Ludwig-Franzius-Institute
for Hydraulic, Estuarine and Coastal Engineering

Leibniz Universität Hannover

Findings on scouring and wind-wave correlation for OWEC design recommendations and offshore operations

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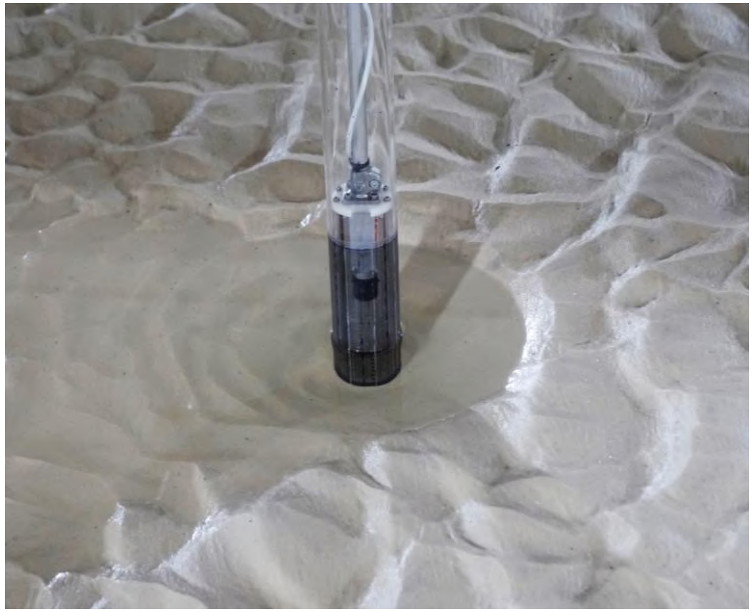

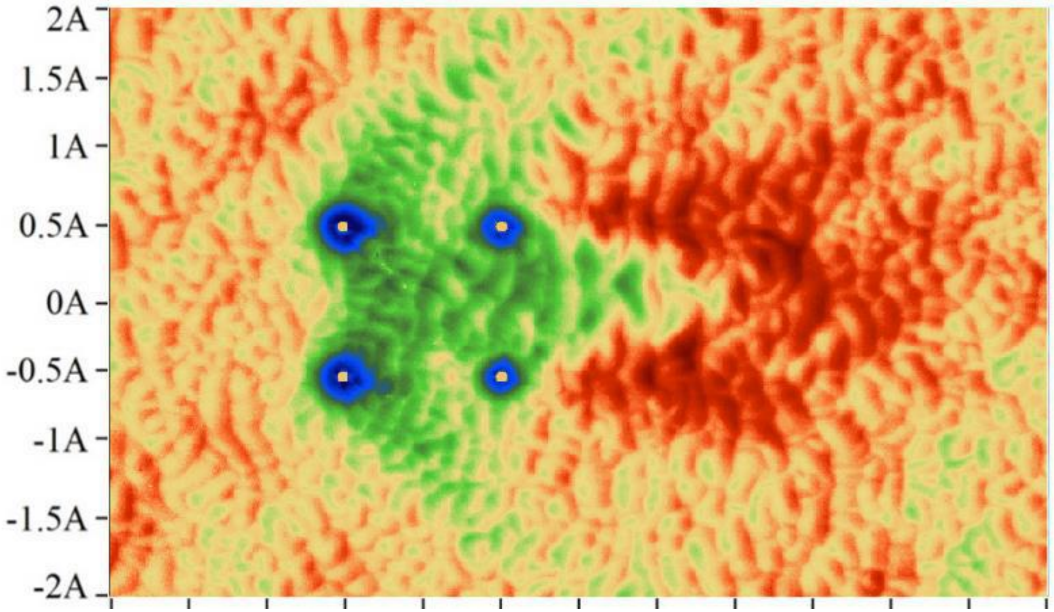

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- Scour development in uni-directional and multi-directional waves
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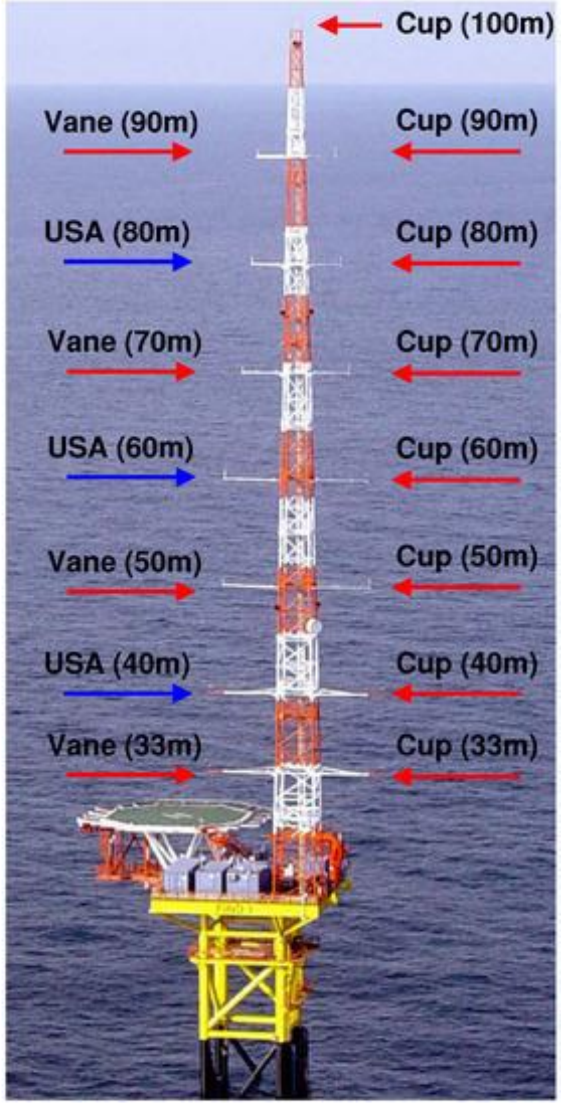
Motivation & Objectives

- Seeking for load factors and lower costs, since offshore wind energy expands further offshore
- Wind driven wave irregularity and directionality are important aspects of offshore sea states
  - Directionality of normal and extreme conditions (Misalignment)
- Lack of empirical data on the scouring processes induced by uni- & multi-directional waves combined with current
- Improvement of scour prediction by conducting experimental studies and to deepen the understanding of scouring process

FINO I Location

Origin: www.fino-offshore.de



Origin: Neumann et al. (2003)

- 45 km North of Borkum island at 30 m water depth
- Wind measurements at heights from 33 to 100 m above LAT
- Cup anemometers, UltraSonic Anemometers (USA), wind vanes
- Datawell WaveRider MKIII, Radar, and Current Profiler

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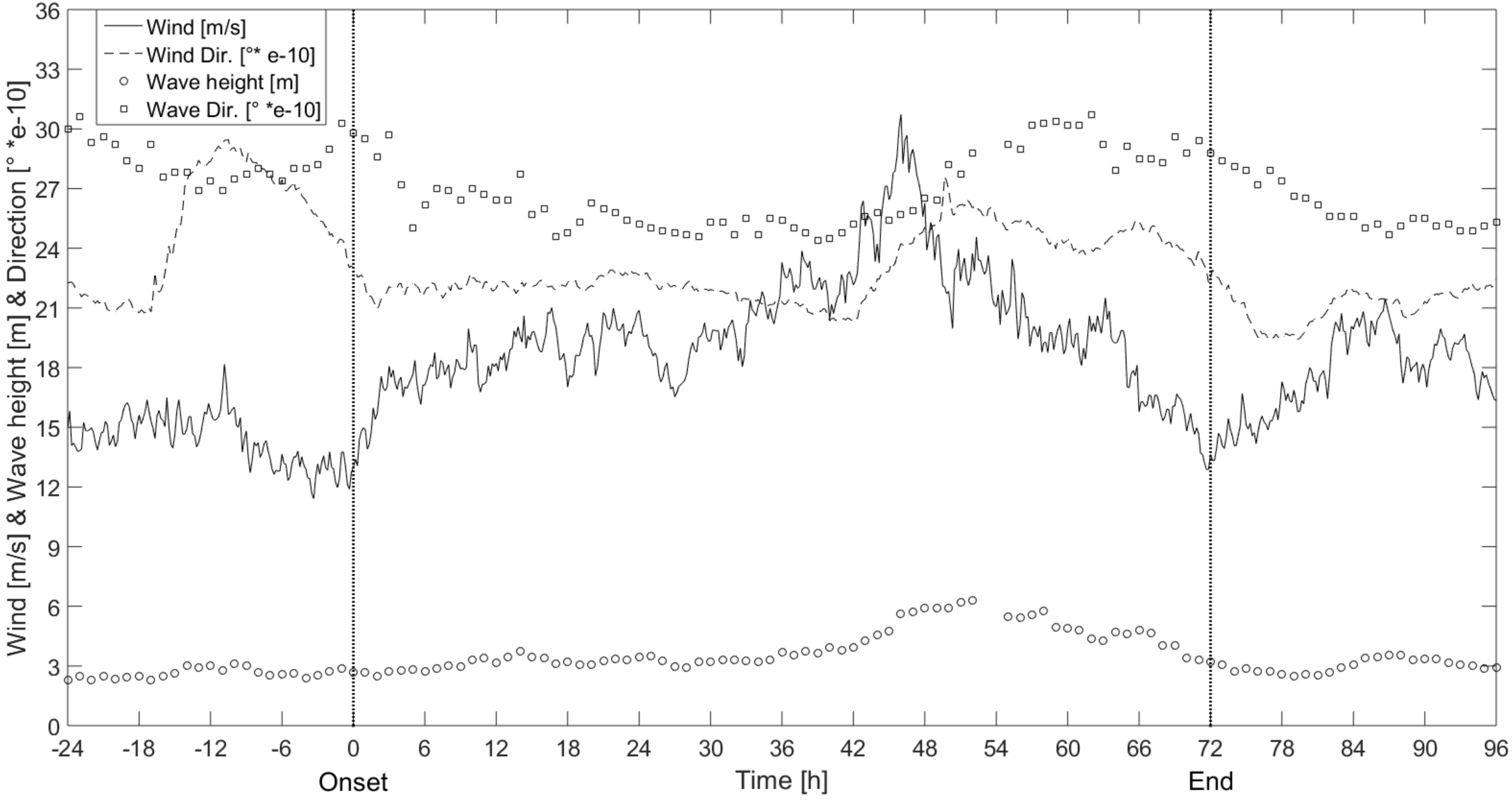
Misalignment – Time Sequence January 2005



