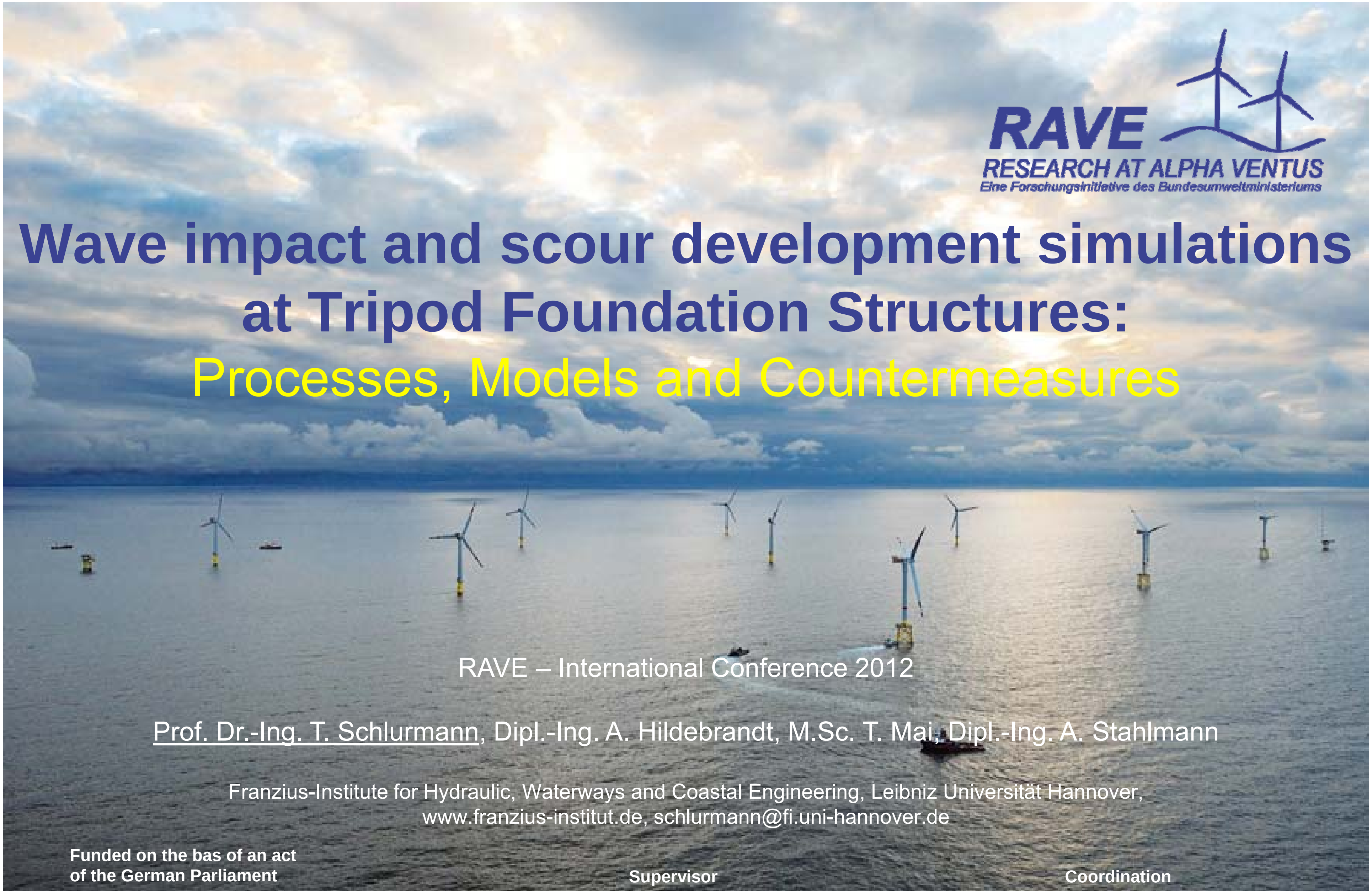

RAVE
RESEARCH AT ALPHA VENTUS
Eine Forschungsinitiative des Bundesumweltministeriums

Wave impact and scour development simulations at Tripod Foundation Structures:

Processes, Models and Countermeasures

RAVE – International Conference 2012

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Supervisor

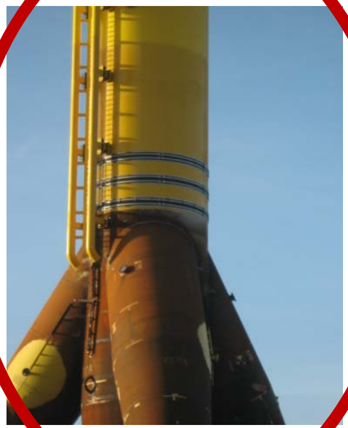
Coordination

Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit

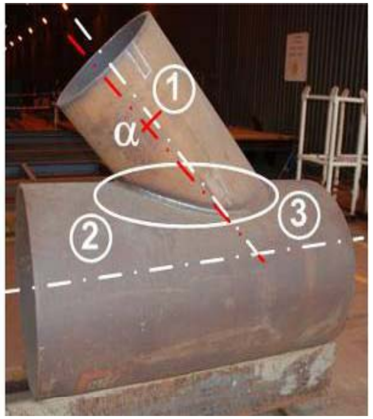
PtJ Projektträger Jülich Forschungszentrum Jülich

Fraunhofer IWES

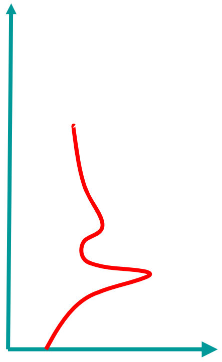
Research project „GIGAWIND alpha ventus“



Loads



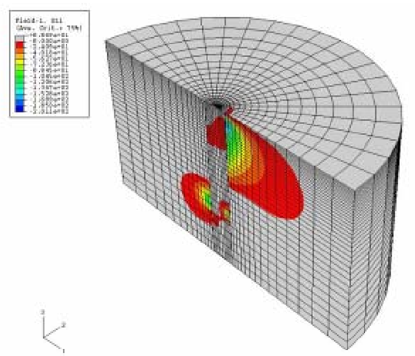
Mass production



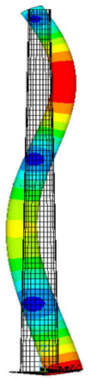
Corrosion

Structure health monitoring

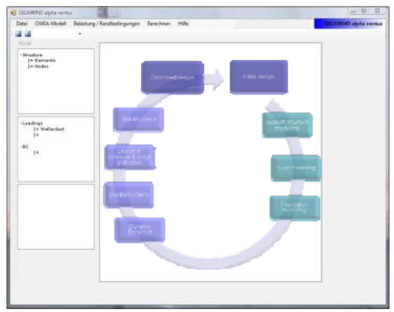
Scour



Structure soil interaction

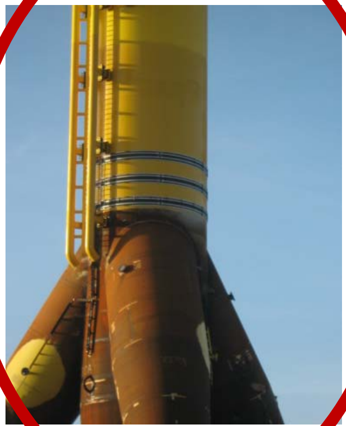


Dynamic response



Holistic design

Contents:



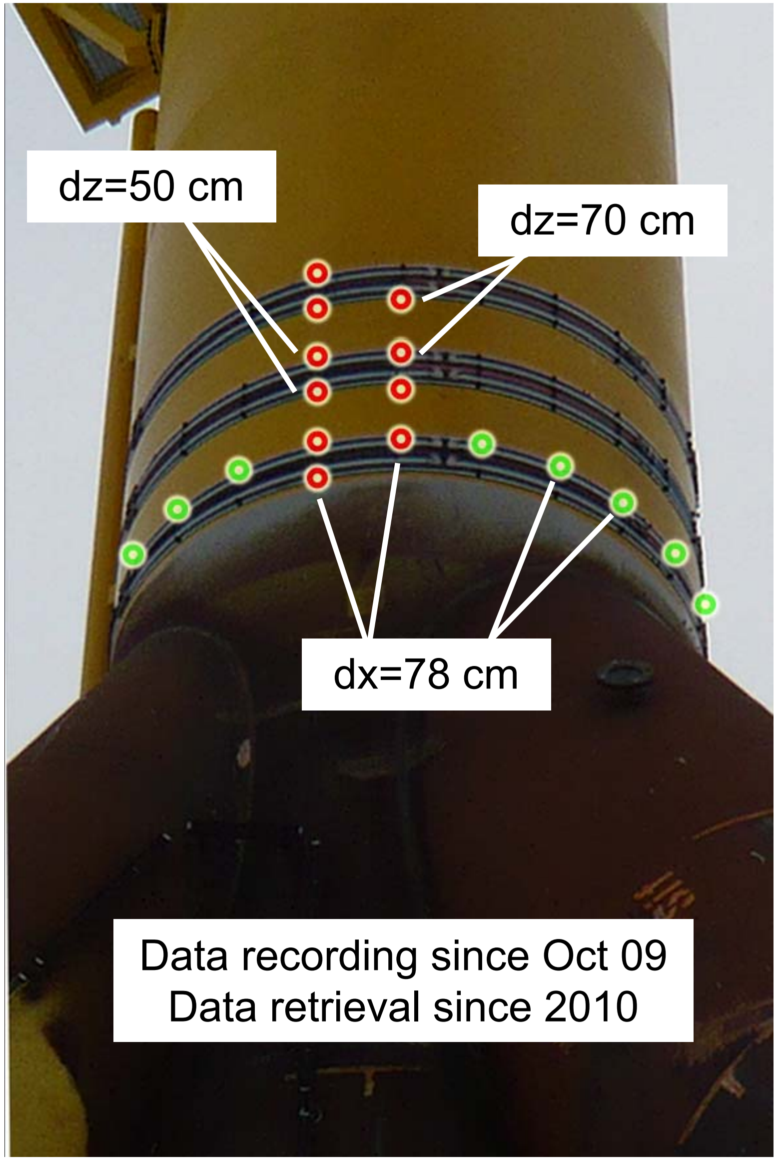
Loads

Scour

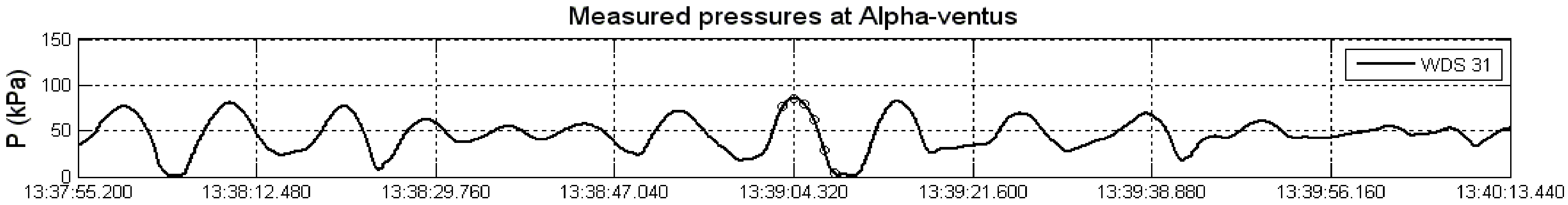
- Estimation of wave loads due to **non-breaking waves**
  - Test field data (3D) ☞ processes
  - Laboratory experiments (2D + 3D) ☞ models
- Estimation of impact loads due to **breaking waves**
  - Large scale experiments (GWK) ☞ models
  - Setup of CFD model ☞ models
  - Spatial and time resolved slamming coefficients for efficient load calculation ☞ models & countermeasures
- **Scour phenomena** and protection measures
  - Test field data (BSH) ☞ processes
  - Large scale experiments (GWK) ☞ models
  - Numerical modeling of scour development

