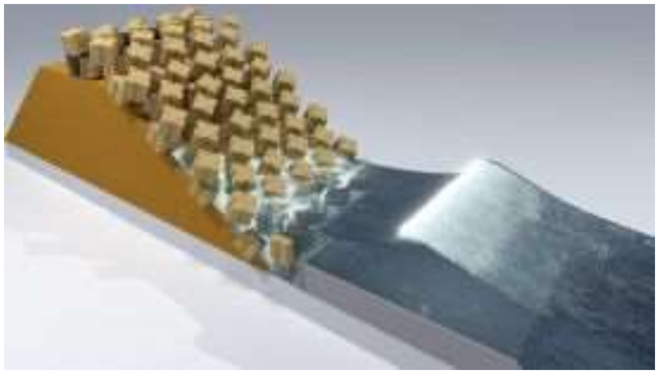
DualSPHysics:
Numerical tool in coastal engineering and marine energy



LABIMA, University of Florence, 27th September 2018

APPLICATIONS TO COASTAL ENGINEERING

Dr. Alex Crespo

<u>Dr Corrado Altomare</u>

Waterbouwkundig Laboratorium
Vlaanderen is wetenschap
GHENT UNIVERSITY

OUTLINE

Validations and applications

I. Dam break

II. Wave generation and absorption

II. Wave-structure interaction

III. Floating bodies

IV. Solid interactions

Coupling with other codes/libraries

With SWASH

With Chrono

With MoorDyn

Wave Energy Converters design

Visualisation

OUTLINE

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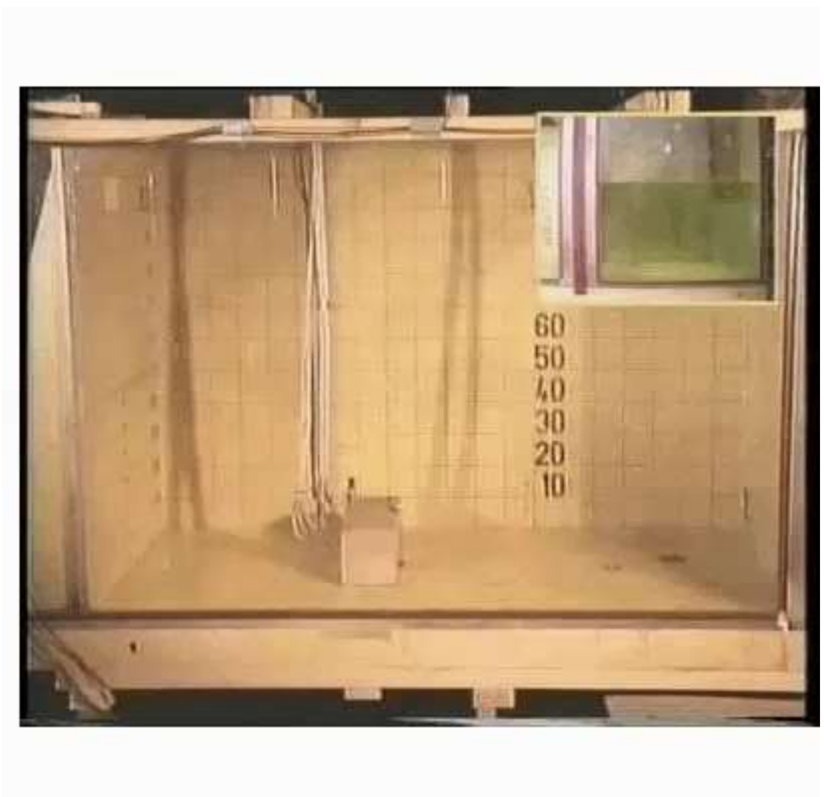
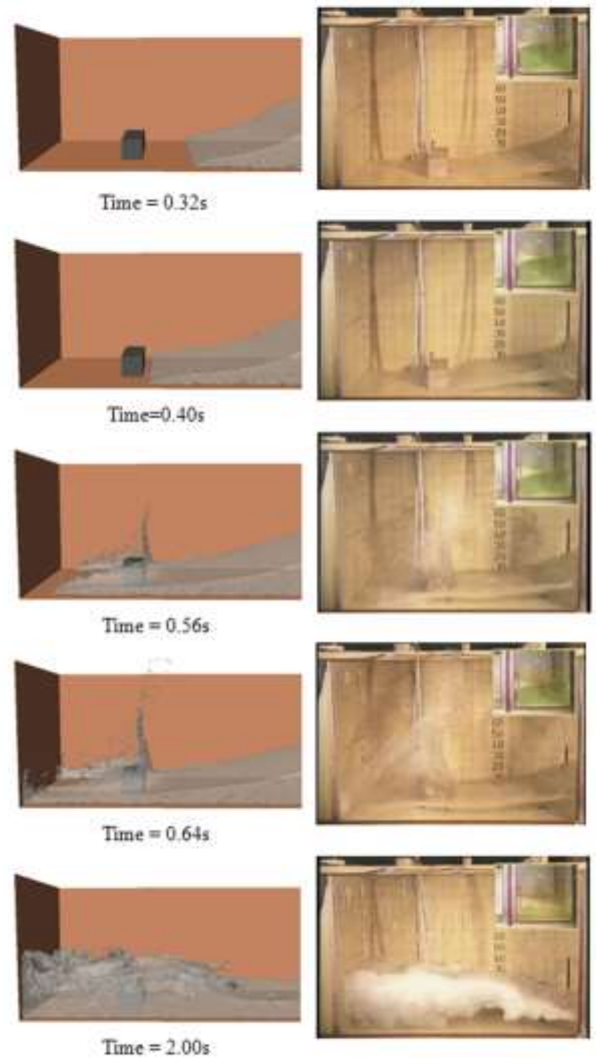
Validations and applications

Crespo et al., 2011

DAM BREAK

Evolution of the free surface SPHERIC BENCHMARK TEST CASE 2





Validations and applications

Crespo et al., 2011

DAM BREAK

Performance

Execution times and speedups with CPU and GPU when simulating one million particles for 8 seconds of physical time.


Device	Runtime	Speedup
CPU (i7 940)	5 days	--
GPU (GTX 480)	~ 2 hours	64

DualSPHysics is accurate and efficient.
Simulations of million particles can be performed in a reasonable computational runtime

The study of real-life engineering problems is possible with DualSPHysics

=> APPLICATIONS

Validations and applications

Altomare et al., 2017

WAVE GENERATION AND WAVE ABSORPTION

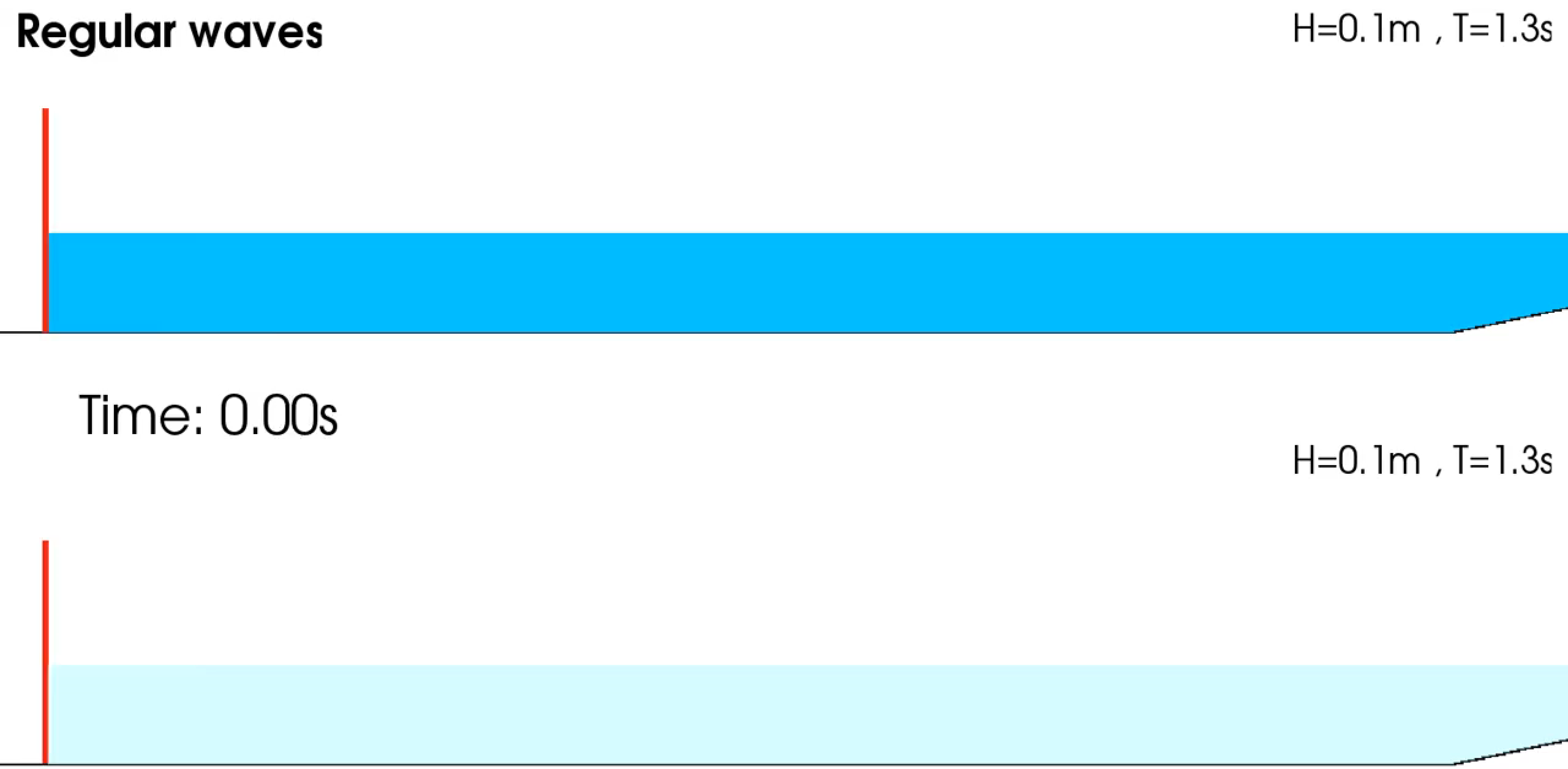
The wave generation in DualSPHysics
mimics the conditions of physical wave facilities.

- 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
- Passive absorption: dissipative beach and sponge layer
- Active wave absorption system

Validations and applications

Altomare et al., 2017

WAVE GENERATION AND WAVE ABSORPTION



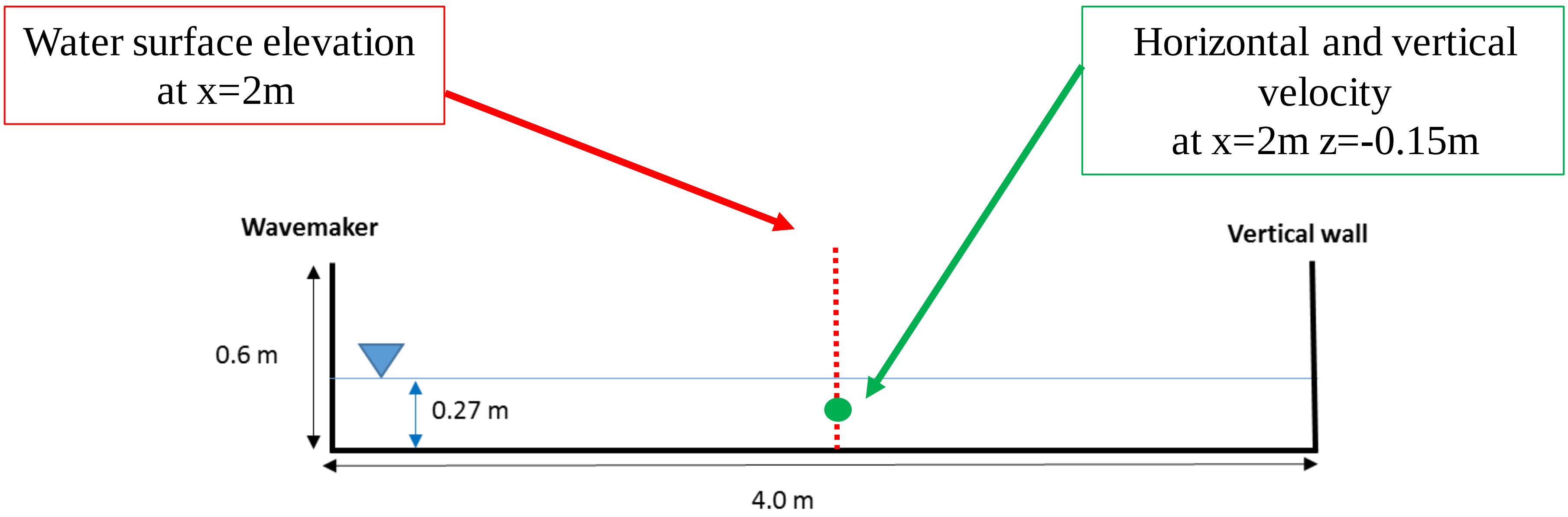
Validations and applications

Altomare et al., 2017

WAVE GENERATION AND WAVE ABSORPTION

The generated waves are:

- Regular waves: H=0.1m, T=1.3s.



Type of paddle: Piston
Movement direction: (1,0,0)
Depth: 0.266

WaveHeight: 0.1
WavePeriod: 1.3
WaveLength: 1.8774
Relative depth (d/L): 0.141685 (Transitional water)
Stroke: 0.113686

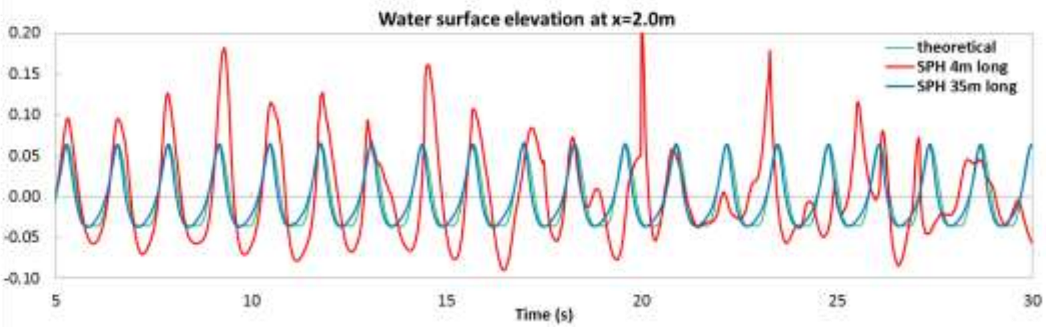
Validations and applications

Altomare et al., 2017

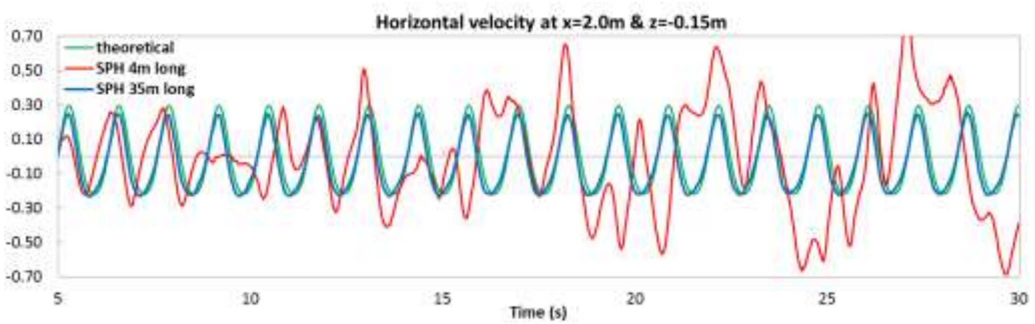
WAVE GENERATION AND WAVE ABSORPTION

Regular waves: H=0.1m, T=1.3s

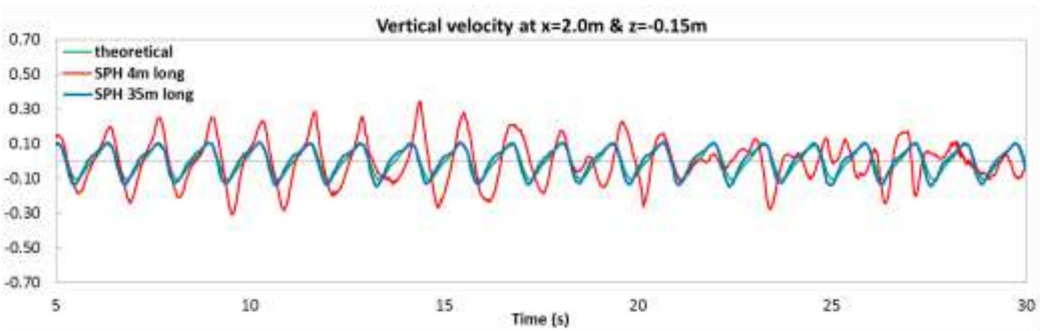
eta (m)



V_x (m/s)



V_z (m/s)



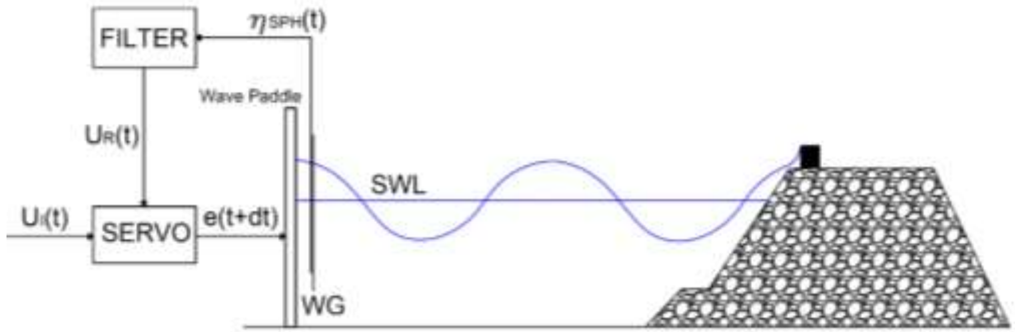
Validations and applications

Altomare et al., 2017

WAVE GENERATION AND WAVE ABSORPTION

Active Wave Absorption System

(Shaffer and Klopman , 2000)



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

Reflected wave at $\mathbf{5} * \boldsymbol{dp}$ from the piston

FILTER

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

Velocity correction (uniform velocity field)

+

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

Theoretical wave maker velocity

$$U_C(t + dt) = U_I(t) + U_R(t)$$

Corrected wave maker velocity

SERVO

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

Wave maker position at $\boldsymbol{t + dt}$

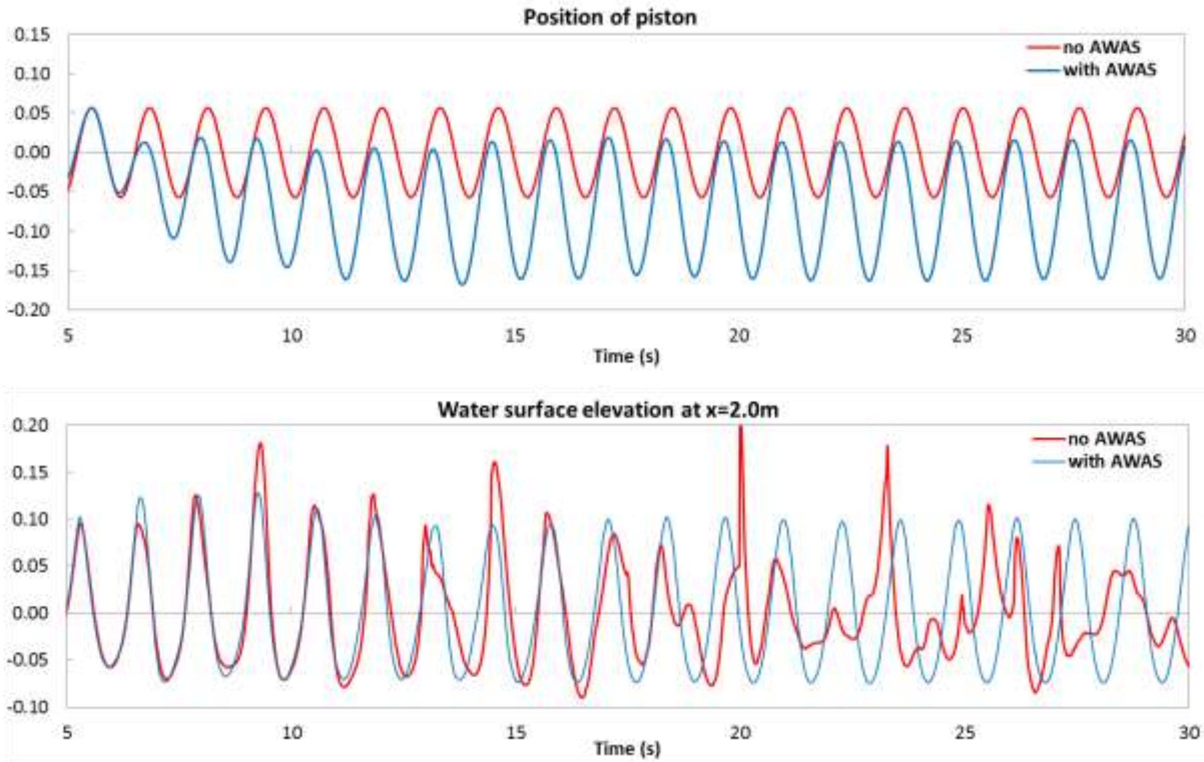
Validations and applications

Altomare et al., 2017

WAVE GENERATION AND WAVE ABSORPTION

Active Wave Absorption System

Regular waves: H=0.1m, T=1.3s

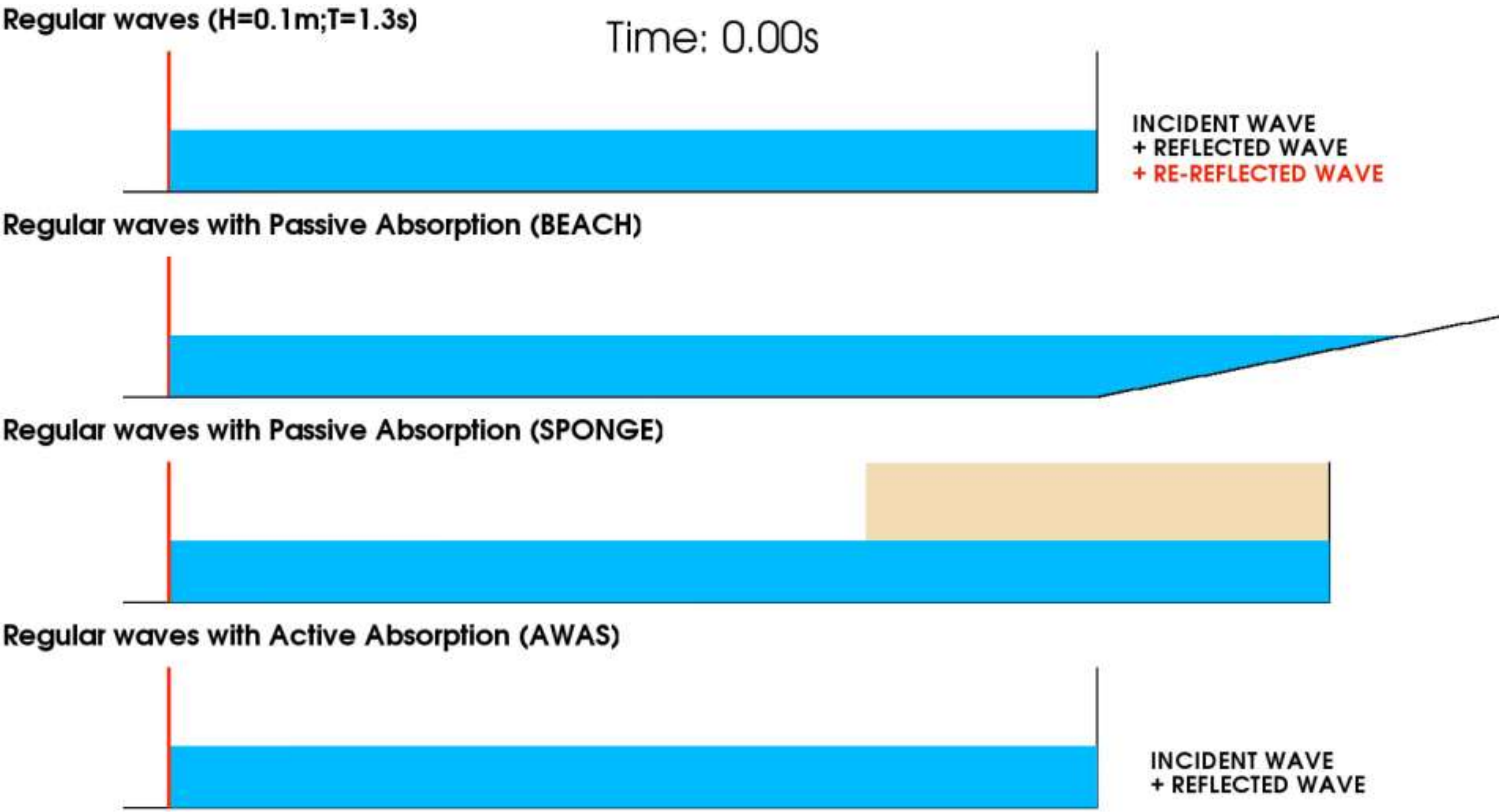


Piston position and water surface elevation for regular waves with and without AWAS.