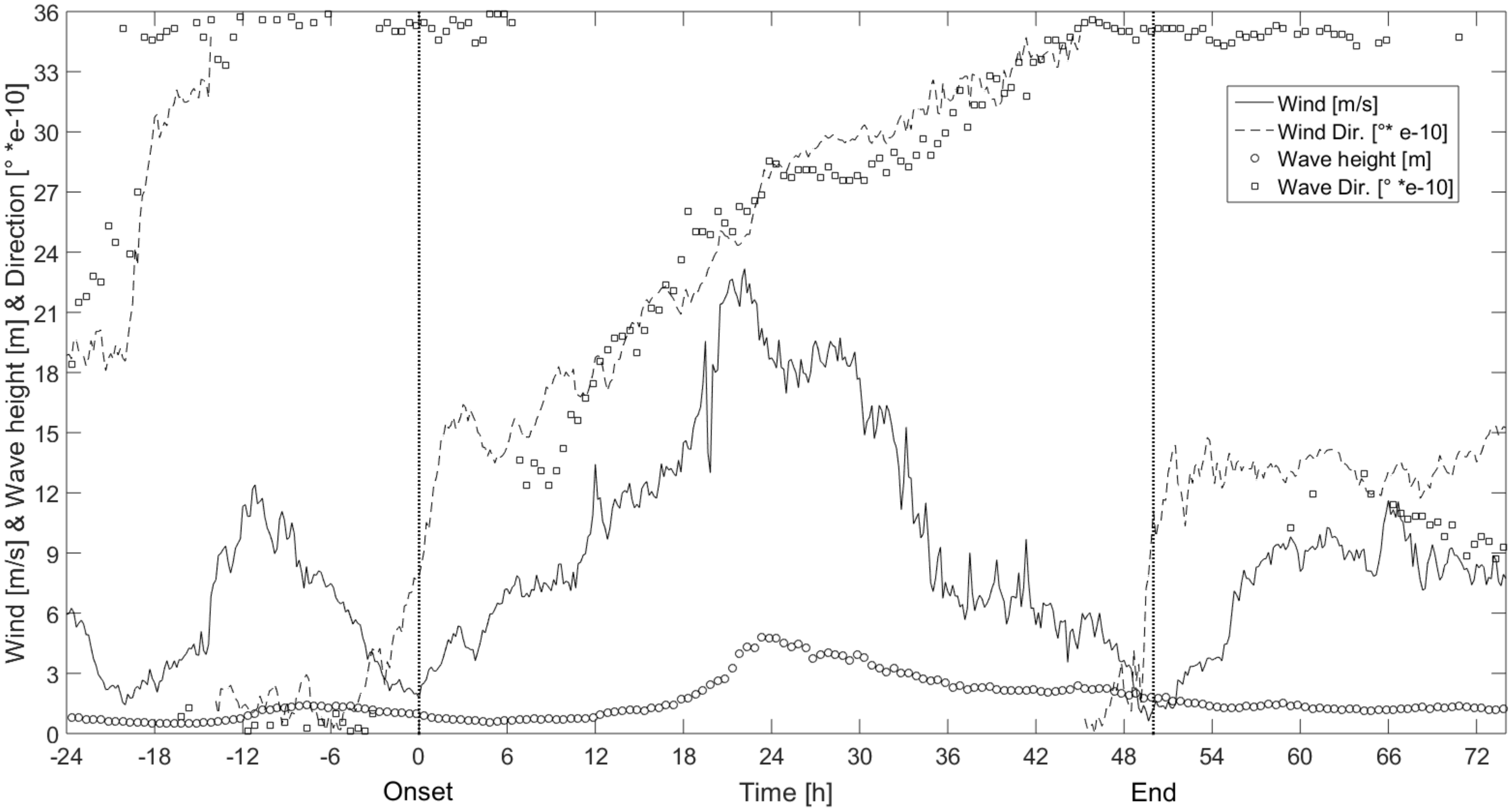
Storm incident
06th of January 2005
at 3 pm - 09th at 3 pm
=> Storm:
>6h & > 16 m/s

Increasing wind at mostly constant wind direction

Wave direction aligns to wind direction

Changing wind direction and misalignment of waves after wind peak

Misalignment – Time Sequence October 2013



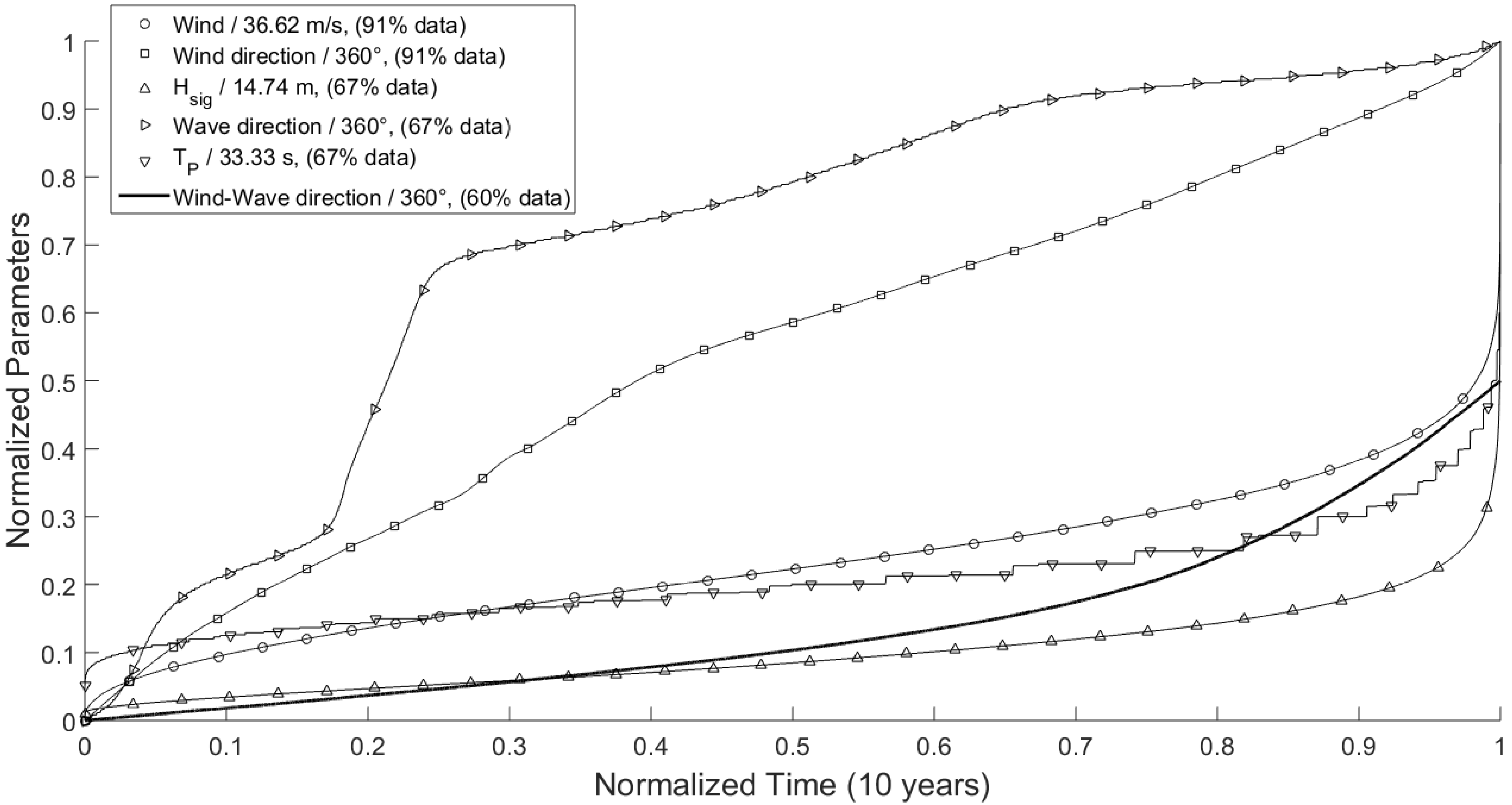
Storm incident 16th of October 2013 at 11 am - 18th at 1 pm
=> Storm:
>6h & > 16 m/s

Wave direction aligns almost instantly to wind direction

Response of waves to wind incidents?

Occurrence of wind and wave peaks and their misalignment?
=> aerodynamic damping of OWEC

Wind-Wave Occurrence & Misalignment – 10 Years



- In-line (< +/- 15°) => 23 %; Opposing (180°+/- 15°) => 2.5 %
- Misalignment >15° for about 75 % of the time (53% for threshold +/-30°)
- Median Misalignment over 10 years (0.5) = 37°