    ☞ models & countermeasures
- **Summary** and “Research in progress”

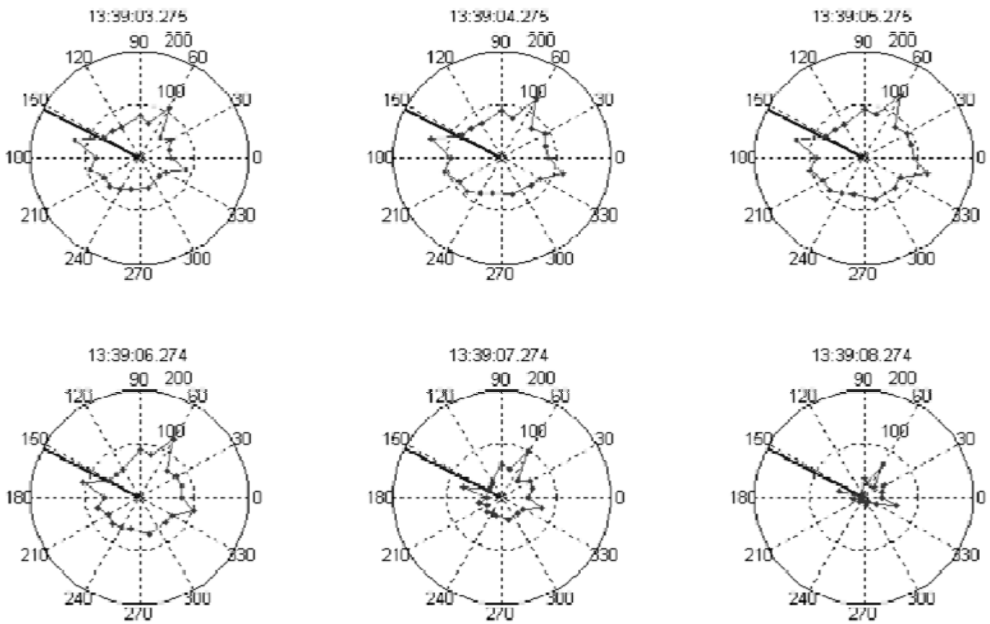
- **Test field data (3D)**
  – devices and data acquisition
  - ➢ Accelerometers (19 + 32 = 51)
  - ➢ Strain gauges (67 + 46 = 113)
  - ➢ Water pressure sensors (32)
    - ☞ 2 vertical profiles: 6 and 4 WPS
    - ☞ 1 horizontal profile: 22 WPS
  - ➢ Current velocity meter
    - ☞ ADCP + FINO 1
  - ➢ Wave recording
    - ☞ Wave buoy + FINO 1
  - ➢ Video camera
    - ☞ Wave run up



Wave data from *alpha ventus* test field site

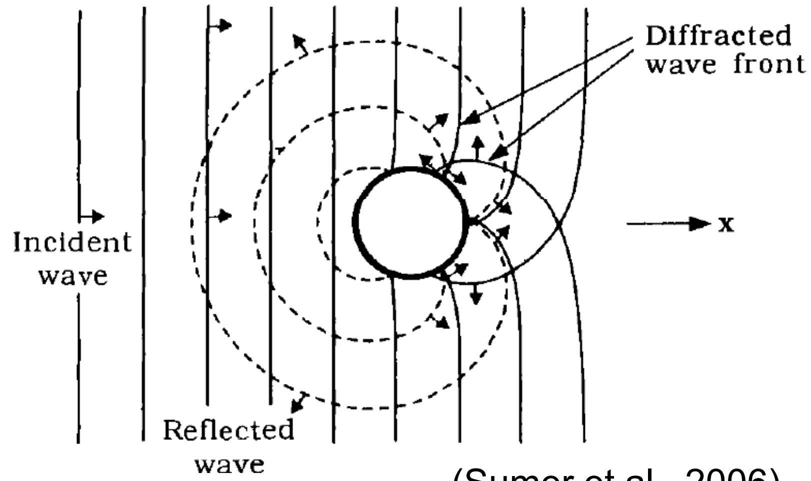


- Measurement of dynamic pressures, e.g. 12th Nov 2011 ($\eta_{max} \approx 10$ m)
- Strong Variation of dynamic pressures exerted on the circumference of monopile
- Integration of dynamic pressures
  ☞ local line force, diffraction process
- Difficulties in test field: multidirectionality and irregularity of wave fields, local effects

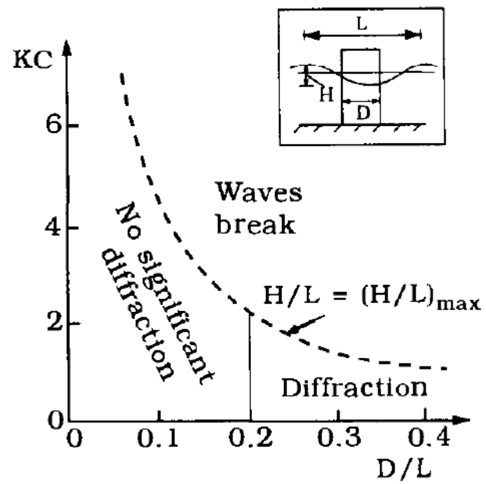


Approach: Diffraction theories

- Unidirectional diffraction wave theories (long-crested) for replication of locally disturbed wave field:
  - First-order diffraction theory introduced by MacCamy & Fuchs (1954)
  - Second-order diffraction theory by Kriebel (1990) – an "exact" solution
- Multi-directional diffraction wave theory (short-crested) for replication of locally disturbed wave field:
  - Zhu (1993) developed an "exact" solution for short-crested waves acting on a circular cylinder.
  - Neither validated by lab nor field data, so far!
- Theories do not consider vortex shedding, run-up processes, splash-up etc. on structure ☞ Significance?



(Sumer et al., 2006)

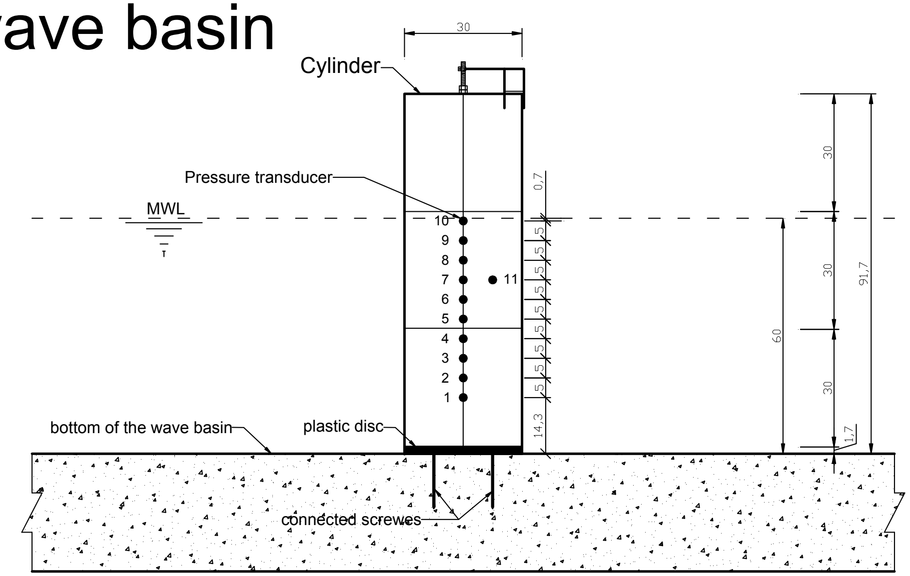


Diffraction experiments in 3D-wave basin

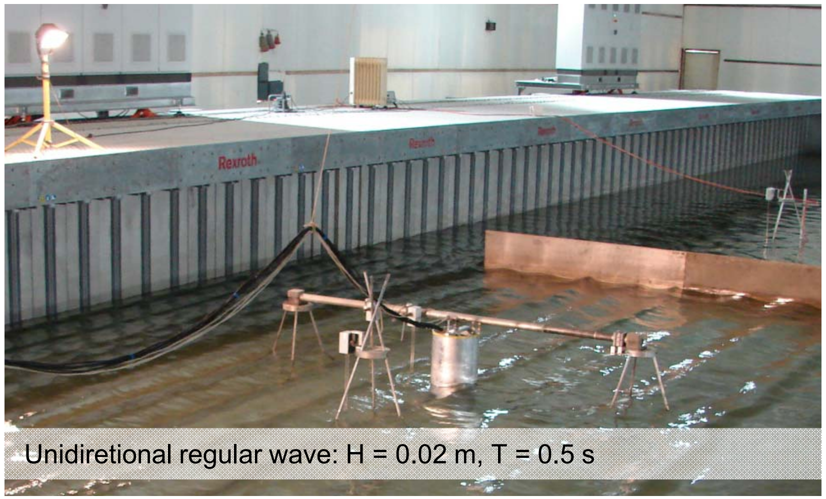
- Unidirectional regular waves
- Unidirectional irregular waves
- Multi-chromatic waves (short-crested)

with: kr_0 = 0.2 to 2.5

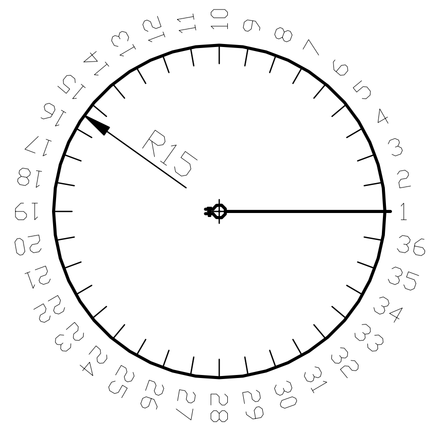
α_{max} = 10° to 30°



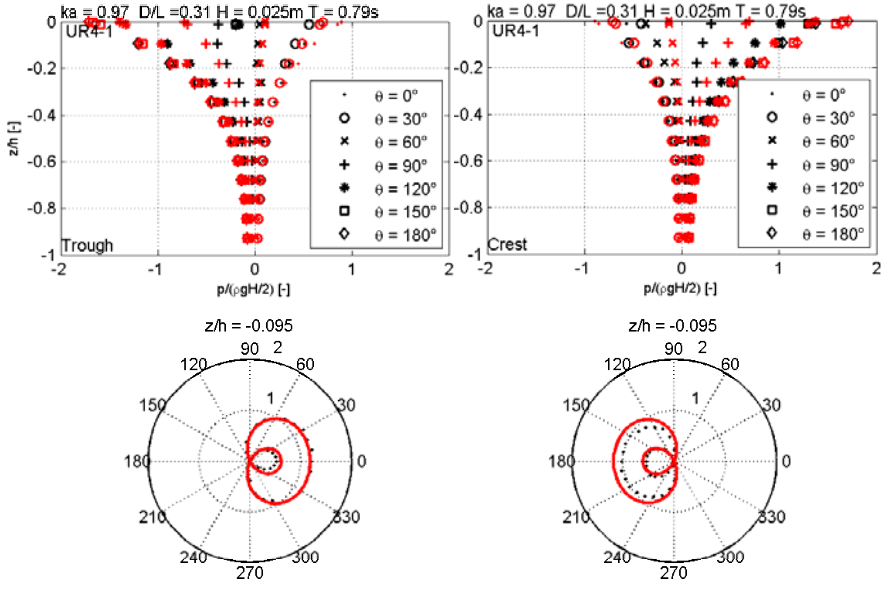
(Note: unit in cm)