Validations and applications

Altomare et al., 2017

WAVE GENERATION AND WAVE ABSORPTION

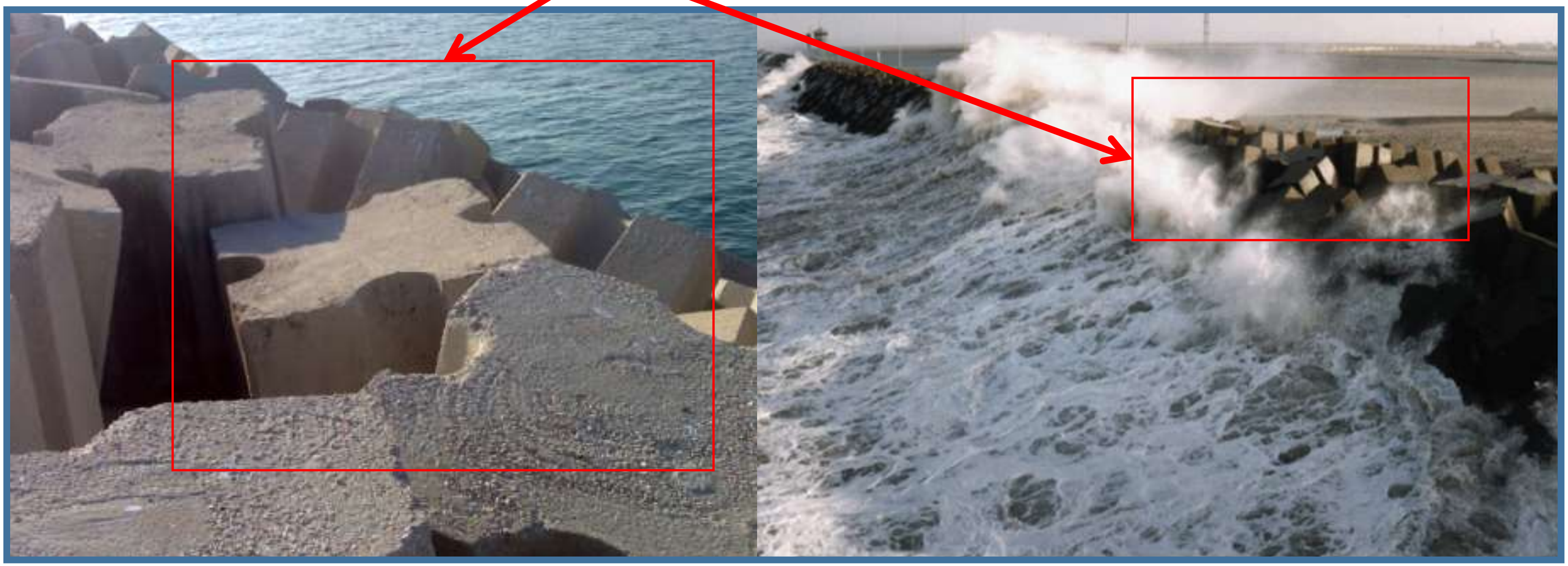


Validations and applications

Altomare et al., 2014

WAVE-STRUCTURE INTERACTION: RUN-UP

Modelling the roughness of a rubble mound breakwater (Zeebrugge)



Represents resilience of the structure against wave run-up and overtopping events

Validations and applications

Altomare et al., 2014

WAVE-STRUCTURE INTERACTION: RUN-UP

DETAILED DESCRIPTION OF THE FLOWS !!!

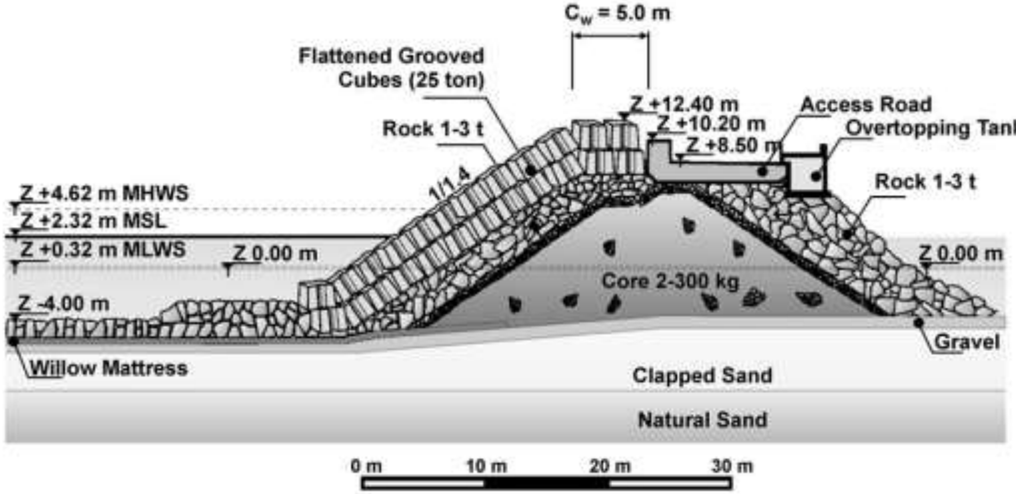
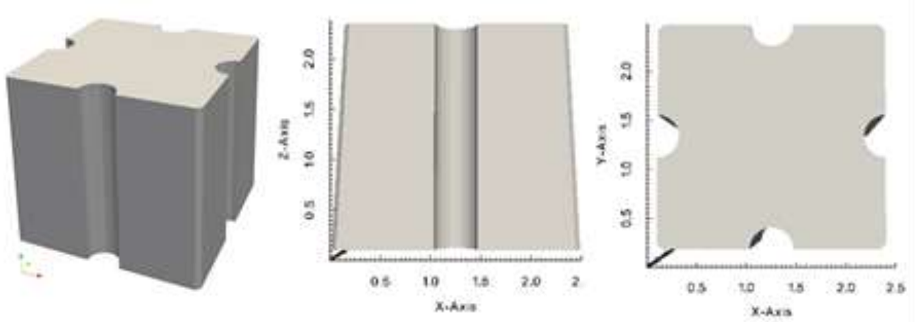


Fig. 2. Cross section of the Zeebrugge rubble mound breakwater at the location of the wave overtopping tank.

Zeebrugge reference geometry (Belgium)



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

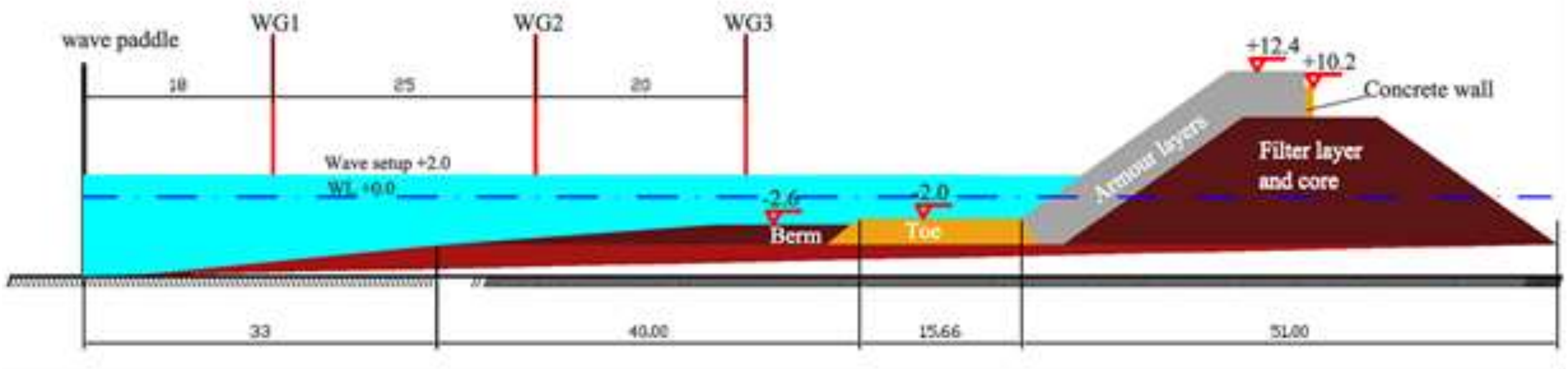
dp = 0.15 m => h = 0.225 m

The SPH domain contains **2,146,095 particles** with 187,353 representing the boundaries

Validations and applications

Altomare et al., 2014

WAVE-STRUCTURE INTERACTION: RUN-UP



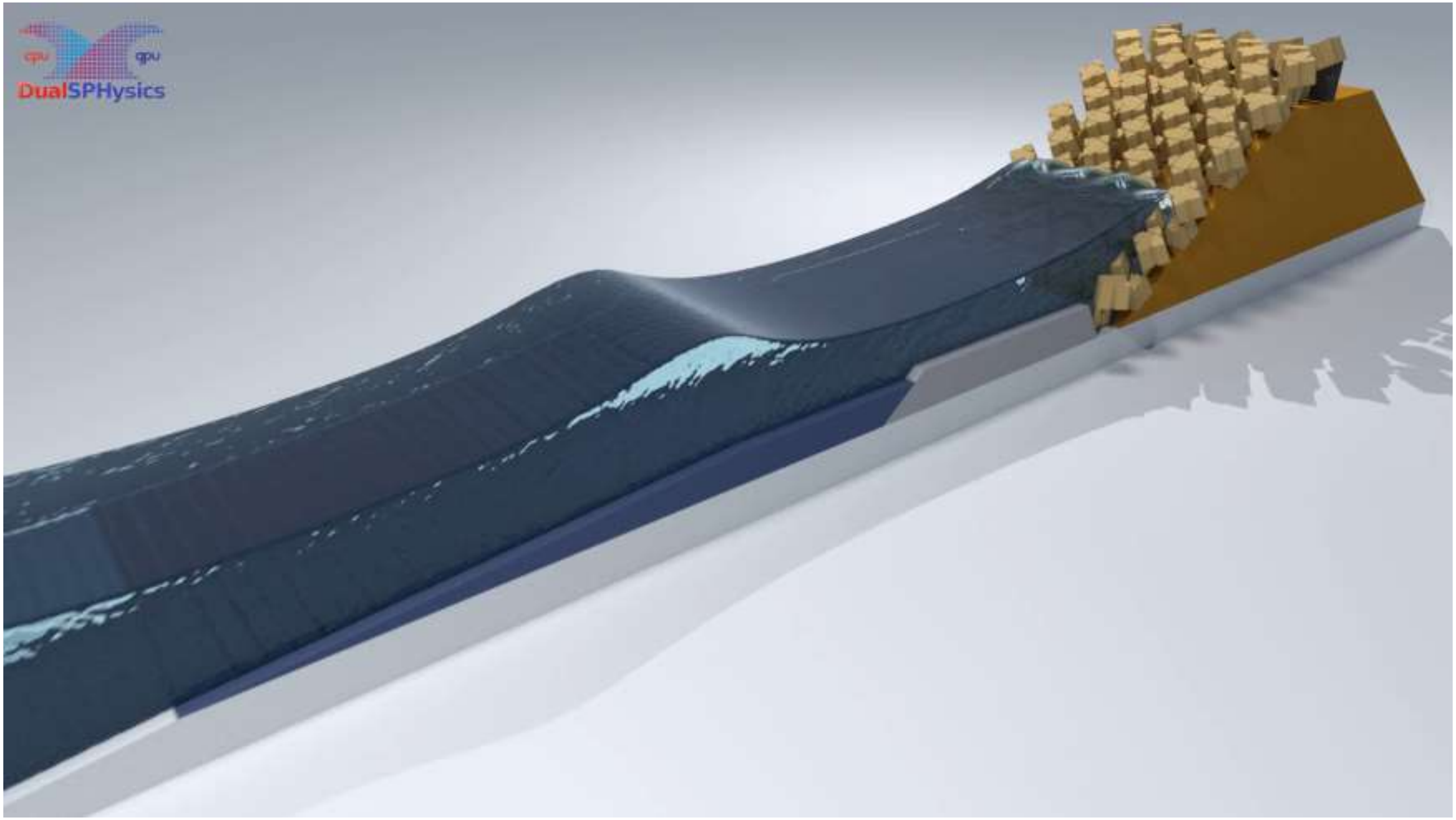
We use SPH to:

- **create the initial condition with real dimensions**
- **measure the water surface elevation at WG1, WG2, WG3**
- **compute run-up on the armour layer**