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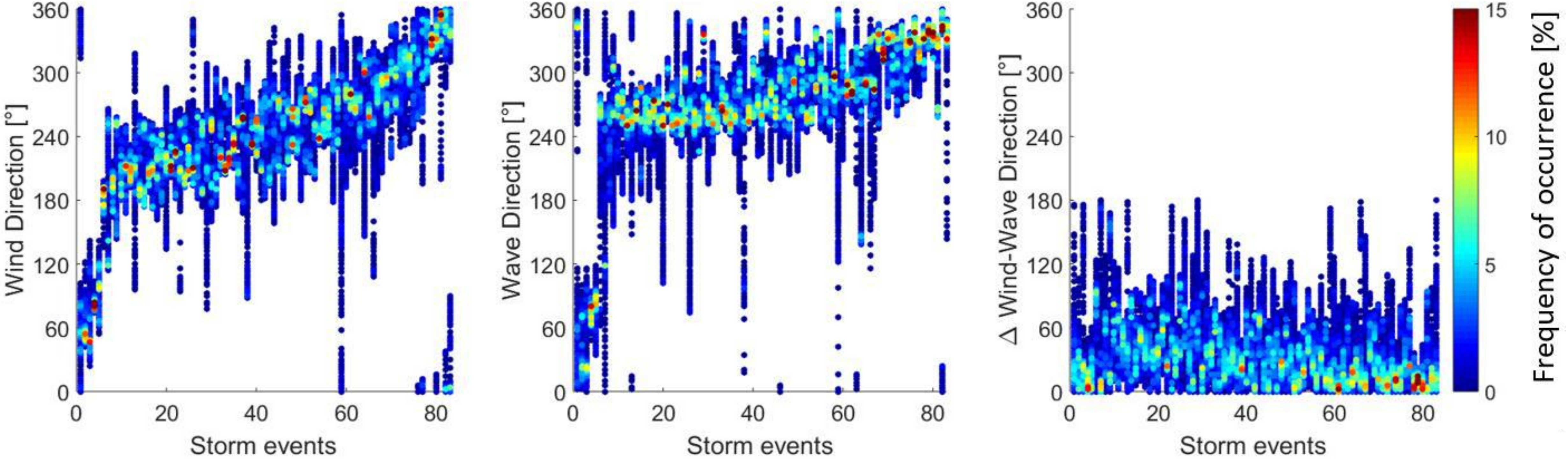
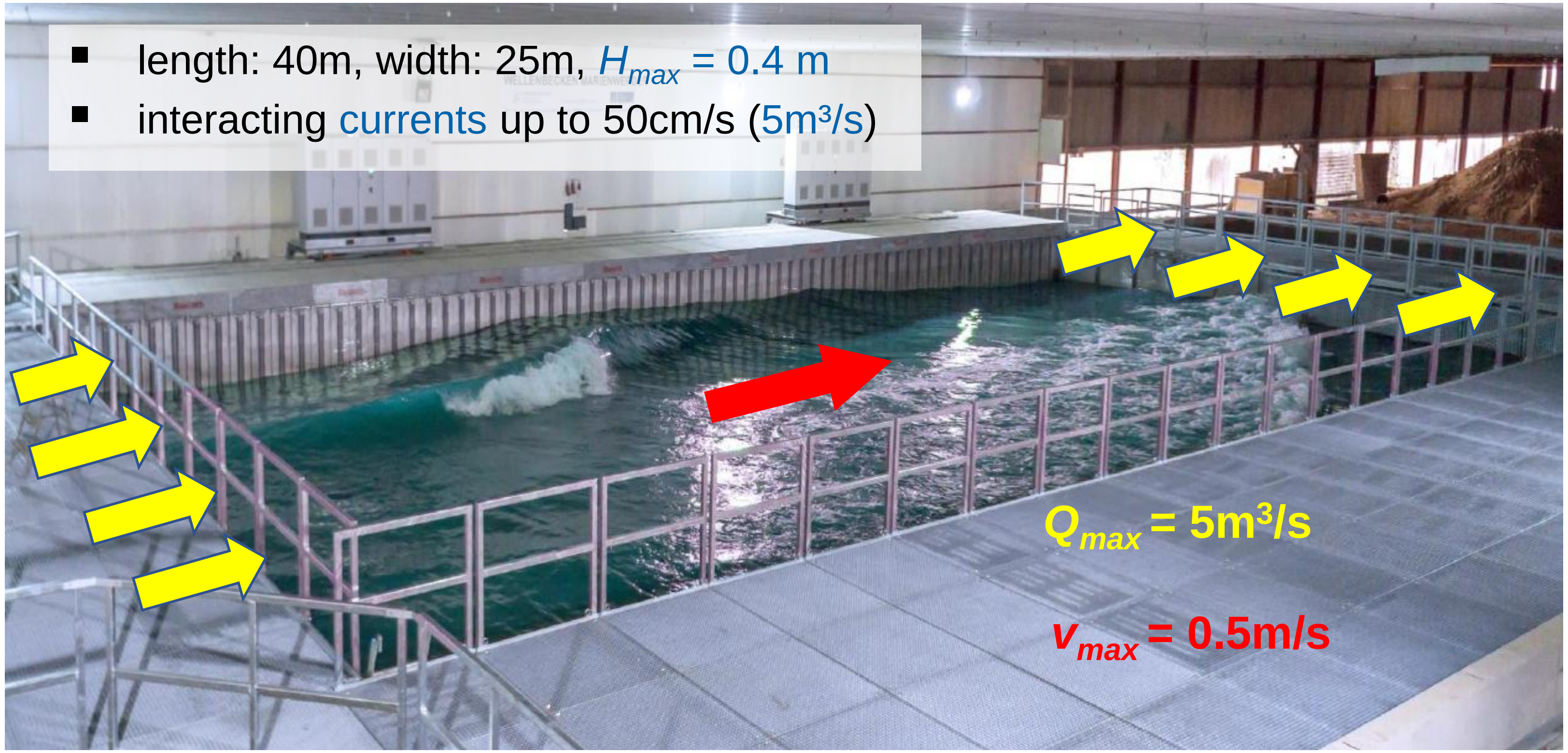
Wind-Wave Occurrence – Directionality of storm incidents



- Storms identified by 10-min average wind > 16 m/s and > 6 hours duration over 10 years from 2004 until 2013
- Storm incidents arranged by increasing mean wind direction versus directional frequency of occurrence of wind- (left), wave direction (middle) and misalignment of wind and waves (right)
- Triangular shape of misalignment with regard to mean wind direction of storm incidents

=> Decreasing misalignment for northern storms

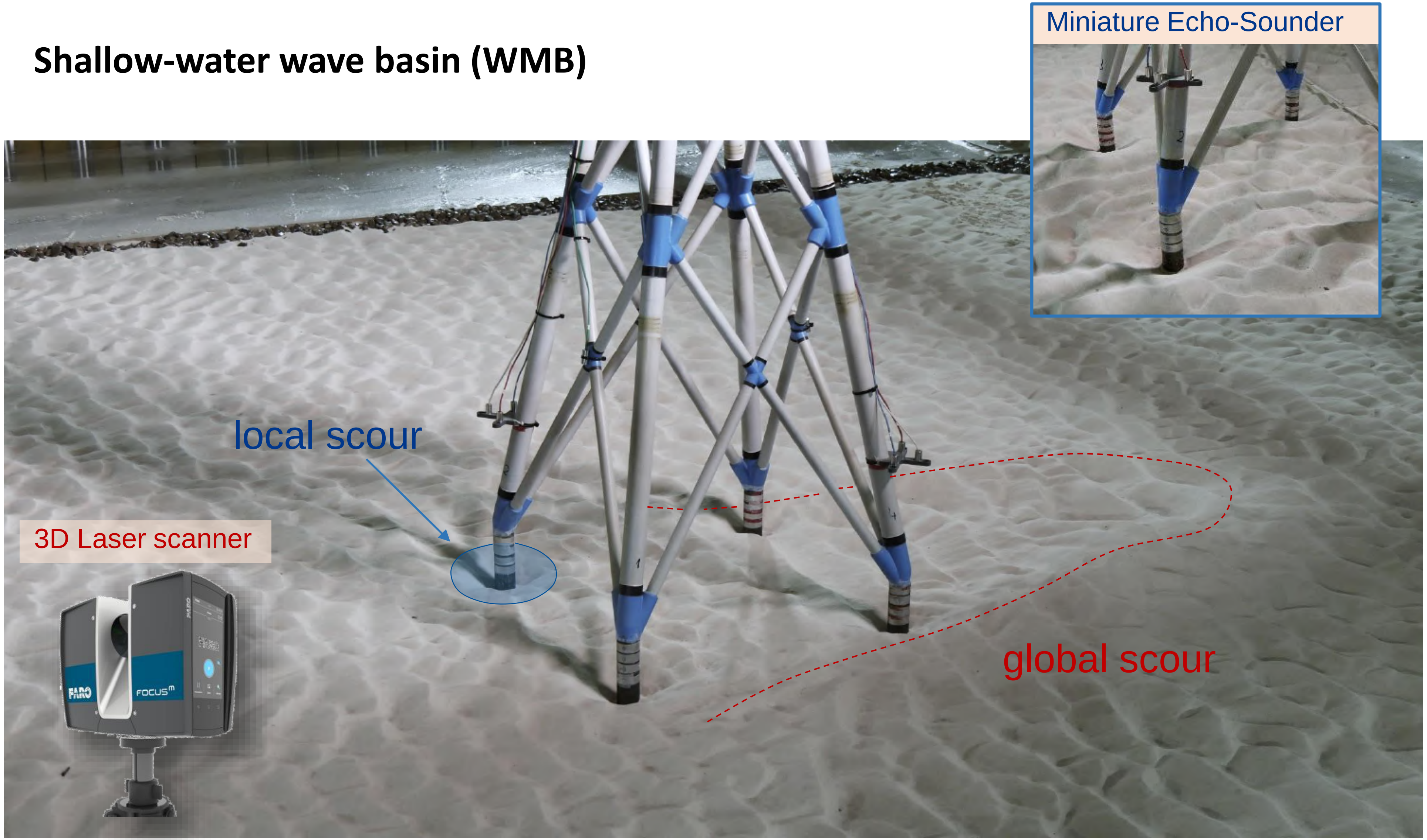
Shallow-water wave basin (WMB)



- 3D wave-current basin, multidirectional wave maker consists of 72 wave paddles
- Generation of regular/irregular waves with a propagation angle of up to ±85°
- Unidirectional current with a maximum discharge of 5m³/s, perpendicular to the waves
- Modular sediment pit: 9.15m x 6.65m x 1.20m
- Quartz sand with d_{50} = 0.19

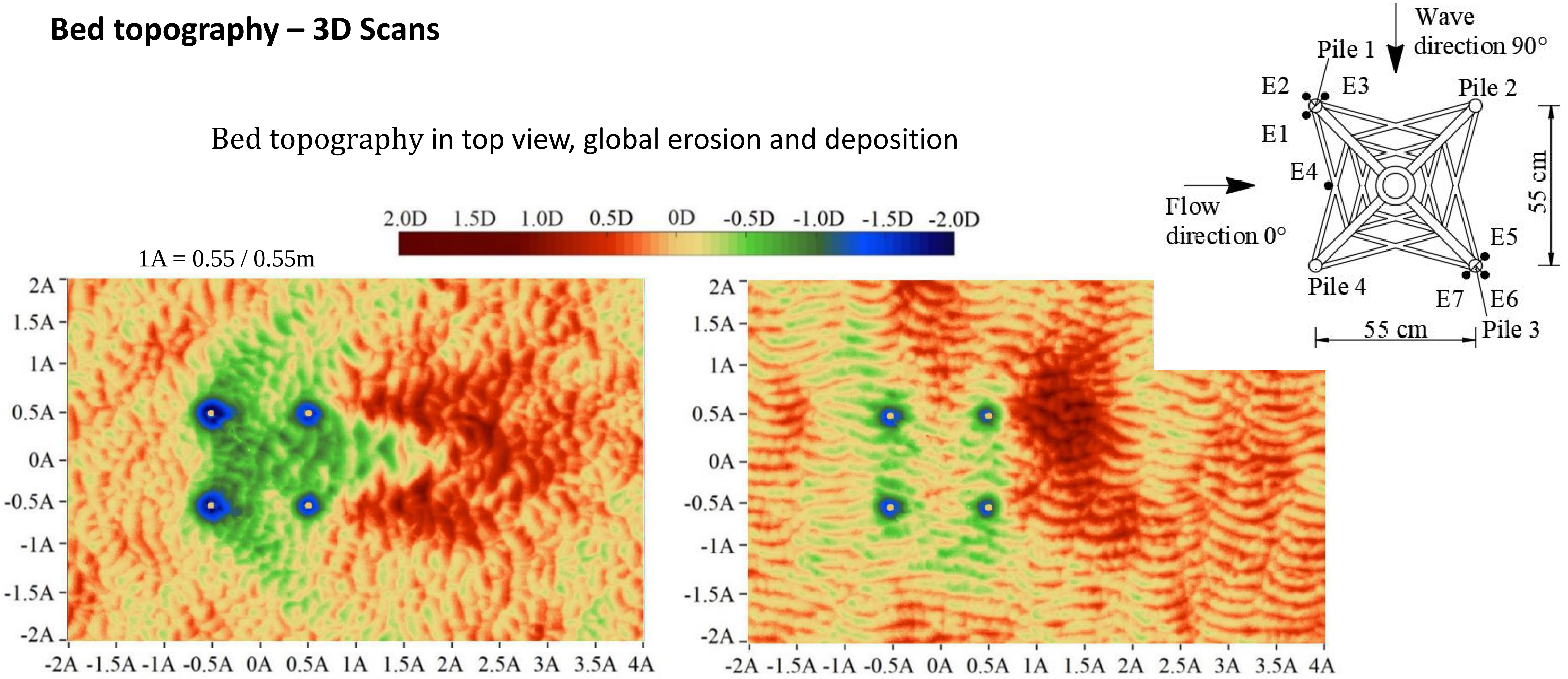
Experimental Setup

Shallow-water wave basin (WMB)