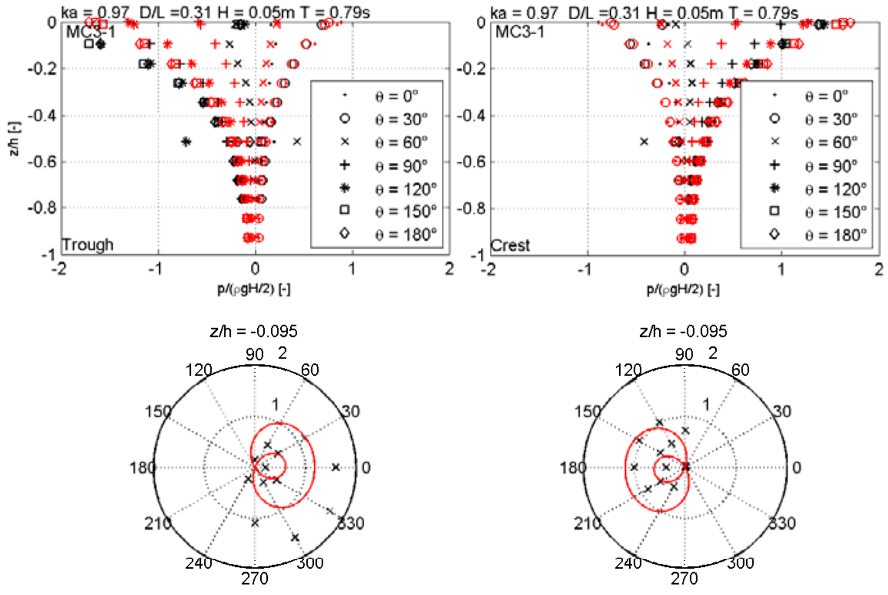
Unidiretional regular wave: H = 0.02 m, T = 0.5 s



Dimensionless dynamic pressures (monopile)



E.g. unidirectional regular wave:
- H = 0.025 m, T = 0.79 s, kr_0 = 0.97



E.g. multi-chromatic waves:
Here bi-chromatic, bi-directional waves
Wave 1&2: $H_{1,2}$=0.025, $T_{1,2}$=0.79s, kr_0 = 0.97, α_1=0°, α_2 = 10°

Note:
Red markers: theoretical estimations by MacCamy&Fuchs (1954) (first-order)
Black markers: experimental data from 3D-wave basin
All data refer to dimensionless dynamic pressure: $\frac{p}{\rho g H / 2}$, in which p is the pressure, H is the wave height, ρ is the water density, g is the gravity acceleration

Estimation of loads due to **breaking waves**:

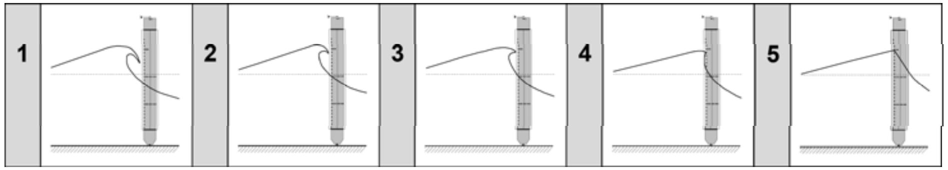
Goda (1966)

$$F_{\text{Impact}} = \int_{(1-\lambda)\cdot\eta}^{\eta} F \; dz = \frac{1}{2}\cdot\pi\cdot\rho\cdot C^2\cdot D\cdot\left(1-t/\tau\right)\cdot\lambda\cdot\eta \qquad mit\ \tau = \frac{D}{2\cdot C}$$

Sawaragi & Nochino (1984)

$$F_{total} = F_{Morison} + F_{\text{Impact}} + F_{Level}$$

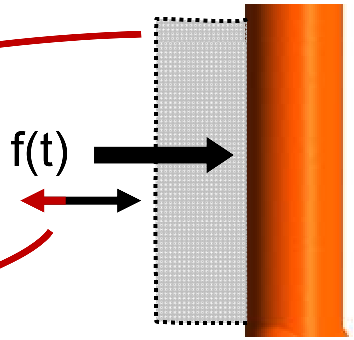
Wienke (2005)

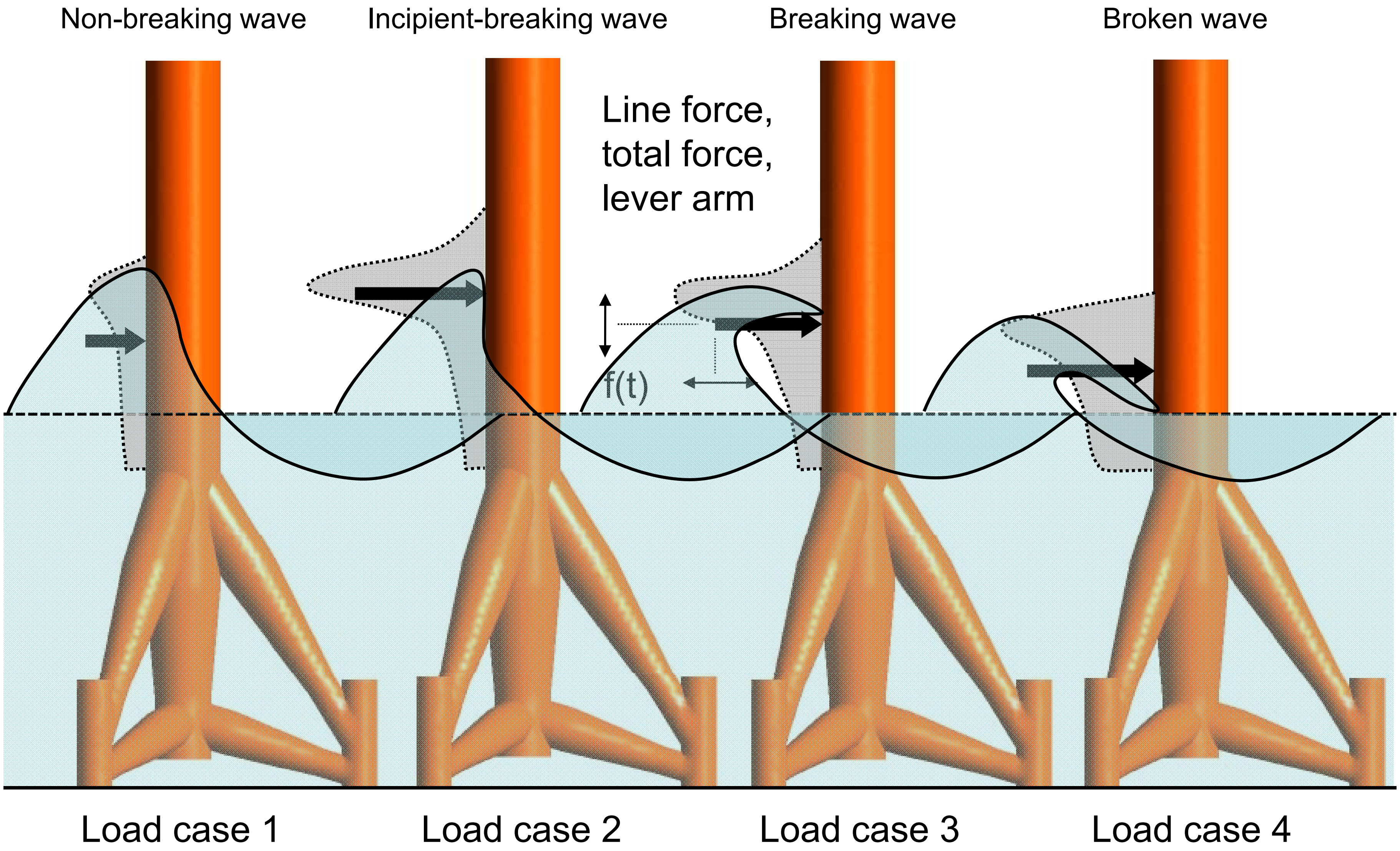


$$F_{\text{Impact}} = \lambda\cdot\eta_b\cdot\rho\cdot R\cdot V^2\cdot\cos^2\gamma\cdot\left(2\pi - 2\sqrt{\frac{V\cdot\cos\gamma}{R}\cdot t}\cdot ar\tanh\sqrt{1-\frac{1}{4}\frac{V\cdot\cos\gamma}{R}\cdot t}\right)$$

Assumptions/Simplifications:

Rise time, double peak loads, vertical distribution




Non-breaking wave
Incipient-breaking wave
Breaking wave
Broken wave
Line force,
total force,
lever arm
f(t)
Load case 1
Load case 2
Load case 3
Load case 4

Physical modeling of breaking waves

- Scale 1:12   Tripod main column diameter = 0.50 m, water depth d = 2.50 m
- 30 pressure sensors (+shifts), 2 acceleration meters, 8 strain gauges, 24 wave gauges
- Breaking wave height H = 1.5 m, T = 4.16 s (transient wave)

30 Presssure Sensors (PS)

=> Vertical profile, 14+4 PS

=> Horizontal profile with 7 PS

=> Upper braces with 6 PS

2 Acceleration meters (xyz)

8 Strain gauges

Current meters

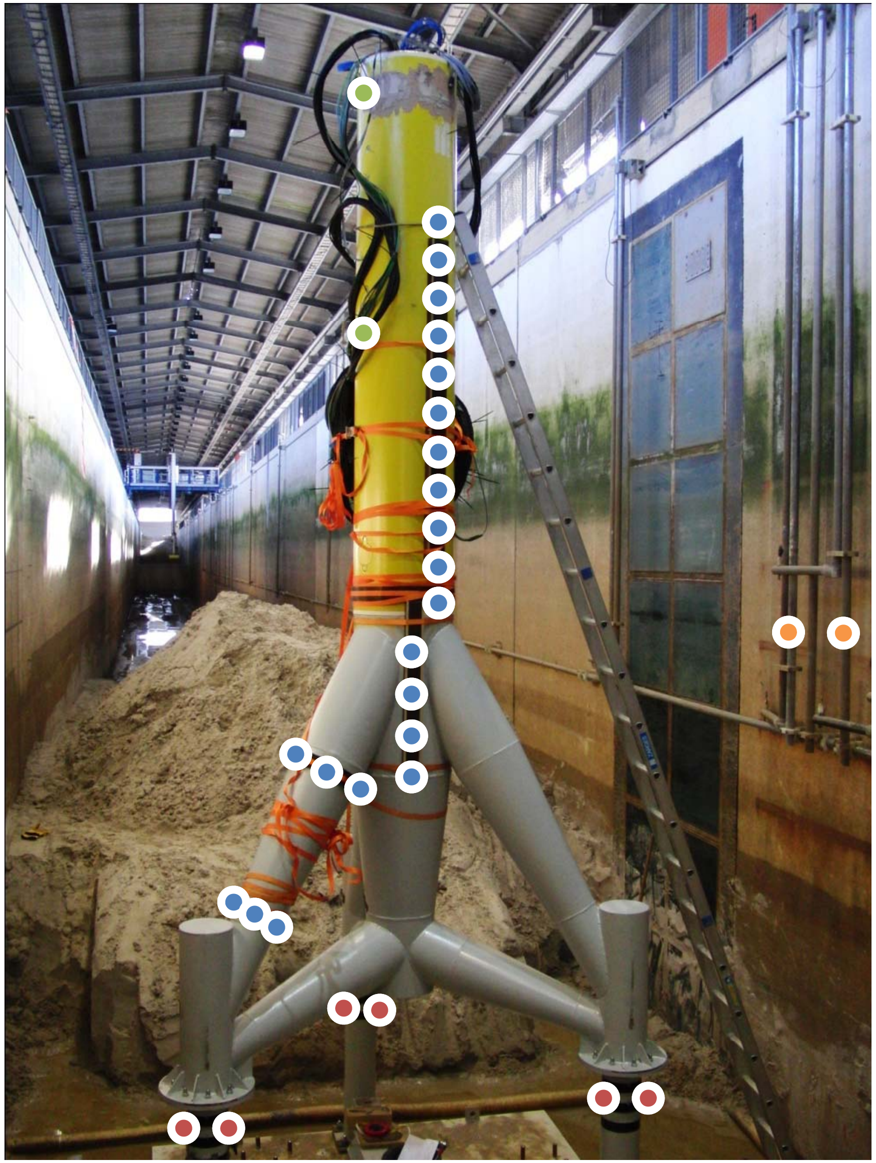
=> 2 x 3 NSW probes (xz)

