Outline of Presentation

- DualSPHysics in coastal protection
  - Wave generation & wave absorption
  - Wave-structure interaction
  - Coupling with wave propagation models

- DualSPHysics in wave energy
  - Wave interaction with floating bodies
  - Catenary moorings
  - Simulation of an Oscillating Water Column
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Motivation

The problems we are interested on:
Wave generation and wave absorption

The wave generation in DualSPHysics mimics the conditions of physical wave facilities.

- The wave-maker (piston, flap, flap with variable draft) consists of a rigid body formed by boundary particles.

- The motion of the wave generator is prescribed controlling its position (linear or angular) at each instant of time.

- **AUTOMATIC WAVE GENERATION:**
  - Regular & Irregular
  - 1st and 2nd Order
Wave generation and wave absorption

PISTON-type wavemaker, REGULAR waves, 2nd Order
(Frigaard et al., 1993; Madsen, 1971)

\[ \eta(x,t) = \frac{H}{2} \cdot \cos(\omega t - kx + \delta) + \left( \frac{kH^2}{16} \right) [3\coth(kd)^3 - \coth(kd)] \cos(2\omega t - 2kx + 2\delta) \]

\[ m_1 = \frac{H}{S_0} = \frac{2\sinh^2(kd)}{\sinh(kd) \cosh(kd) + kd} \quad \text{Biesel transfer function (1951)} \]

Piston displacement

\[ e(t) = \frac{S_0}{2} \sin(\omega t + \delta) + \left[ \left( \frac{H^2}{32d} \right) \cdot \left( \frac{3\cosh(kd)}{\sinh^3(kd)} \right) - \frac{2}{m_1} \right] \sin(2\omega t + 2\delta) \]
Wave generation and wave absorption

PISTON-type wavemaker, IRREGULAR waves, 1st Order (Frigaard et al., 1993)

1. Define the wave spectrum (peak frequency, spectrum shape, etc.).
2. Define the frequency band width $\Delta f$.
3. Determine frequency $\omega_i$, $a_i$ and $\delta_i$ (random between 0 and 2$\pi$) of each linear wave.

$$\omega_i = 2\pi f_i \quad a_i = \sqrt{2S_\eta(f_i)\Delta f} = \frac{H_i}{2}$$

4. Apply Biesel:

$$\frac{H_i}{S_{0,i}} = \frac{2\sinh^2(k_i h)}{\sinh(k_i h)\cosh(k_i h) + k_i h}$$

5. Compose all the components into the time series of the piston displacement as:

$$e(t) = \sum_{i=1}^{N} \frac{S_{0,i}}{2} \cos(\omega_i t + \delta_i)$$

In DualSPHysics:

a) JONSWAP and Pierson-Moskowitz
b) Phase seed
Wave generation and wave absorption

PISTON-type wavemaker, IRREGULAR waves, 2\textsuperscript{nd} Order BOUND LONG waves (Hughes, 1993)

Bound long waves (BLW) refer to the set-down of the water level that is generated by wave groups.
Wave generation and wave absorption

Passive wave absorption

This system can be either:

- dissipative beach

\[ v = v_0 \cdot f(x, dt) \]

\[ f(x, dt) = 1 - dt \cdot \beta \cdot \left( \frac{x - x_0}{x_1 - x_0} \right)^2 \]

applied at each time step
Wave generation and wave absorption

Active wave absorption

\[ \eta_R(t) = \eta_I(t) - \eta_{SPH}(t) \]

\[ U_R(t) = \eta_R(t) \sqrt{g/d} \]

\[ U_I(t) = \omega \frac{S_0}{2} \sin(\omega t + \delta) \]

\[ U_C(t + dt) = U_I(t) + U_R(t) \]

\[ e(t + dt) = e(t) + (U_C(t + dt) + U_C(t)) \frac{dt}{2} \]

Reflected wave at 4 * h from the piston

Velocity correction (uniform velocity field)

Theoretical wave maker velocity

Corrected wave maker velocity

Wave maker position at t + dt

(Shaffer and Klopman, 2000)
Wave generation and wave absorption (passive and active)
AWAS system in SPH models

<table>
<thead>
<tr>
<th>Regular waves ((H=0.1m; T=1.3s))</th>
<th>Time: 0.00s</th>
</tr>
</thead>
<tbody>
<tr>
<td>INCIDENT WAVE + REFLECTED WAVE + RE-REFLECTED WAVE</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Regular waves with Passive Absorption (BEACH)</th>
</tr>
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<td>INCIDENT WAVE + REFLECTED WAVE + RE-REFLECTED WAVE</td>
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</tbody>
</table>