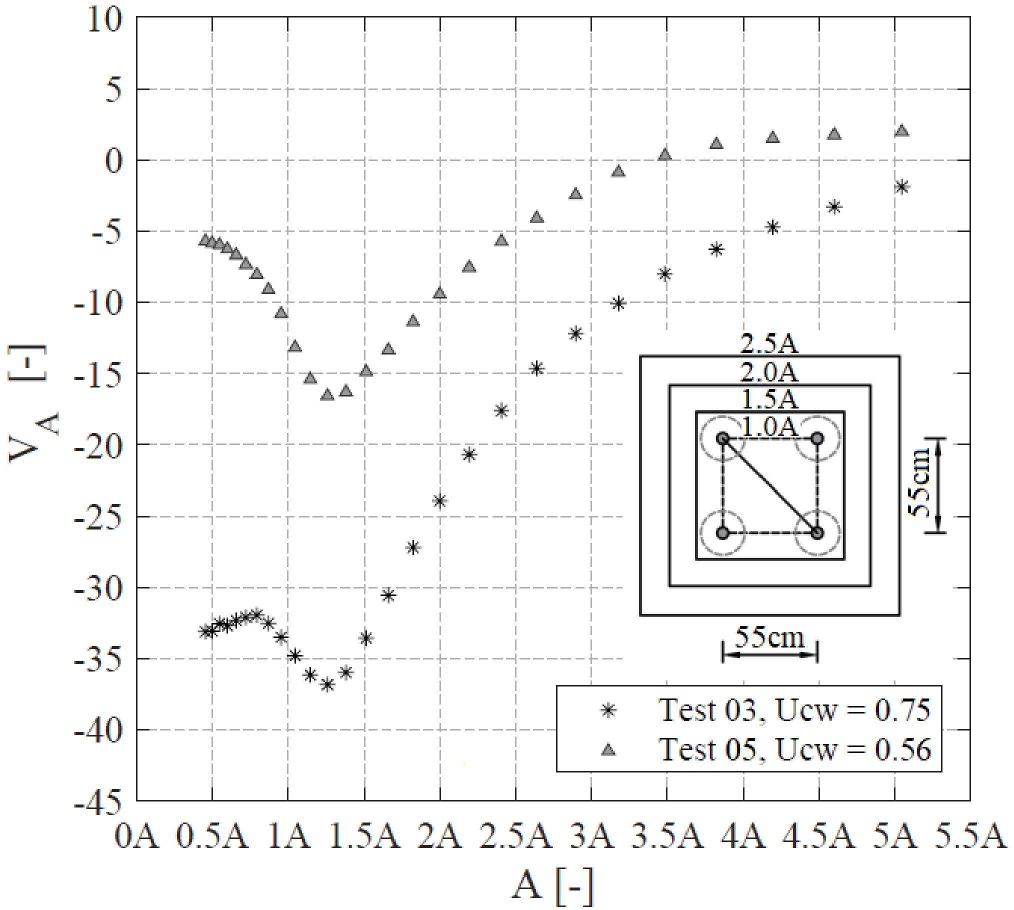


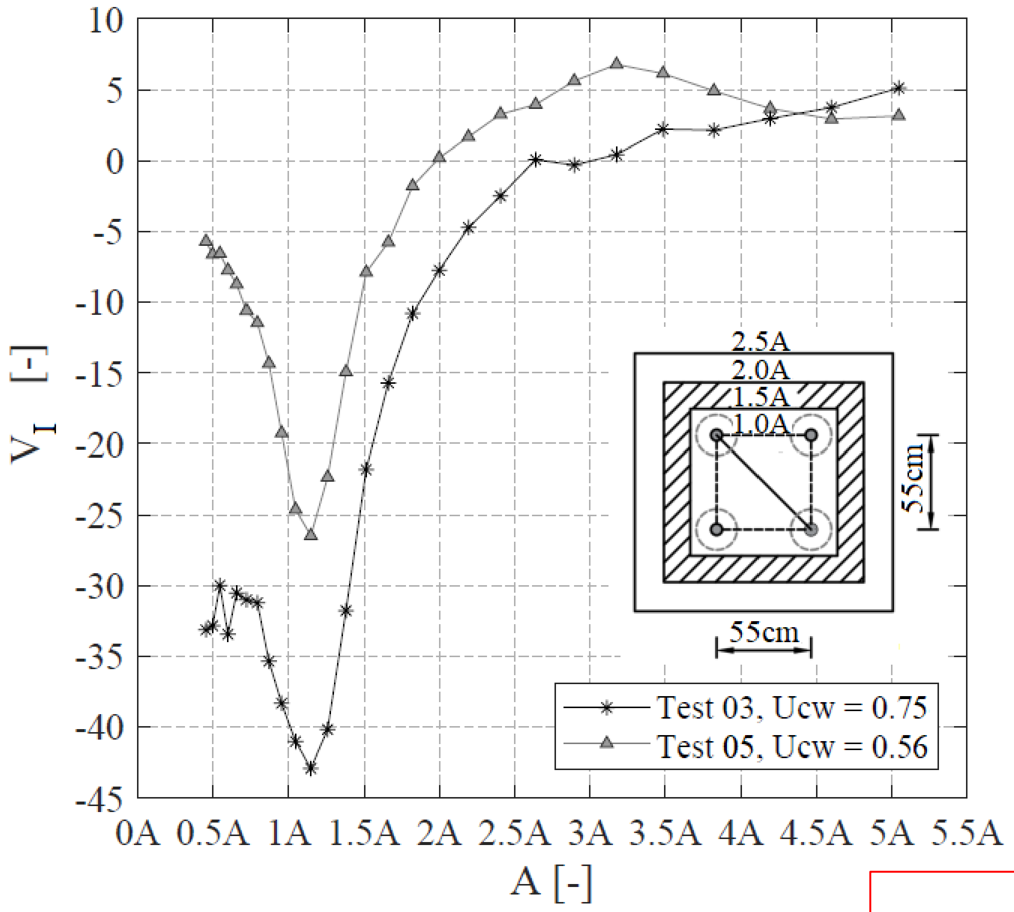
Bed topography – 3D Scans

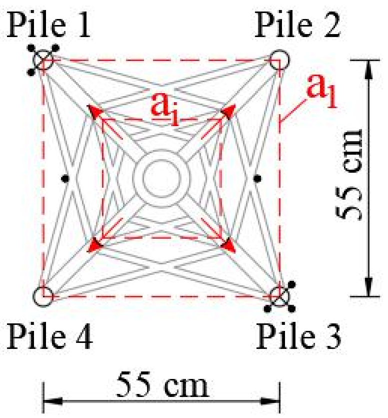
Bed topography in top view, global erosion and deposition