Water elevation

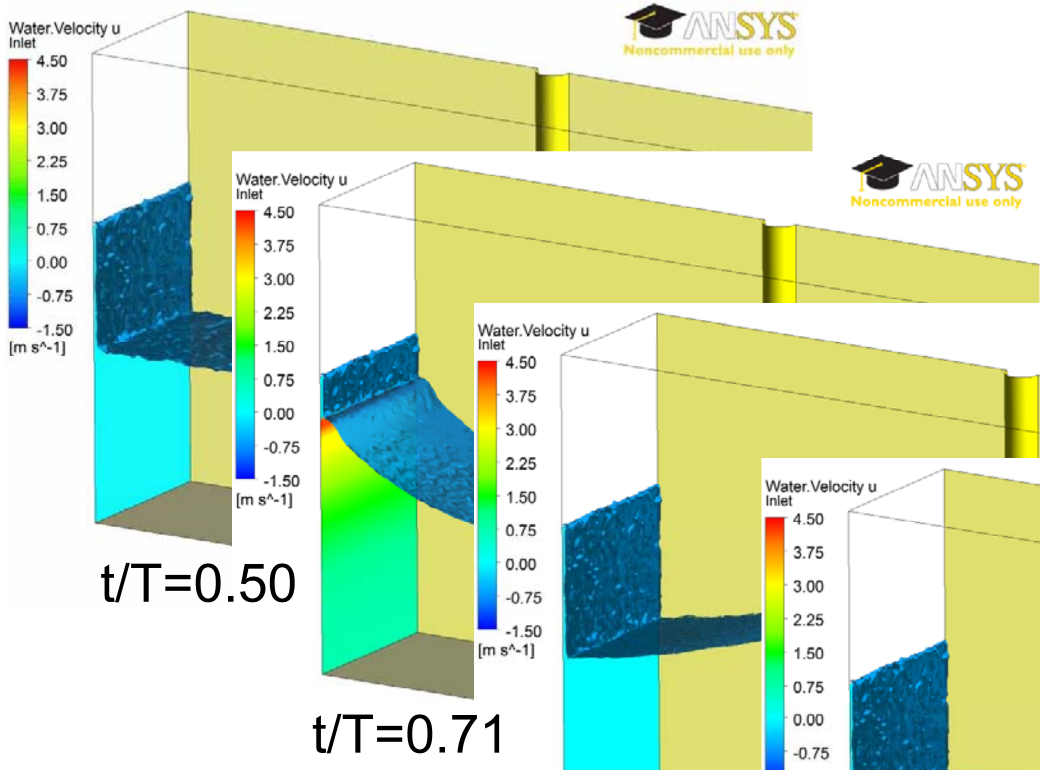
=> 24 Wave gauges

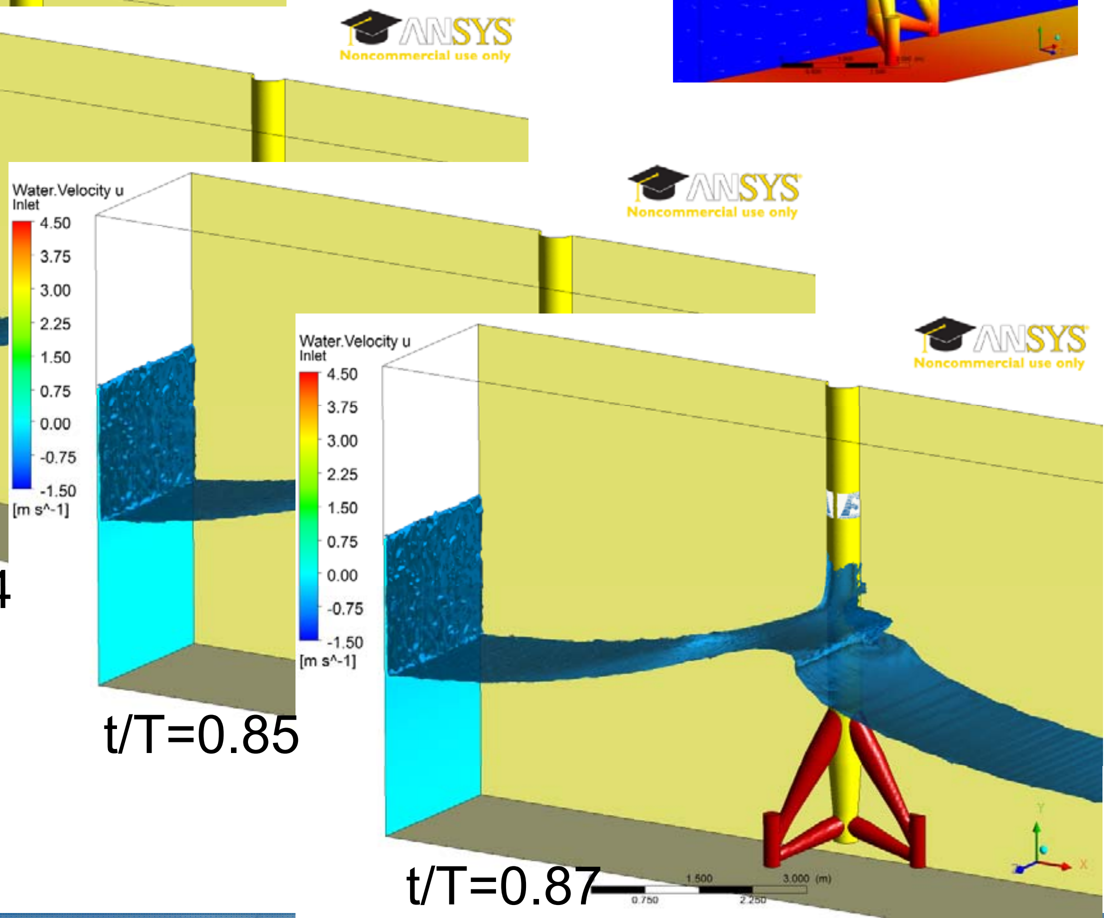
Cameras (front-, back view)

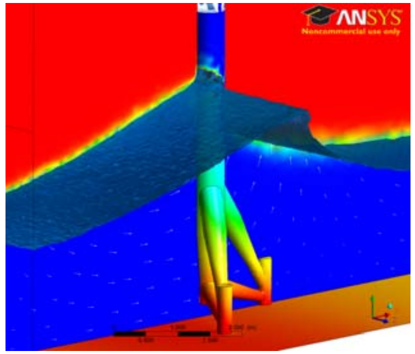
=> Wave runup, wave geometry




1:15:26



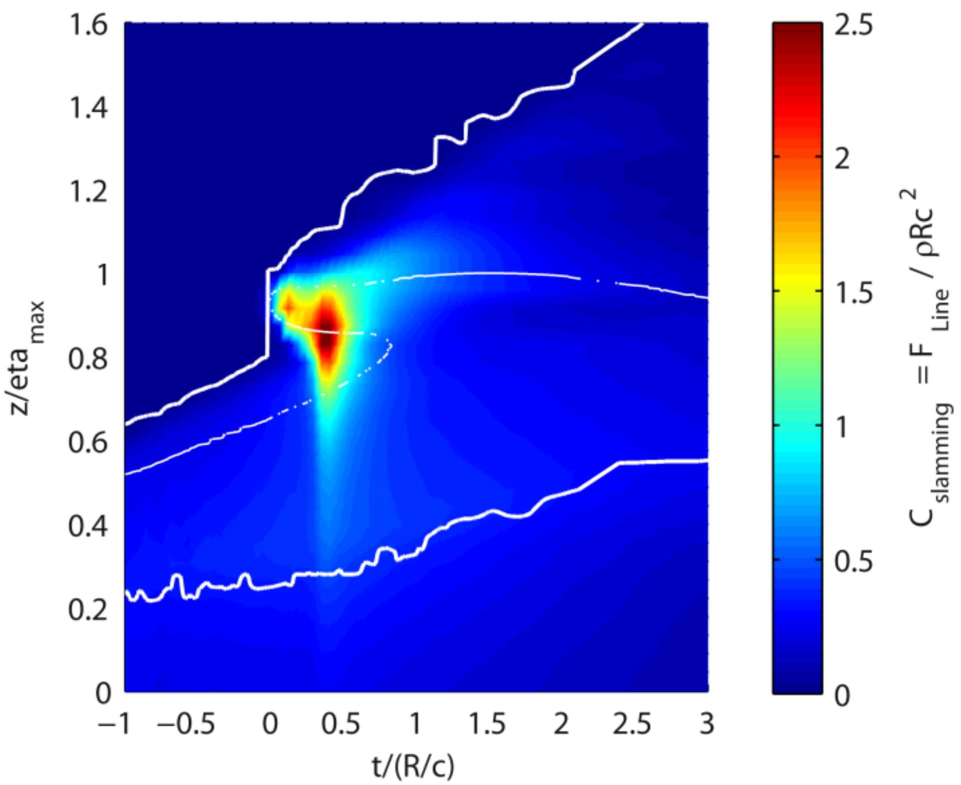




Comparison of physical
and numerical models:

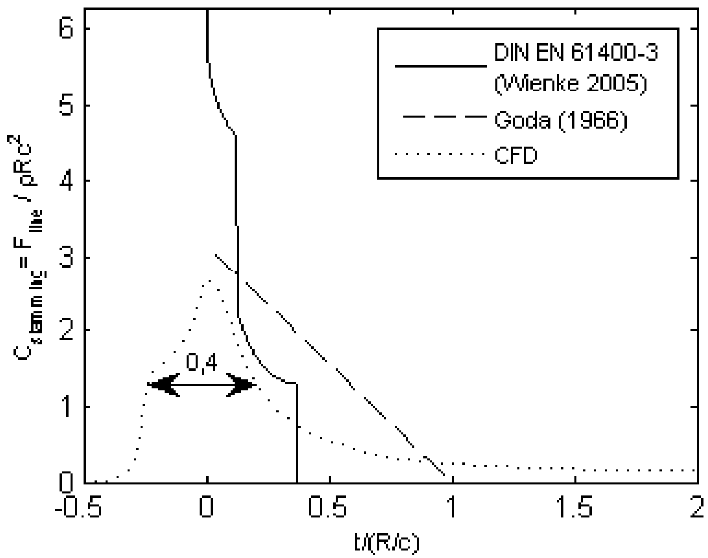
Hildebrandt, A., Schlurmann, T.:
Wellenbrechen an Offshore Tripod
Gründungen – Versuche und Simulationen
im Vergleich zu Richtlinien.
Bautechnik 89 (2012), H. 5

