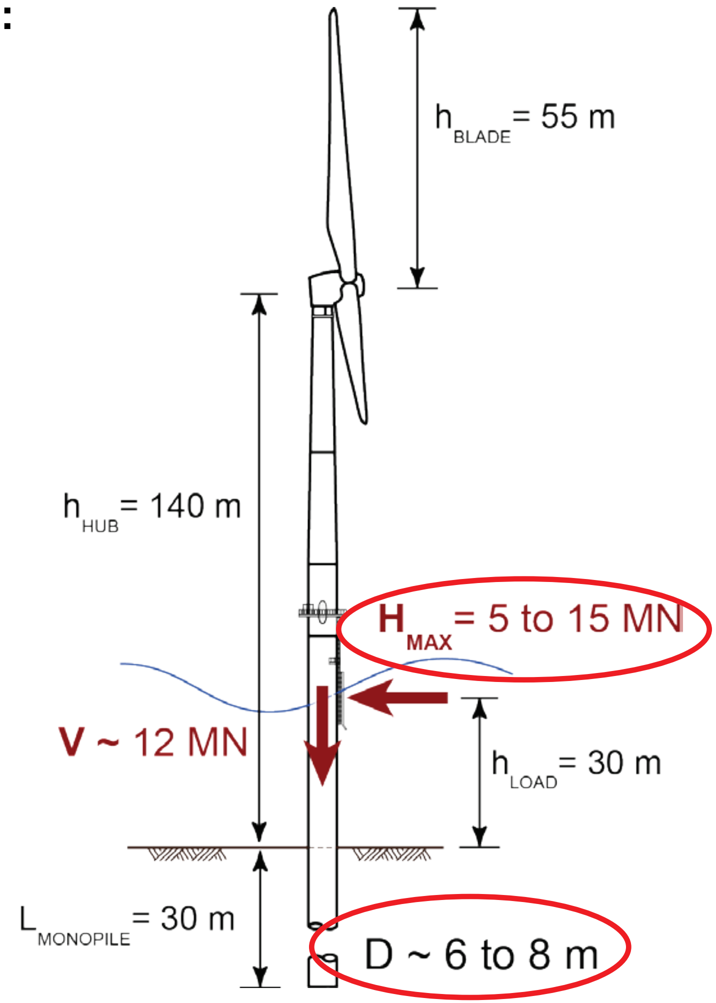
- **TU Berlin** Prof. Dr.Ing. S. Savidis
- **GuD Consult** Prof. Dr.-Ing. Th. Richter
- **Multibrid** Dr. A. Hofmann



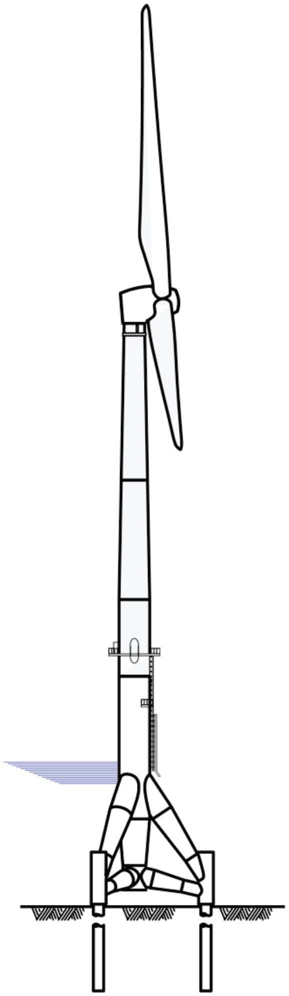
Pile foundations for OWT's

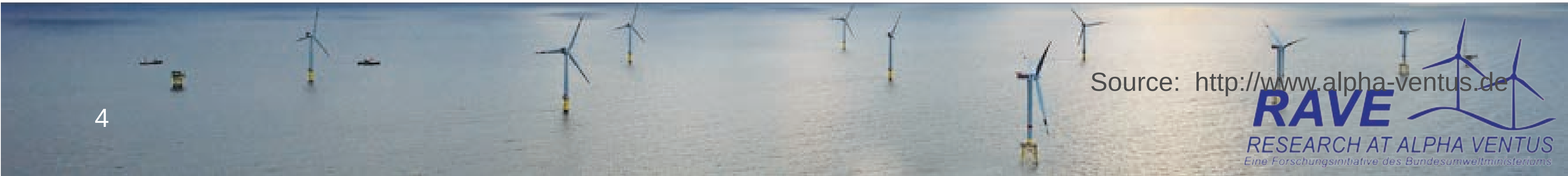
- **Deviate from previous offshore experience:**
  - **Large ratio H / V**
  - **Large pile diameters**





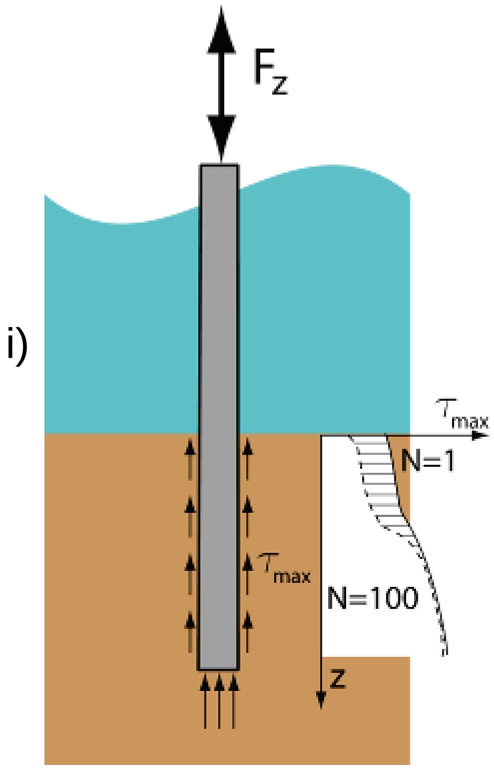
Piled Foundations for Offshore Wind Turbines