Validations and applications

Altomare et al., 2014

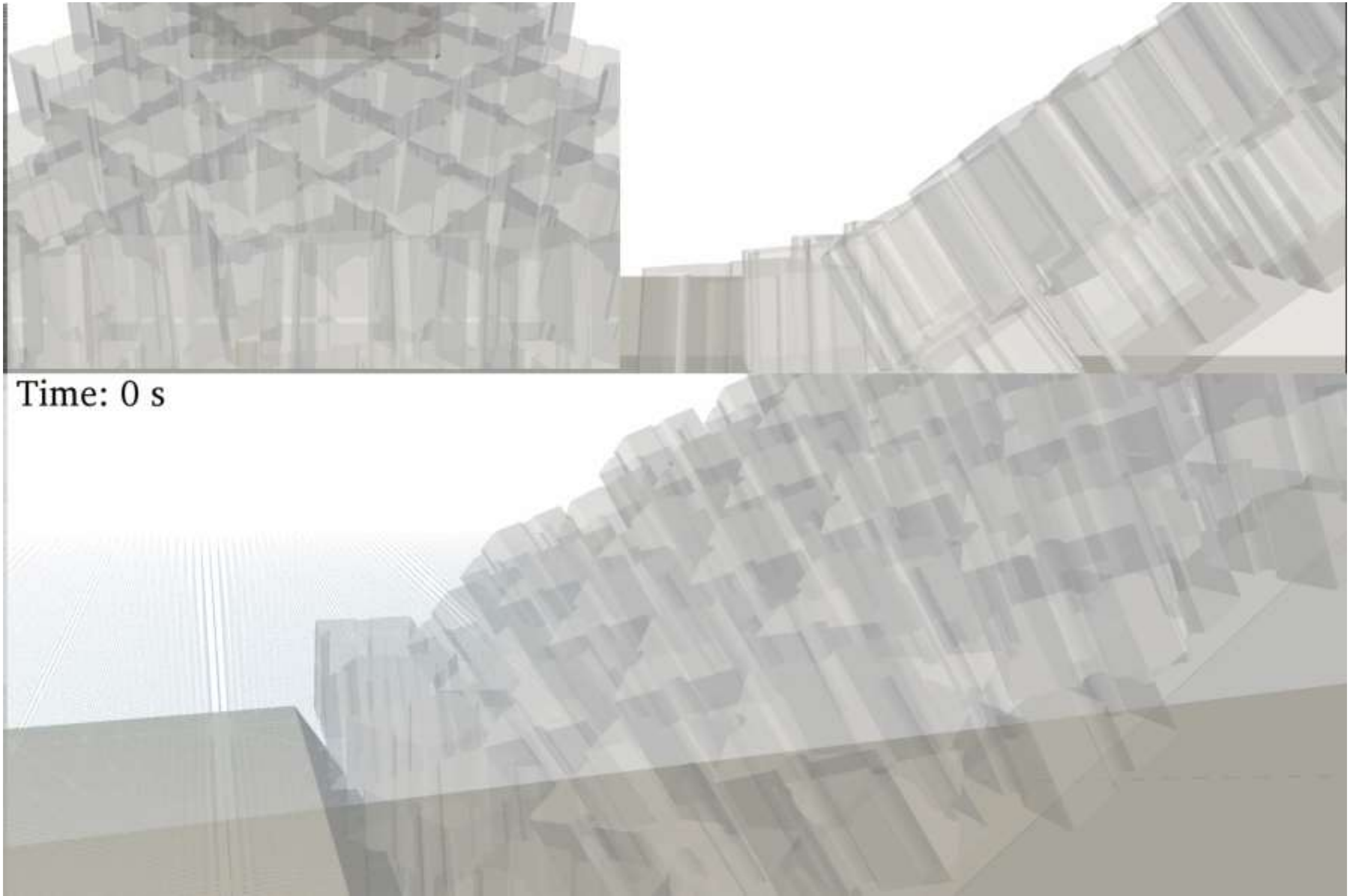
WAVE-STRUCTURE INTERACTION: RUN-UP



Validations and applications

Altomare et al., 2014

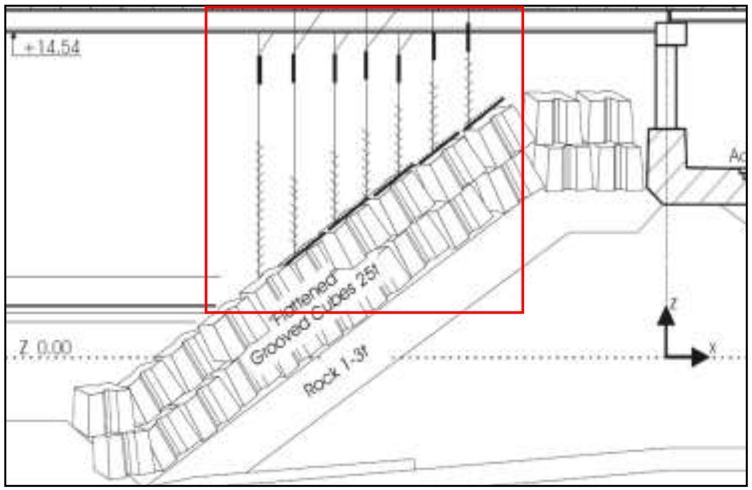
WAVE-STRUCTURE INTERACTION: RUN-UP



Validations and applications

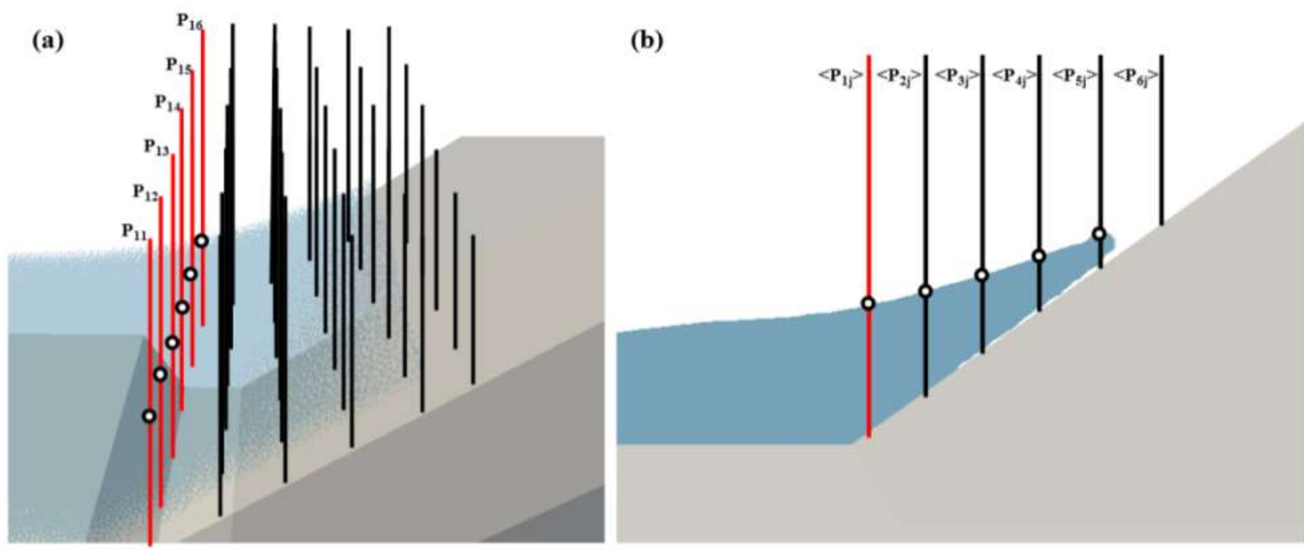
Altomare et al., 2014

WAVE-STRUCTURE INTERACTION: RUN-UP



Measurement system:
IN THE FIELD

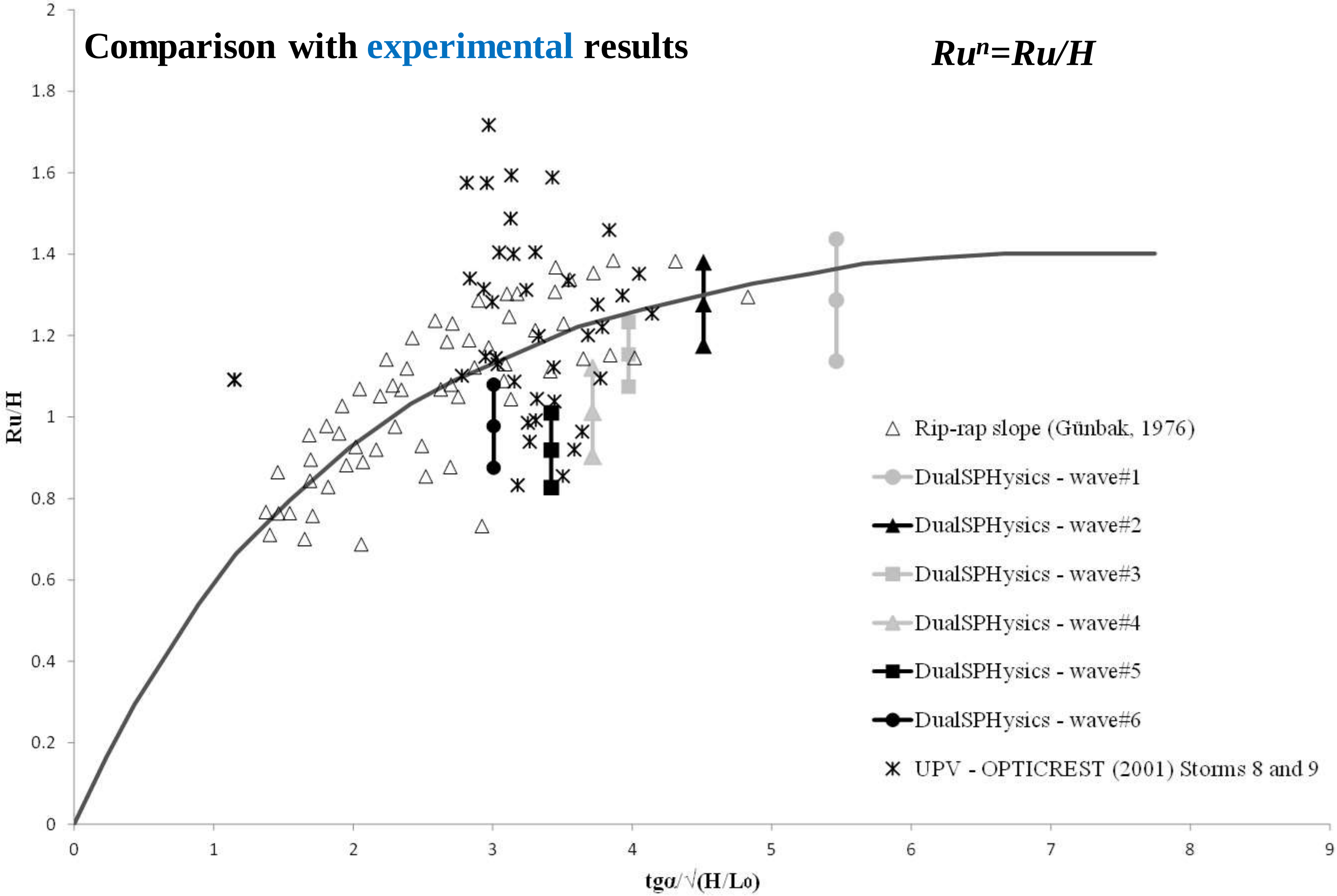
NUMERICALLY



Validations and applications

Altomare et al., 2014

WAVE-STRUCTURE INTERACTION: RUN-UP



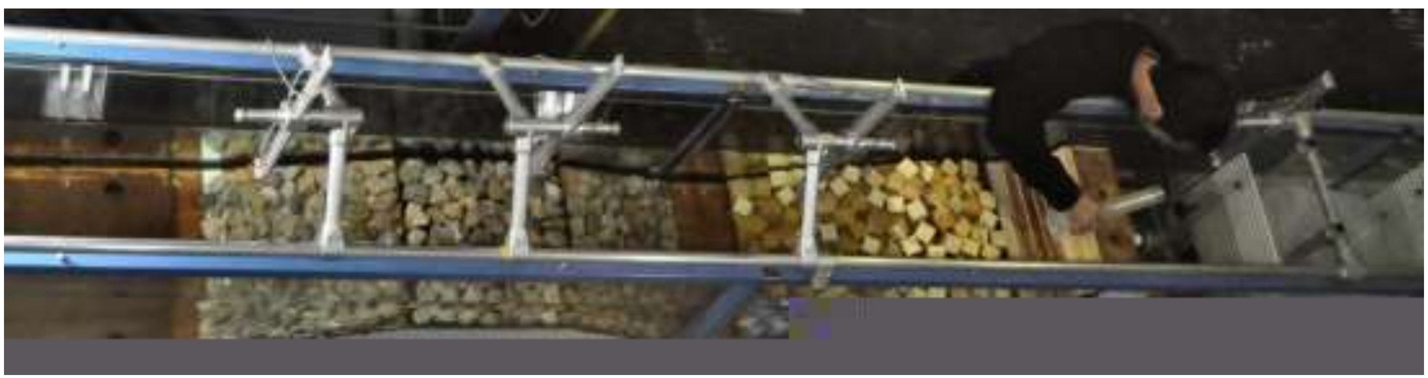
Validations and applications

Zhang et al., 2017

WAVE-STRUCTURE INTERACTION: RUN-UP

DualSPHysics was validated using maximum Ru^n=Ru/H

But also using TIME SERIES of Run-up!!!



Experiments performed in the CIEMito wave flume at LIM-UPC (Barcelona)

Web: http://ciemlab.upc.edu/

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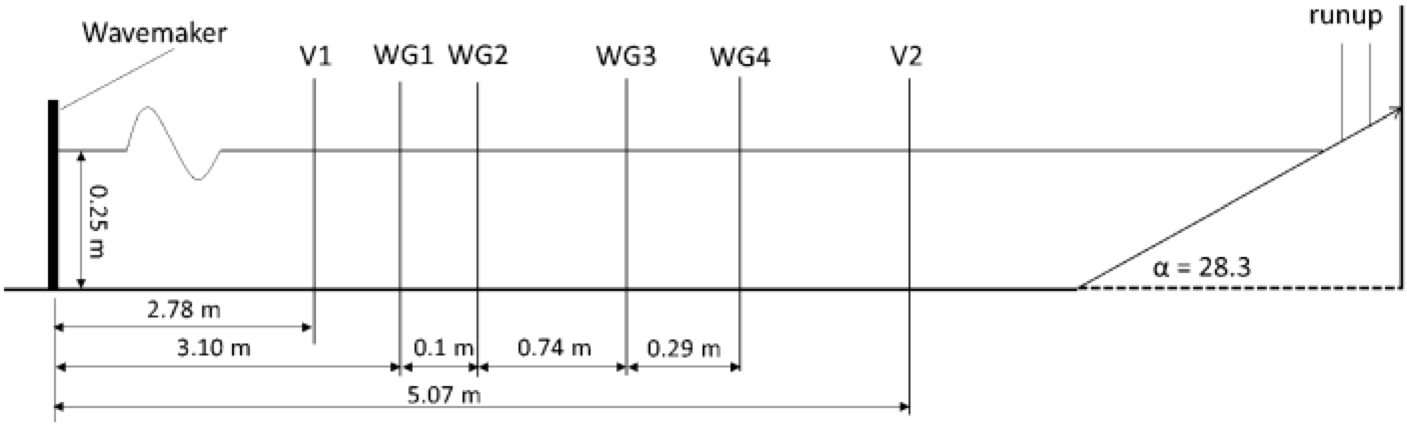
Validations and applications

Zhang et al., 2017

WAVE-STRUCTURE INTERACTION: RUN-UP

EXPERIMENTAL SETUP

SMOOTH DIKE

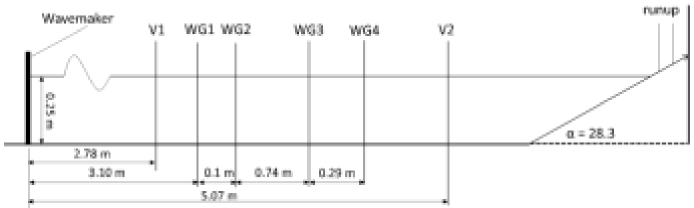


AMOUR BLOCK DIKE

Validations and applications

Zhang et al., 2017

WAVE-STRUCTURE INTERACTION: RUN-UP



SMOOTH DIKE

2-D simulation (same results as in 3D)

Initial particle distance: dp=0.008 m with h/dp=2.12
Wendland kernel with interaction distance of 2h

Total number of particles with depth=0.25 leads to 22,862 particles

Physical time to be simulated: 15 seconds

GPU computational time using GeForce GTX TITAN GPU card was 15 min

Piston motion following external file (time and x-position)

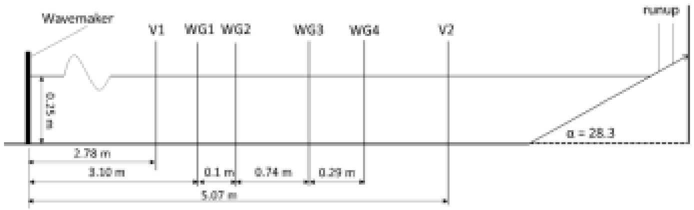
Validations and applications

Zhang et al., 2017

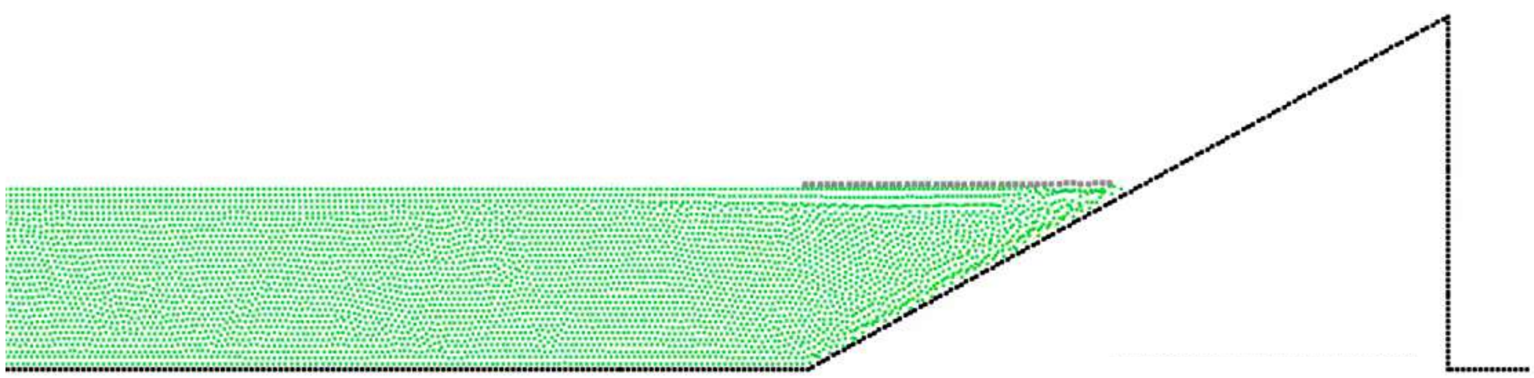
WAVE-STRUCTURE INTERACTION: RUN-UP

SMOOTH DIKE

Case#6: H=0.1 m, T=1.56 s, d=0.25 m



Time: 2.40 s



Validations and applications

Zhang et al., 2017

WAVE-STRUCTURE INTERACTION: RUN-UP

SMOOTH DIKE

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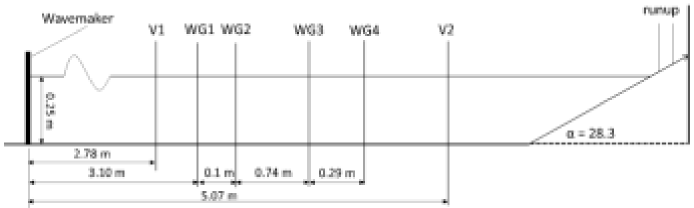

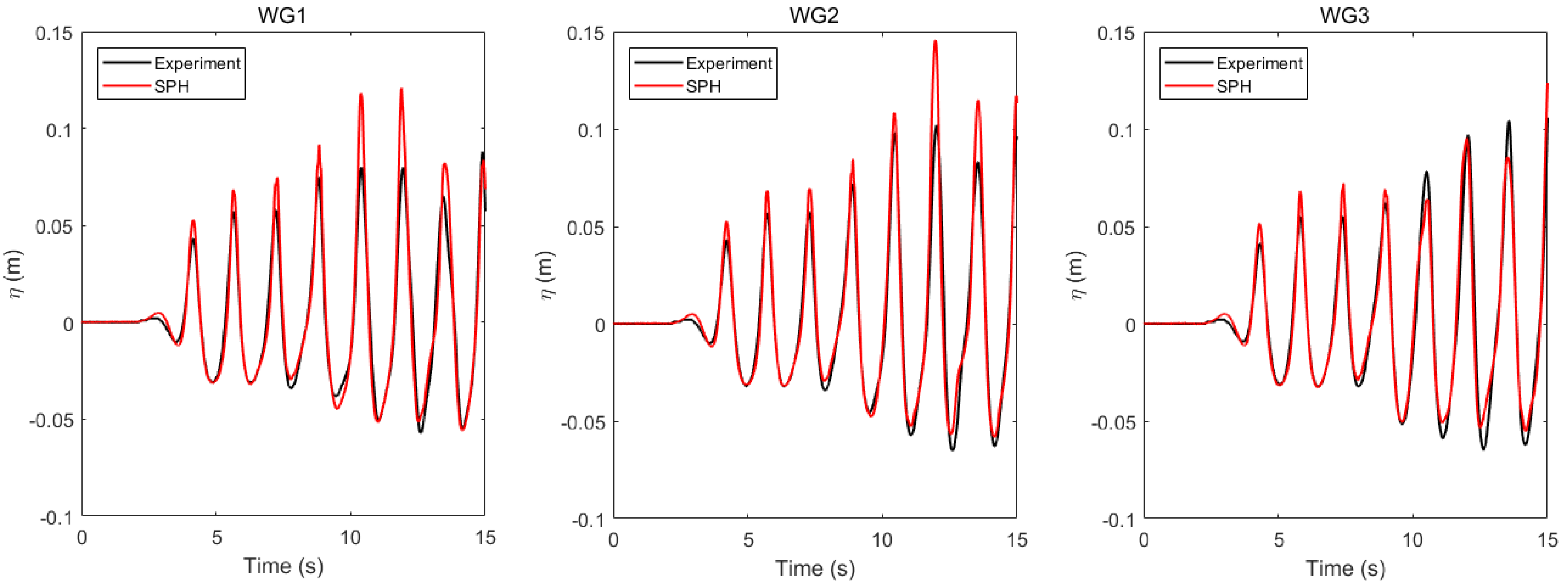

Time series of the experimental and numerical surface elevation

Validations and applications

Zhang et al., 2017

WAVE-STRUCTURE INTERACTION: RUN-UP

SMOOTH DIKE

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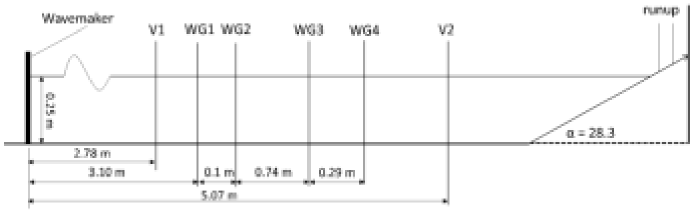
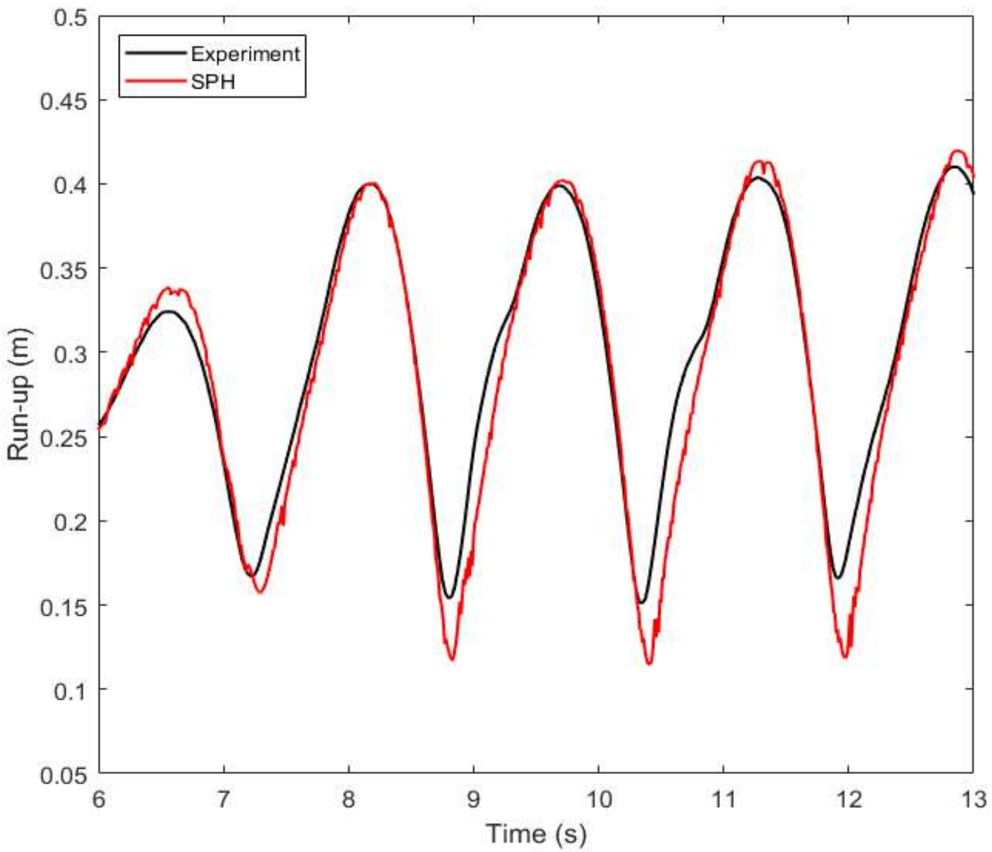




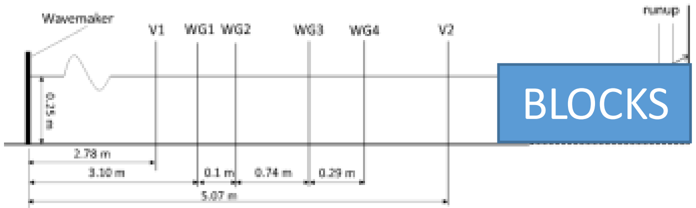
Time series of the experimental and numerical RUNUP

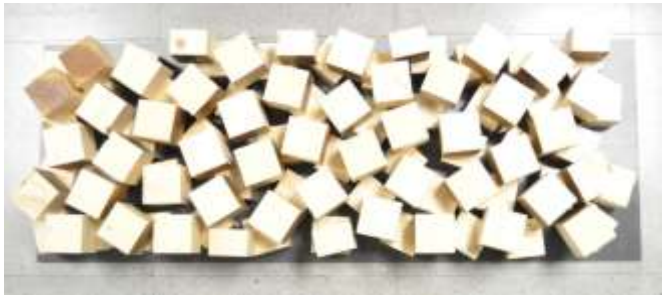
Validations and applications

Zhang et al., 2017

WAVE-STRUCTURE INTERACTION: RUN-UP

AMOUR BLOCK DIKE

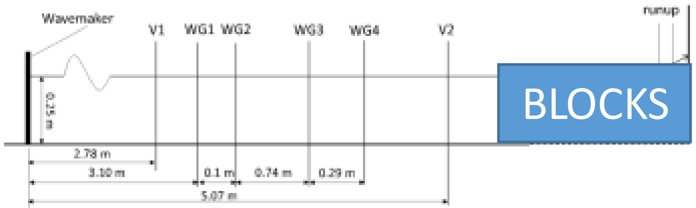




Validations and applications

Zhang et al., 2017

WAVE-STRUCTURE INTERACTION: RUN-UP



AMOUR BLOCK DIKE

Initial particle distance: dp=0.008 m with h/dp=2.6
Wendland kernel with interaction distance of 2h

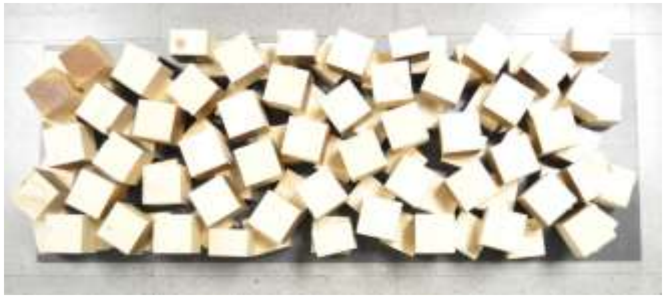
Total number of particles with depth=0.25 leads to 1,135,818

Physical time to be simulated: 15 seconds

GPU computational time using GeForce GTX TITAN GPU card was 17.5h

Piston motion following external file (time and x-position)