Time and spatial resolved “Slamming coefficients”



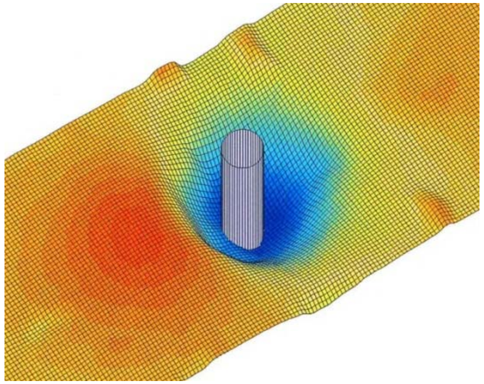
Taken from: Hildebrandt & Schlurmann (2012)

- Maximum „Slamming-Coefficient“ for LC 2 = 2.7, relative height z/eta_{max} = 0.9
- Coefficients include non-linear wave kinematics
- Results show high potential for optimization in regard of i) max. value and ii) vertical distribution

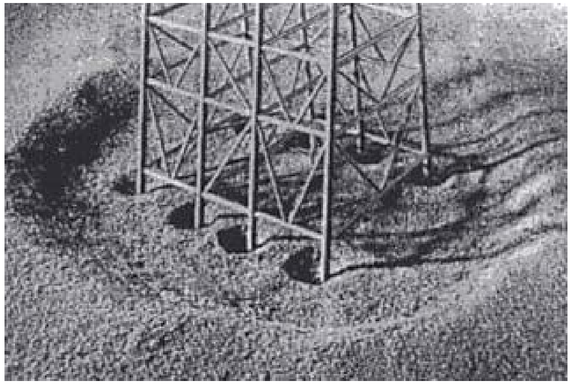


Scour around offshore and OWT structures

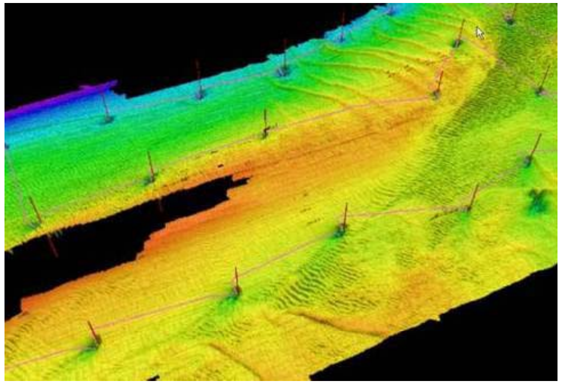
- **Interaction**: Sea state conditions, tide, structure and sea bed
  ⇨ Scouring around OWT structures
- Numerous investigations provided in literature, but for **“simple” structures, i.e. monopiles**, less for complex geometries; huge lack of validation data
- **Extent and development of scour** often not predictable in detail due to complexity
  ⇨ oversized structural dimensions (yet, secure but cost-ineffective strategy)
- **Open scour or scour protection questions remain:** Design criteria, durability, stability, remedial effects (“de-scouring”?)



Scour around a monopile,
Large Wave Flume, FZK (2007)



Global and local scour around jacket,
Angus and Moore (1982)



Measurement with echo sounders
in Scroby Sands, UK (2005)

Scours around Pile Foundations

- **Practical design approaches** for scour depth estimation

  S/D = 1.3 (DNV)

  S/D = 1.4 – 1.9 (CERC)

  S/D < 2.5 (GL)

- Sumer & Fredsoe (2002)

  $$S/D = 1.3\cdot(1-e^{(-m\cdot(KC-6))})$$

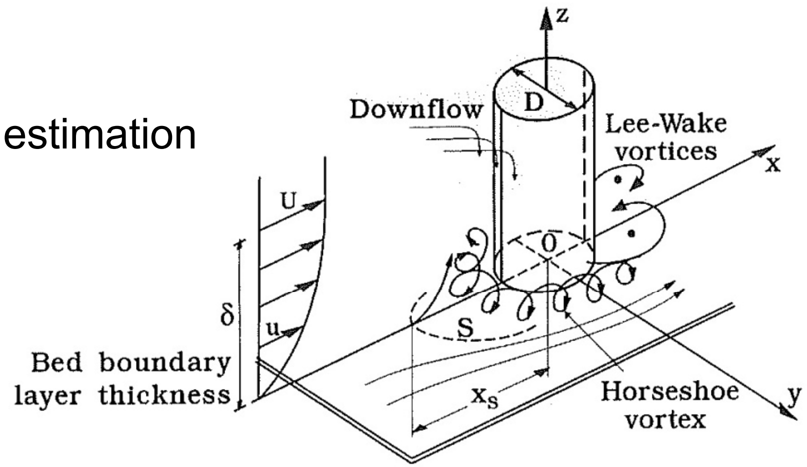
- Melville & Coleman (2000)

  $$S/D = 2\cdot(1-e^{(-0.03\cdot(KC-6))})$$

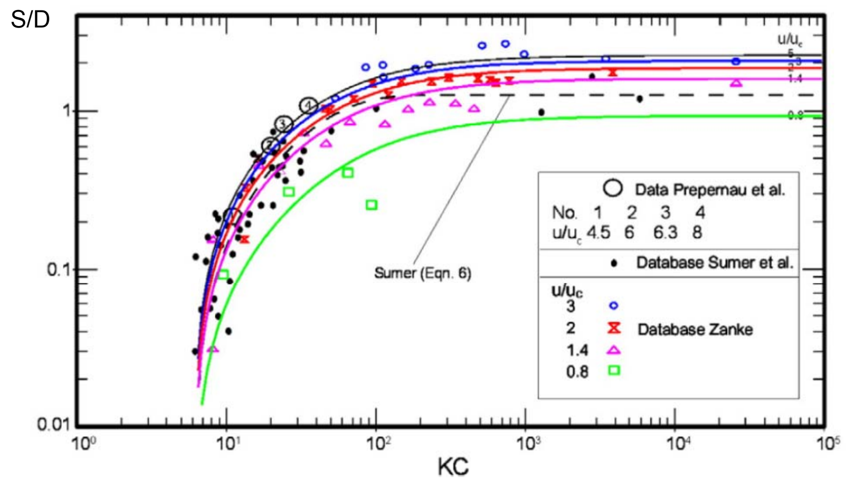
- Zanke et al. (2011)

  $$S/D = 2.5\cdot(1-0.5\cdot u/u_c)\cdot x_{rel}$$

Exclusively valid for **Monopiles!**



Flow system around a slender pile, Sumer (2002)



Equilibrium relative scour depth S/D versus KC number (Zanke et al., 2011)

Scouring Phenomena at Tripod Foundations

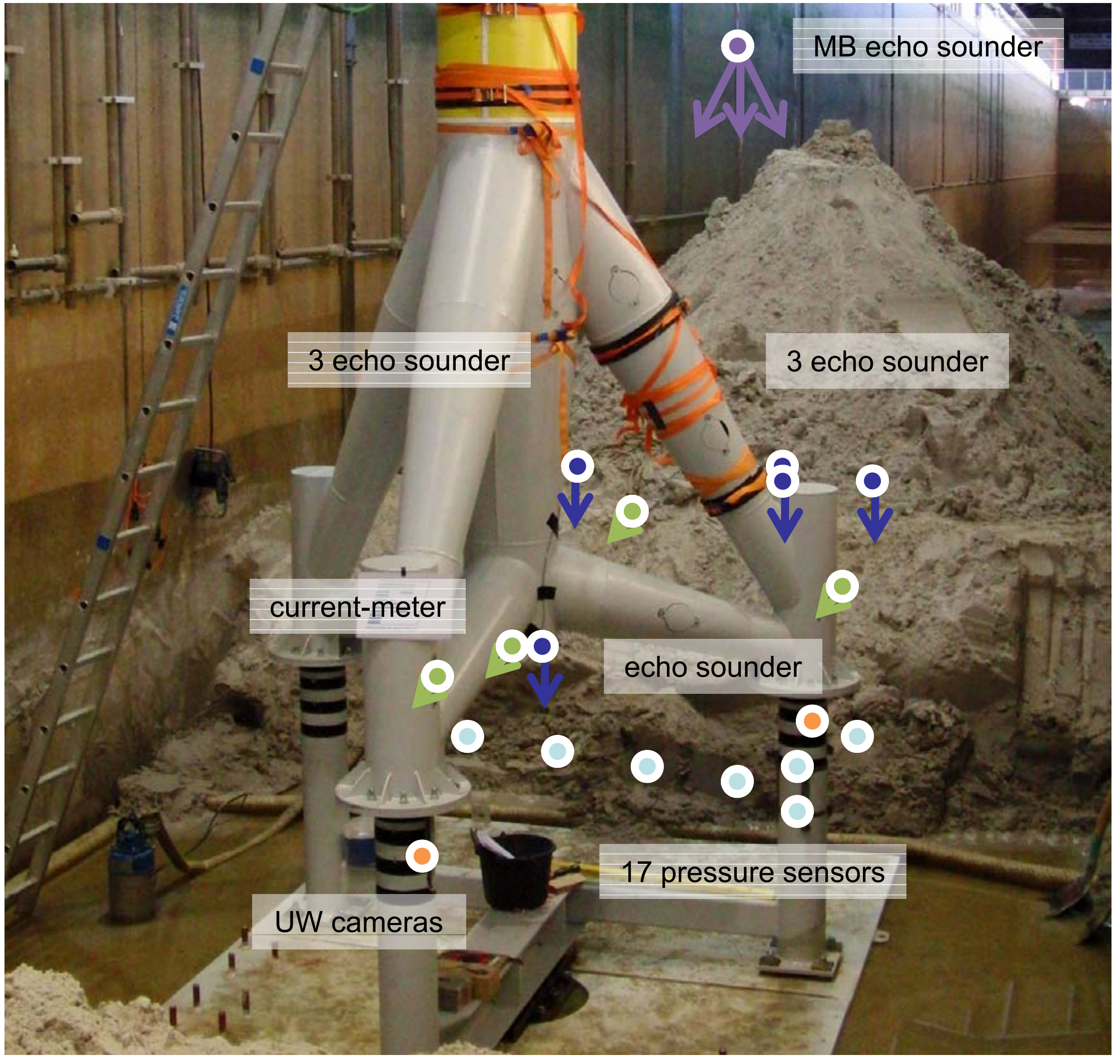
- Offshore test site **alpha ventus**: 12 pilot installations, commissioned 04/2010
- **Sea state boundary conditions FINO1**: d~30 m, $H_{s,50}$=10.38m, $T_{p,50}$=13.6s, $v_{m,50}$=1.3m/s

---

- **Physical modeling** of scour in wave flumes: 1:40 (WKS) and 1:12 (GWK) for calibration/verification
- **Field data**: Scour monitoring in the test site (BSH)
- **Numerical modeling**: OpenFOAM®, flow pattern and scour development