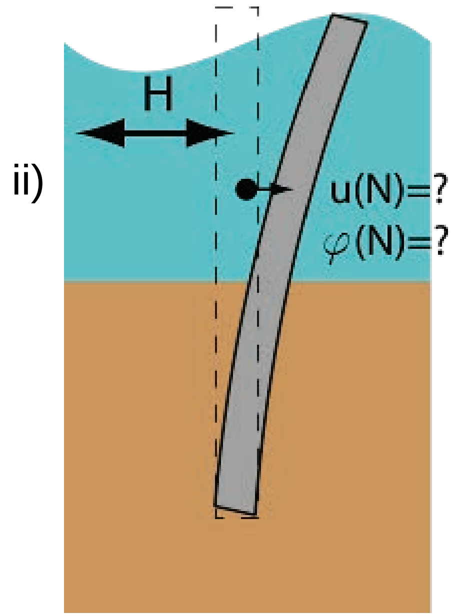


Source: http://www.alpha-ventus.de

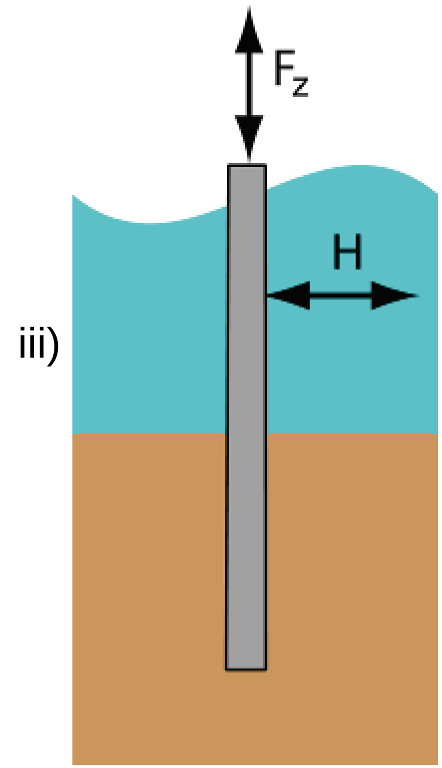
OPEN QUESTIONS



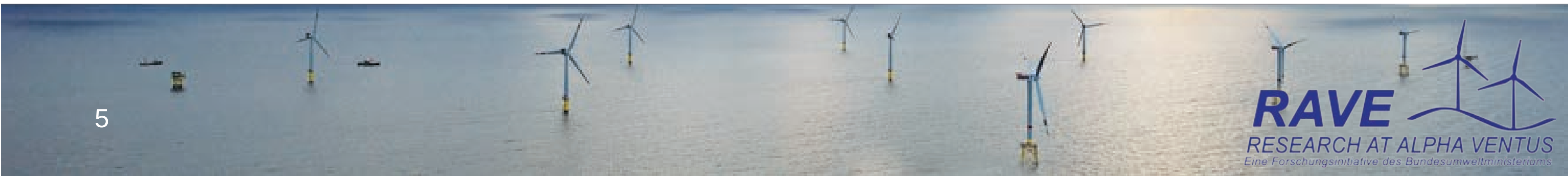
Bearing capacity cyclic axial
(N>10^9 cycles)