Erosion/deposition volume around the Jacket-structure





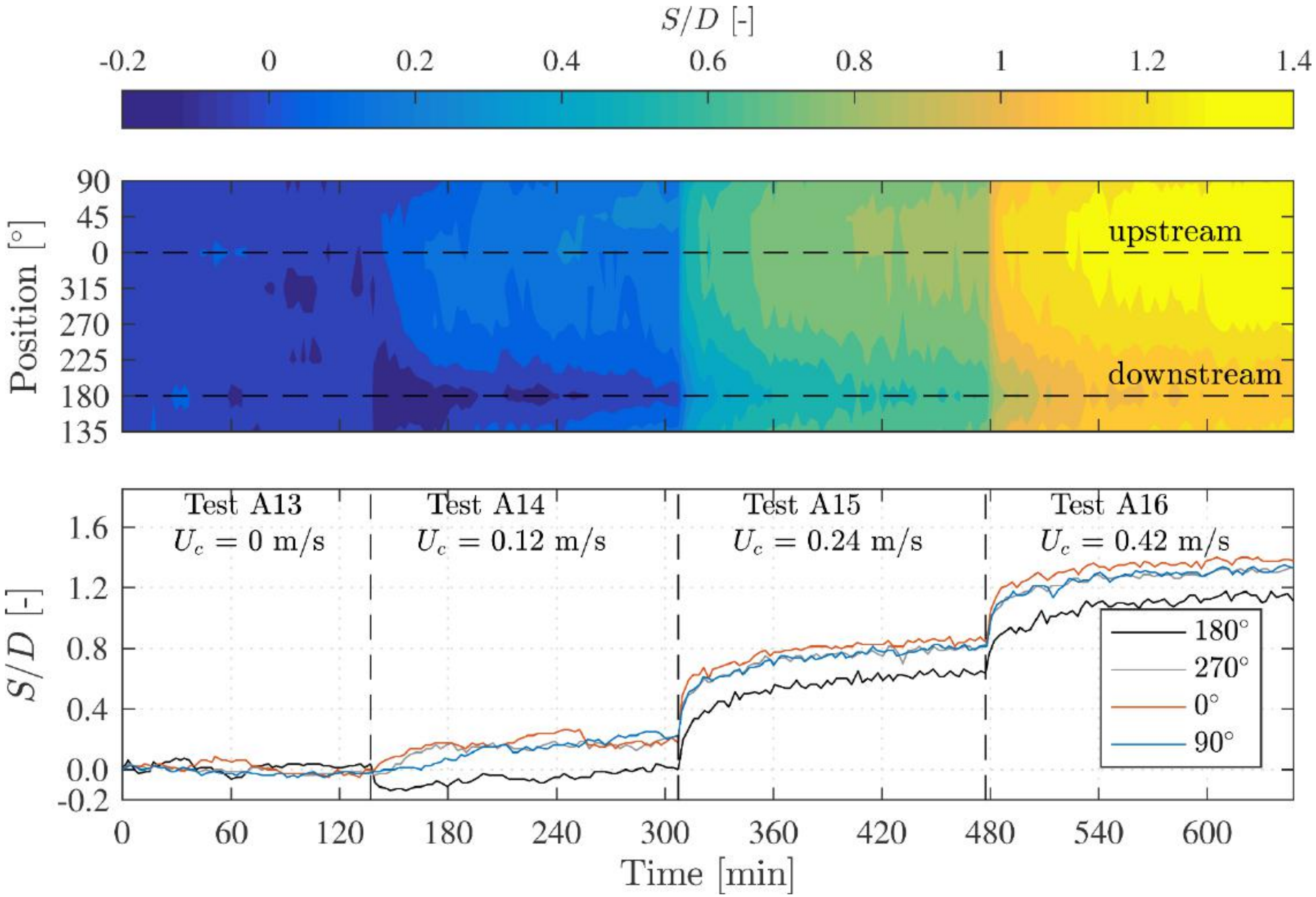


$$V_D = \frac{V_{erosion}}{n \cdot D^3}$$

$$V_{A,i} = \frac{V_{D,i}}{a_i/a_1} \; [-]$$

$$V_{I,i} = \frac{V_{D,i} - V_{D,i-1}}{a_i/a_1 - a_{i-1}/a_1} \; [-]$$

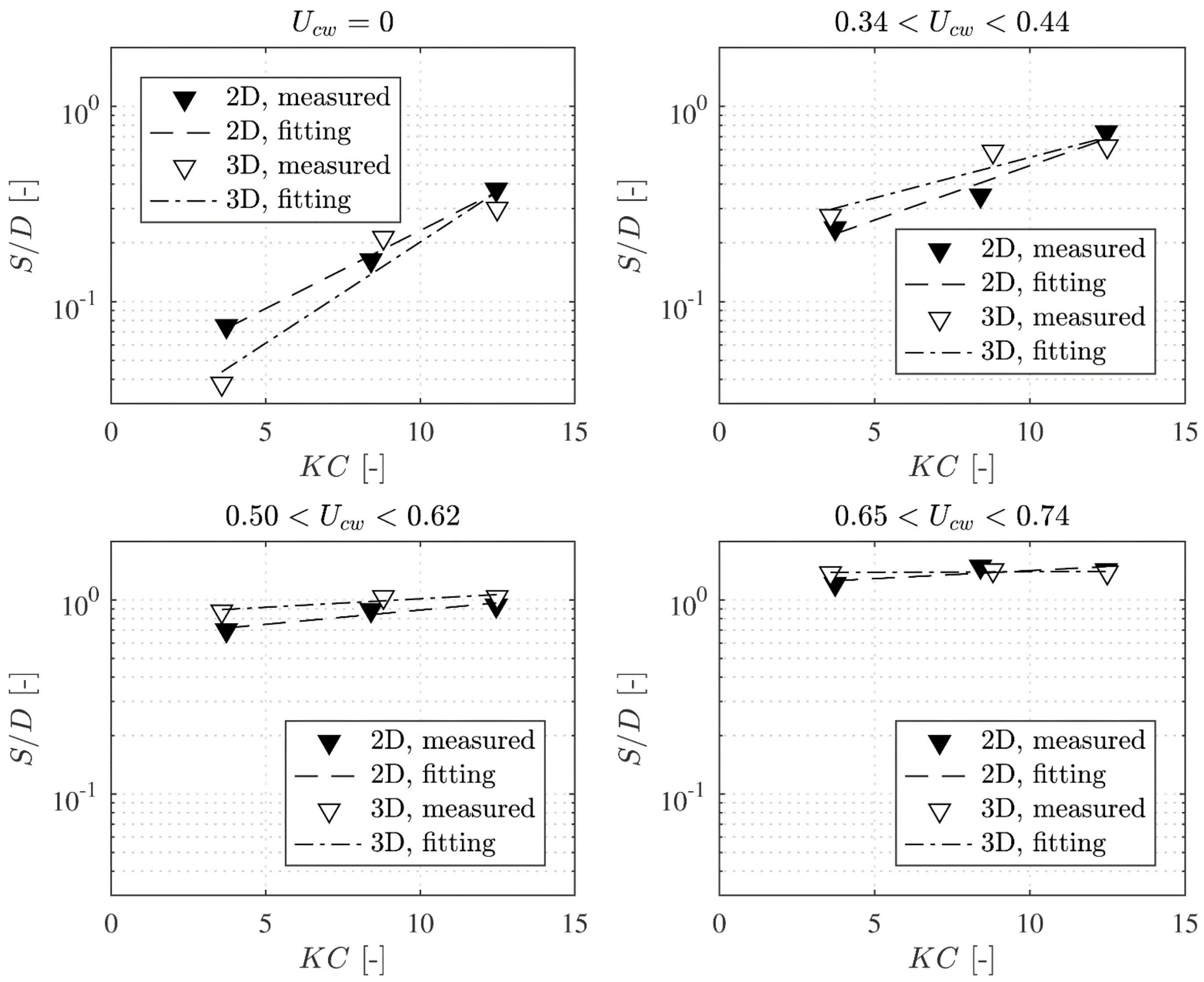
Scour development over time



$H_{m0} = 0.14, T_p = 1.95,\ KC = 3.6$

- Significant increase of scour depth once a current is superimposed
- With every increase of the current velocity the scouring processes resembles that under current only conditions more and more:
  - Position of maximum scour depth relocates to the upstream side of the pile
  - Asymptotically increasing scour depth
- Large imbalance of scour depth around a pile similar to the scour pattern induced by current

Comparison to unidirectional waves



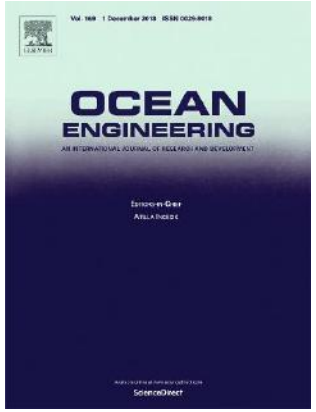
- U_{cw} = 0: On average 33% smaller scour depths in multidirectional waves
- 0 .3 < U_{cw} < 0.6: Wave directionality leads to slightly larger scour depths
- U_{cw} → 1: Differences in scour depths are declining

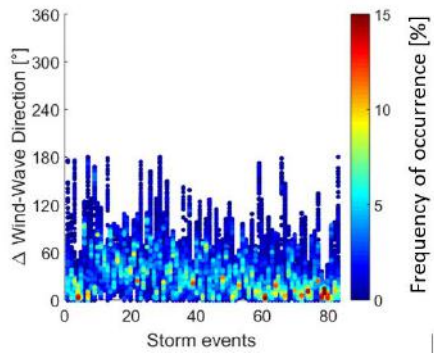
> ➢ Multidirectional waves are less dominant, resulting in:
>
> → increased influence of current
>
> → larger scour depths in combined conditions

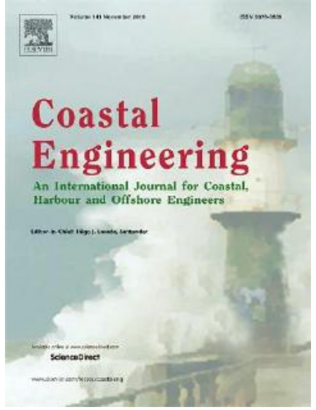
Summary

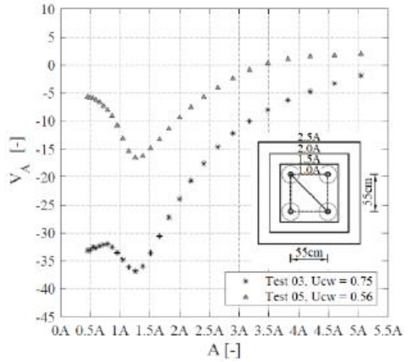
- Wind-Wave Misalignment:
  - Perpendicular misalignment of wind and waves with respect to +/- 15° appears for 10% of the time, while wind and waves are aligned 25% of the time
  - The observed misalignment of predominantly Northern storms amounts up to 30° and increases more or less gradually until 60° for southerly storm directions
- Scouring wave-only conditions:
  - Scour depths in multidirectional waves were on average 33% smaller than those in unidirectional waves
  - Growing dependency on KC numbers with increasing wave spreading
- Scouring combined wave-current conditions:
  - Scour progresses faster over time when exposed to multidirectional than to unidirectional waves
  - Wave directionality led to slightly larger scour depths
  - Strong scour erosion volumes until approx. 1.25-1.5 x A (Jacket) and decreasing gradients beyond that area
  - Increasing global erosion volumes for increasing current

- Wind-Wave Correlation/Misalignment:
  - Hildebrandt, A., Schmidt, B., Steffen, M.: ***Wind-wave misalignment and a combination method for direction-dependent extreme incidents***, (Under revision at Ocean Engineering, Elsevier - International Journal of Research and Development)
- Wave-Current induced Scouring:
  - Schendel, A., Hildebrandt, A., Goseberg, N., Schlurmann, T. (2018): ***Processes and evolution of scour around a monopile induced by tidal currents***, Coastal Engineering, Vol. 139, pp. 65-84
  - Schendel A., Hildebrandt A., Schlurmann T. (2018): ***Experimental study on scour around a pile in multidirectional (spreading) random waves***, Proc. of the 9th Intl. Conf. on Scour and Erosion (ICSE), Taiwan
  - Welzel M., Schlurmann T., Hildebrandt A. (2018): ***Scour Development and Sediment Redistribution Potential at a Jacket-Structure in combined Waves and Current*** , Proc. of the 9th Intl. Conf. on Scour and Erosion (ICSE), Taiwan