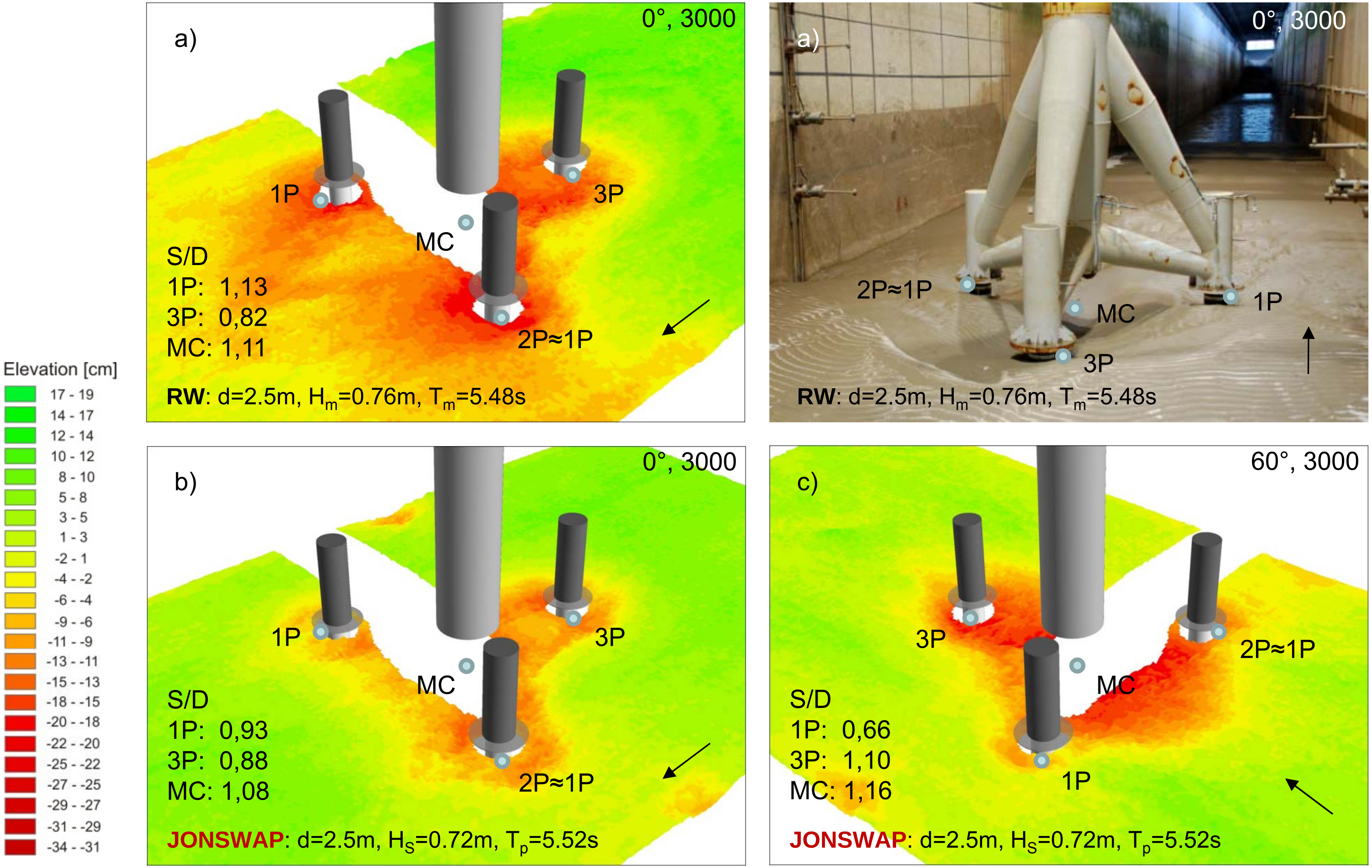
Source: Stiftung Offshore Windenergie/DOTI, 2008

Physical modeling, Large Wave Flume (1:12)



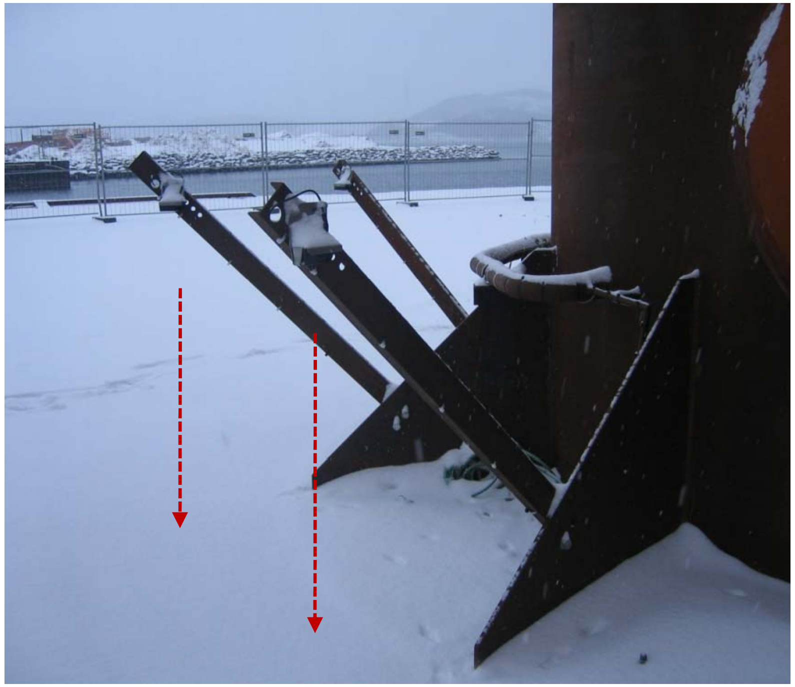
- Large Wave Flume:
  310 x 5 x 7m
- Fine sand, d_{50}=0.15mm
- **Wave boundary cond.**:
  RW and JONSWAP
  d=2.50m, H=50-76cm,
  T=2.8-5.5s,
  2,500–4,000 waves

- **Scour measurement**:
  MB echo sounder
  SB echo sounders
  UW video
- **Flow**: ADV + 1D
- Pore-pressure


Elevation [cm]
17 - 19
14 - 17
12 - 14
10 - 12
8 - 10
5 - 8
3 - 5
1 - 3
-2 - 1
-4 - -2
-6 - -4
-9 - -6
-11 - -9
-13 - -11
-15 - -13
-18 - -15
-20 - -18
-22 - -20
-25 - -22
-27 - -25
-29 - -27
-31 - -29
-34 - -31
a)
0°, 3000
1P
3P
MC
2P≈1P
S/D
1P: 1,13
3P: 0,82
MC: 1,11
RW: d=2.5m, H_m=0.76m, T_m=5.48s
a)
0°, 3000
2P≈1P
MC
1P
3P
RW: d=2.5m, H_m=0.76m, T_m=5.48s
b)
0°, 3000
1P
3P
MC
2P≈1P
S/D
1P: 0,93
3P: 0,88
MC: 1,08
JONSWAP: d=2.5m, H_S=0.72m, T_p=5.52s
c)
60°, 3000
3P
2P≈1P
MC
1P
S/D
1P: 0,66
3P: 1,10
MC: 1,16
JONSWAP: d=2.5m, H_S=0.72m, T_p=5.52s

Scour monitoring in the test site (field data)

- Measuring campaign by the German Maritime and Hydrographic Agency (BSH)
- 19 (5) **single beam** echo sounders (few minutes measuring interval)
- Surveys using **multi beam** echo sounders in the near-field

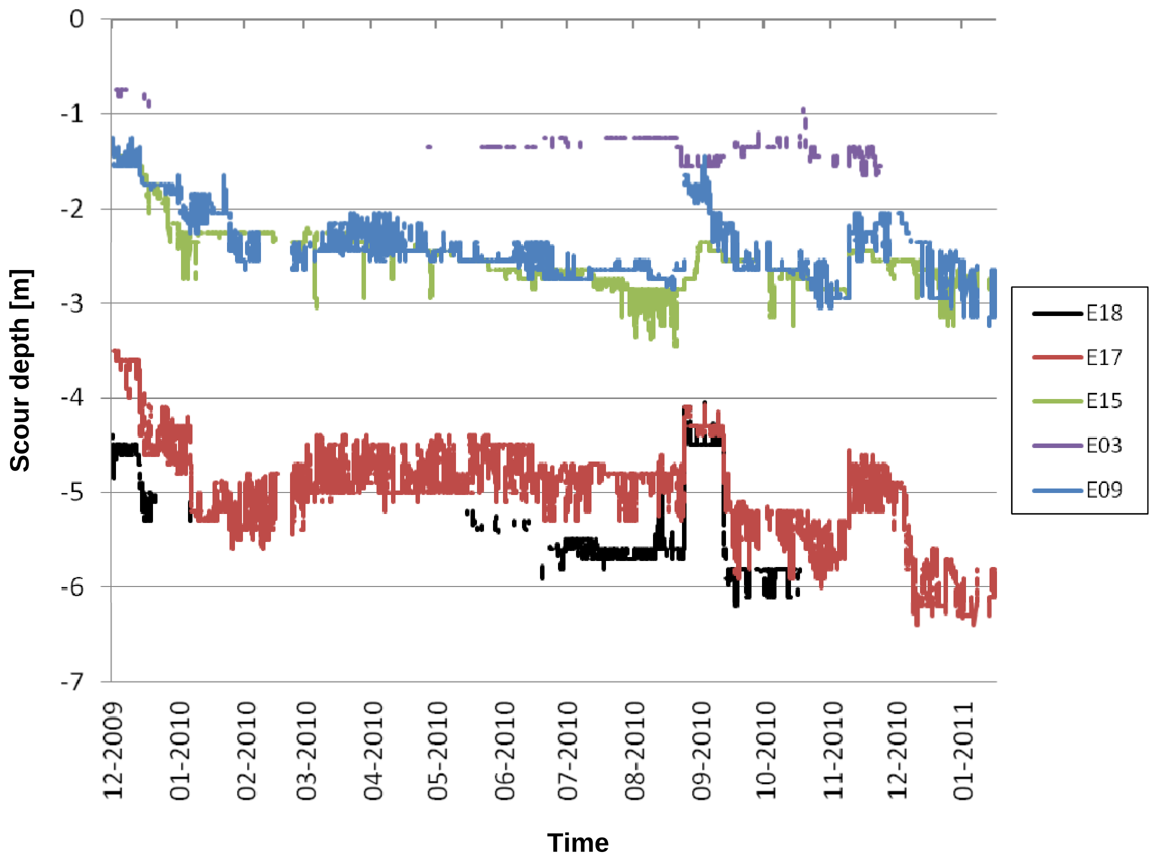


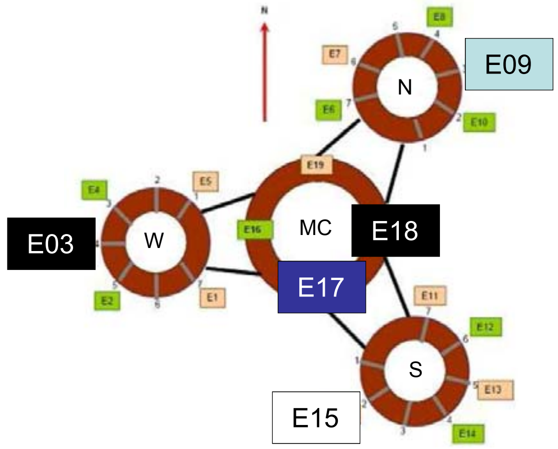
Source: BSH, 2009

Source: Stiftung Offshore Windenergie/alpha ventus, 2008

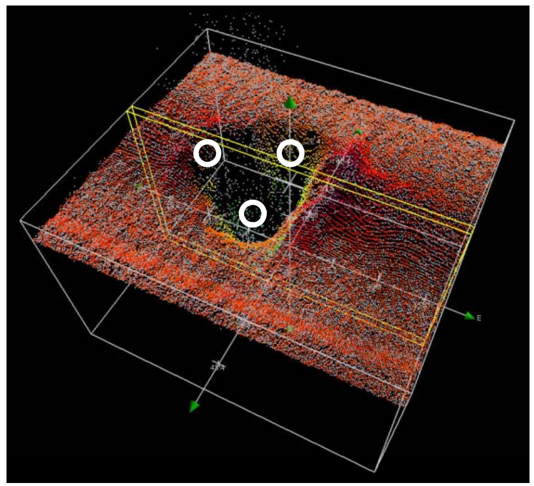
Scour monitoring in the test site (field data)