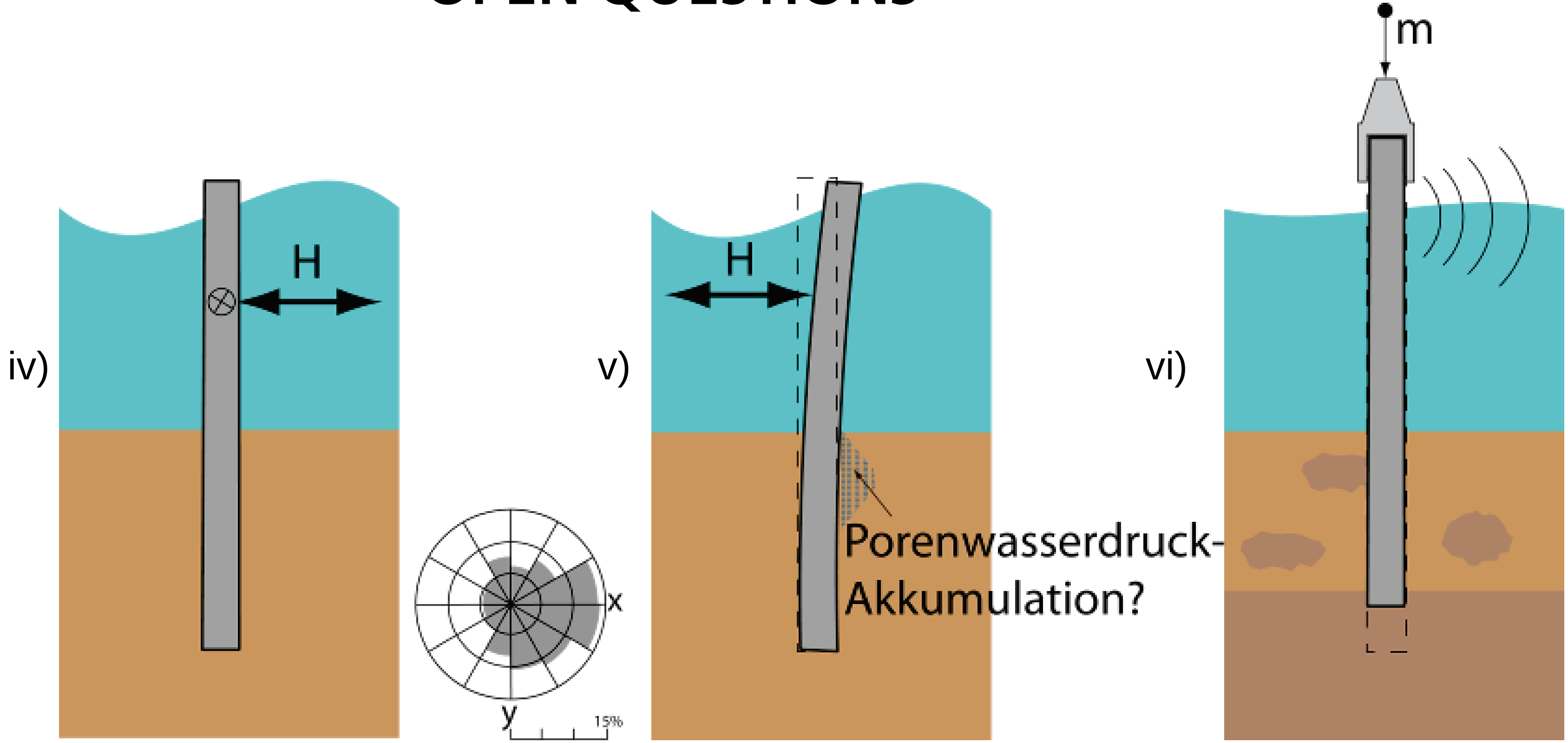
Bearing capacity cyclic lateral



Combined loading (axial and lateral) Order of cyclic loading



OPEN QUESTIONS



Variable directions and irregular loading, Ageing

Pore water accumulation, Ageing

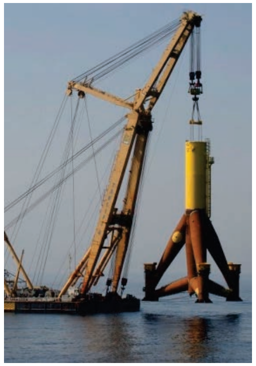
Pile driving, Static Load bearing capacity, environment, …

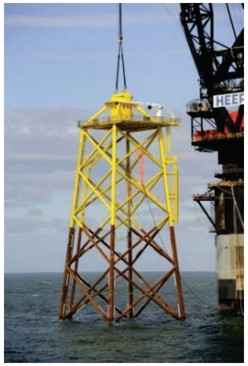
BAM

METHODOLOGY

Field observations and tests

- Offshore prototypes (Alpha-Ventus, BARD, …)
- Field tests onshore (Horstwalde testing site)



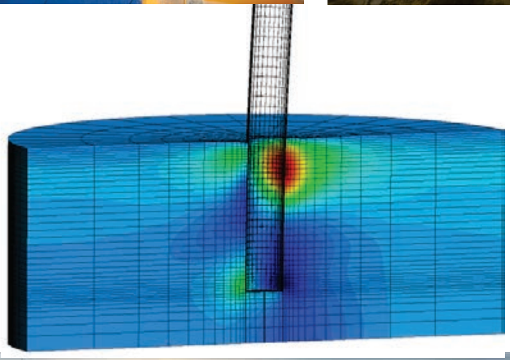


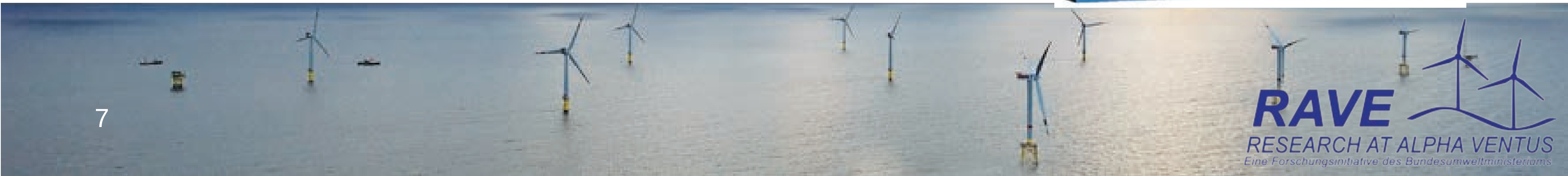
Physical testing in the lab

- Model tests in 1:100 and 1:30 scales
- Element Tests, i.e. Simple-Shear, Triaxial-Test

Computational models

- Coupled FE models: Water-Soil-Structure interaction
- Winkler models for design (lateral loaded piles)
- Cyclic degradation models (axial loaded piles)



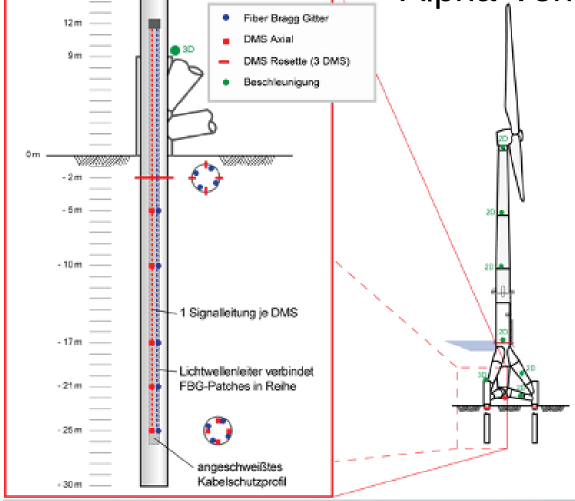


Field observations and tests

Offshore prototypes

- **Alpha-Ventus**: Turbine with tripod support structure
    - **Structure**: Strain gauges, accelerometers, inclinometers
    - **Foundation:** Strain gauges and Fiber Bragg Grating sensors along a tripod-pile

- **BARD**: Turbine with tripile support structure
    - **Structure**: Strain gauges, accelerometers, inclinometers