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<tr>
<th>Regular waves with Passive Absorption (SPONGE)</th>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Regular waves with Active Absorption (AWAS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>INCIDENT WAVE + REFLECTED WAVE</td>
</tr>
</tbody>
</table>
Wave generation and wave absorption

Validation with theoretical results

<table>
<thead>
<tr>
<th></th>
<th>Wave #1</th>
<th>Wave #2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height $H$ or $H_m$</td>
<td>0.15m</td>
<td>0.10m</td>
</tr>
<tr>
<td>Period $T$ or $T_p$</td>
<td>2.00s</td>
<td>3.00s</td>
</tr>
<tr>
<td>Depth $d$</td>
<td>0.66m</td>
<td>1.50m</td>
</tr>
<tr>
<td>Steepness $s$</td>
<td>0.033</td>
<td>0.010</td>
</tr>
<tr>
<td>Wavelength $L$</td>
<td>4.52m</td>
<td>10.22m</td>
</tr>
</tbody>
</table>

Wave gauges (WG) x=6.0, 6.5, 7.1m x=13.0, 14.0, 15.5m
Velocity gauge (VG) x=6.5m ; z=0.4m x=14m ; z=1m
Domain length (LX) 11m 26m
Test duration ($t_{max}$) 35s 50s
Wave generation and wave absorption

Validation with theoretical results: WAVE GENERATION

Wave #1
Wave generation and wave absorption

Validation with theoretical results: WAVE GENERATION

Wave #1
Wave generation and wave absorption

Validation with theoretical results: WAVE GENERATION
Wave generation and wave absorption

Validation with theoretical results: PASSIVE ABSORPTION
Wave generation and wave absorption

Validation with theoretical results: PASSIVE ABSORPTION

Wave #1

<table>
<thead>
<tr>
<th>Cr</th>
<th>Wave #1</th>
<th>Wave #2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Regular</td>
<td>Irregular</td>
</tr>
<tr>
<td>BEACH</td>
<td>11.4%</td>
<td>8.5%</td>
</tr>
<tr>
<td>DAMPING</td>
<td>12.2%</td>
<td>8.6%</td>
</tr>
</tbody>
</table>
Wave generation and wave absorption

Validation with theoretical results: ACTIVE ABSORPTION
Wave generation and wave absorption

Efficiency

![Wave #1 Efficiency Chart](image1)
![Wave #2 Efficiency Chart](image2)
Wave generation and wave absorption

Wave generation and wave absorption (passive and active)
AWAS system in SPH models

Regular waves
H=0.1m, T=1.3s

Time: 0.00 s

WE NEED PASSIVE AND ACTIVE ABSORPTION TO MIMIC THE REAL SEA STATE CONDITIONS
Coastal protection

Study of the run-up in an existing armour block sea breakwater

DETAILED DESCRIPTION OF THE FLOWS !!!

Zeebrugge reference geometry (Belgium)

The size of the numerical simulation depends on the initial inter-particle distance

\[ dp = 0.15 \text{ m} \Rightarrow h = 0.225 \text{ m} \]

The SPH domain contains \(2,146,095\) particles with \(187,353\) representing the boundaries.
Coastal protection

Study of the run-up in an existing armour block sea breakwater

- Equivalent Smooth
- Antifers Irregular Pattern
- Antifers Regular 1 Pattern
- Antifers Regular 2 Pattern

Time: 28.5 s
Coastal protection

Study of the run-up in an existing armour block sea breakwater

Time: 0 s
Coastal protection

Study of the run-up in an existing armour block sea breakwater

Measurement system: IN THE FIELD

NUMERICALLY
Coastal protection

Study of the run-up in an existing armour block sea breakwater

Comparison with experimental results

$Ru^n = Ru/H$
Coastal protection
Coastal protection

Estimation of sea wave impact on coastal structures

Assessment of wave loadings on the dikes and storm return walls in the Blankenberge Marina

\[ H_{m0} = 0.101 \text{m} \]
\[ T_p = 2.683 \text{s} \]
Coastal protection

Wavemaker displacement without and with Active Absorption

Comparison between numerical and experimental wave forces

DualSPHysics has been also used as assessment tool for consultancy!!!