- Tripod M07: Single Beam data **2009-11**



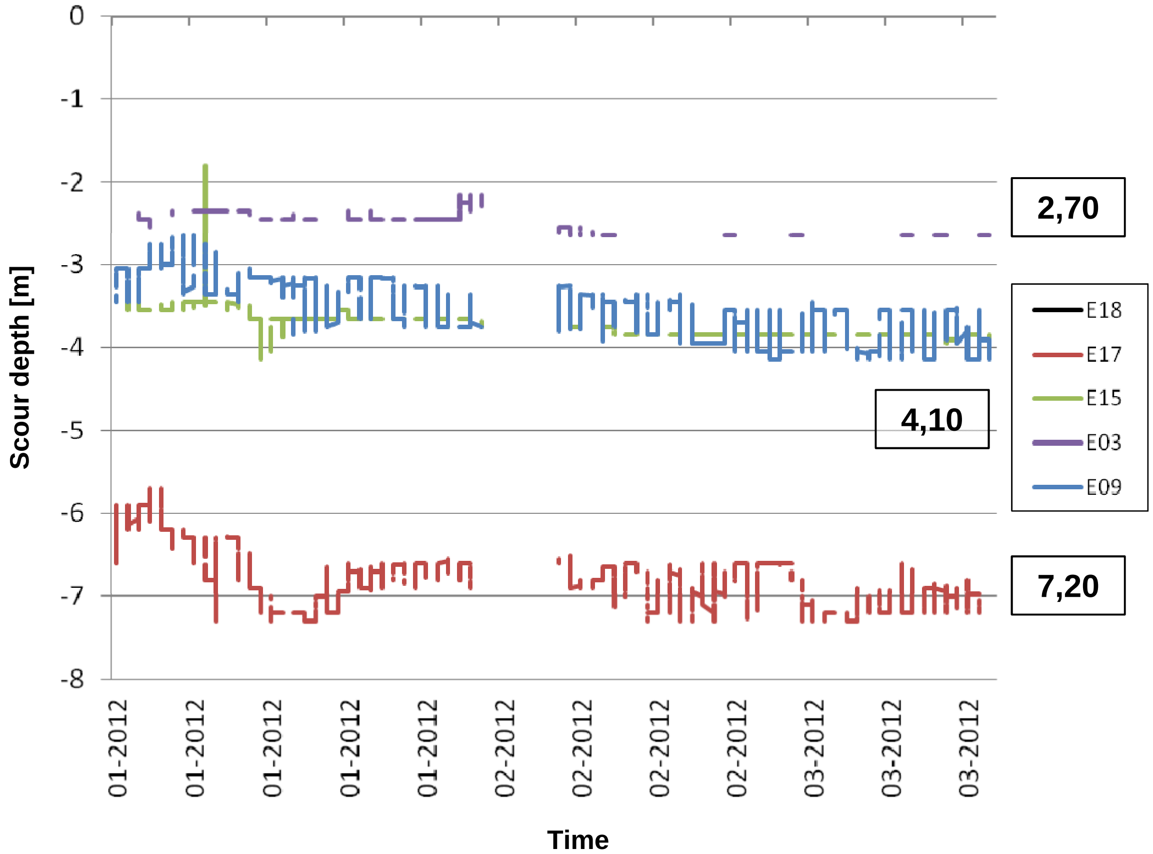


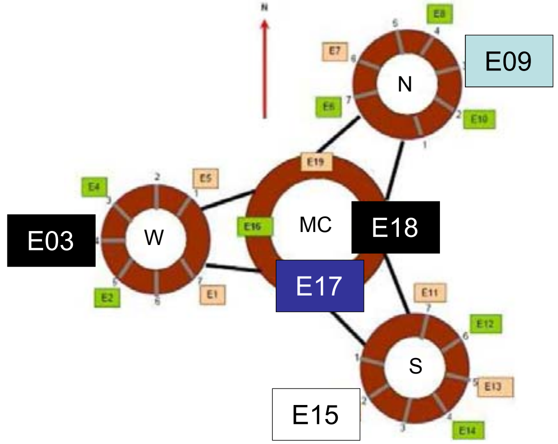
Original source: BSH, 2010


Multi beam survey, Oktober 2011
Source: BSH 2011

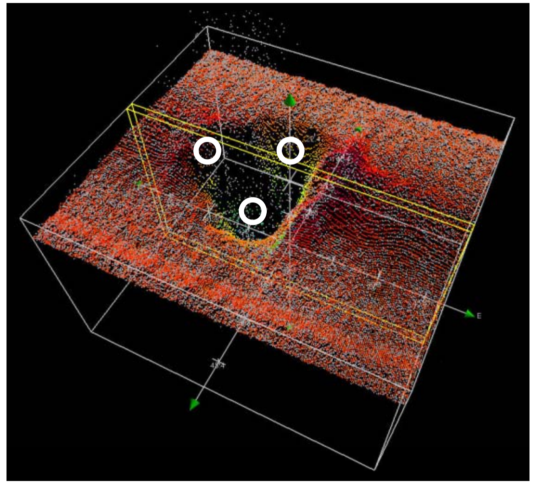
Scour monitoring in the test site (field data)

- Tripod M07: Single Beam data **2012**



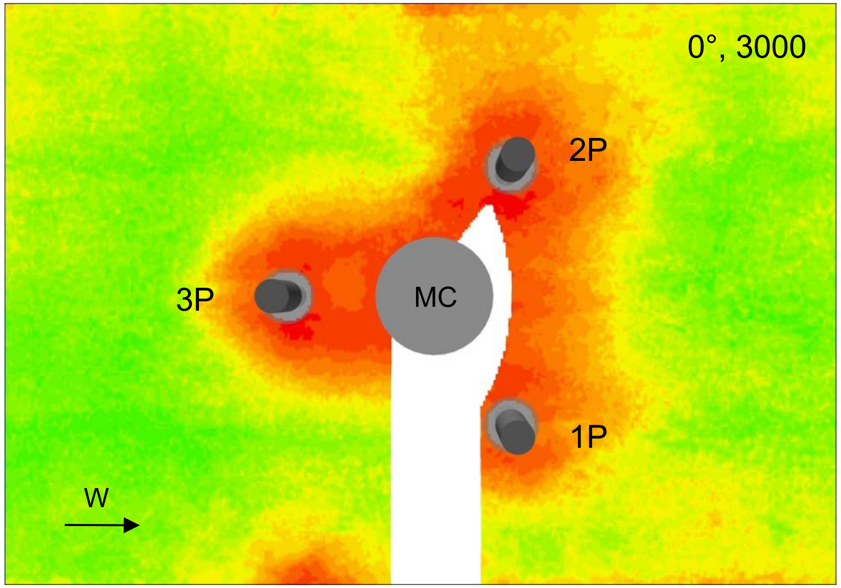


Original source: BSH, 2010

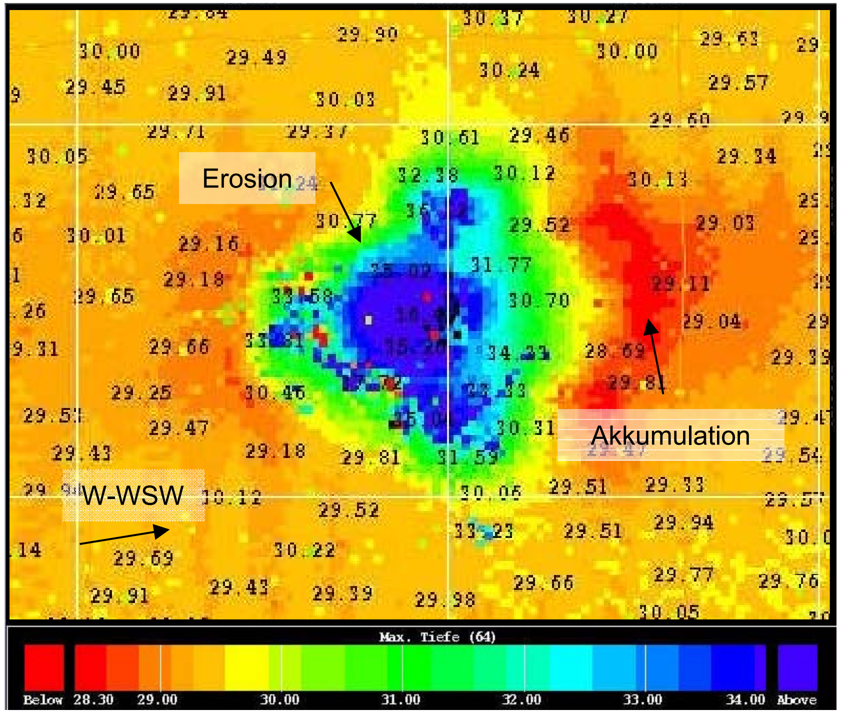


Multi beam survey, Oktober 2011
Source: BSH 2011

Physical model (1:12) vs. Prototype (1:1)



JONSWAP spectrum: d=2.5m, H_S=0.72m, T_p=5.52s



Multi beam survey April 2010, 1x1m grid, uncorrected values
Source: Lambers-Huesmann & Zeiler, BSH 2010

Real depths locally underestimated:

- scaling effects (esp. model sediment)
- unidirectional wave loads
- wave-only conditions (no tide)

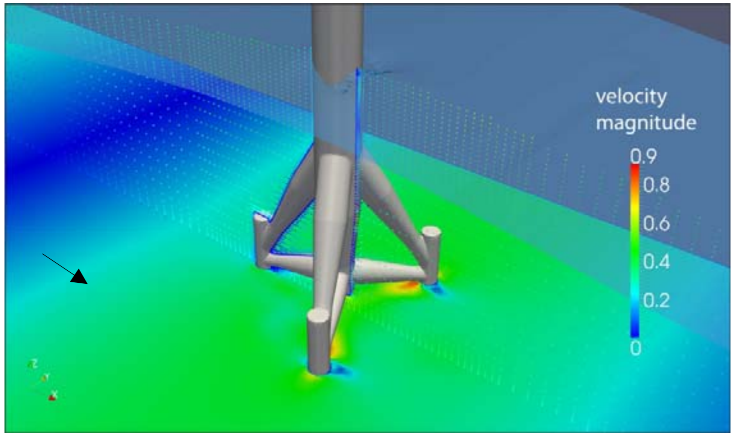
	Ø Piles [m]	S/D 1P	S/D 2P	S/D 3P	S/D MC
1:12	0,19	0,93	-	0,88	1,08
1:1	2,3	**1,42**	1,42	1,08	**2,50**

Numerical modeling of Flow and Scour

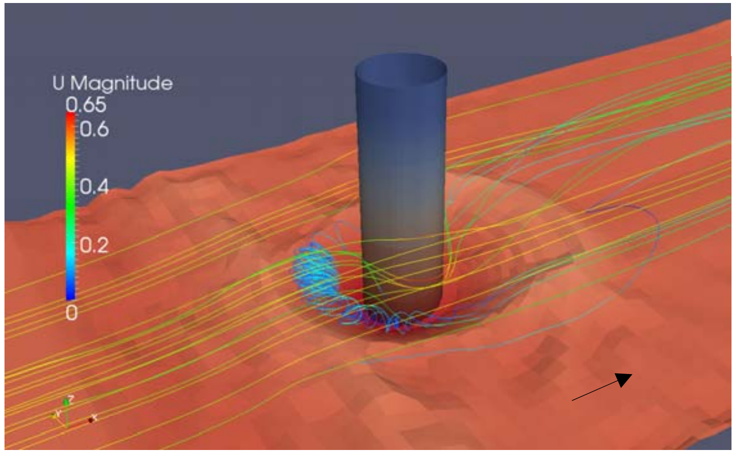
3D CFD model: OpenFOAM®

- Flow pattern & turbulence,
  bed shear stresses
- Scaling effects
- **Scour development** (moving bed)
  bed load and suspended load
- **Load conditions**:
  waves, (tidal) currents,
  combined loads,
  varying directions
- **Structural analyses**:
  Optimization regarding scour