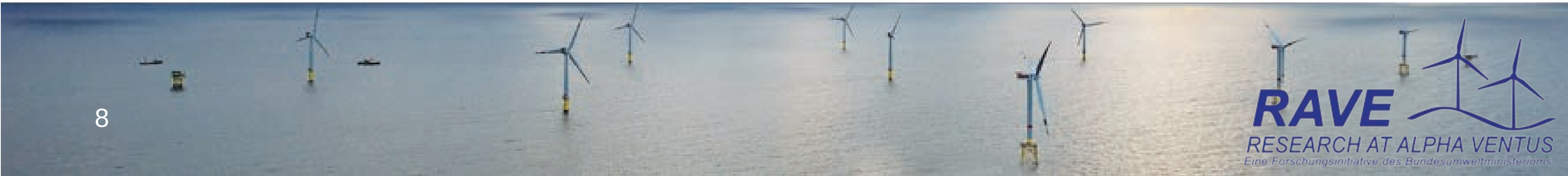


Alpha-Ventus

BARD Offshore 1

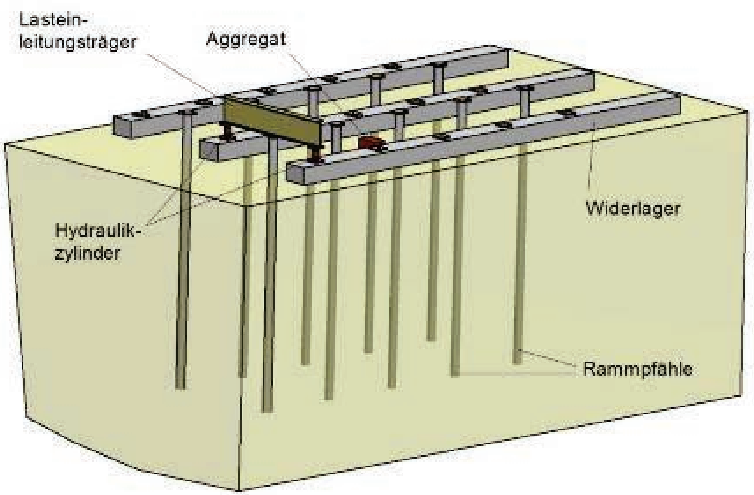
Field tests at Horstwalde

- Large-scale pile tests

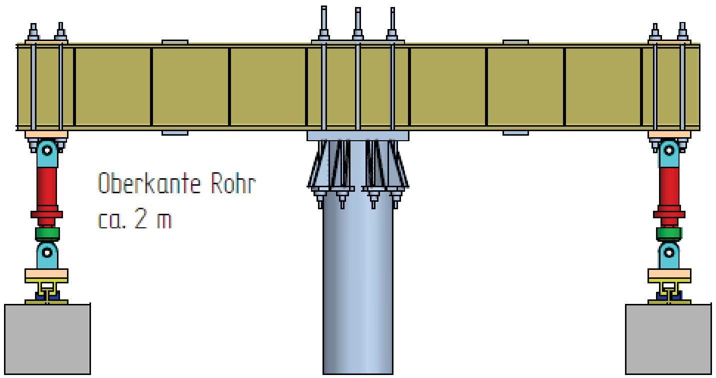


Cyclic Loading and Ageing of Pile Foundations – Field tests BAM-Horstwalde

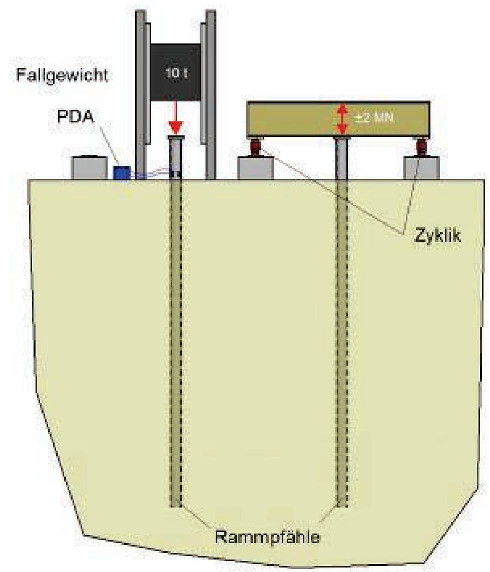
BAM



Pile testing area – driven piles ~ 4MN

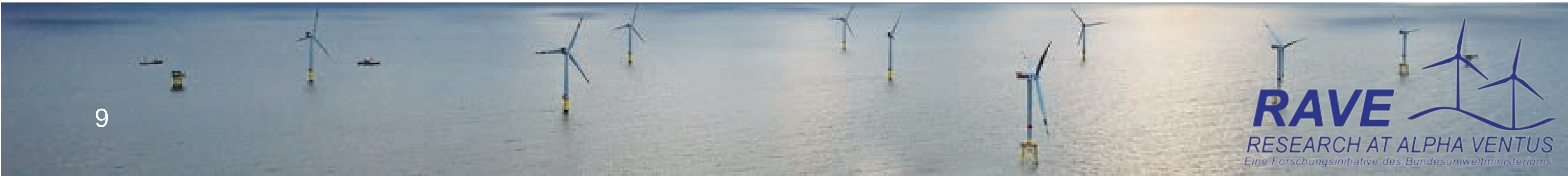


- 10 piles under static and cyclic axial loads
- Pile Capacity using dynamic pile testing
- Aims: Cyclic friction fatigue, ageing effects, …