Exact position of the blocks in STL file



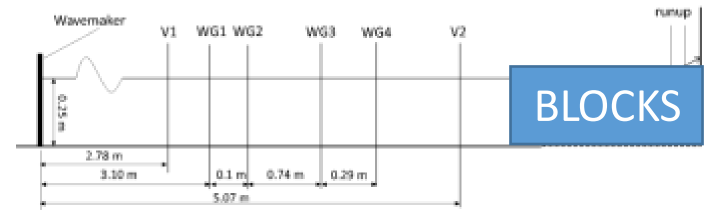
Validations and applications

Zhang et al., 2017

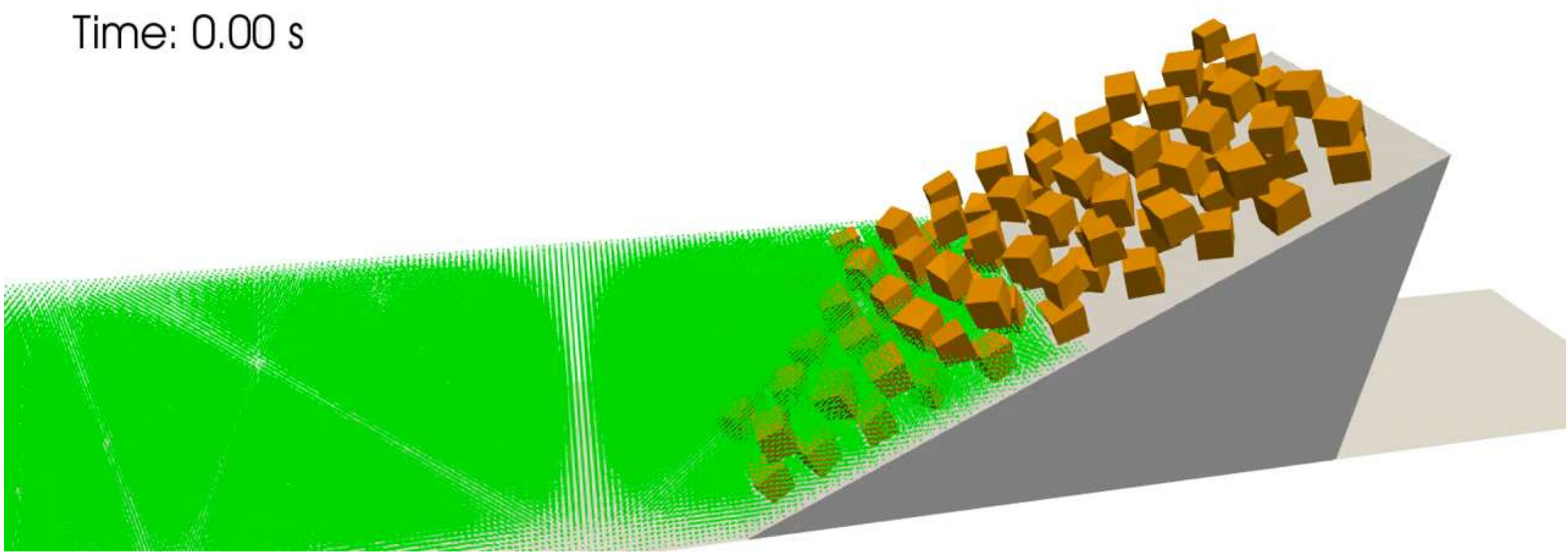
WAVE-STRUCTURE INTERACTION: RUN-UP

AMOUR BLOCK DIKE

Case#7: H=0.08 m, T=0.87 s, d=0.25 m



H=0.08 m, T=0.87 s, d=0.25 m



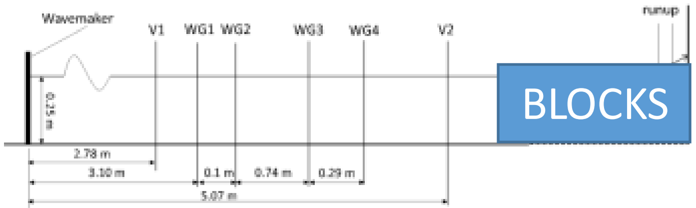
Validations and applications

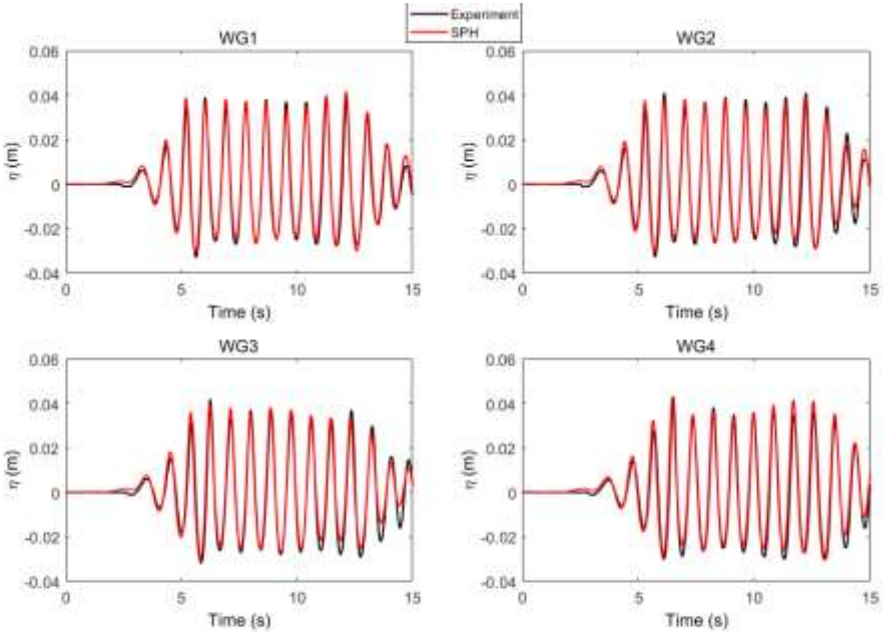
Zhang et al., 2017

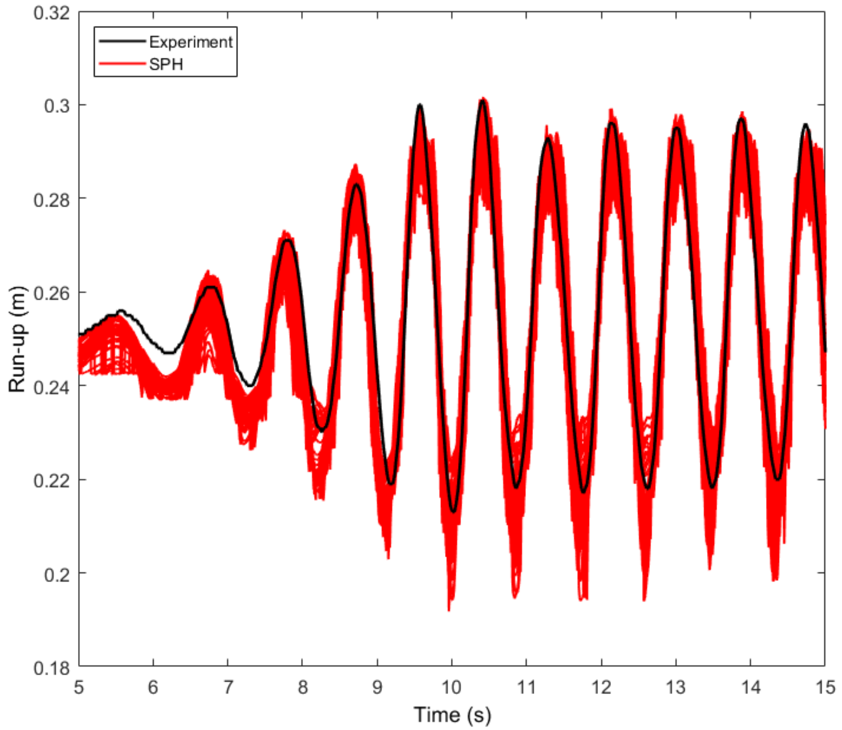
WAVE-STRUCTURE INTERACTION: RUN-UP

AMOUR BLOCK DIKE

Case#7: H=0.08 m, T=0.87 s, d=0.25 m







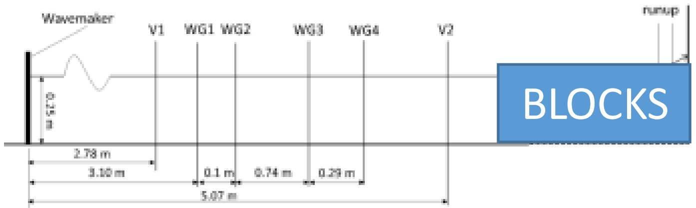
Time series of the experimental and numerical surface elevation

Time series of the experimental and numerical RUNUP

Validations and applications

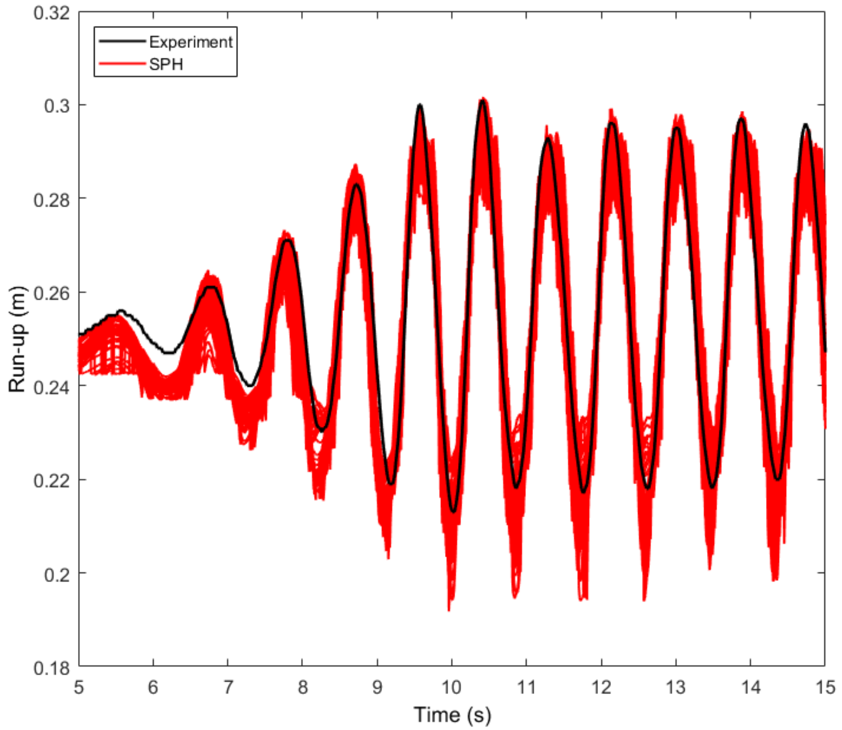
Zhang et al., 2017

WAVE-STRUCTURE INTERACTION: RUN-UP



AMOUR BLOCK DIKE

Case#7: H=0.08 m, T=0.87 s, d=0.25 m



Run-up is numerically computed at 52 positions along the width to catch the 3-D behavior

BUT only 2 positions were used in the EXP

Time series of the experimental and numerical RUNUP

Validations and applications

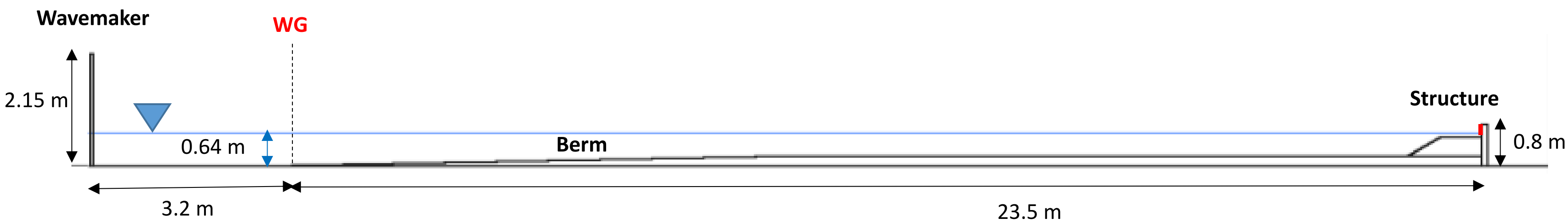
Altomare et al., 2017

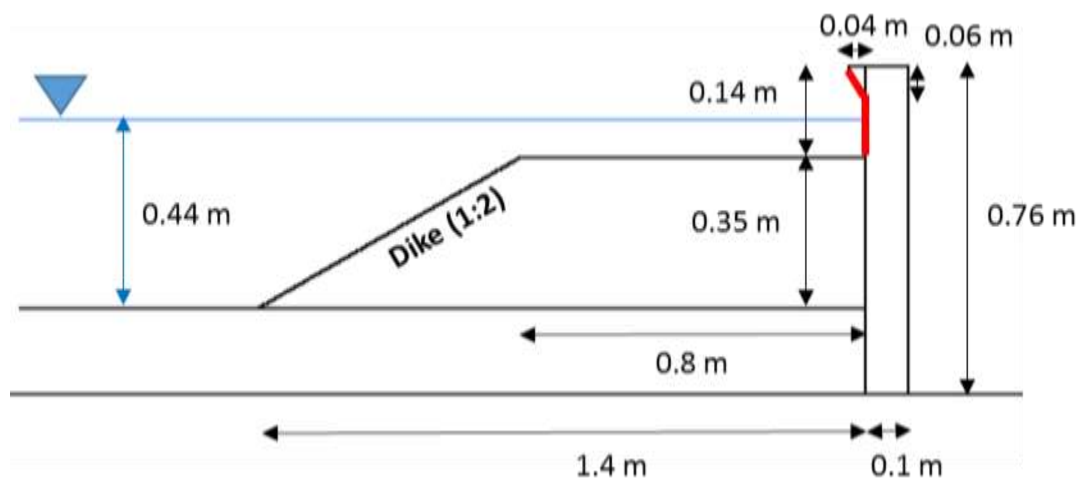
WAVE-STRUCTURE INTERACTION: FORCE

Estimation of sea wave impact on coastal structures

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

UNIVERSITEIT GENT





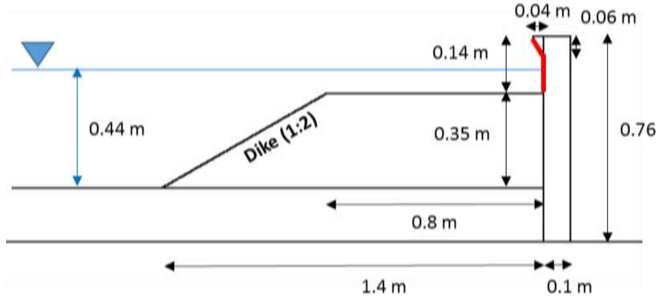
H_{m0}=0.101m

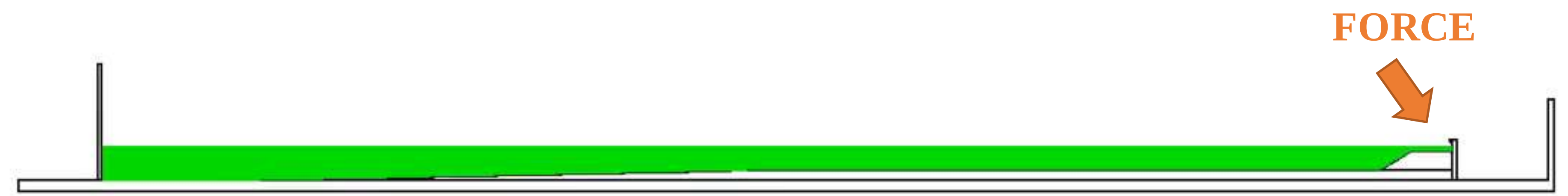
T_p=2.683s

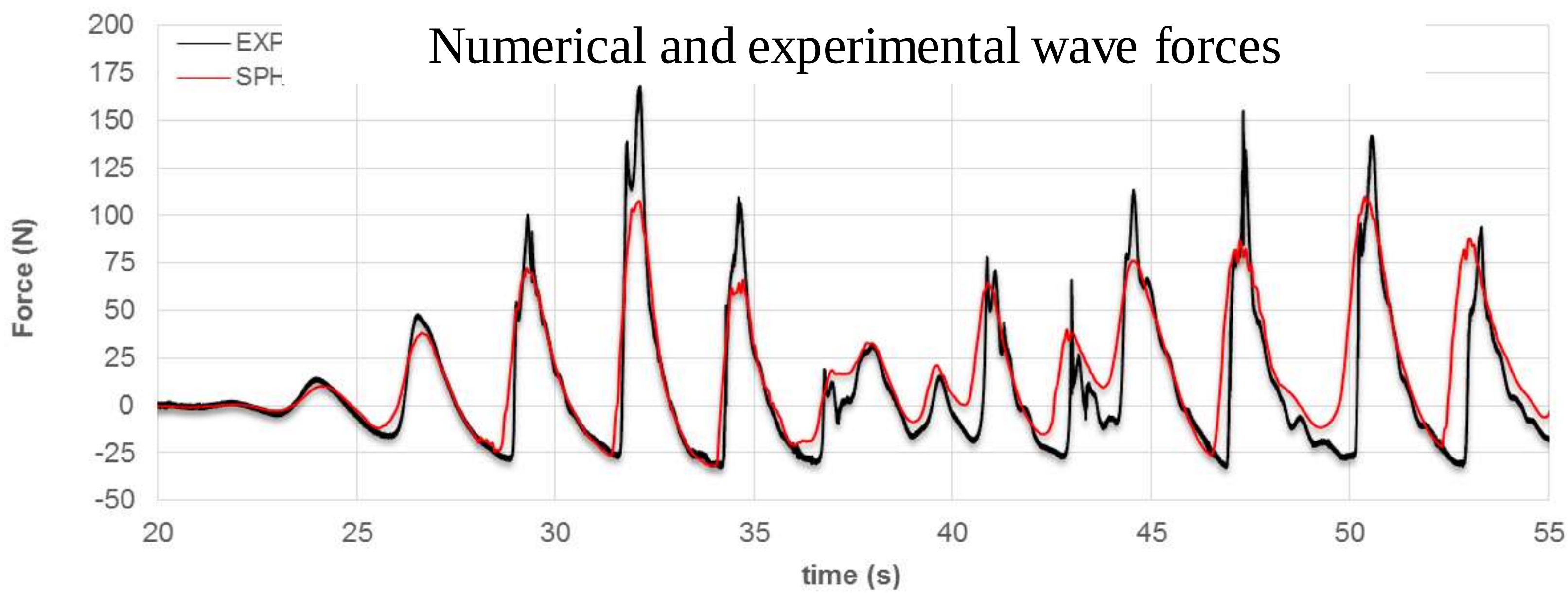
Validations and applications

Altomare et al., 2017

WAVE-STRUCTURE INTERACTION: FORCE



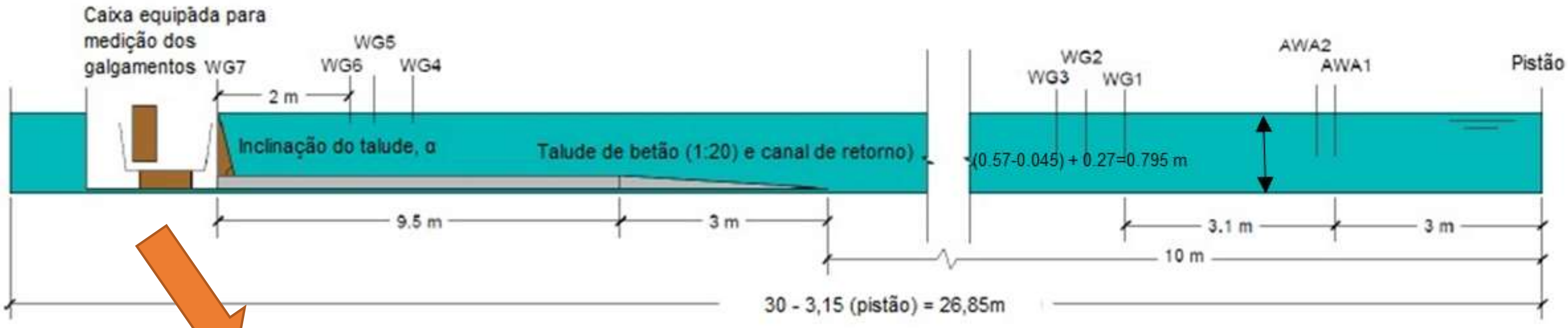


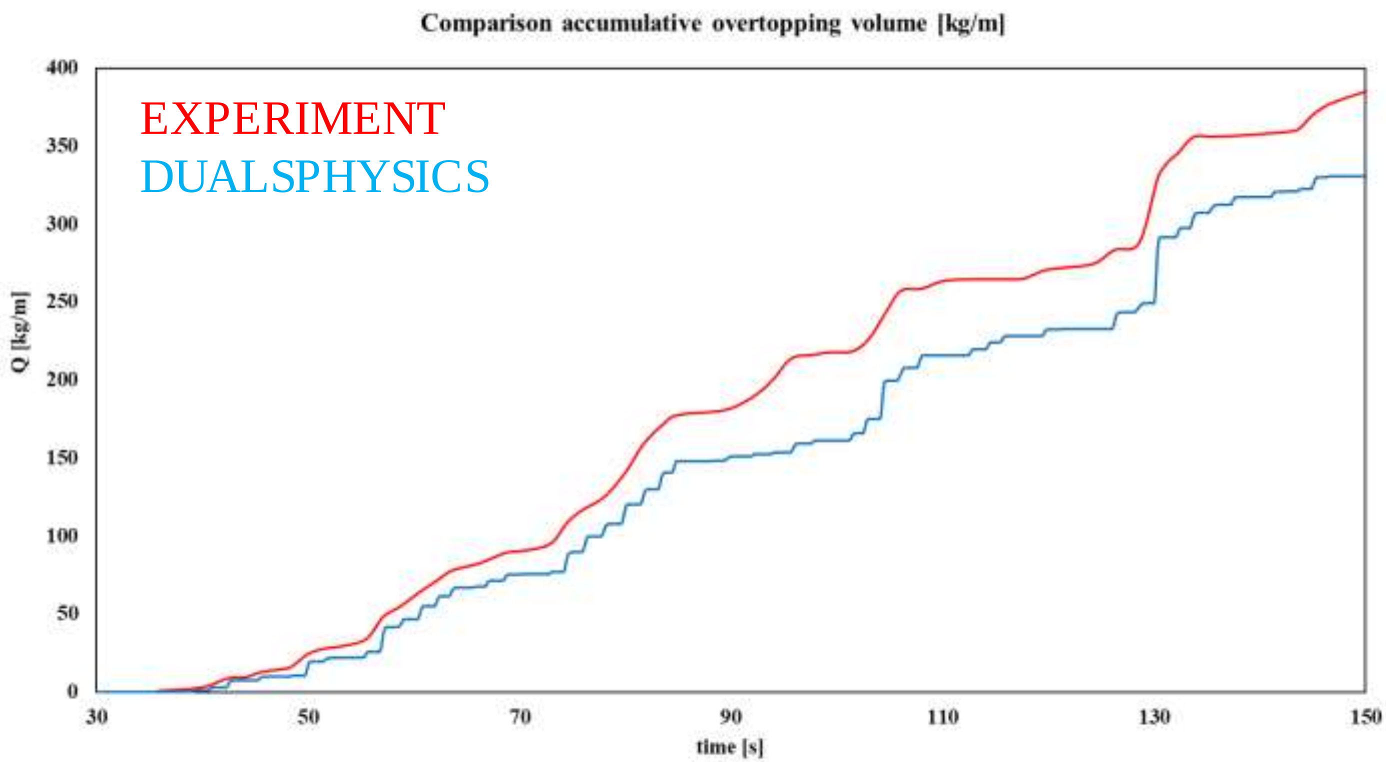


Validations and applications

Queiros et al., 2016

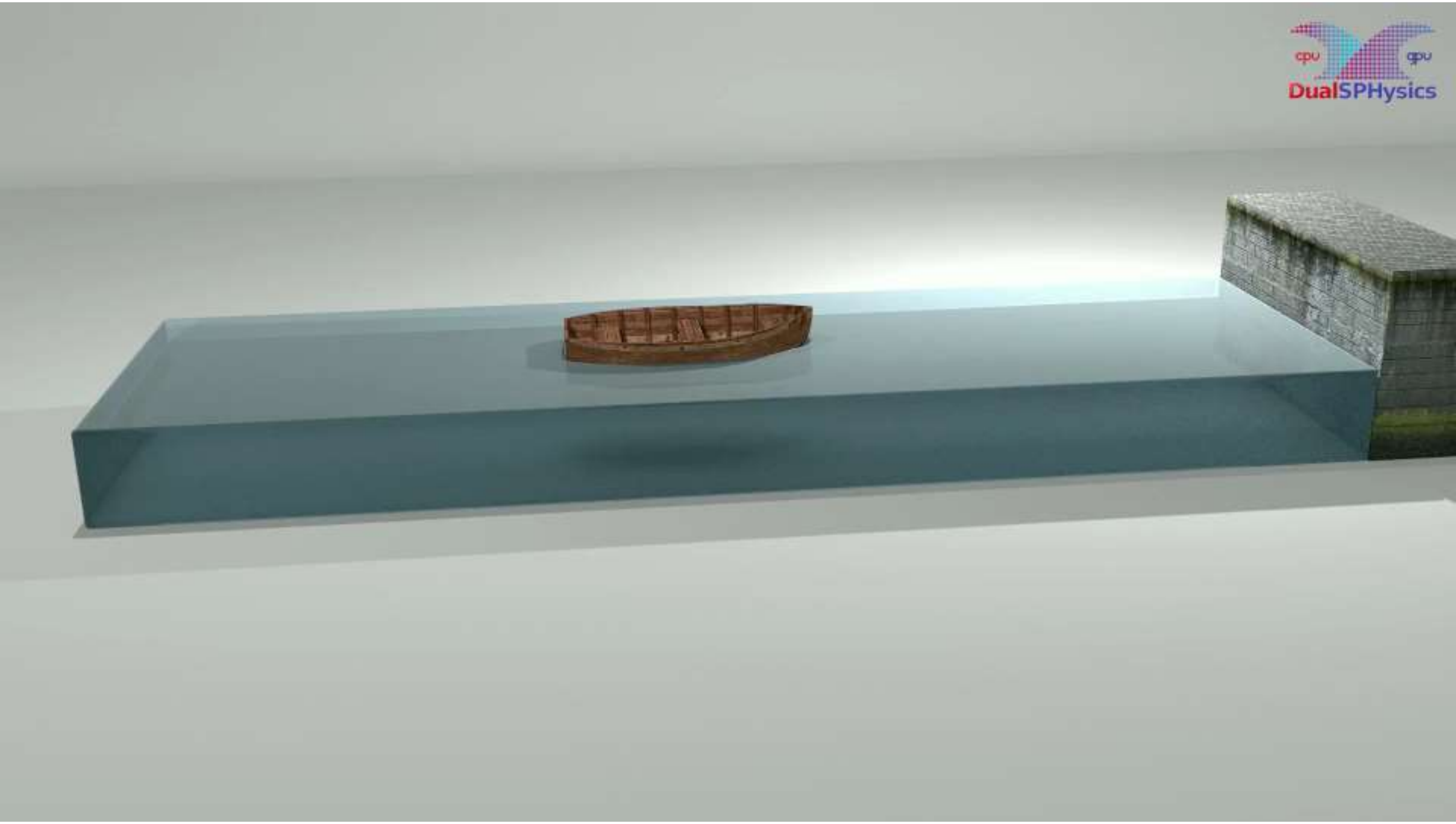
WAVE-STRUCTURE INTERACTION: OVERTOPPING





Validations and applications

FLOATING BODIES



Validations and applications

FLOATING BODIES

Each particle k (FB) experiences a force per unit mass given by

$$\boldsymbol{f}_k = \sum_{a \in WPs} \boldsymbol{f}_{ka}$$

where $\boldsymbol{f}_{ka}$ is the force per unit mass exerted by the fluid a on the particle k,

$$m_k \boldsymbol{f}_{ka} = -m_a \boldsymbol{f}_{ak}$$

Newton's equations for rigid body dynamics:

$$M \frac{d\boldsymbol{V}}{dt} = \sum_{k \in BPs} m_k \boldsymbol{f}_k$$

$$I \frac{d\boldsymbol{\Omega}}{dt} = \sum_{k \in BPs} m_k \left(\boldsymbol{r}_k - \boldsymbol{R}_0 \right) \times \boldsymbol{f}_k$$

$$\boldsymbol{u}_k = \boldsymbol{V} + \boldsymbol{\Omega} \times \left(\boldsymbol{r}_k - \boldsymbol{R}_0 \right)$$

The movement of FB is derived by considering its interaction with fluid particles and using these forces to drive its motion

Validations and applications

Canelas et al., 2015

FLOATING BODIES

BUOYANCY: Simulation of buoyancy-driven motion of an unrestricted rigid body

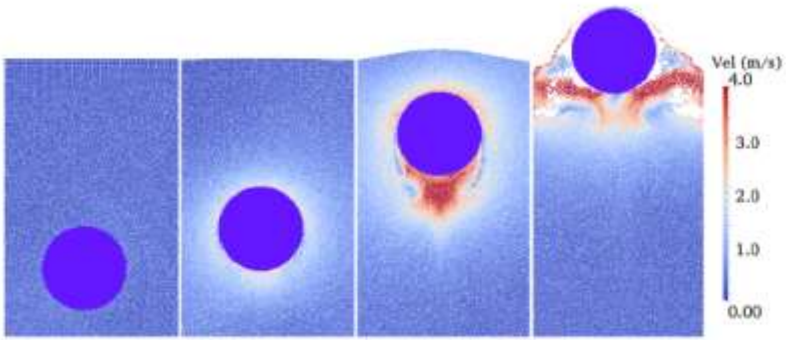


Figure 5. Rising cylinder with $\rho = 0.6\rho_w$. $T = 0$, $T = 3.13$, $T = 6.26$ and $T = 9.40$.