Taken from: Stahlmann & Schlurmann (2012)

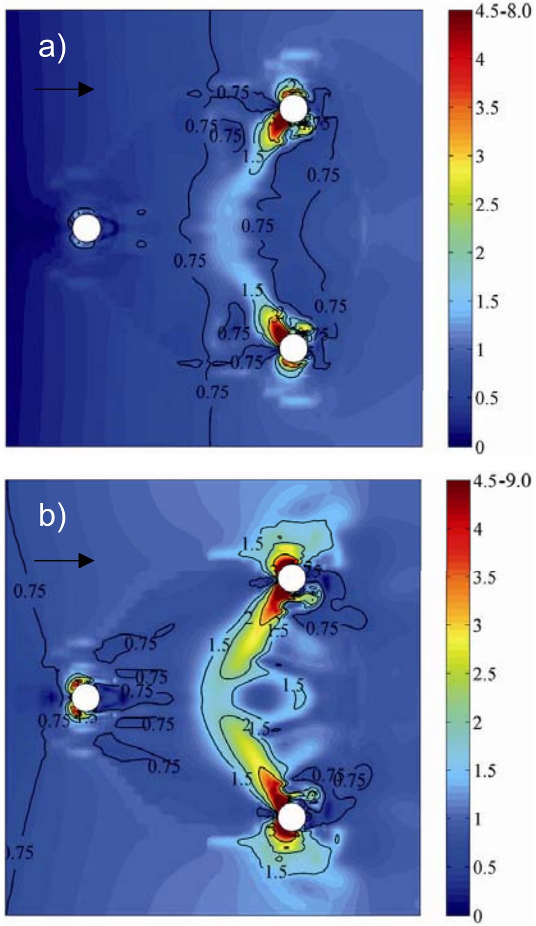


1:40 tripod model: surface elevation and near-bottom velocities due to wave action

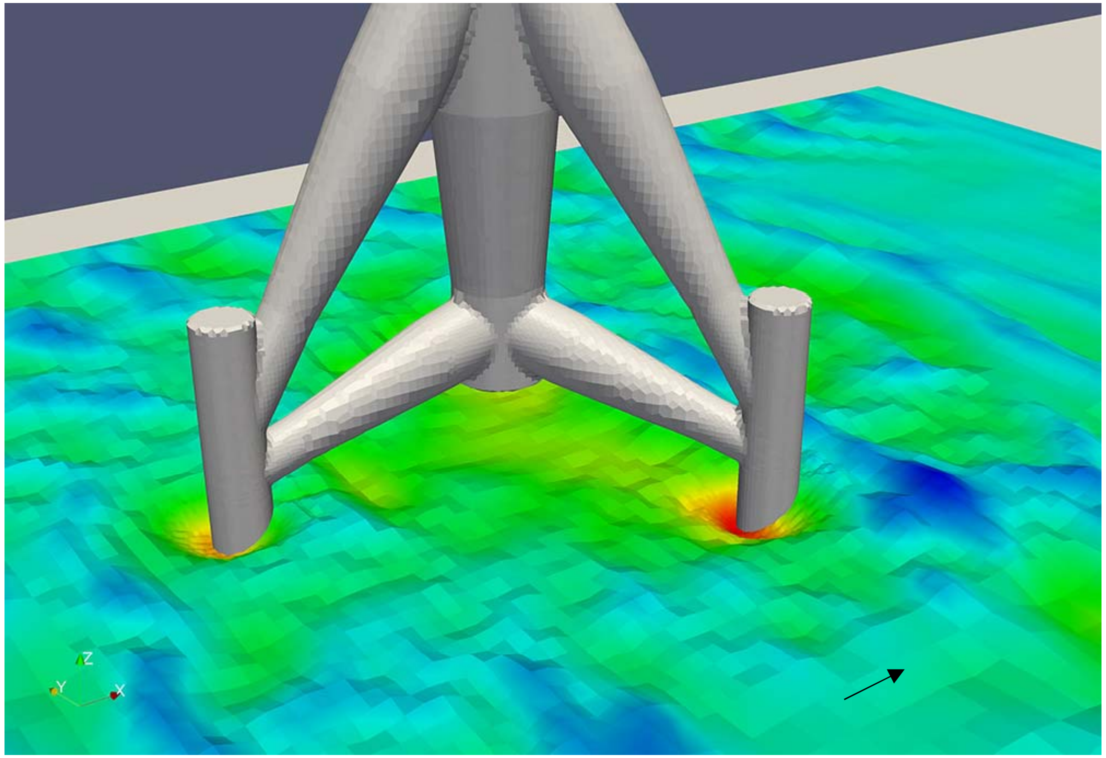


1:40 cylinder model: scour hole and stream lines with vortex formation due to steady current

Numerical modeling of Flow and Scour



Bed shear stress amplification
(a) waves, (b) waves + tide



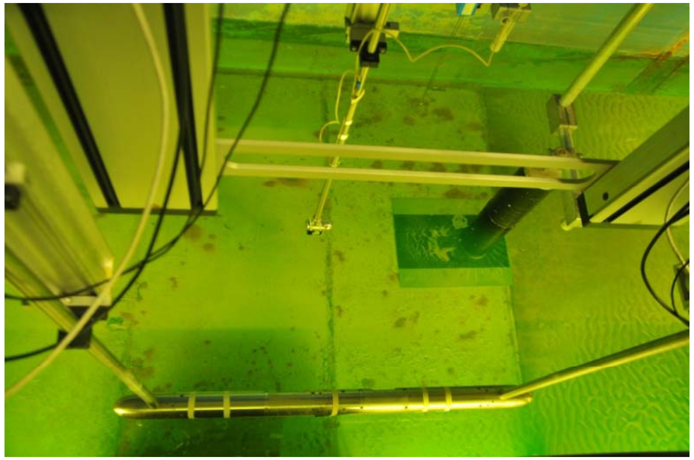
Scour development in the numerical CFD model,
waves + tidal current (in the developing scour stage)

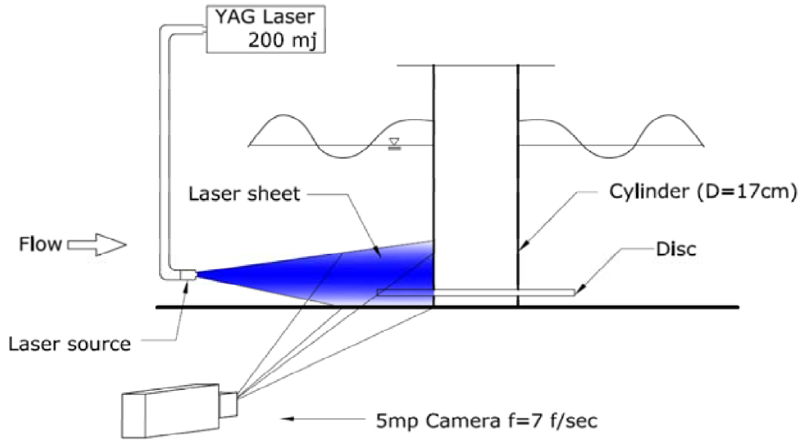
Taken from: Stahlmann & Schlurmann (2012)

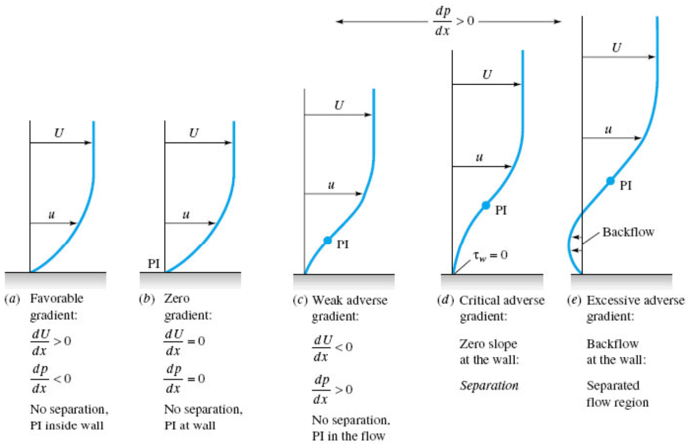
Summary and Outlook

- Fair understanding of **<u>processes</u>** regarding wave loads and impacts: Assessment of wave loads due to non-breaking waves based on unidirectional regular waves is state-of-the-art design practice and is validated by means of field and laboratory experiments as well as sophisticated numerical **<u>models</u>**. Limitations and drawbacks comprise:
  - Effects of and design rules for breaking waves
  - Effects of multidirectionality largely unknown and consequency of locally induced effects (vortex, splash-up) on structure is still imprecise.
- Weak understanding of inherent **<u>processes</u>** in terms of scour phenomena: State-of-the-art design approaches proven exclusively for monopile structures by means of field and laboratory experiments and simplified <u>models</u>, but numerical attempts (significantly) lack behind. Objectives and outlook address research on:
  - Establish new design criteria and practices for scour generation and development in regard of location, geometry (beyond monopiles) and loads (waves and tidal currents)
  - New coupled hydro- and morphodynamical models to be set-up and validated
  - Develop and validate innovative scour protection systems (geotextile SC, wide-graded materials (0-200mm), heavy-density concrete) including development of so-called SPHM - Scour Protection Health Monitoring system

Summary and Perspectives:







- With disc: boundary layers reach the critical adverse gradient, but they rarely separate
- Single cylinder: the cylinder boundary layers separate and develop vortexes

Vortex at upstream side of single cylinder

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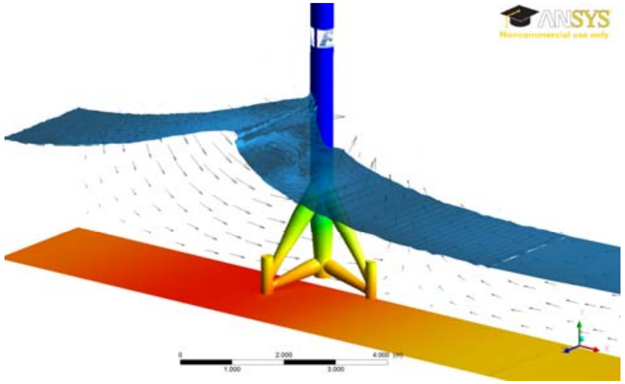

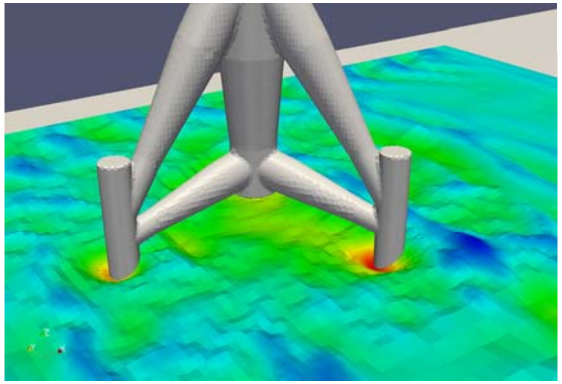

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Thank you for your attention!