Cyclic Loading

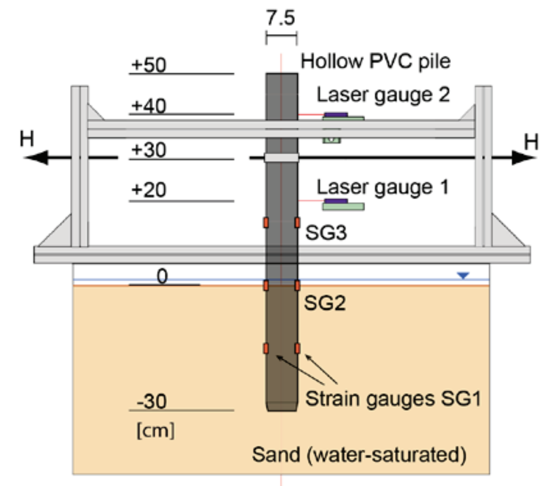
Pile Testing & Cyclic Loading



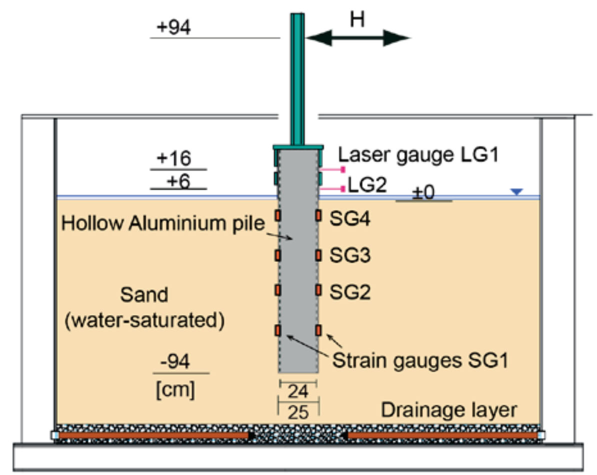
Model tests at BAM

Monopile and Tripod models at reduced scales

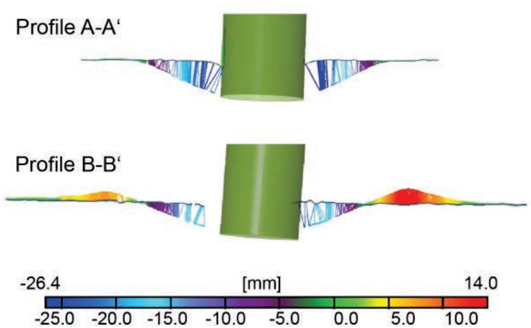
- **Conditions:** Water-saturated, natural gravity (1-g)
- **Measurements:**
  - PILE: Loads, displacements, strains, …
  - SOIL: Point displacements, earth pressures, …
  - WATER: Pore pressures (so far, inconclusive)
  - Surface (and inside) topographic scans