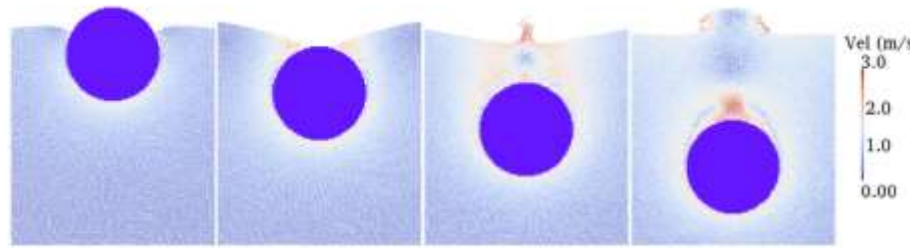


Figure 7. Sinking cylinder with $\rho = 1.2\rho_w$. $T = 1.57$, $T = 3.13$, $T = 4.70$ and $T = 6.27$.

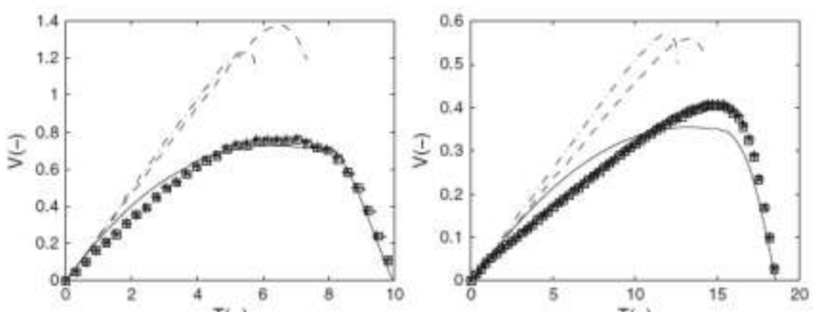


Figure 6. Non-dimensional vertical velocity for a cylinder. Left: $\rho = 0.6\rho_w$ and right: $\rho = 0.9\rho_w$. Added mass model (analytical) [27](–·–); Moyo and Greenhow(analytical) [26](– – –); Fekken (Volume of Fluid) [27](–); and DualSPHysics $D/dx = 66(\bullet)$, $D/dx = 100(*)$ and $D/dx = 150(\square)$.

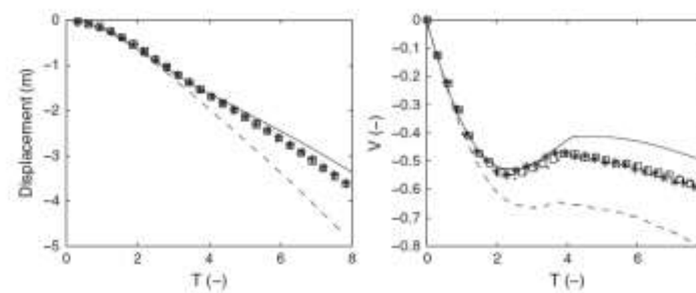


Figure 8. Left: displacement of cylinder and right: non-dimensional vertical velocity for a cylinder of $\rho = 1.2\rho_w$. Moyo and Greenhow (analytical) [26](– – –); Fekken (Volume of Fluid) [27](–); and DualSPHysics $D/dx = 66(\bullet)$, $D/dx = 100(*)$ and $D/dx = 150(\square)$.

RISING SPHERE

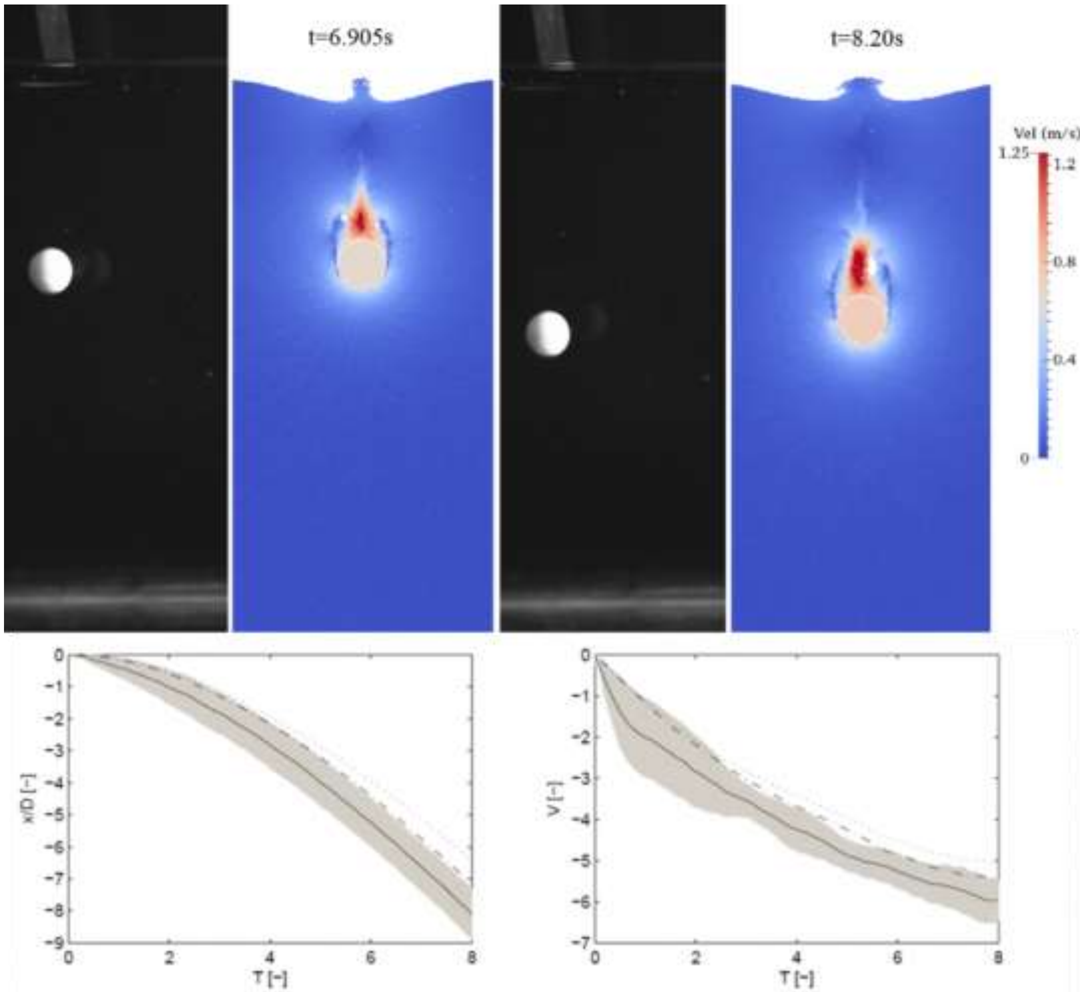
SINKING SPHERE

Validations and applications

Canelas et al., 2015

FLOATING BODIES

BUOYANCY: Simulation of buoyancy-driven motion of an unrestricted rigid body



Sinking sphere with $\rho = 2.54\rho_w$. Experimental(-), experimental error region (shaded gray), DualSPHysics $D/dx = 20$ $(\cdots)$ $D/dx = 50$ $(-\cdot-)$

SINKING SPHERE

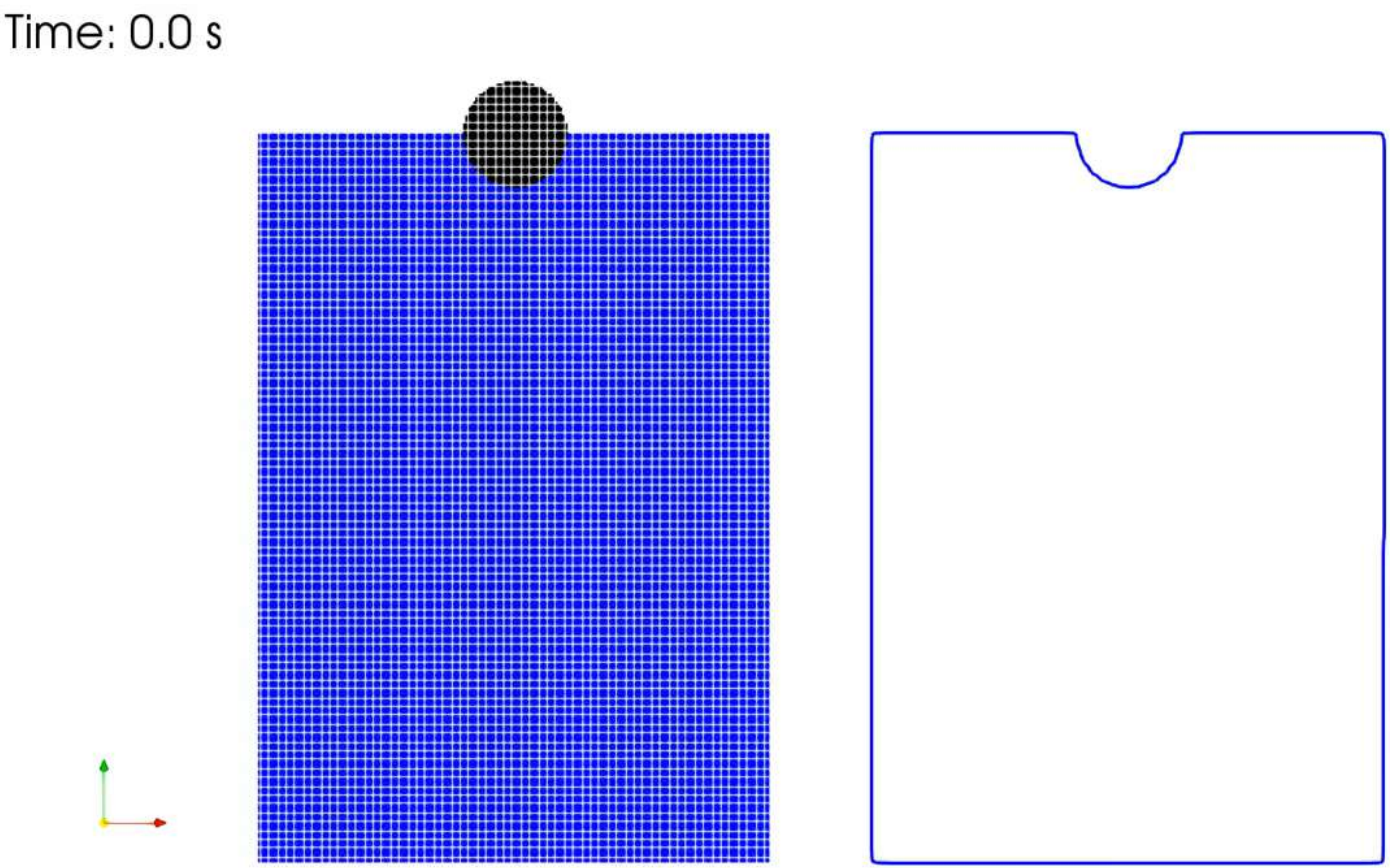
compared with experimental data

Validations and applications

Canelas et al., 2015

FLOATING BODIES

BUOYANCY: Simulation of buoyancy-driven motion of an unrestricted rigid body

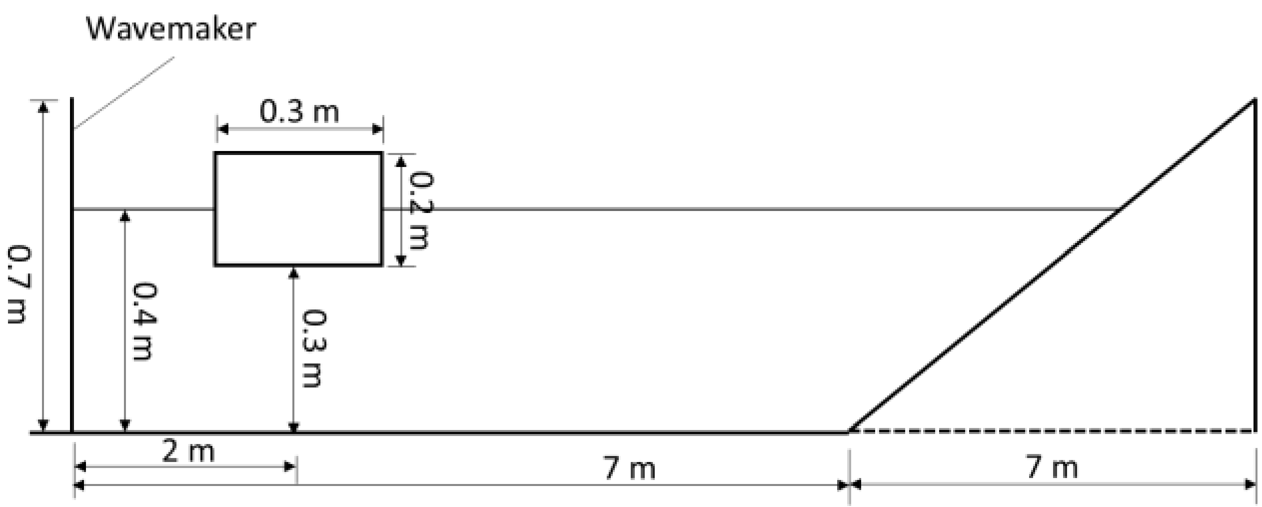


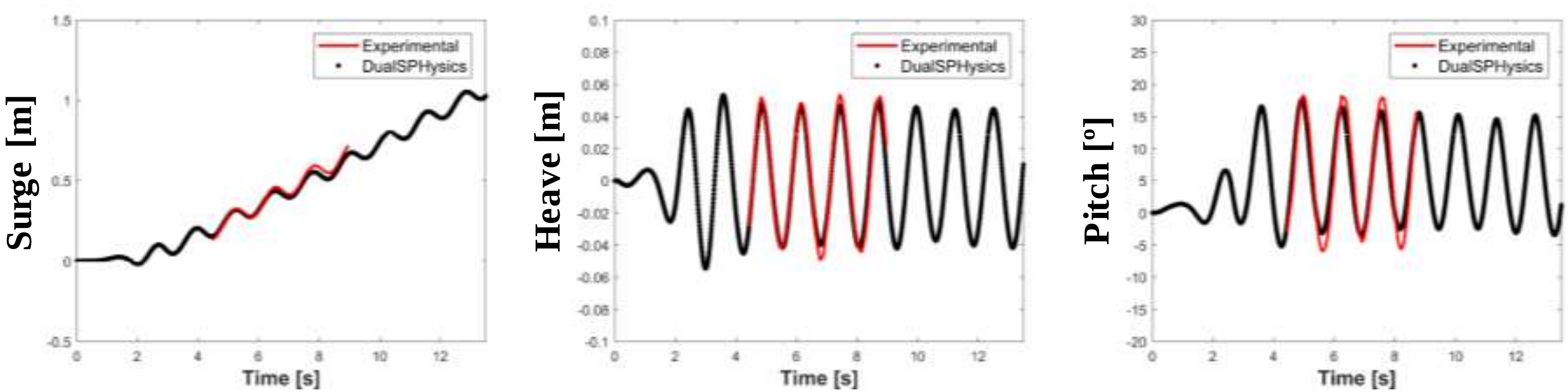
Validations and applications

FLOATING BODIES

Ren et al., 2015

Floating body subjected to REGULAR WAVES



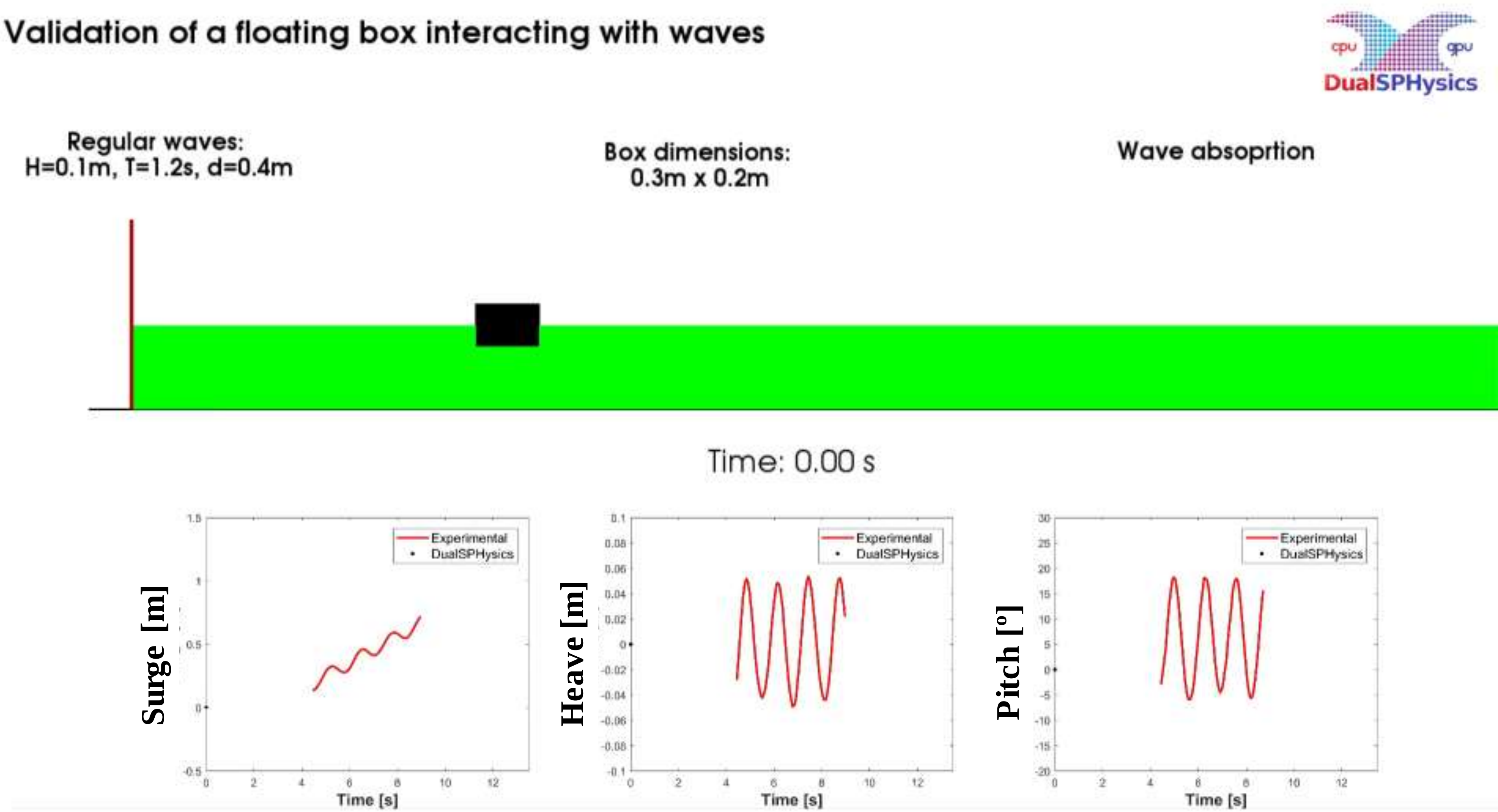


Validations and applications

FLOATING BODIES

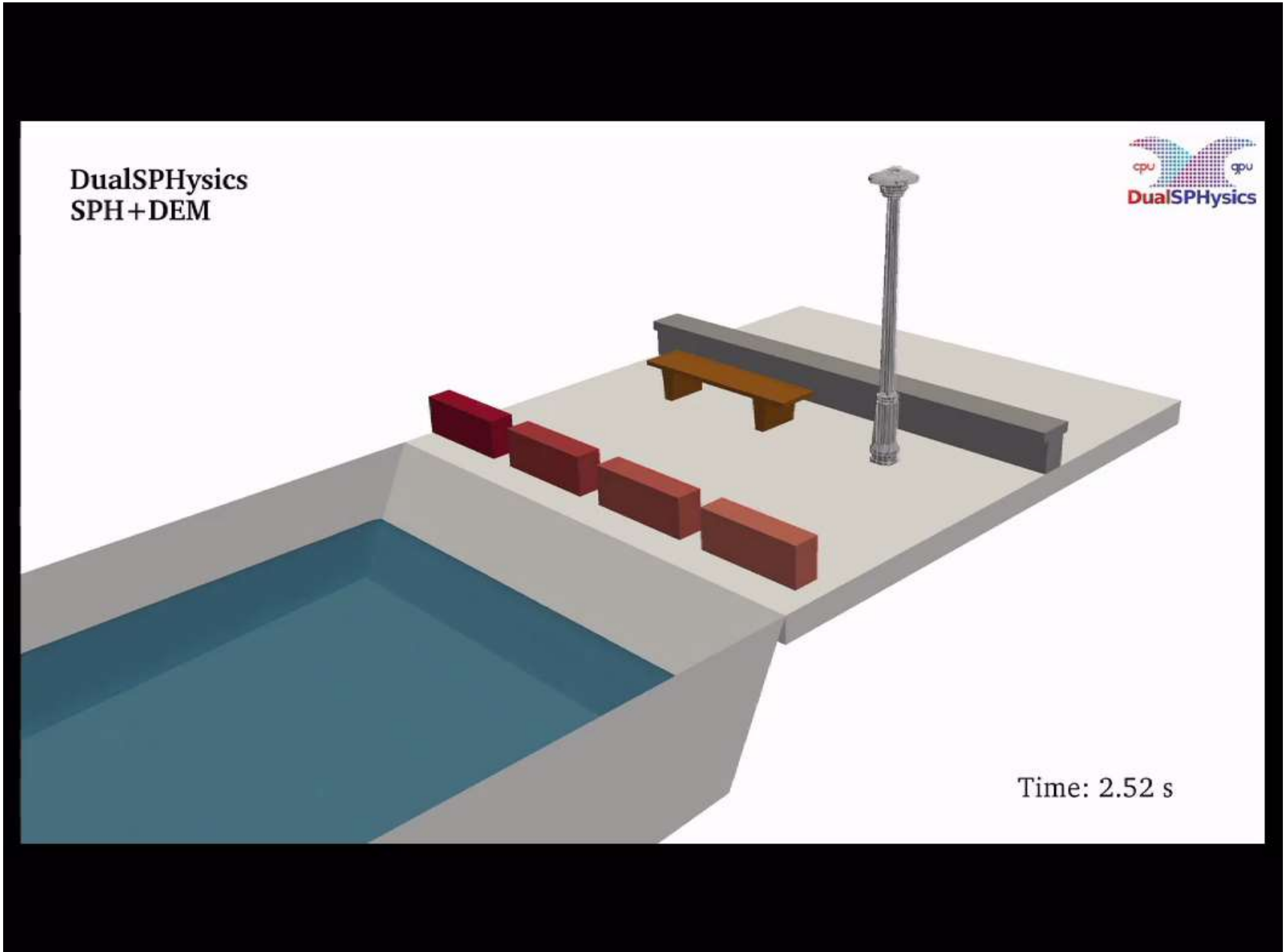
Ren et al., 2015

Floating body subjected to REGULAR WAVES



Validations and applications

SOLID INTERACTIONS



Validations and applications

SOLID INTERACTIONS

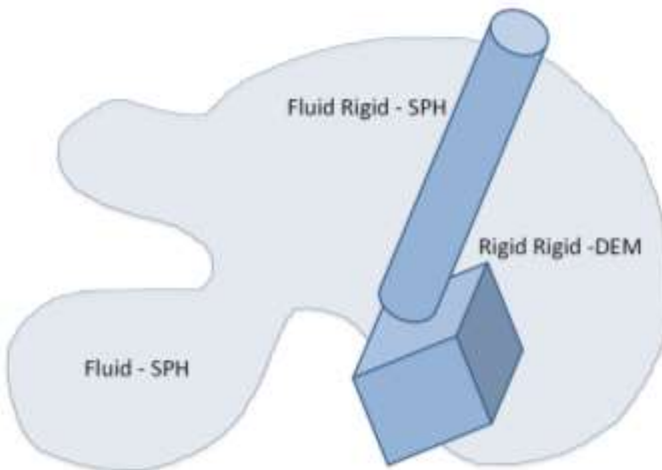
A generalized SPH-DEM discretization

Discrete Element Method (DEM) allows for the computation of rigid particle dynamics, by considering contact laws to account for interaction forces.