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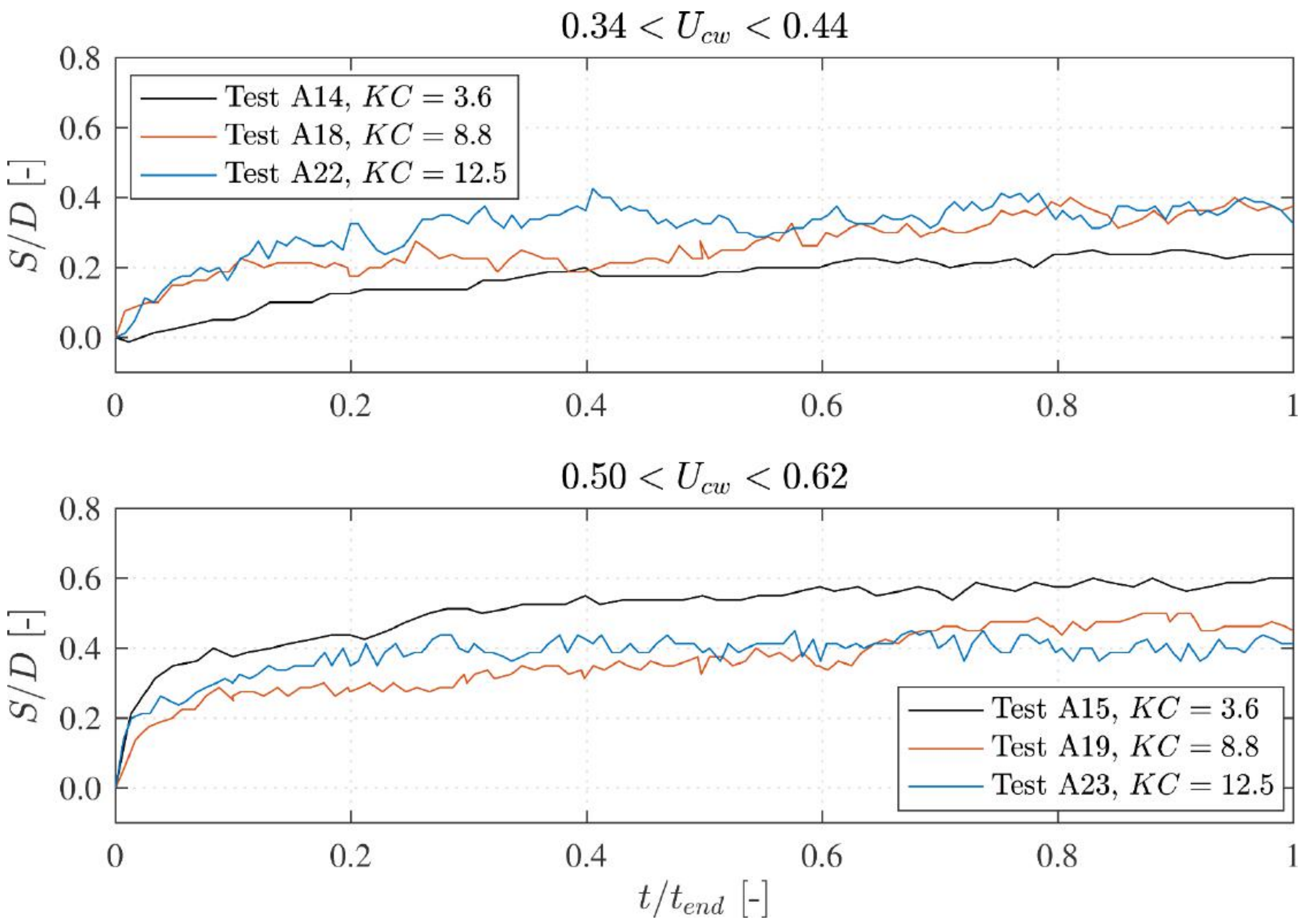
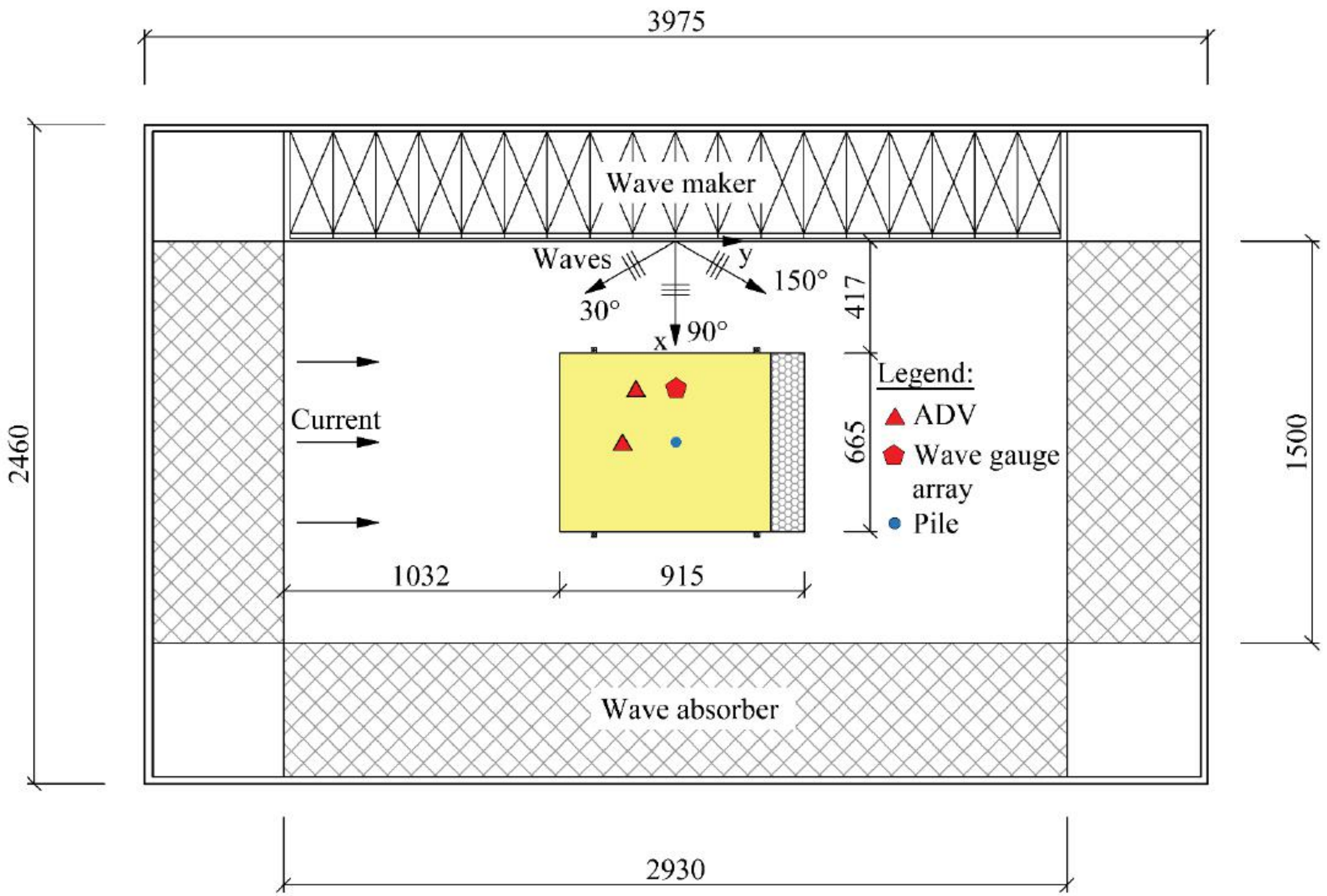
Thanks for your attention

Influence of KC number on scour development



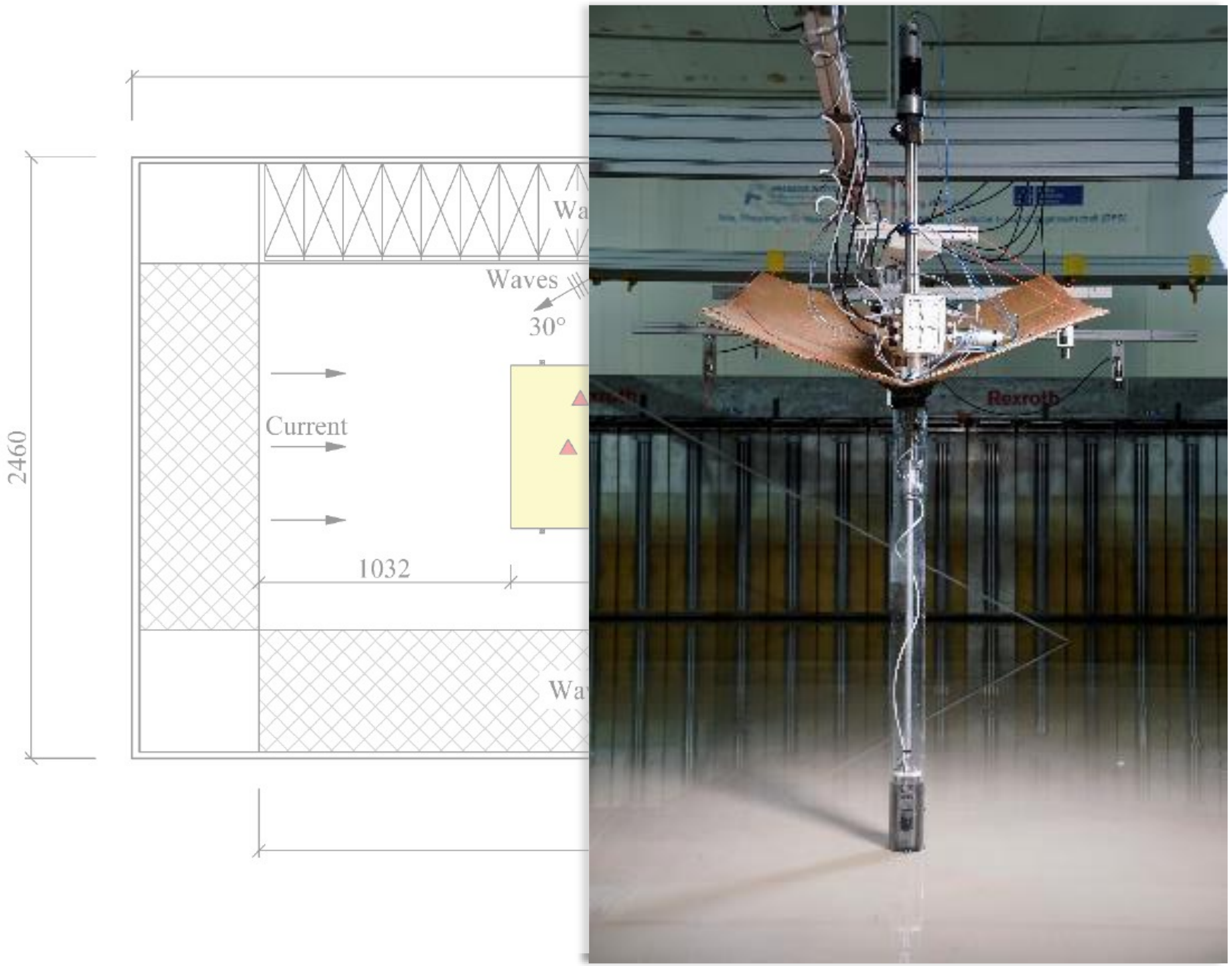
- Scour depth represent the maximum scour depth around the pile for each time step
- U_{cw} = Ratio of current induced velocity to wave induced velocity
  - U_{cw} → 0; wave dominated regime
  - U_{cw} → 1; current dominated regime
- $U_{cw} < 0.44$: Scouring rate increases with increasing KC number
- $U_{cw} > 0.50$: Scouring rate decreases with increasing KC number

Experimental Setup



- 3D wave-current basin, multidirectional wave maker consists of 72 wave paddles
- Generation of regular/irregular waves with a propagation angle of up to ±85°
- Unidirectional current with a maximum discharge of 5m³/s, perpendicular to the waves
- Modular sediment pit: 9.15m x 6.65m x 1.20m
- Quartz sand with d_{50} = 0.19 and σ_g = 1.4

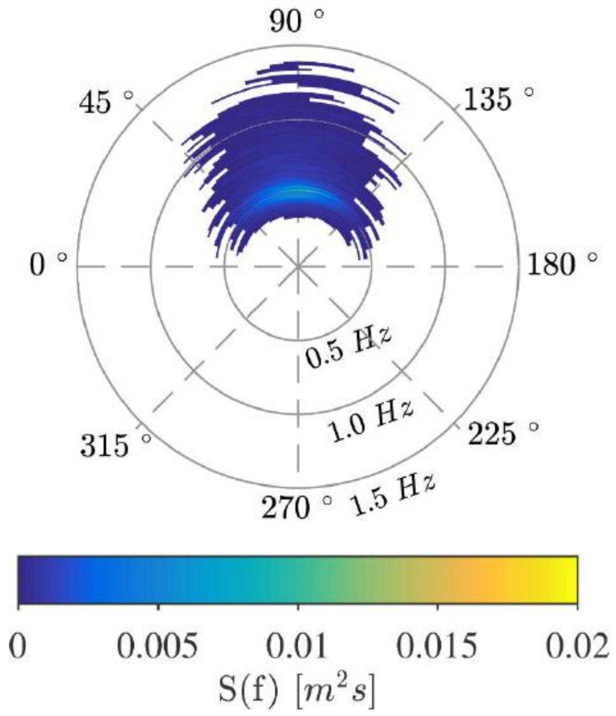
Experimental Setup



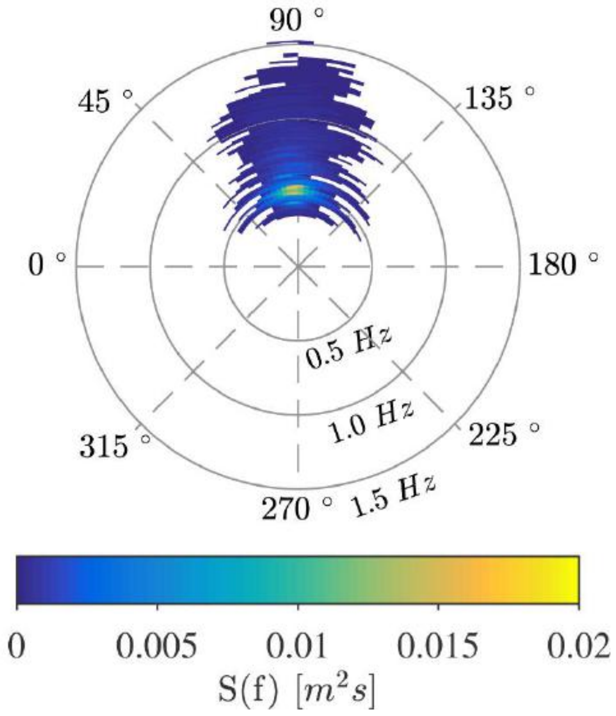
- Multidirectional waves were recorded by a CERC6 wave gauge array consisting of six echo-sounder
- Wave and current induced flow velocities were measured by two ADVs
- Monopile foundation structure was simulated by a transparent pile
- Scour measurements were carried out by a camera system inside the pile
- Height and vantage point of camera could be adjusted to follow scour progression