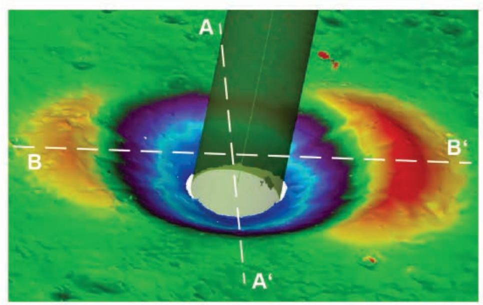


Modelling scale 1:100



Modelling scale 1:30



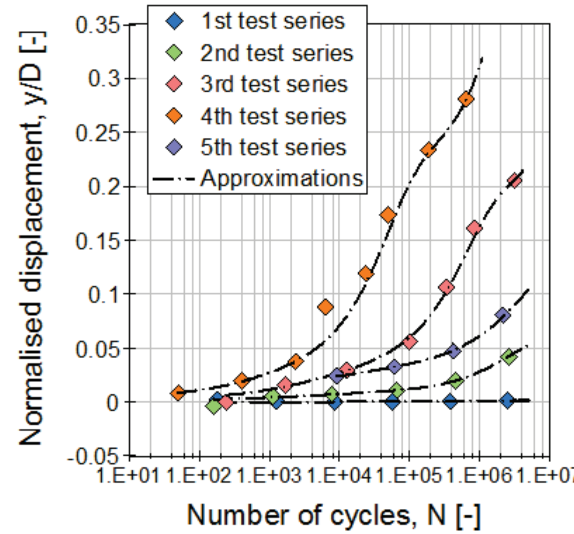


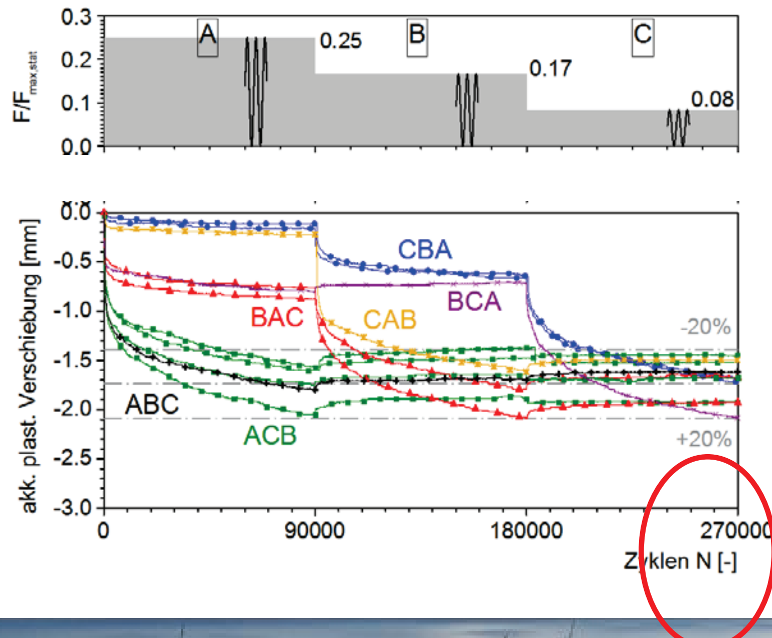
Physical test at 1:100 scale

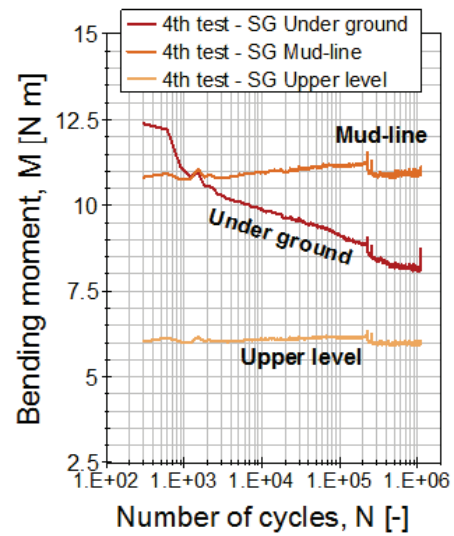
Some experimental results…

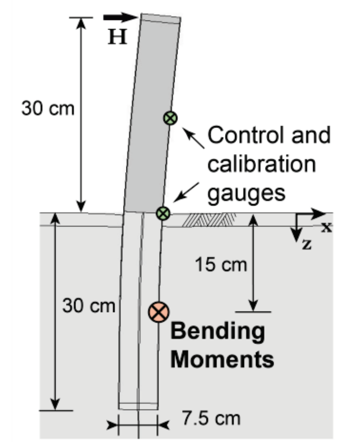
Cyclic laterally loaded piles

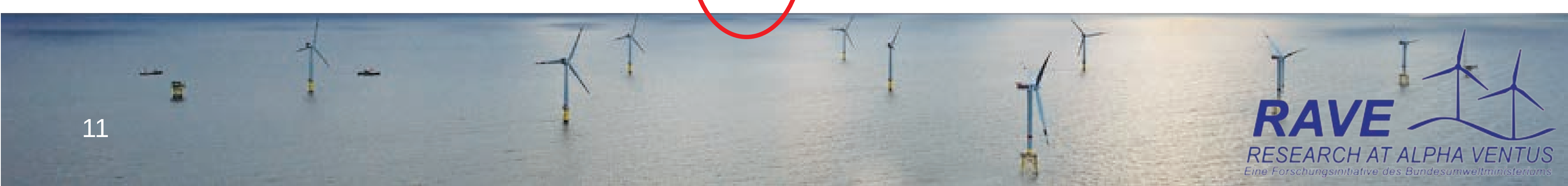
- Generalised accumulation law for the long-term
- Decreasing cyclic amplitude → Sand densification
- Decreasing bending moments → Sand stiffening
- In fully drained conditions, order effects not relevant









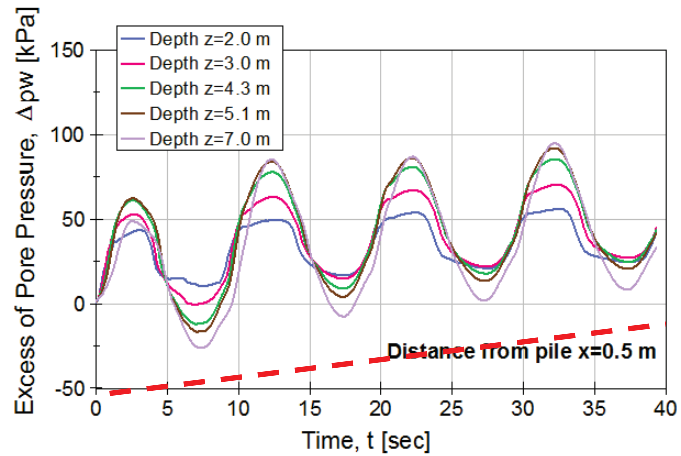


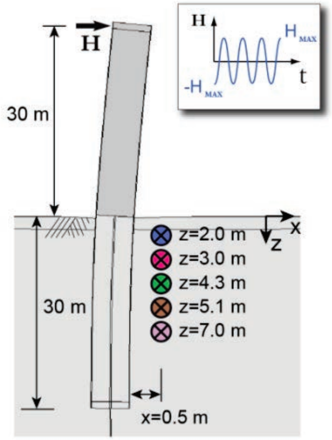
Some numerical results…

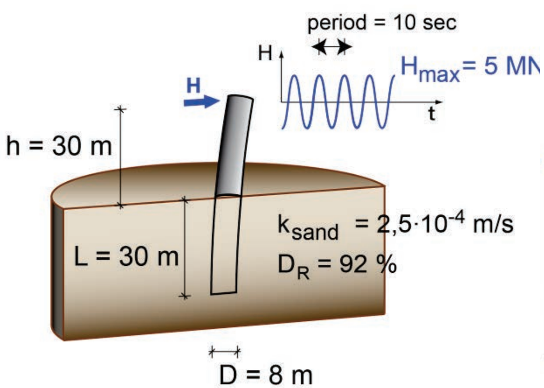
Pore water accumulation at monopile foundation

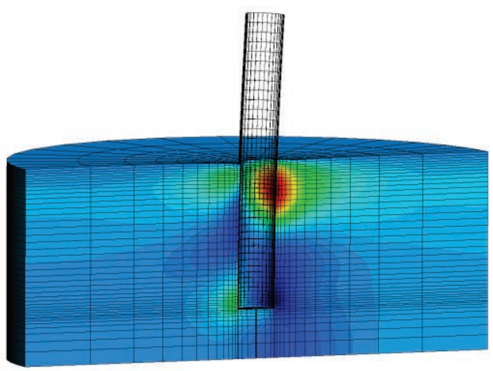
- Excess pore pressure accumulates progressively
- Thereby, soil's effective stress decreases