CLIENT: Coastal Division of the Flemish Gov.
Coupling with SWASH

Impacts of wave overtopping flows on coastal defenses and buildings along the Flemish coast
Coupling with SWASH

Large domains

Multi-scaled modeling

Long events
Coupling with SWASH

- +8.38m TAW
  Level of seaward edge of dike
- +6.70m TAW
  Eroded level of foreshore at dike

DualSPHysics  overlap  SWASH
Coupling with SWASH

Using the experimental water surface elevation signal

**SWASH**

Multi-layered approach to get velocity distribution in time

\[ \eta_{EFX}(x,t) \]

**Coupling Point**

**Velocity data**

**DualSPHysics**

SWASH velocity is converted into the displacement of the Moving Boundary
Coupling with SWASH

[Sketch of the CIEM wave flume and locations of AWGs, ADVs and selected Coupling Points (CP)]

<table>
<thead>
<tr>
<th>Test case</th>
<th>$H_{target}$ [m]</th>
<th>$T_{target}$ [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.2</td>
<td>5.5</td>
</tr>
<tr>
<td>B</td>
<td>0.2</td>
<td>3.0</td>
</tr>
<tr>
<td>C</td>
<td>0.3</td>
<td>5.5</td>
</tr>
<tr>
<td>D</td>
<td>0.3</td>
<td>3.0</td>
</tr>
</tbody>
</table>
Coupling with SWASH

AWG free surface elevation: comparison between **numerical** and **physical** results (CP1, test case B)
Coupling with SWASH

Horizontal and vertical velocity profiles (experimental in blue, numerical in red): mean values and confidence intervals (CP1, test case D).
Coupling with SWASH

Improvements in time with different hybridisation points (domain sizes and runtimes)

<table>
<thead>
<tr>
<th></th>
<th>WP</th>
<th>CP1</th>
<th>CP2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DualSPHysics domain size</strong></td>
<td>100%</td>
<td>78.42%</td>
<td>56.90%</td>
</tr>
<tr>
<td><strong>Number of Particles</strong></td>
<td>100%</td>
<td>62.89%</td>
<td>26.89%</td>
</tr>
<tr>
<td><strong>Runtime</strong></td>
<td>100%</td>
<td>70.49%</td>
<td>40.98%</td>
</tr>
</tbody>
</table>
Coupling with SWASH

Source Generation (under development)
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Wave interaction with floating bodies
Wave interaction with floating bodies

Floating body subjected to a wave packet is validated with experimental data

Hǎdzić et al., 2015
Wave interaction with floating bodies

Floating body subjected to a wave packet is validated with experimental data

Hǎdzić et al., 2015
Wave interaction with floating bodies

Flap wavemaker

Surface elevation at $x=1.16\text{m}$

Surface elevation at $x=2.66\text{m}$
Wave interaction with floating bodies

**Sway motion**

- Experiment
- DualSPHysics

**Heave motion**

- Experiment
- DualSPHysics
Floating moored objects

These objects are floating in the water and moored, thus a proper formulation is needed and must be validated.
Floating moored objects

The **catenary function** refers to the mathematical description of a line with mass hanging between two points.

\[ y = \xi \cosh \left( \frac{x}{\xi} \right) \]

\(\xi\) is the form parameter

The maths from the work of Faltinsen (1993) is behind this implementation.
Floating moored objects

FOUR different conditions for moorings are considered: the resting chain, partially resting chain, partially extended chain and the fully extended chain.

(a) 
(b) 
(c) 
(d)
Floating moored objects

Validation with experimental data from Johanning et al (2006; 2007)
Floating moored objects

Validation with experimental data from Johanning et al (2006; 2007)
Floating moored objects
Floating moored objects

Wave-maker

Floating Wind Turbine

22 m
20 m
38 m

30 m
75 m

4.7 m
1 m
2.5 m
2 m
4 m
10.2 m

4 m
4 m
Floating moored objects
Floating moored objects

WE ARE NOW VALIDATION MOORINGS WITH MORE EXPERIMENTS
Design of Oscillating Water Column
Hydrodynamic interaction between WECs and ocean waves is a complex high order non-linear process.
EXPERIMENT IN IH-CANTABRIA

The experiment (scale of 1/30) was carried out in the IH-Cantabria: Laboratory wave flume (left) and chamber model (right).

EXPERIMENT IN IH-CANTABRIA

The experiment (scale of 1/30) was carried out in the IH-Cantabria wave flume. The tank is 20.60 m long and the water depth was of 0.60 m. A dissipative beach appeared at the end of the flume to avoid reflection.