Test Conditions

s = 10, wide spreading



s = 40, narrow spreading

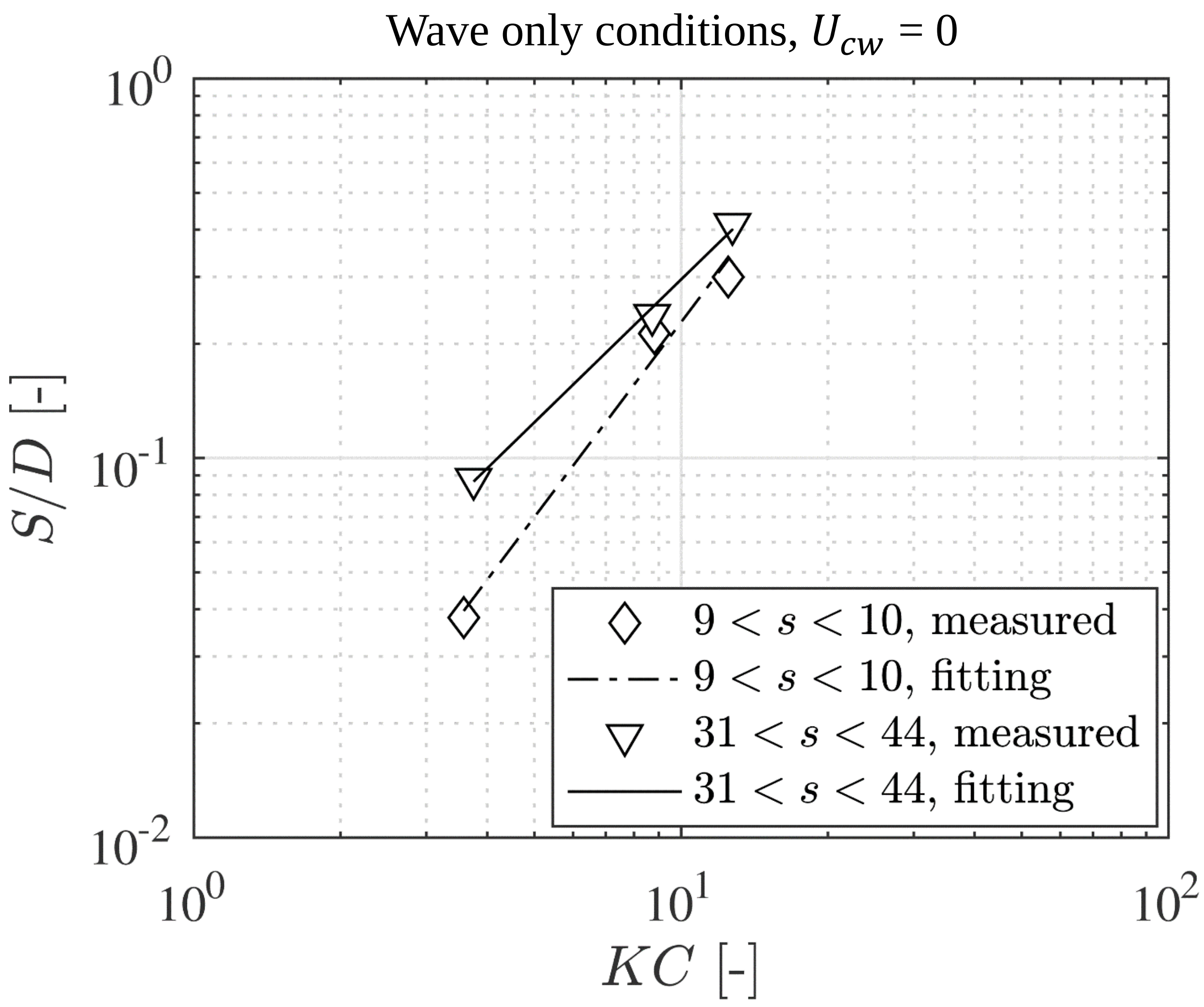


- Uni- and multidirectional JONSWAP wave spectra → KC = 3.6 – 12.5
- Uni- and multidirectional wave spectra with identical total wave energy were generated
- Two different wave spreadings based on Mitsuyasu-type (cos2s), with s =10 and s = 40

$$D(f,\Theta) = cos^{2s}\left\{\frac{\Theta - \Theta_0(f)}{2}\right\}$$

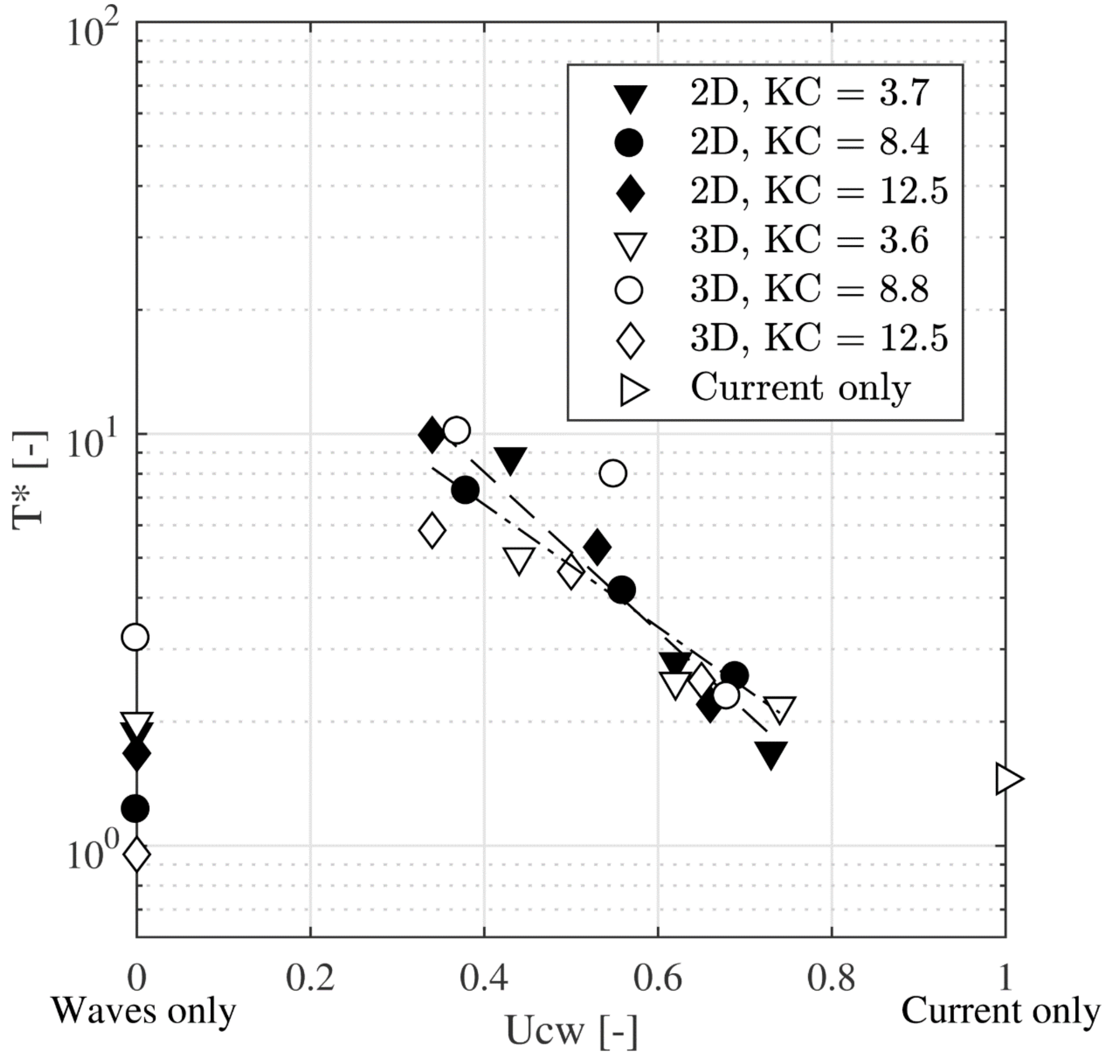
- Superposition with unidirectional current, stepwise increase of current velocity after 6000 waves → U_{cw} = 0 – 0.74
- 27 tests, with a fixed water level of 60cm

Influence of wave spreading



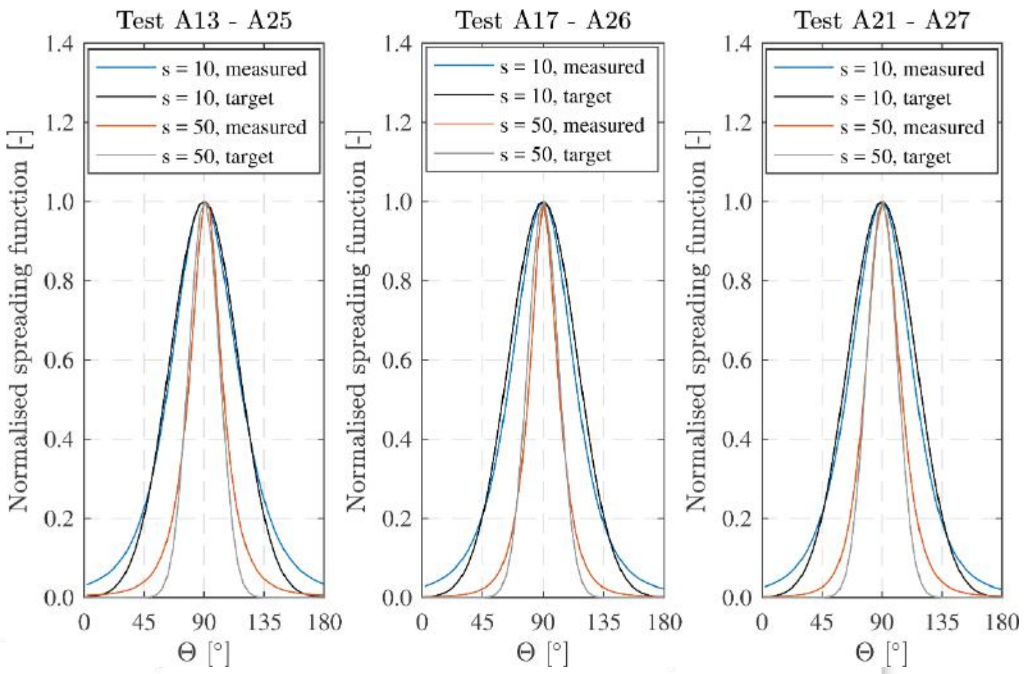
- Maximum scour depths obtained in wave only conditions as a function of KC number and spreading parameter s
- Scour depths decrease with increasing wave spreading, particularly for small values of KC
- Only limited number of data points → verification for additional spreading parameter needed