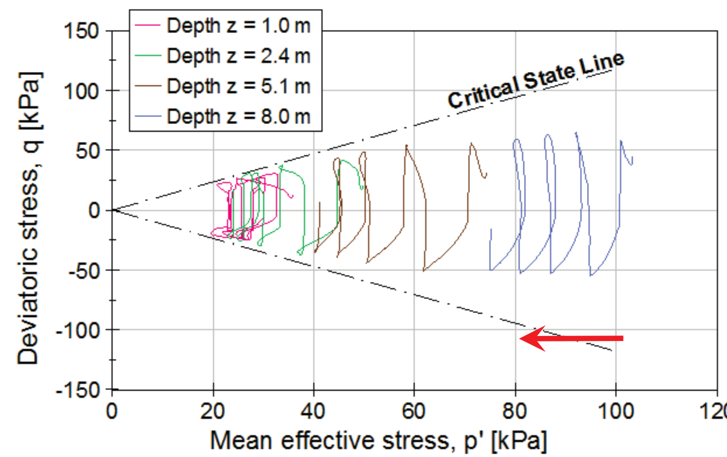
→ Softening





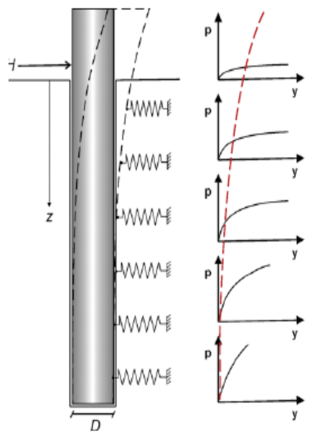




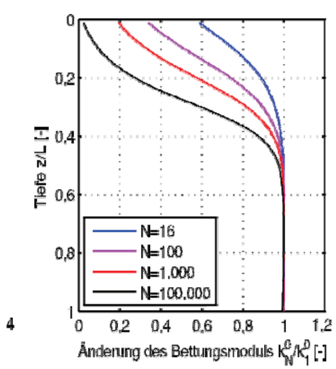


Design model for cyclic lateral loading

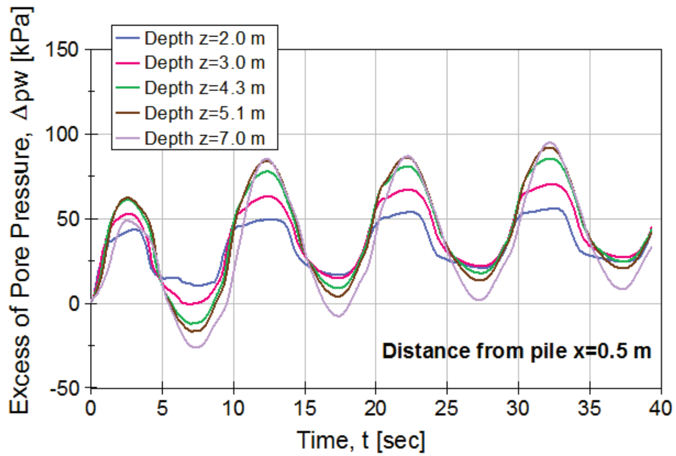
Equilibrium at Winkler beam
With modified stiffness values



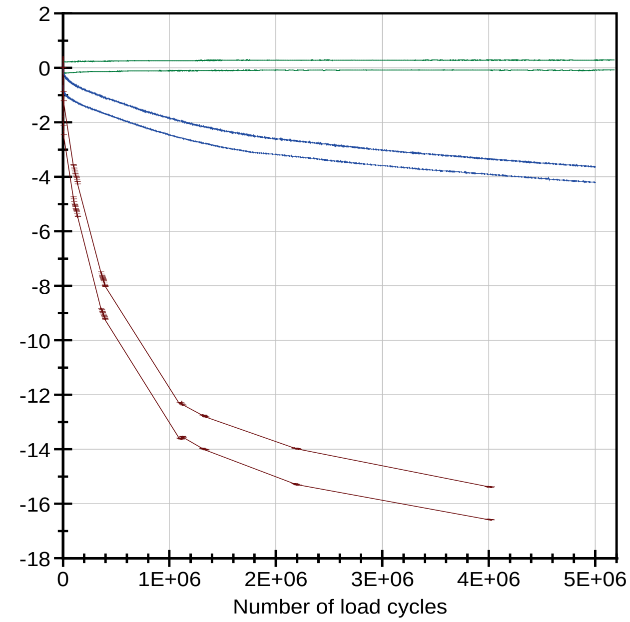
modifiziertes P-y Verfahren



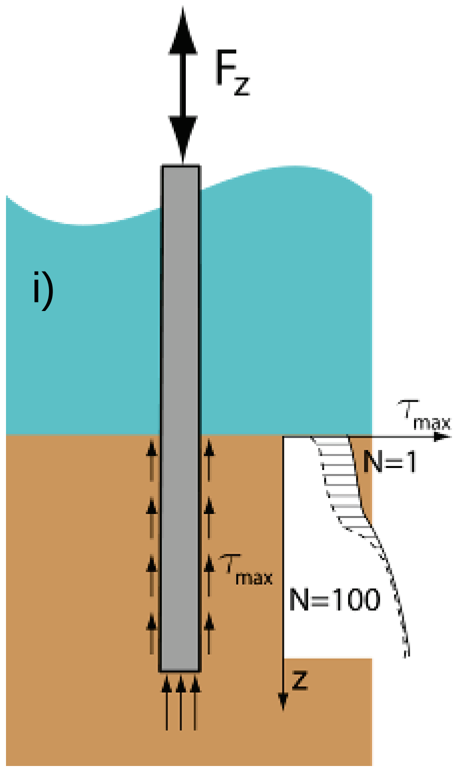
Pore water accumulation
from numerical models
(Cuellar, Tasan)



