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

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- Experimental Conditions
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- Summary
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

- 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

Origin: www.fino-offshore.de

Origin: Neumann et al. (2003)
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
Wind-Wave Misalignment

Misalignment – Time Sequence October 2013

Storm incident 16\textsuperscript{th} of October 2013 at 11 am - 18\textsuperscript{th} 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 Misalignment

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°
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
Experimental Setup

Shallow-water wave basin (WMB)

- length: 40m, width: 25m, \( H_{\text{max}} = 0.4 \text{ m} \)
- interacting currents up to 50cm/s (5m³/s)

\( Q_{\text{max}} = 5\text{m}^3/\text{s} \)
\( v_{\text{max}} = 0.5\text{m}/\text{s} \)

- 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)

local scour

3D Laser scanner

global scour

Miniature Echo-Sounder
Experimental Setup

Bed topography – 3D Scans

Bed topography in top view, global erosion and deposition

1A = 0.55 / 0.55m
Scour development - areal

Erosion/deposition volume around the Jacket-structure

\[ V_A = V_D, \Delta_i - V_D, \Delta_i - 1, \Delta_1 - \Delta_1, \Delta_1 \]

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

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

\[ V_{l,i} = \frac{V_{D,i} - V_{D,i-1}}{a_i/a_1 - a_{i-1}/a_1} \] [-]
Scour development over time

- 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

\[ H_{m0} = 0.14, T_p = 1.95, \ K_C = 3.6 \]
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
- $U_{cw} \rightarrow 1$: 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 $K_C$ 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.
References for Results

- **Wind-Wave Correlation/Misalignment:**

- **Wave-Current induced Scouring:**
  - 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
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

\[ U_{cw} = \frac{\text{Ratio of current induced velocity}}{\text{wave induced velocity}} \]

- \( U_{cw} \rightarrow 0 \); wave dominated regime
- \( U_{cw} \rightarrow 1 \); 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 $\sigma_g = 1.4$
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

- Uni- and multidirectional JONSWAP wave spectra $\rightarrow KC = 3.6 - 12.5$
- Uni- and multidirectional wave spectra with identical total wave energy were generated
- Two different wave spreadings based on Mitsuyasu-type $(\cos^2 s)$, with $s = 10$ and $s = 40$

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

- Superposition with unidirectional current, stepwise increase of current velocity after 6000 waves $\rightarrow U_{cw} = 0 - 0.74$
- 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 $\rightarrow$ 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
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

- 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 $(\cos^2s)$, $s = 10$ and $s = 50$
**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**

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

<table>
<thead>
<tr>
<th>St</th>
<th>Number of waves N</th>
<th>Spectral wave height $H_{0}$</th>
<th>Peak wave period $T_{p}$</th>
<th>Keulegan-Carpenter number $KC$</th>
<th>Maximum orbital velocity at the bed $U_{w}$</th>
<th>Undisturbed current velocity (at 10 cm) $U_{c}$</th>
<th>Combined wave-current velocity $U_{w}$</th>
<th>Shields parameter $\theta$</th>
<th>Spreading parameter $s$</th>
<th>Maximum scour depth $S_{max}/D$</th>
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</table>

\[
S(f, \Theta) = S(f) D(f, \Theta) \quad \int_{\Theta_{\text{min}}}^{\Theta_{\text{max}}} D(f, \Theta) d\Theta = 1 \quad D(f, \Theta) = \cos^{2k} \left\{ \frac{\Theta - \Theta_{0}(f)}{2} \right\}
\]
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 conditions

Wave directionality does affect the scour development!

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