Wave conditions of the experiments in Iturrioz et al. (2014)

<table>
<thead>
<tr>
<th>Height (H)</th>
<th>Period (T)</th>
<th>Depth (d)</th>
<th>Wavelength (L)</th>
<th>Relative depth (d/L)</th>
<th>Wave order</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.08 m</td>
<td>3.2 s</td>
<td>0.6 m</td>
<td>7.46 m</td>
<td>0.08</td>
<td>Stokes 2nd order</td>
</tr>
</tbody>
</table>

EXPERIMENT IN IH-CANTABRIA

Experiment from Iturrioz et al. 2014
Regular waves: H=0.08m ; T=3.2s

Time: 0 s
Design of OWC

EXPERIMENT IN IH-CANTABRIA

2\textsuperscript{nd} order: T=3.2s, H=0.08m, d=0.6m, L=7.46 m

Elevation inside the chamber:

Experiment vs Time-domain vs IHFoam vs DualSPHysics
Design of OWC

ONSHORE OWC IN MUTRIKU (SPAIN)
Design of OWC

ONSHORE OWC IN MUTRIKU (SPAIN)

Cross section of Mutriku breakwater

OWC CHAMBER  BREAKWATER
Design of OWC

ONSHORE OWC IN MUTRIKU (SPAIN)

Cross section of Mutriku breakwater
Design of OWC

ONSHORE OWC IN MUTRIKU (SPAIN)

Real dimensions for DualSPHysics simulation
ONSHORE OWC IN MUTRIKU (SPAIN)

Real dimensions for DualSPHysics simulation

Realistic wave conditions in the Cantábrico coast

<table>
<thead>
<tr>
<th>Test</th>
<th>Height (H)</th>
<th>Period (T)</th>
<th>Depth (d)</th>
<th>Wavelength (L)</th>
<th>Relative d (d/L)</th>
<th>Wave theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>0.8 m</td>
<td>10 s</td>
<td>10 m</td>
<td>92.4 m</td>
<td>0.108</td>
<td>Stokes, 2nd order</td>
</tr>
<tr>
<td>M2</td>
<td>1.2 m</td>
<td>10 s</td>
<td>10 m</td>
<td>92.4 m</td>
<td>0.108</td>
<td>Stokes, 2nd order</td>
</tr>
<tr>
<td>M3</td>
<td>1.6 m</td>
<td>10 s</td>
<td>10 m</td>
<td>92.4 m</td>
<td>0.108</td>
<td>Stokes, 2nd order</td>
</tr>
<tr>
<td>M4</td>
<td>2.0 m</td>
<td>10 s</td>
<td>10 m</td>
<td>92.4 m</td>
<td>0.108</td>
<td>Stokes, 2nd order</td>
</tr>
<tr>
<td>M5</td>
<td>2.4 m</td>
<td>10 s</td>
<td>10 m</td>
<td>92.4 m</td>
<td>0.108</td>
<td>Stokes, 2nd order</td>
</tr>
<tr>
<td>M6</td>
<td>0.8 m</td>
<td>8 s</td>
<td>10 m</td>
<td>70.9 m</td>
<td>0.141</td>
<td>Stokes, 2nd order</td>
</tr>
<tr>
<td>M7</td>
<td>0.8 m</td>
<td>8.5 s</td>
<td>10 m</td>
<td>76.4 m</td>
<td>0.131</td>
<td>Stokes, 2nd order</td>
</tr>
<tr>
<td>M8</td>
<td>0.8 m</td>
<td>9 s</td>
<td>10 m</td>
<td>81.7 m</td>
<td>0.122</td>
<td>Stokes, 2nd order</td>
</tr>
<tr>
<td>M9</td>
<td>0.8 m</td>
<td>9.5 s</td>
<td>10 m</td>
<td>87.1 m</td>
<td>0.115</td>
<td>Stokes, 2nd order</td>
</tr>
<tr>
<td>M1</td>
<td>0.8 m</td>
<td>10 s</td>
<td>10 m</td>
<td>92.4 m</td>
<td>0.108</td>
<td>Stokes, 2nd order</td>
</tr>
<tr>
<td>M10</td>
<td>0.8 m</td>
<td>10 s</td>
<td>7.75 m</td>
<td>82.7 m</td>
<td>0.094</td>
<td>Stokes, 2nd order</td>
</tr>
<tr>
<td>M11</td>
<td>0.8 m</td>
<td>10 s</td>
<td>8.88 m</td>
<td>87.8 m</td>
<td>0.101</td>
<td>Stokes, 2nd order</td>
</tr>
<tr>
<td>M1</td>
<td>0.8 m</td>
<td>10 s</td>
<td>10 m</td>
<td>92.4 m</td>
<td>0.108</td>
<td>Stokes, 2nd order</td>
</tr>
<tr>
<td>M12</td>
<td>0.8 m</td>
<td>10 s</td>
<td>11.12 m</td>
<td>96.6 m</td>
<td>0.115</td>
<td>Stokes, 2nd order</td>
</tr>
<tr>
<td>M13</td>
<td>0.8 m</td>
<td>10 s</td>
<td>12.25 m</td>
<td>100.6 m</td>
<td>0.122</td>
<td>Stokes, 2nd order</td>
</tr>
</tbody>
</table>
Design of OWC