Prognosis of permanent deflection
by numerical methods bases on
model tests



Design model for axial loaded piles



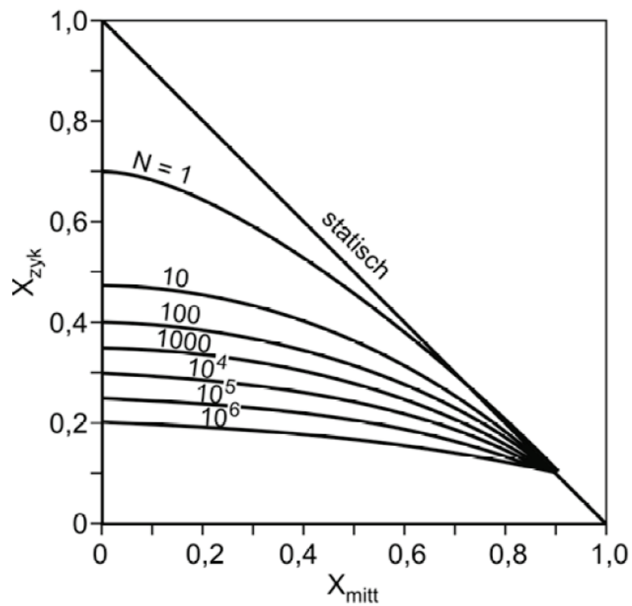
Bearing capacity cyclic axial

(N>10⁹ cycles)

$$F_d \le R_d(N) \qquad R_d(N) = R_k / \gamma_P - \Delta R_{zykl} \cdot \eta_{zykl}$$

ΔR_{zyk} from Interactionsdiagramms

z.B. „*Kirsch/Richter/Mittag*“



Analytische Beschreibung der Interaktionskurven:

$$X_{zyk} = \kappa\,[1 - 1{,}11^{EXP} \cdot X_{mitt}^{EXP}] + 0{,}1235 \cdot X_{mitt}^{EXP}$$

mit $\kappa = 0{,}5 + 0{,}67[\log(N+1) - 1{,}0746 \log(N)]$

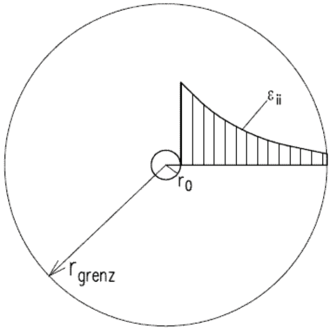
$EXP = 2 - 1{,}5[\log(N+1) - \log(N)]$

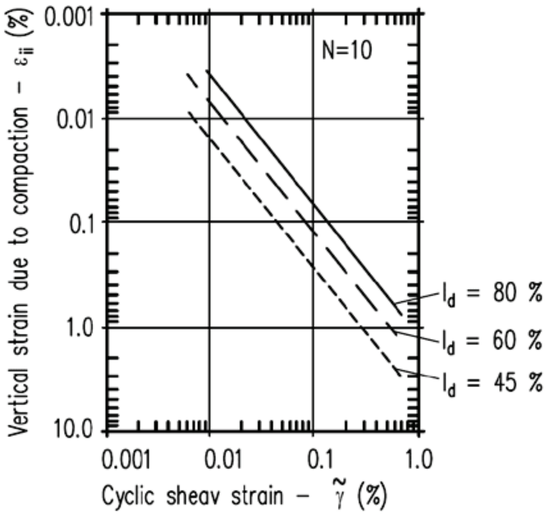
Degradation of bearing capacity at the pile shaft due to cyclic compaction

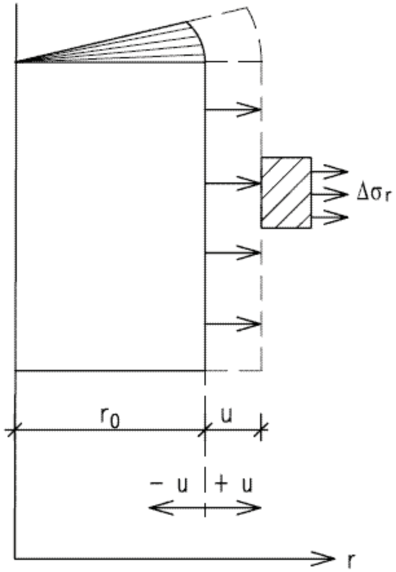
$$\Delta\tau(N) = 2 \cdot G_w \cdot \tan\delta \cdot \Delta D^* \cdot \left[\tilde{\gamma} \cdot \left(\frac{\tilde{\gamma}}{\gamma_{grenz}} - 1 \right) - \frac{1}{2} \cdot \alpha \cdot \gamma_{grenz} \left[\left(\frac{\tilde{\gamma}}{\gamma_{grenz}} \right)^2 - 1 \right] \right]$$

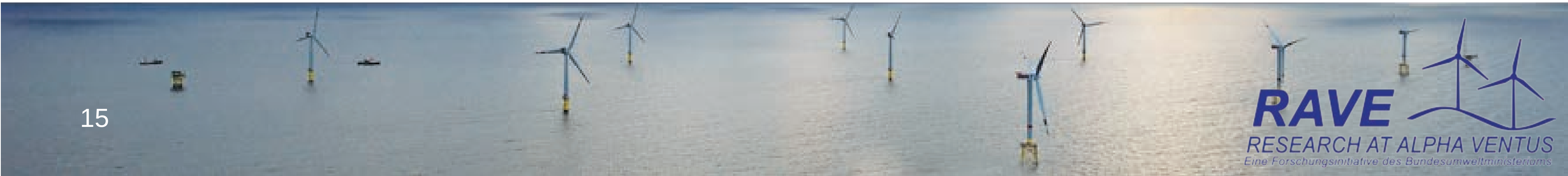
$$\Delta D^* = \Delta D \cdot \lg N = 0{,}5 \cdot I_D^{-2{,}32} \cdot \lg N$$

N	Zyklenanzahl,
G_W	Schubmodul bei Wiederbelastung,
δ	aktivierter Reibungswinkel,
I_d	Initiale Lagerungsdichte,
$\tilde{\gamma}$	zyklische Schubverzerrung,
$\tilde{\tau}$	zyklische Schubspannung,
$\tilde{G}$	Schubmodul bei zyklischer Belastung,
γ_{grenz}	Grenzschubverzerrung,
α	Dilatationsparameter.









THANKS FOR YOUR ATTENTION

RAVE
RESEARCH AT ALPHA VENTUS
Eine Forschungsinitiative des Bundesumweltministeriums