The coupled numerical solution, based on SPH and DEM discretizations, resolves solid-solid and solid-fluid interactions **in broad range of scales**.

DEM considers **contact forces**. It is **completely rigid** and is **generalized for any shape**.

We can have different materials with the **real** parameters:
E (Young modulus),
ν (Poisson ratio) and
μ (kinetic friction coefficient).



Validations and applications

SOLID INTERACTIONS

Validation of SPH-DEM

Facilities: 8.0 m long and 0.70 m wide flume, with **smooth bed**. Mechanical gate → 'instantaneous' removal for upstream depth of $h_0 = 0.40$ m.

Objects: 0.15m side PVC cubes with a relative density of 0.8.

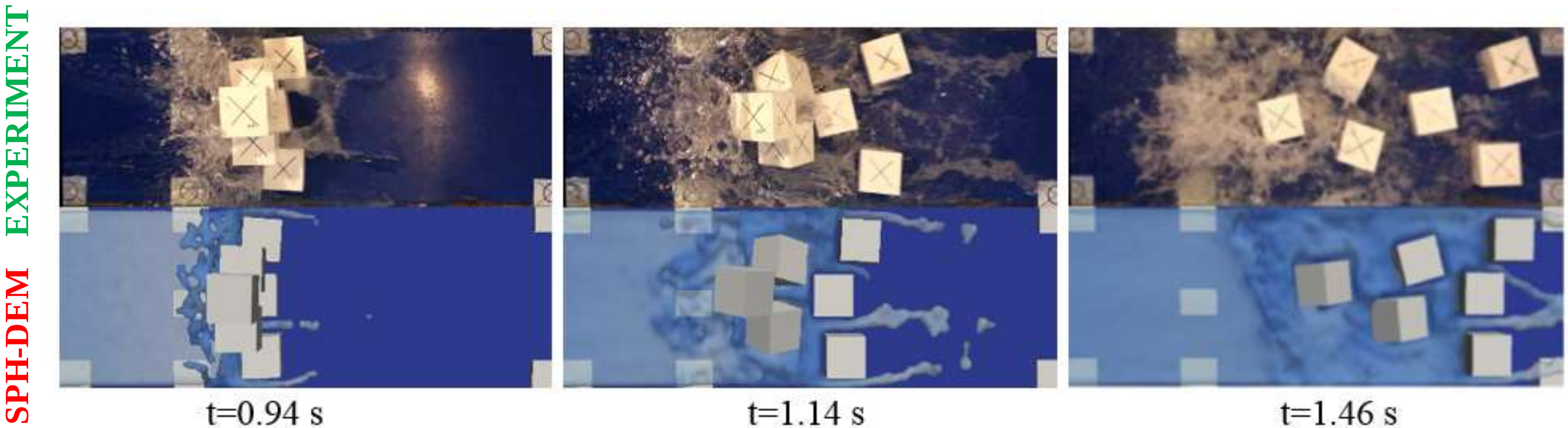
Instrumentation: three synchronized video cameras pointing from the upstream, top and downstream directions, as well as a high-speed camera on the side, normal to the flume wall. PIV measurements were also taken.

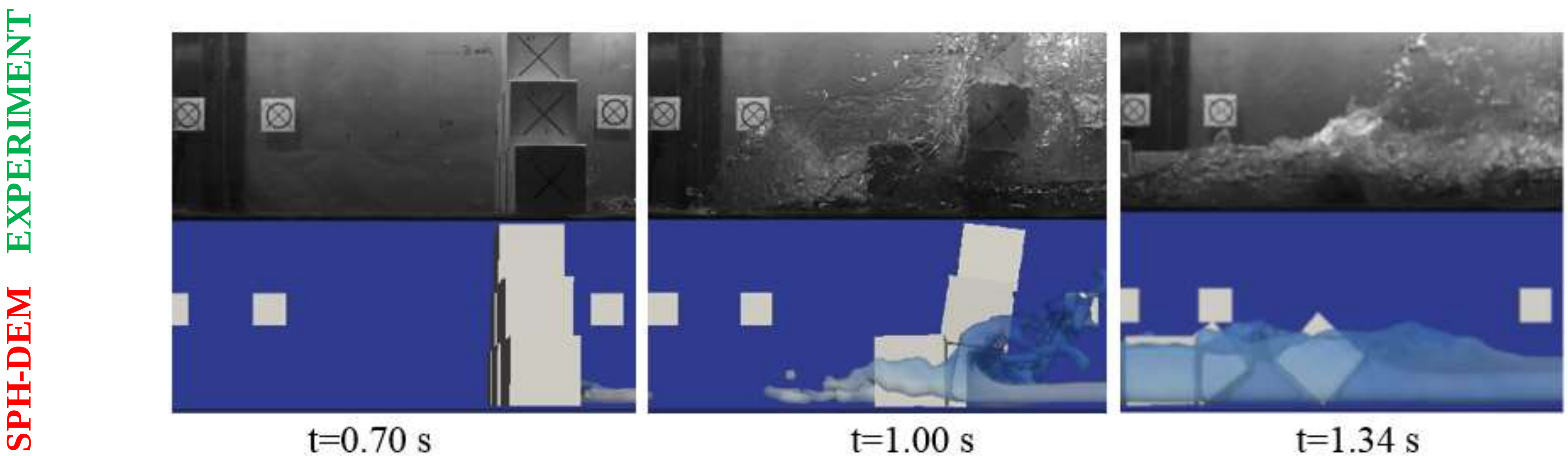
Validations and applications

Canelas et al., 2016

SOLID INTERACTIONS

Validation of SPH-DEM





Validations and applications

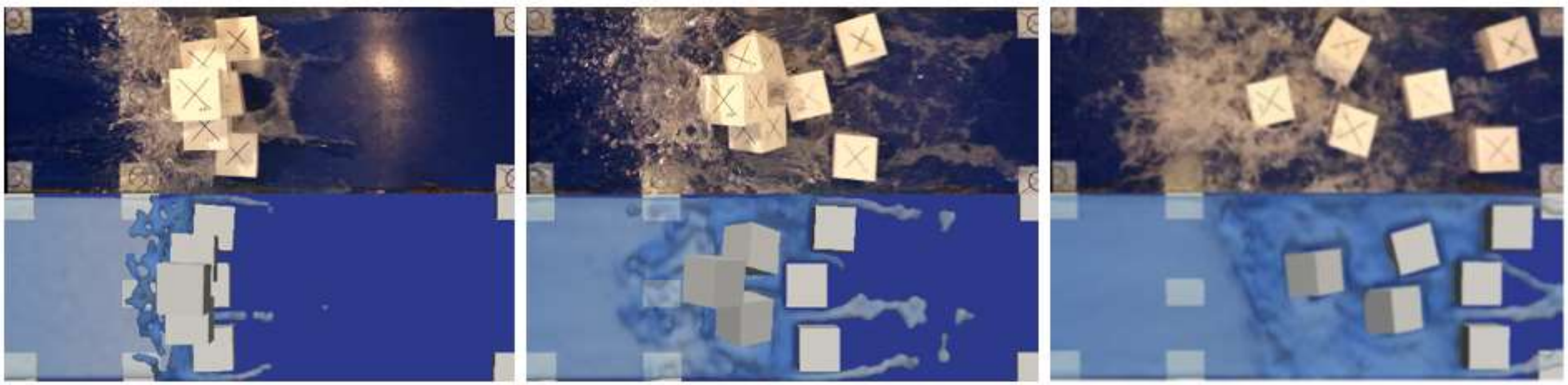
Canelas et al., 2016

SOLID INTERACTIONS

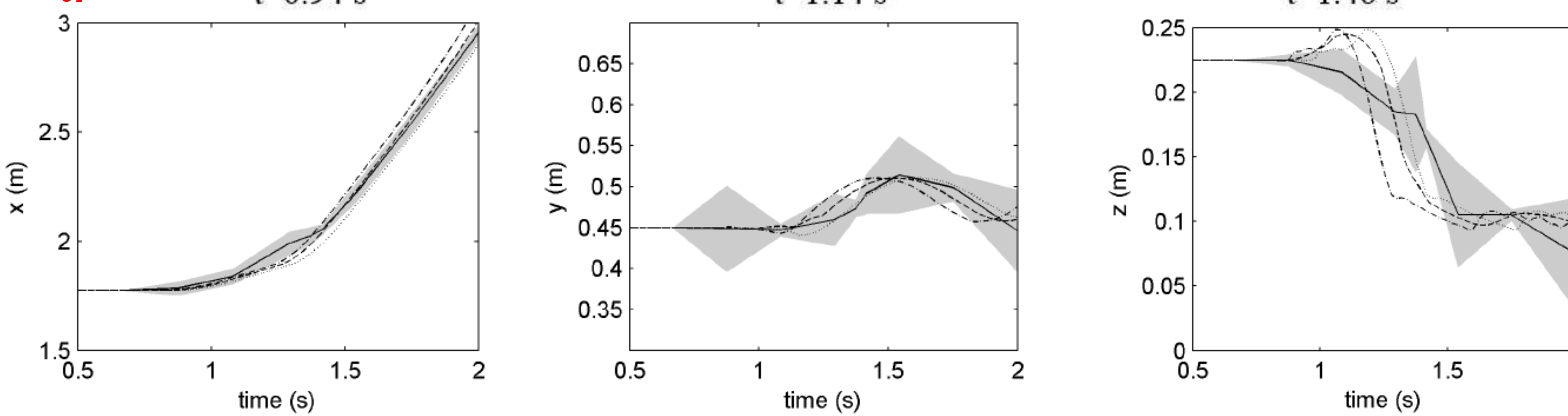
Validation of SPH-DEM

EXPERIMENT

SPH-DEM



t=0.94 s t=1.14 s t=1.46 s



Top left cube: Experimental (-), DualSPHysics L/Dp = 15(--), L/Dp = 10(-.-), L/Dp = 45(…)

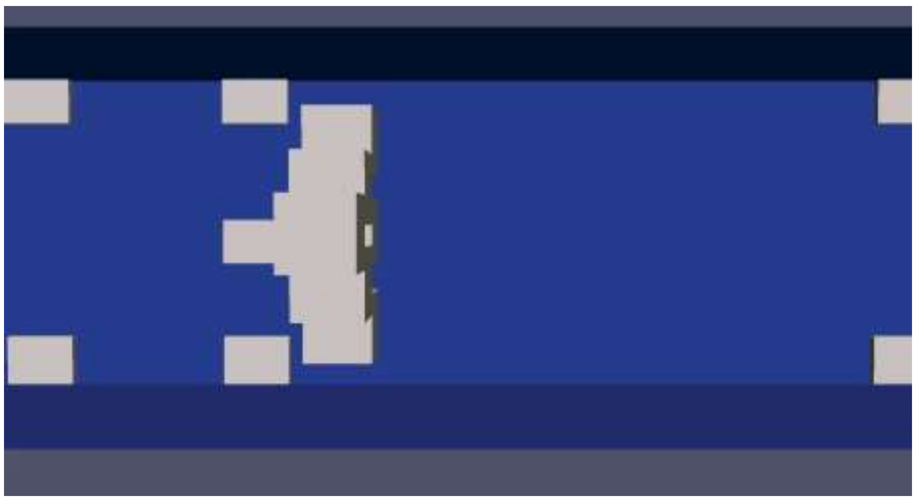
Validations and applications

Canelas et al., 2016

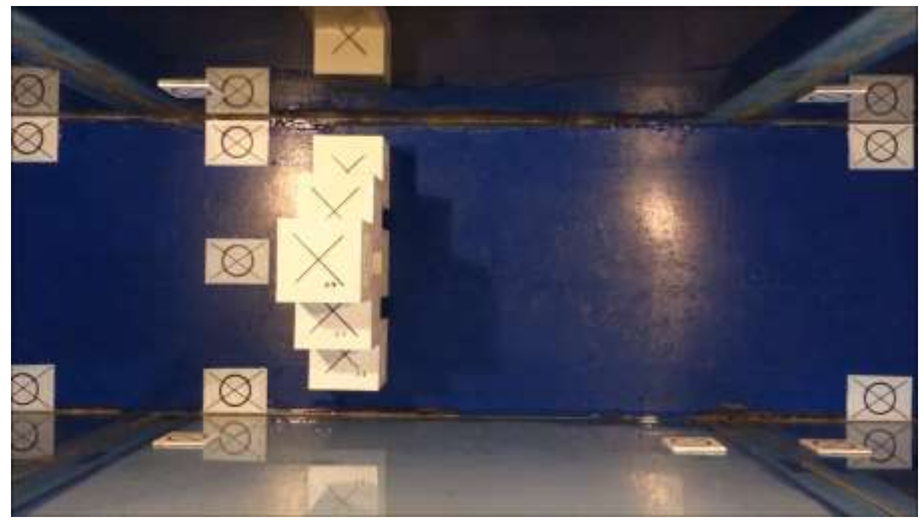
SOLID INTERACTIONS

Validation of SPH-DEM

SPH-DEM



EXPERIMENT



Interactions Fluid-Fluid, Fluid-Solid, Solid-Solid, Solid-Walls are very promising even with low resolution.

Validations and applications

SOLID INTERACTIONS

Table of STEEL

E (Young modulus)=500000000 N/m^2

ν (Poisson ratio)=0.3

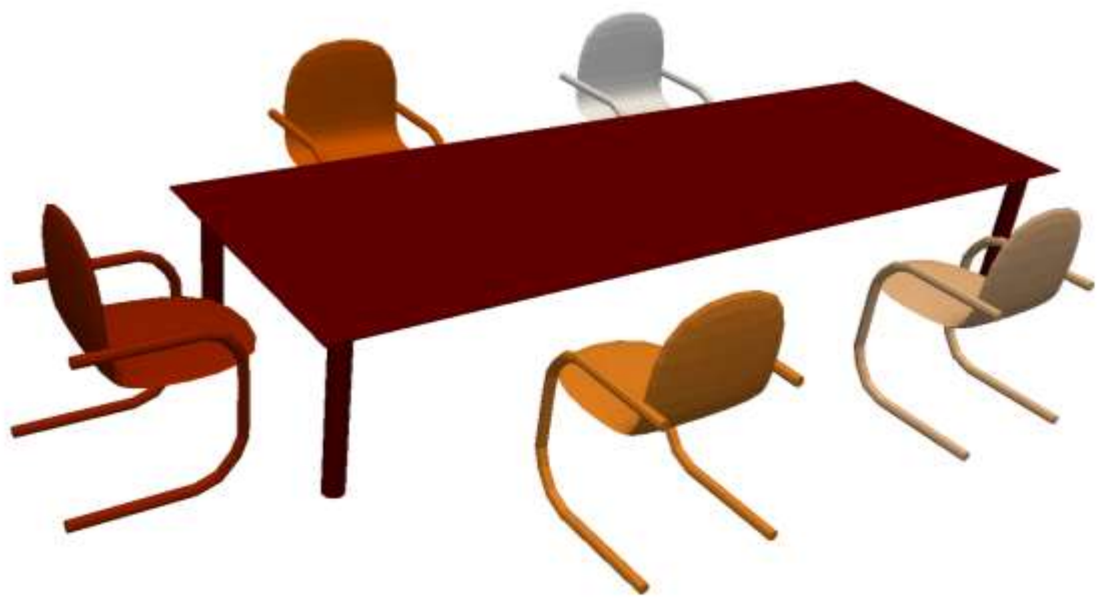
μ (kinetic friction coefficient)=0.55

Chairs of HARD-WOOD

E (Young modulus)=200000000N/m^2

ν (Poisson ratio)=0.2

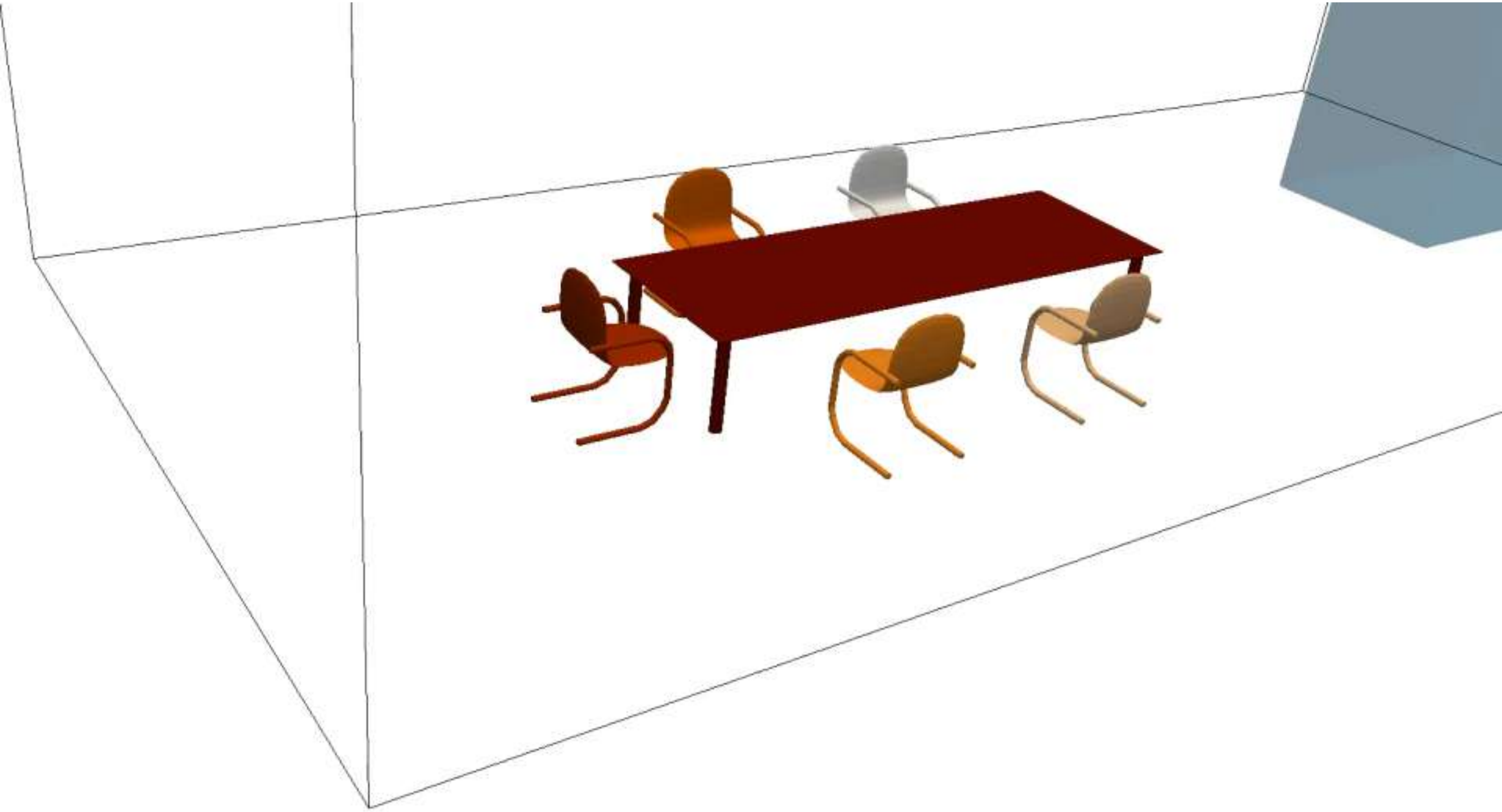
μ (kinetic friction coefficient)=0.70



Validations and applications

SOLID INTERACTIONS

Simulation of more than 4 million particles
8 seconds of physical time (187,353 steps)
took 31.73 hours using GeForce GTX TITAN Black



Validations and applications

SOLID INTERACTIONS

There are no complete and general conceptual models for the smaller scales.
Rheological approaches are greately insuficient.
The option is to attempt to model and finally study the details of the phenomena.