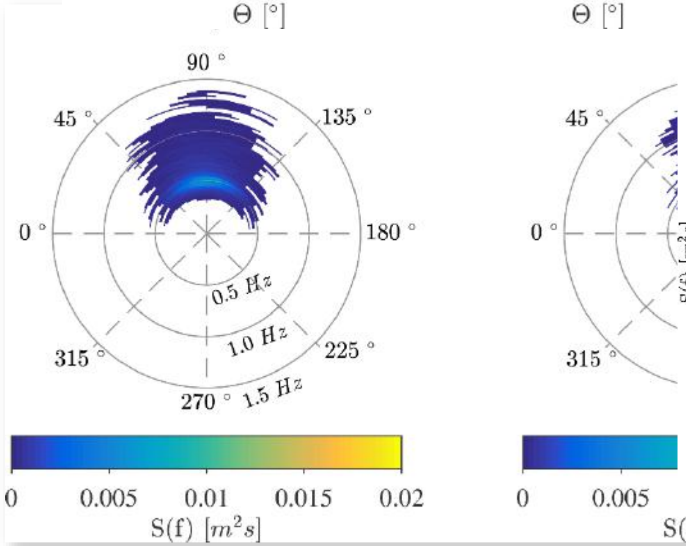
Comparison to unidirectional waves

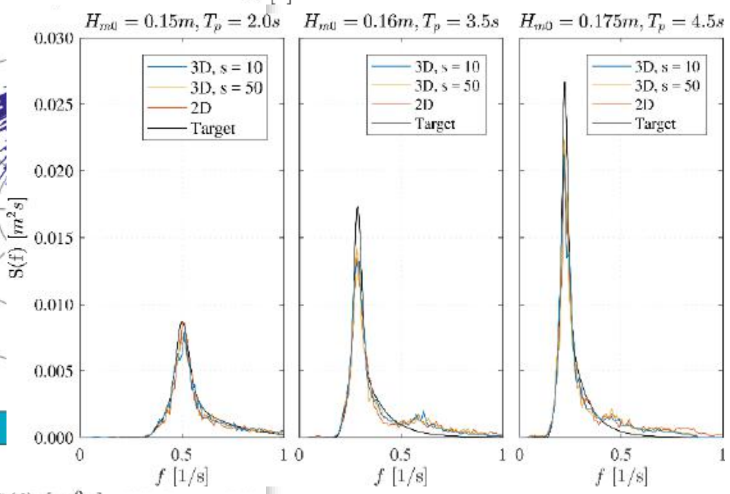


- Time scale increases significantly once a current is superimposed to the waves
- Time scale decreases with further increasing current flow velocity
  - Faster scour progression for larger values of U_{cw}
- Time scale in unidirectional waves is slightly more dependent on U_{cw} than that in multidirectional waves

Generation of multidirectional waves







- <u>Objectives:</u>
  - Understanding of scouring process induced by multidirectional waves (and current)
  - Systematically investigate the influence of wave spreading on the scouring process
  - Improve the scour prediction by comparing the results to unidirectional wave induced scour

- JONSWAP spectra, model scale 1:75, stepwise increase of current velocity after 6000 waves
- Uni- and multidirectional wave spectra with identical total wave energy
- Different wave spreading based on Mitsuyasu-type (cos2s), s =10 and s = 50

Table 3.2: Test conditions and maximum scour depths for multidirectional (short-crested) wave experiments.

t	Number of waves N [-]	Spetral wave height H_{m0} [m]	Peak wave period T_p [s]	Keulegan-Carpenter number KC [-]	Maximum orbital velocity at the bed U_w [m/s]	Undistur-bed current velocity (at 10cm) U_c [m/s]	Combined wave-current velocity U_{cw} [-]	Shields parame-ter θ [-]	Spreading parame-ter s [-]	Maximum scour depth S_{max}/D [-]
3	5215	0.143	1.95	3.58	0.147	-	0	0.086	8.90	0.038
4	6519	0.143	1.95	3.58	0.147	0.115	0.44	0.079	8.90	0.275
5	6519	0.143	1.95	3.58	0.147	0.244	0.62	0.089	8.90	0.875
6	6519	0.143	1.95	3.58	0.147	0.421	0.74	0.147	8.90	1.375
7	5183	0.159	3.56	8.81	0.198	-	0	0.086	9.21	0.213
8	6479	0.159	3.56	8.81	0.198	0.115	0.37	0.090	9.21	0.588
9	6479	0.159	3.56	8.81	0.198	0.244	0.55	0.103	9.21	1.038
0	5183	0.159	3.56	8.81	0.198	0.421	0.68	0.156	9.21	1.425
1	4960	0.172	4.40	12.49	0.227	-	0	0.088	9.87	0.300
2	6200	0.172	4.40	12.49	0.227	0.115	0.34	0.098	9.87	0.625
3	6200	0.172	4.40	12.49	0.227	0.244	0.50	0.111	9.87	1.038
4	4960	0.172	4.40	12.49	0.227	0.421	0.65	0.162	9.87	1.388
5	5224	0.144	2.00	3.75	0.150	-	0	0.086	31.34	0.088
6	4951	0.158	3.56	8.72	0.196	-	0	0.085	43.50	0.238
7	4974	0.171	4.55	12.74	0.224	-	0	0.086	31.26	0.413

$$S(f,\Theta) = S(f)\,D(f,\Theta)$$

$$\int_{\Theta_{min}}^{\Theta_{max}} D(f,\Theta)\,d\Theta = 1$$

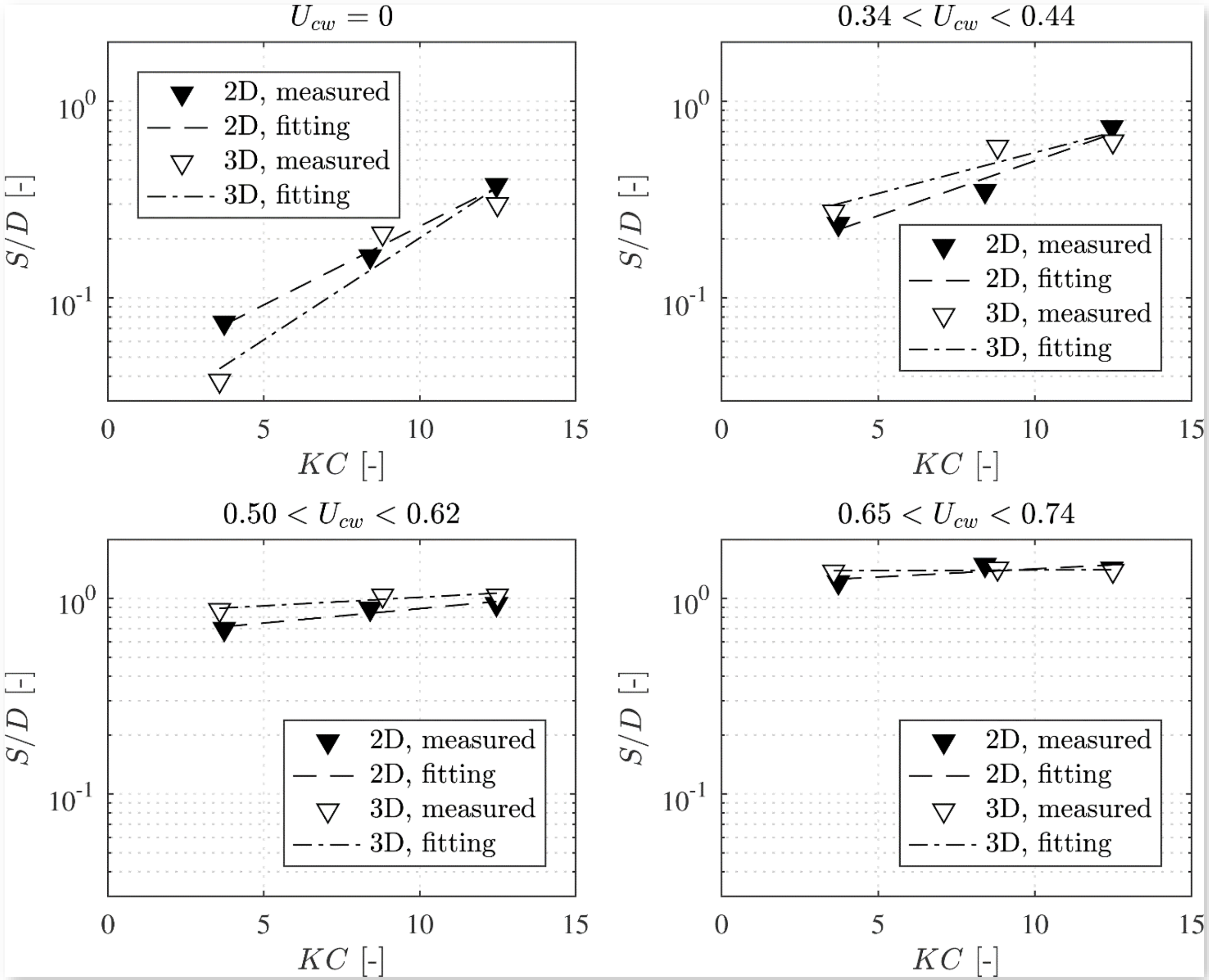
$$D(f,\Theta) = cos^{2s}\left\{\frac{\Theta - \Theta_0(f)}{2}\right\}$$

Objectives:

- Understanding of scouring process induced by multidirectional waves (and current)
- Systematically investigate the influence of wave spreading on the scouring process
- Improve the scour prediction by comparing the results to unidirectional wave induced scour

Scour development - Multidirectional waves (& current)

Comparison to unidirectional (long-crested) waves



- Reduction of scour depths in multidirectional waves by (hypothesis!):
  - Smaller concentration of erosion potential in main wave direction
  - Reduction of accumulation effects of a recurring, bidirectional vortex system
- Multidirectional waves are less dominant
  - → increased influenced of current
  - → larger scour depth in combined

Wave directionality does affect the scour development!

For $U_{cw} > 0.7$ depths approach current value → conservative assumption for design

Scour development - Multidiretional waves

Paper 01: Schendel et al. (2015)