ONSHORE OWC IN MUTRIKU (SPAIN)

WAVE PROPAGATION??  Test M5: H=2.4m T=10s in a long tank of constant depth

Elevation and orbital velocity: Theoretical vs DualSPHysics
Design of OWC

ONSHORE OWC IN MUTRIKU (SPAIN)

ACTIVE ABSORPTION??

Test M5: H=2.4m T=10s

Wave Surface Elevation at OWC Chamber

Wave Surface Elevation at x=115m

OWC chamber

AWAS

x=115m
Design of OWC

ONSHORE OWC IN MUTRIKU (SPAIN)

Regular waves: $H=0.8\text{m} \ ; \ T=10\text{s}$
Active Wave Absorption System

Time: 24 s
Design of OWC

ONSHORE OWC IN MUTRIKU (SPAIN)

T with different H
H=0.8m T=10s
H=1.6m T=10s
H=2.4m T=10s

H with different T
H=0.8m T=8s
H=0.8m T=10s
H=0.8m T=12s

Different tides
H=0.8m T=10s
H=0.8m T=10s low
H=0.8m T=10s high

Elevation inside the Mutriku chamber
Design of OWC

ONSHORE OWC IN MUTRIKU (SPAIN)

Maximum amplitudes of the free-surface elevations inside the OWC chamber of Mutriku for different wave conditions.
NEW SPH FUNCTIONALITIES

- Wave generation (1\textsuperscript{st} & 2\textsuperscript{nd} order)

- Wave active absorption AWAS

- Fluid-driven objects

- Mooring lines
OFFSHORE FLOATING OWC IN THE OPEN SEA

The simulation of a floating OWC in open sea with SPH includes:
- Wave generation of regular waves with T=9s & H=1.8m.
- Passive wave absorption at the end of the tank with dissipative beach.
- AWAS system to generate a regular train that interacts with floating OWC
- Forces of catenary moorings are added to the total force of the floating structure
The simulation of a floating OWC in open sea with SPH includes:
- Wave generation of regular waves with $T=9s$ & $H=1.8m$.
- Passive wave absorption at the end of the tank with dissipative beach.
- AWAS system to generate a regular train that interacts with floating OWC
- Forces of catenary moorings are added to the total force of the floating structure
Design of OWC

OFFSHORE FLOATING OWC IN THE OPEN SEA

Elevation inside the floating OWC chamber
OFFSHORE FLOATING OWC IN THE OPEN SEA

Time histories of the motions of the floating OWC (surge, sway and heave motion, and roll, pitch and yaw rotation).
Design of OWC

OFFSHORE FLOATING OWC IN THE OPEN SEA

Regular waves with AWAS: T=9s, H=1.8m
Interaction with floating OWC

Time: 4.8 s
Future developments

• Source Generation in combination with SWASH

• Multiphase: air+water

• Coupling with MoorDyn [http://www.matt-hall.ca/moordyn/](http://www.matt-hall.ca/moordyn/)
Future developments

- Coupling with MoorDyn
Future developments

- Source Generation in combination with SWASH
- Multiphase: air+water
- Coupling with MoorDyn
- Coupling with Multiphysics (next talk)
Future developments

- Coupling with Multiphysics (next talk)
Thank you

Acknowledgements
• DualSPHysics team: all developers and contributors
• Special thanks to Ghent University and FHR

Website
Free open-source DualSPHysics code:
http://www.dual.sphysics.org