Swiss Pennine Alps

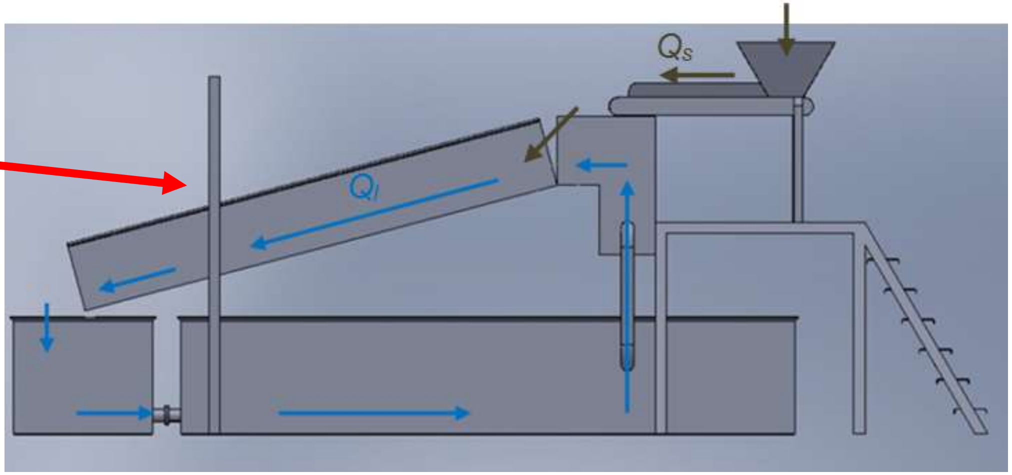
Validations and applications

Canelas et al., 2017

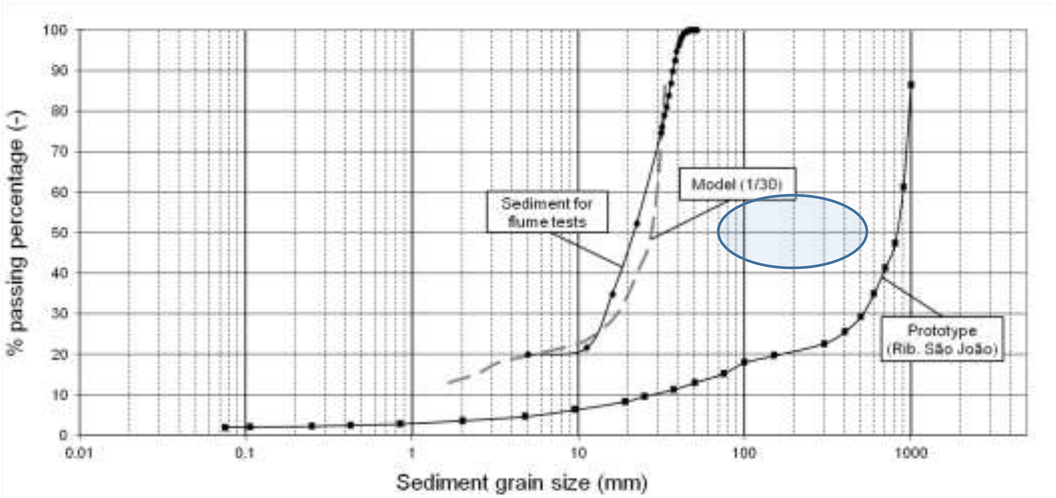
SOLID INTERACTIONS

SLITS

The channel is recirculating and the dam section is modular.



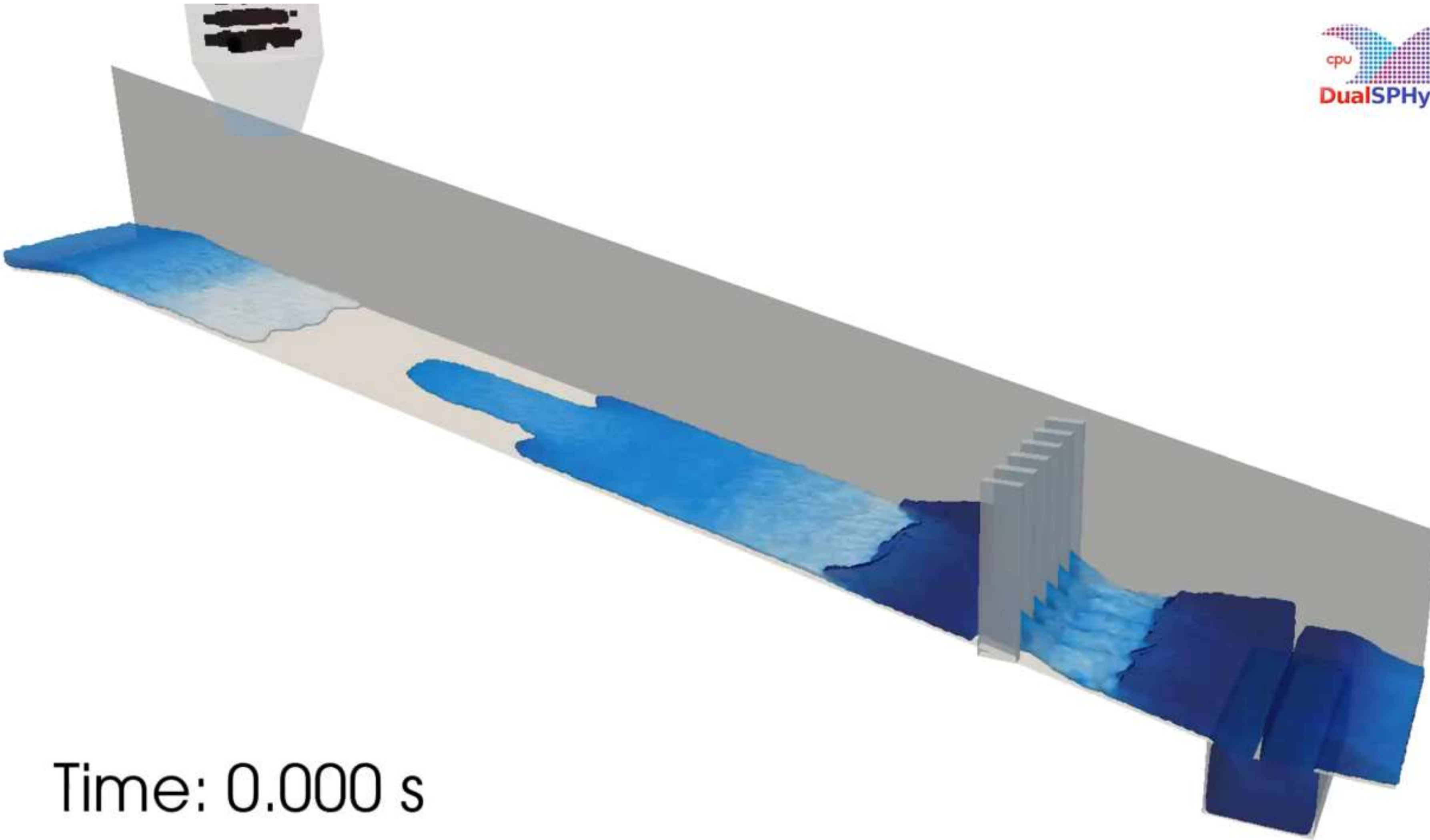
The used granulometric curve corresponds exactly to the experimental curve.



Validations and applications

SOLID INTERACTIONS

DualSPHysics simulation took 280-290h for 70s of physical time with close to 3 million particles with 1600 solids



Validations and applications

Canelas et al., 2017

SOLID INTERACTIONS

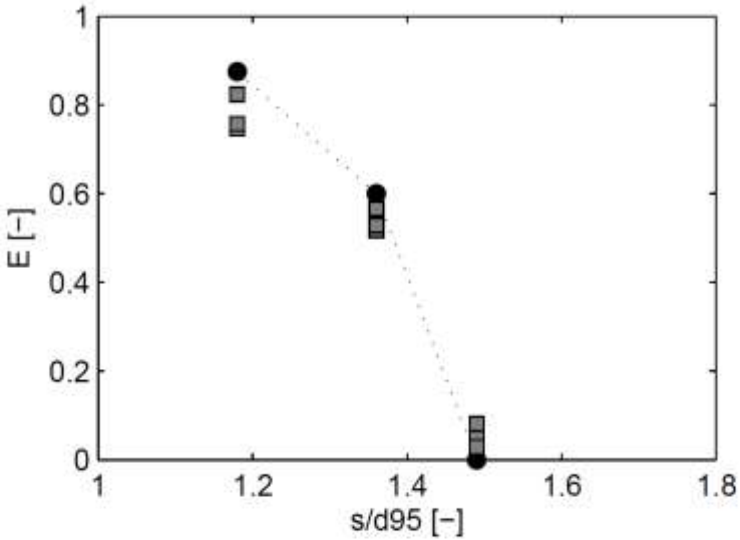
VALIDATION:

- Sediment trapping efficiency, E
is measured by the ratio of retained material to material in circulation.

Sediment trapping efficiency (E) with P1 slits. 1 spacing configuration (s/d95)

s/d95	**E[-] Exp**	*E[-] run1*	*E[-] run2*	*E[-] run3*
1.180	**0.900**	*0.786*	*0.802*	*0.810*

Sediment trapping efficiency (E) with P2 slits. 3 spacing configurations (s/d95)
Experimental (●), DualSPHysics (□)



OUTLINE

Validations and applications

I. Dam break
II. Wave generation and absorption
II. Wave-structure interaction
III. Floating bodies
IV. Solid interactions

Coupling with other codes/libraries

With SWASH
With Chrono
With MoorDyn

Wave Energy Converters design

Visualisation

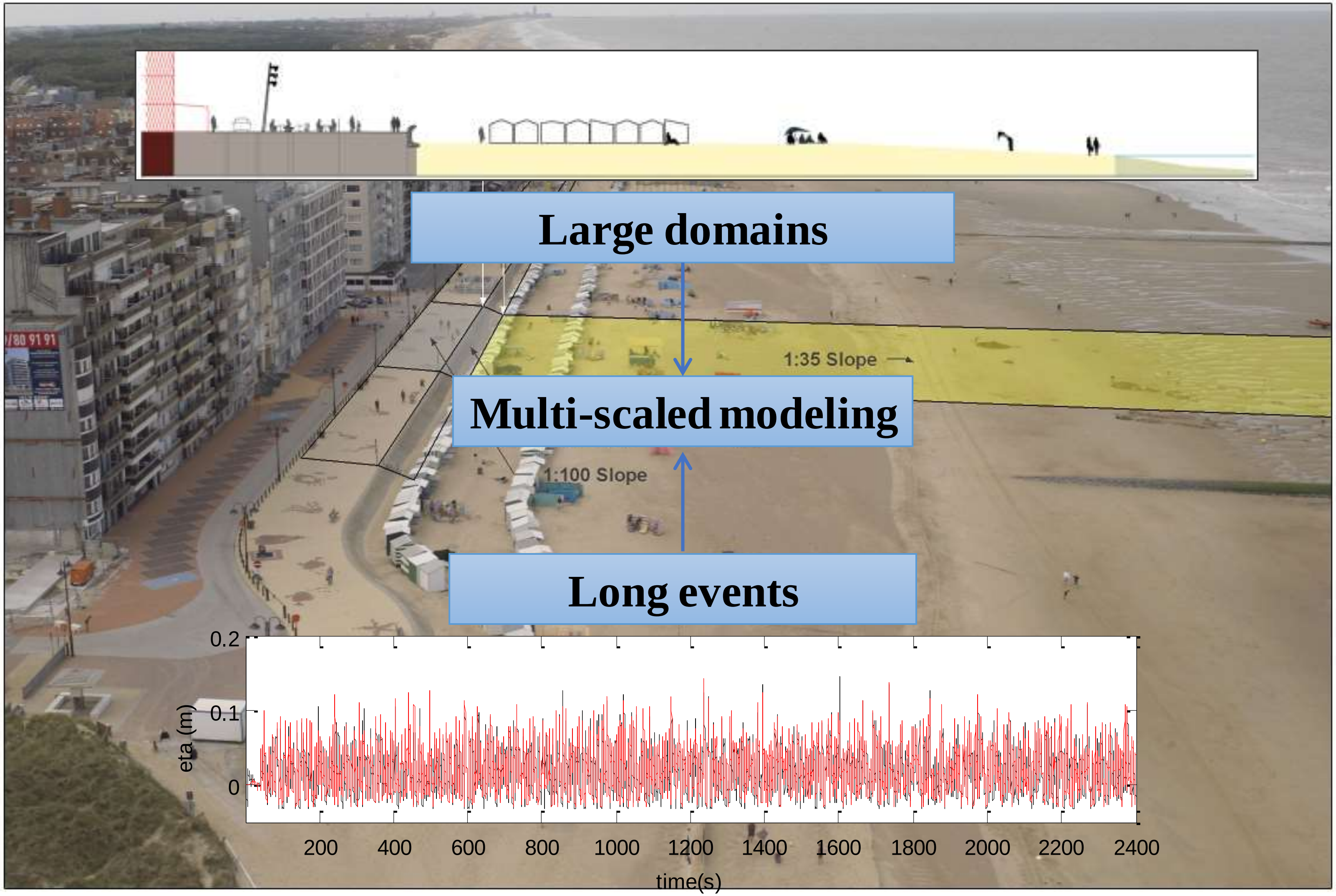
Coupling with SWASH

Altomare et al., 2015

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

Coupling with SWASH

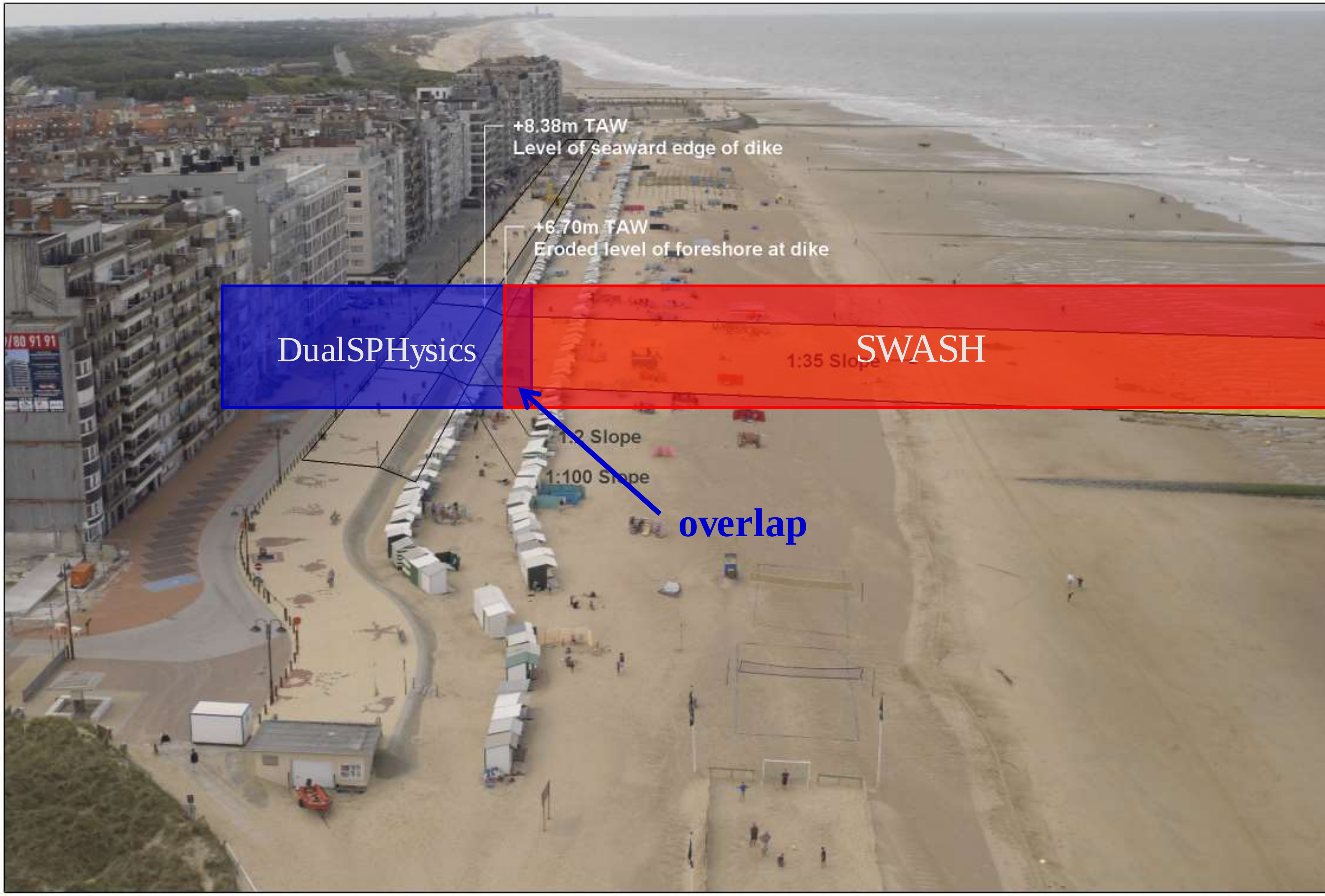
Altomare et al., 2015



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

Coupling with SWASH

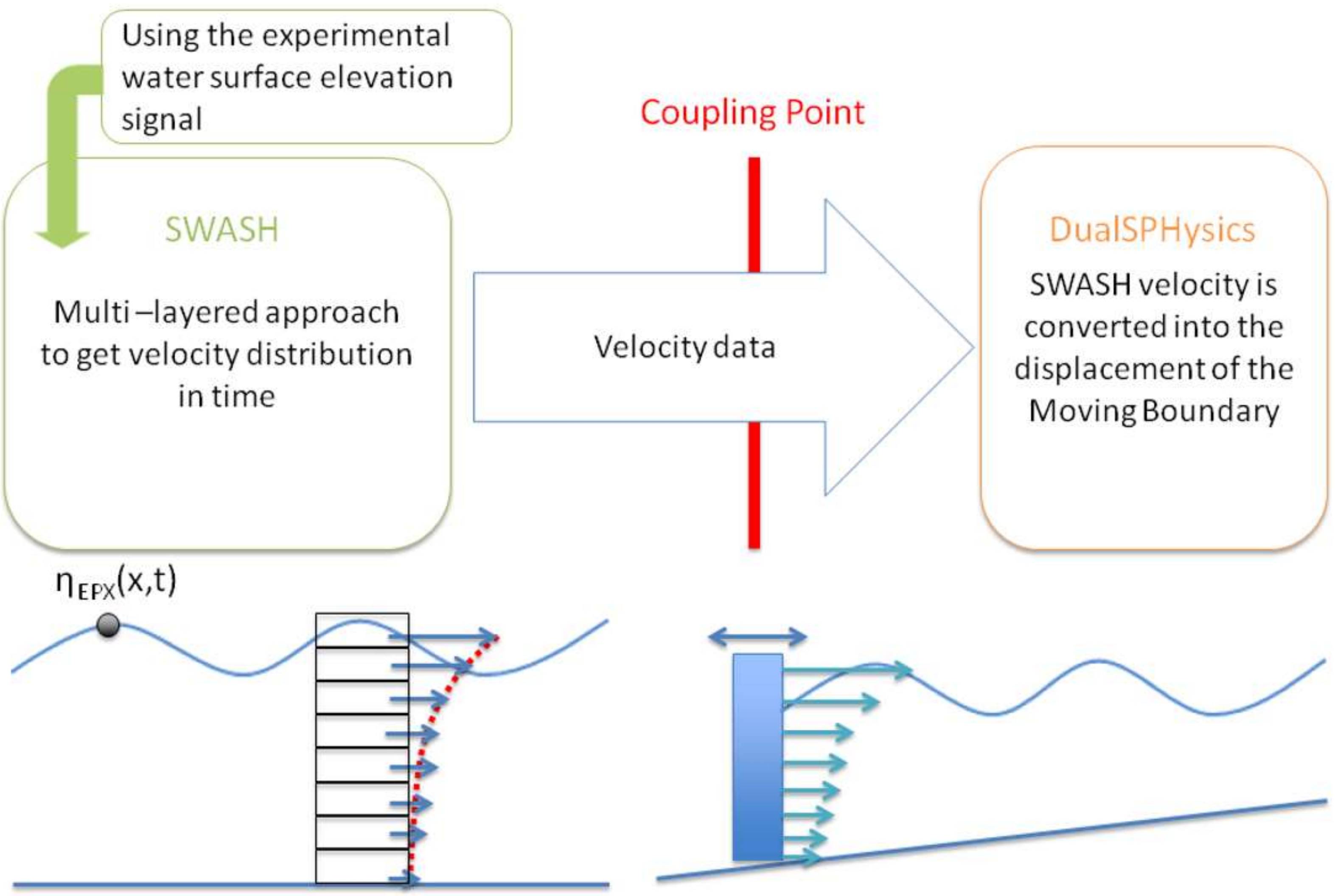
Altomare et al., 2015



Simulating WAve till Shore (**SWASH**) model is a **time domain model** for simulating non-hydrostatic, free-surface and rotational flow

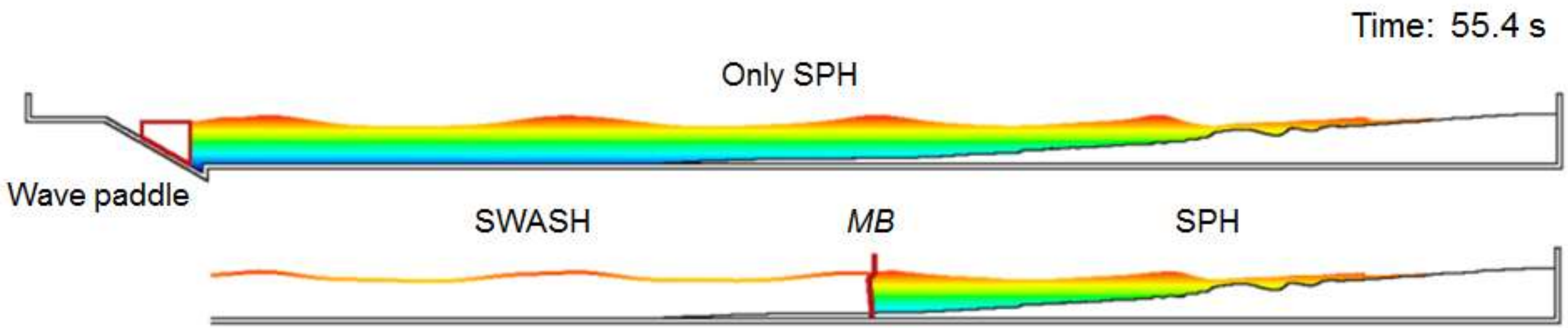
Coupling with SWASH

Altomare et al., 2015

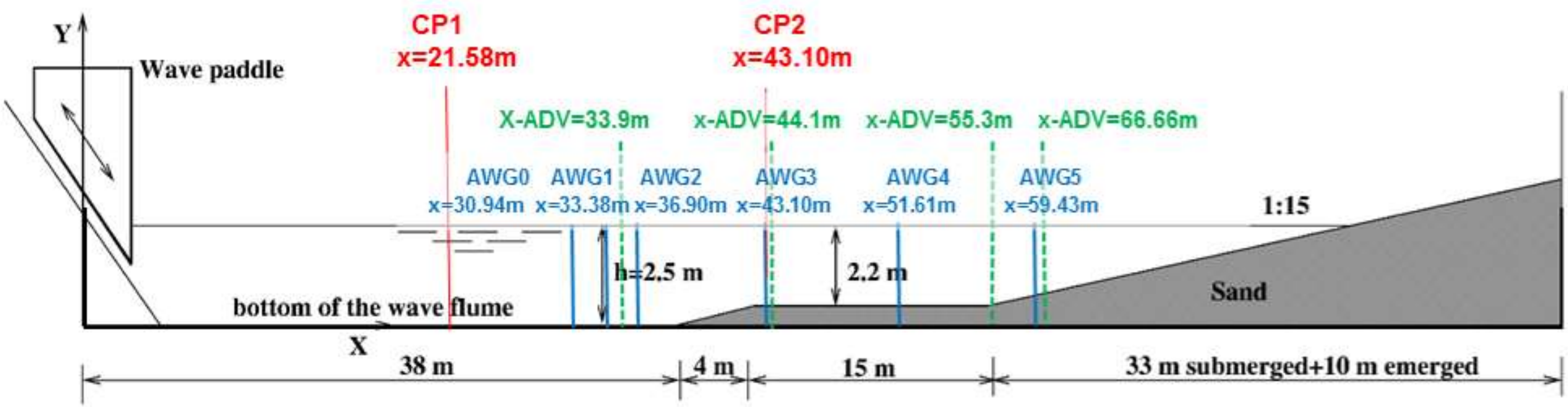


Coupling with SWASH

Altomare et al., 2015



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

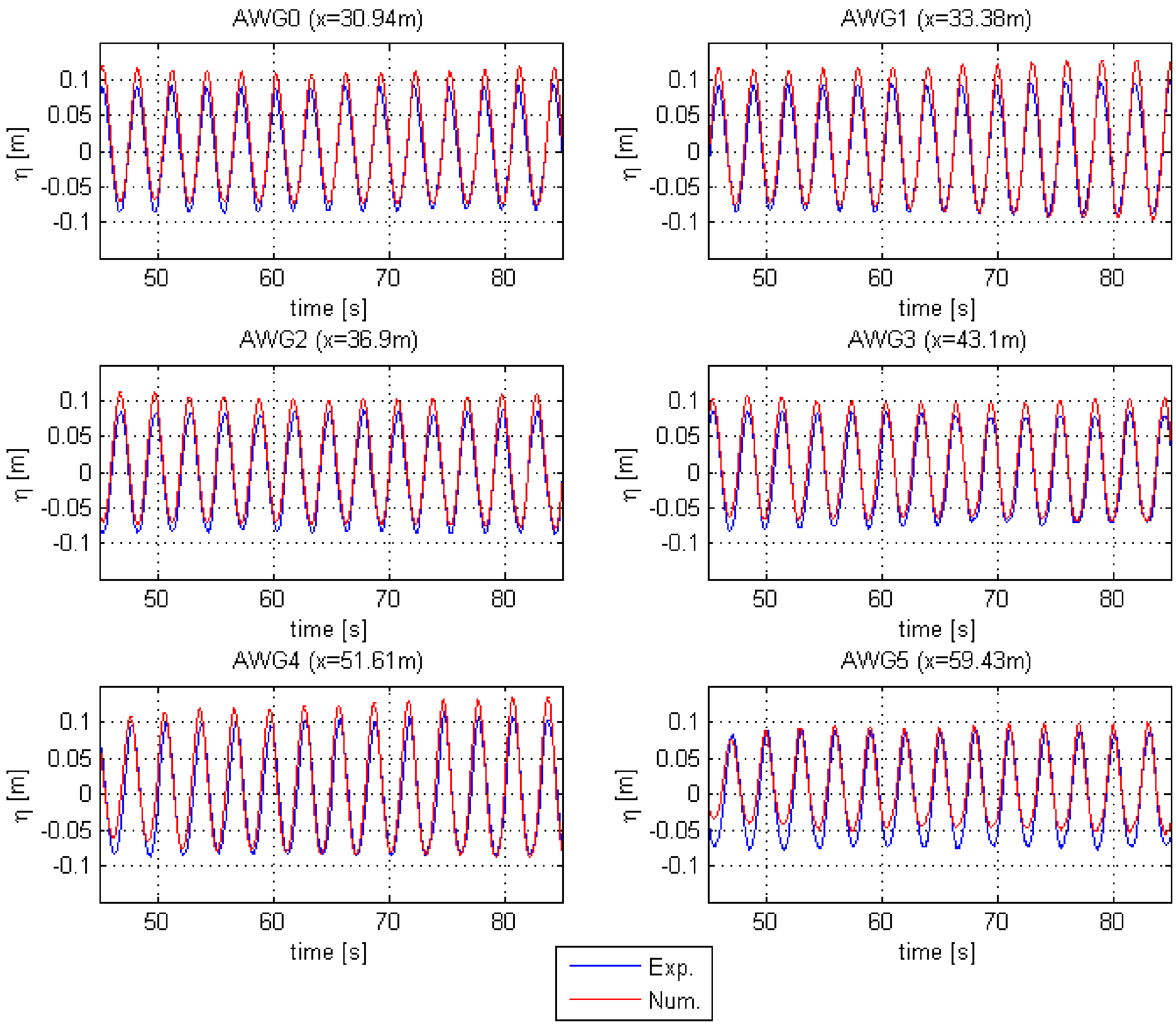


Test case	H_{target} [m]	T_{target} [s]
A	0.2	5.5
B	0.2	3.0
C	0.3	5.5
D	0.3	3.0

Coupling with SWASH

Altomare et al., 2015

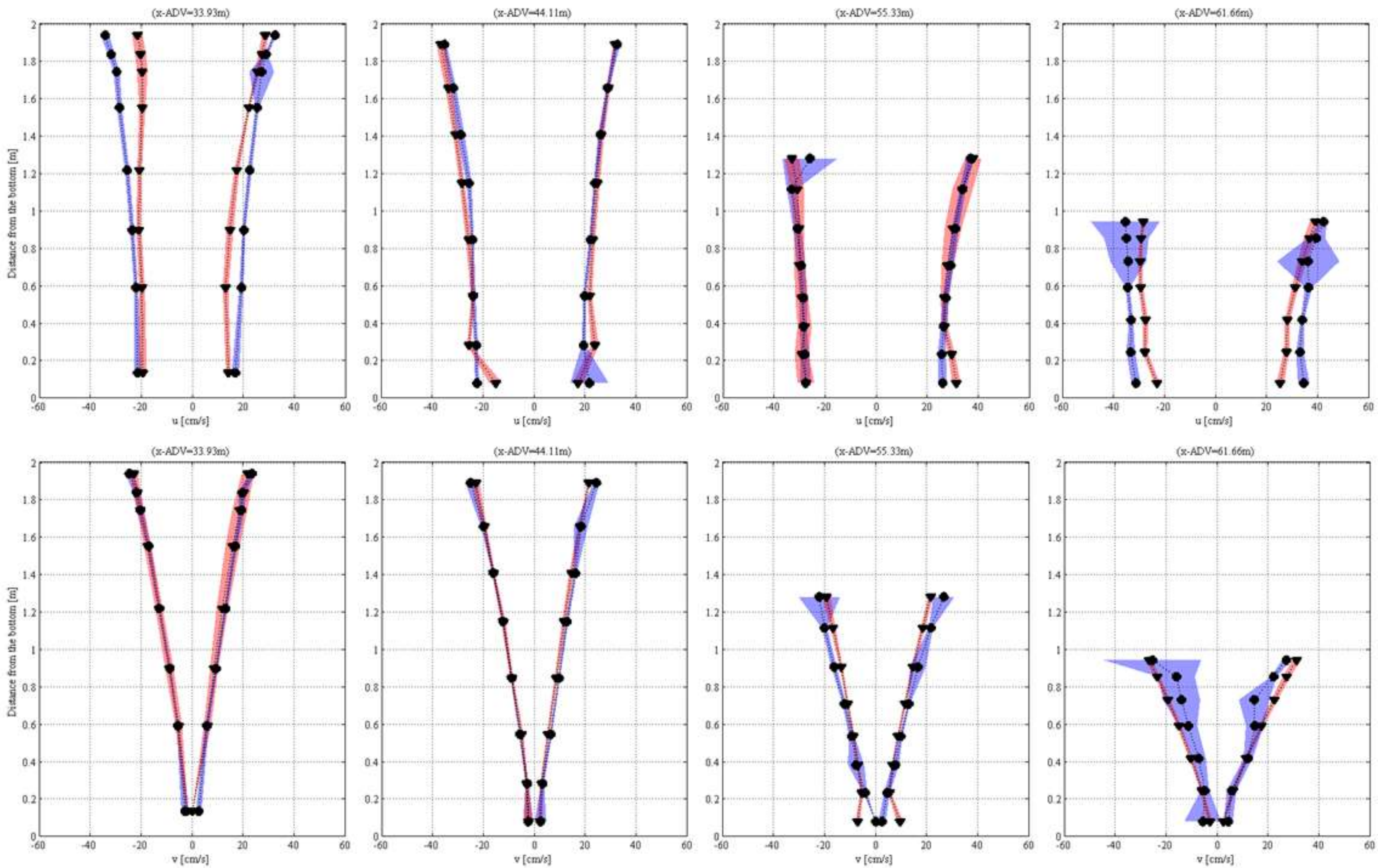
AWG free surface elevation: comparison between numerical and physical results (CP1, test case B)



Coupling with SWASH

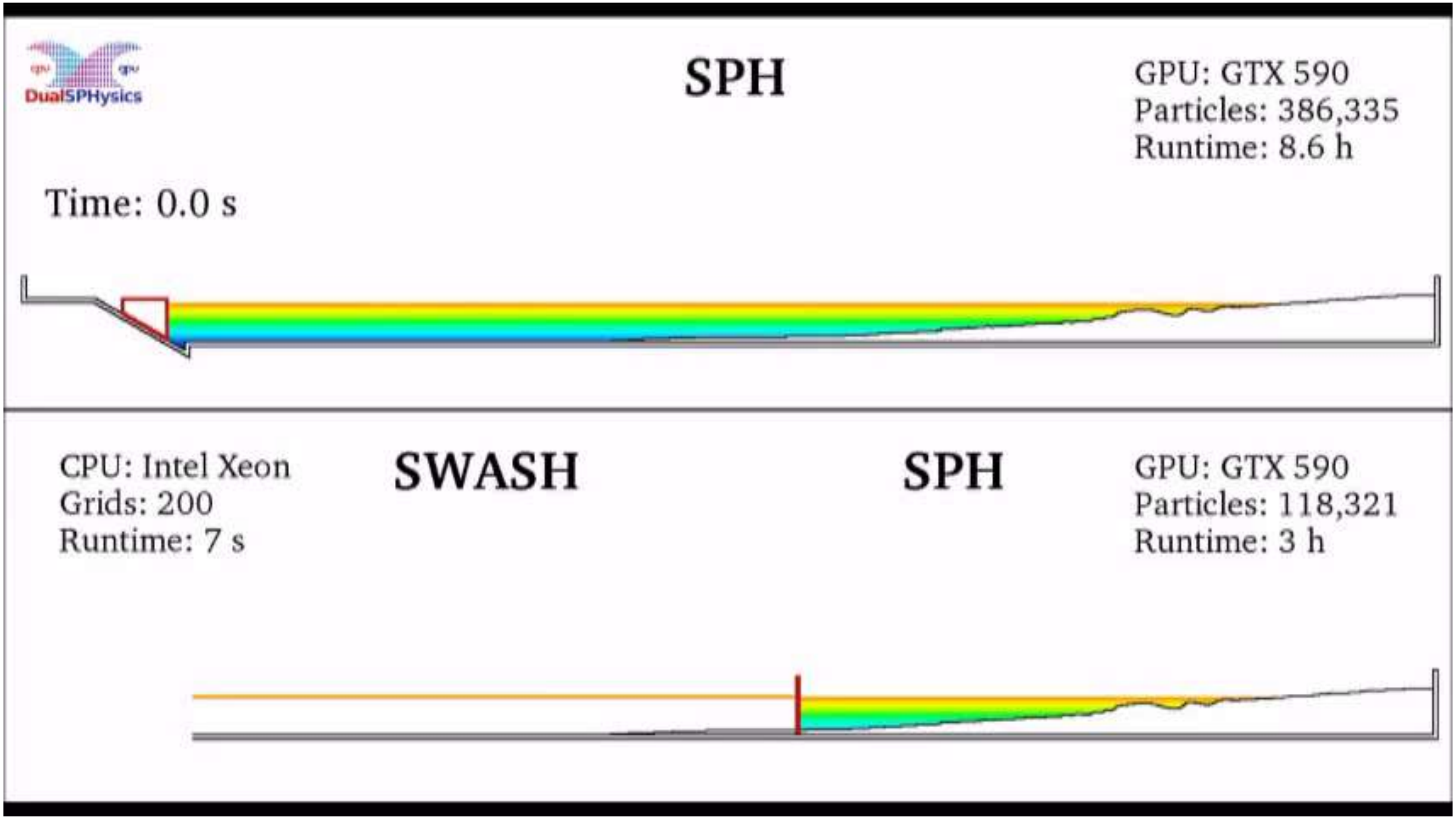
Altomare et al., 2015

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



Coupling with SWASH

Altomare et al., 2015



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

	WP	CP1	CP2
DualSPHysics domain size	100%	78.42%	56.90%
Number of Particles	100%	62.89%	26.89%
Runtime	100%	70.49%	40.98%

Coupling with CHRONO

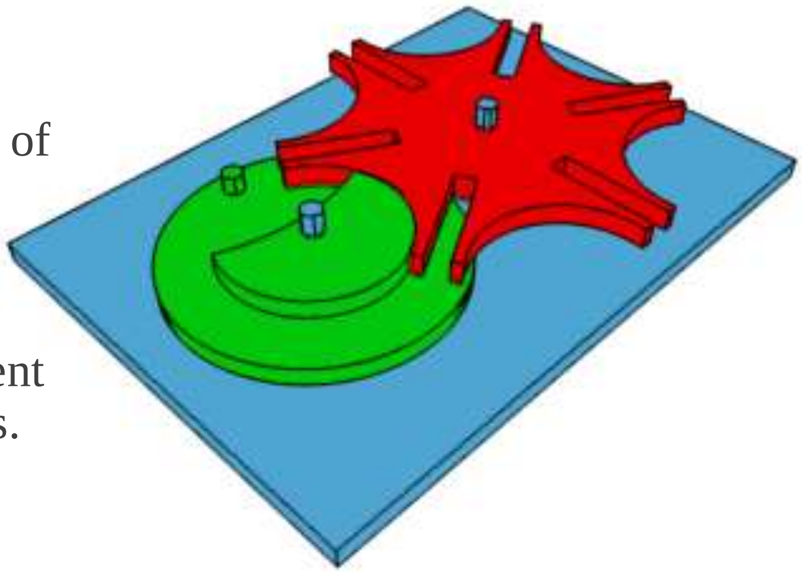
PROJECTCHRONO

An Open Source Multi-physics Simulation Engine

http://projectchrono.org

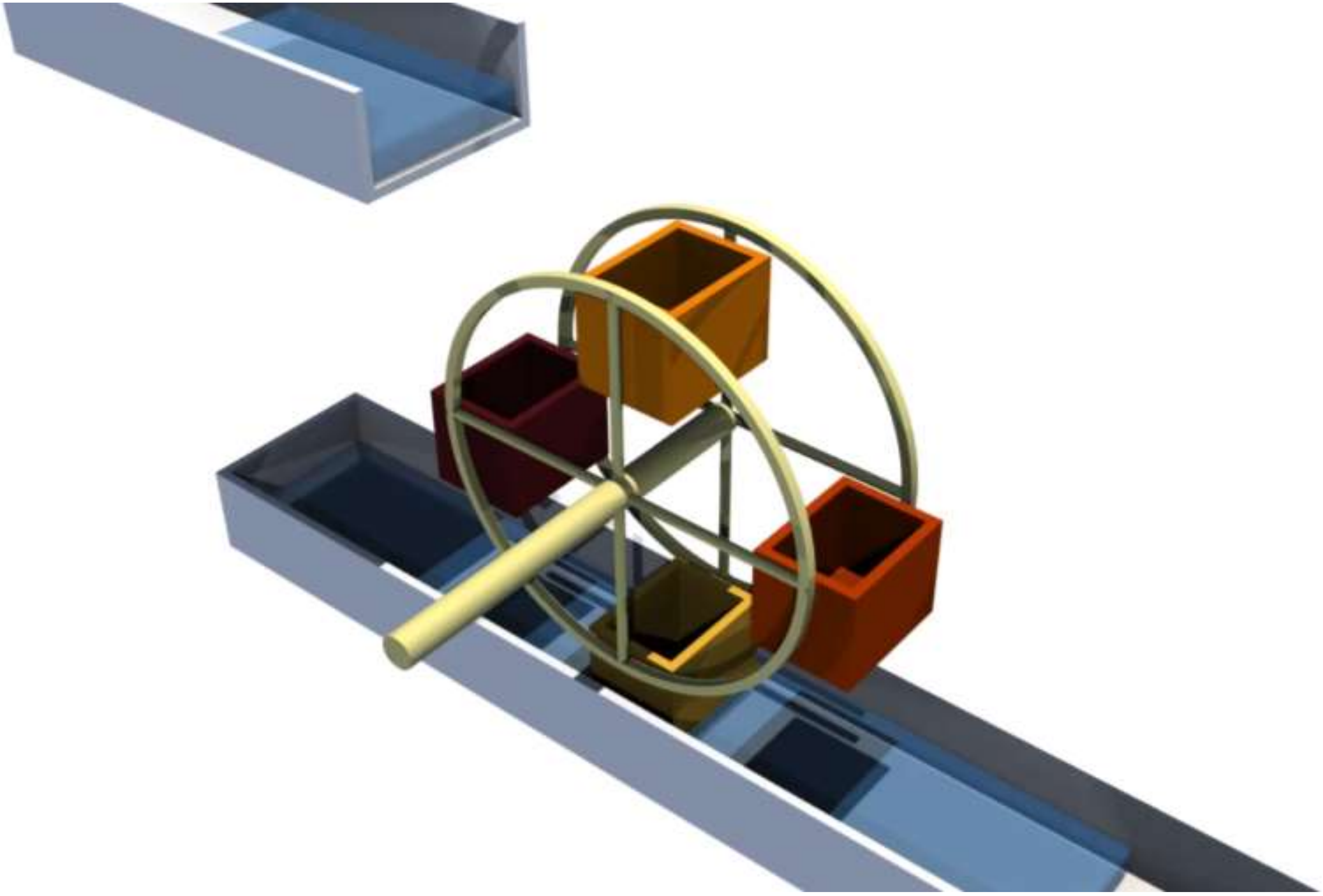
Project Chrono is a **physics-based** modeling and simulation **library** based on a **platform-independent**, **open-source** design - much like DualSPHsysics

- Wide set of joints (spherical, revolute joint, prismatic, universal joint, glyph, with limits, etc.)
- Unilateral constraints
- Exact Coulomb friction model, for precise stick-slip of bodies
- Springs and dampers, even with non-linear features
- Recent support for linear and nonlinear Finite Element Analysis - Euler-Bernoulli beams, bars, shells, cables.



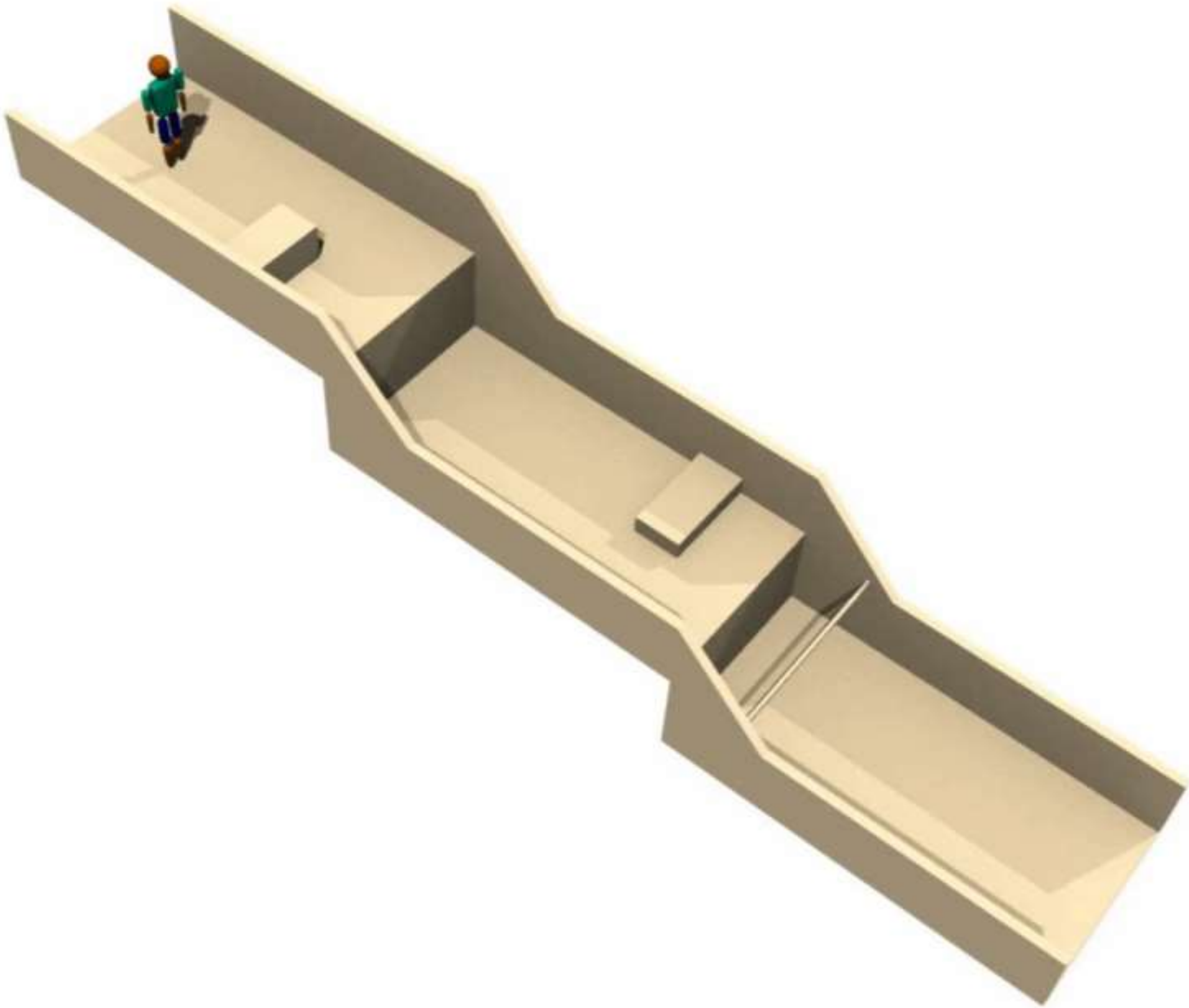
Coupling with CHRONO

Canelas et al., 2018



Coupling with CHRONO

Canelas et al., 2018



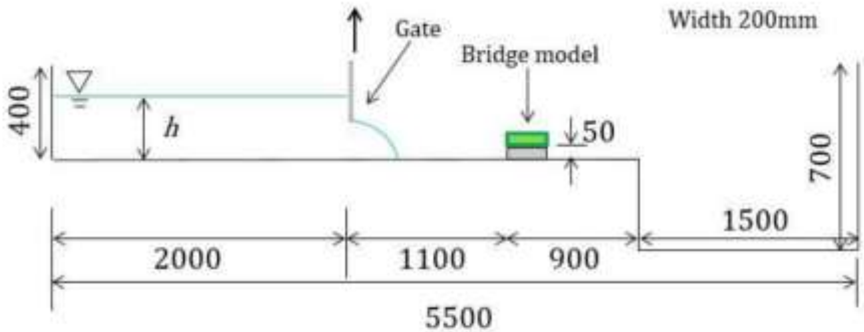
Coupling with CHRONO

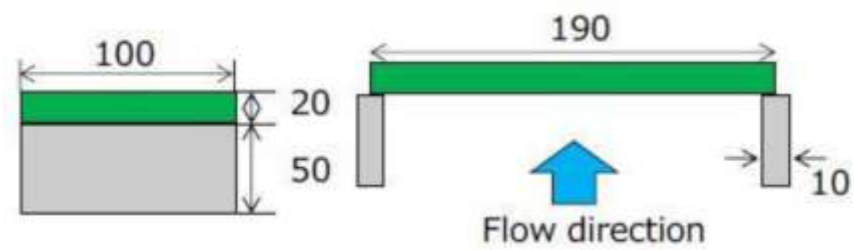
Canelas et al., 2018

VALIDATION

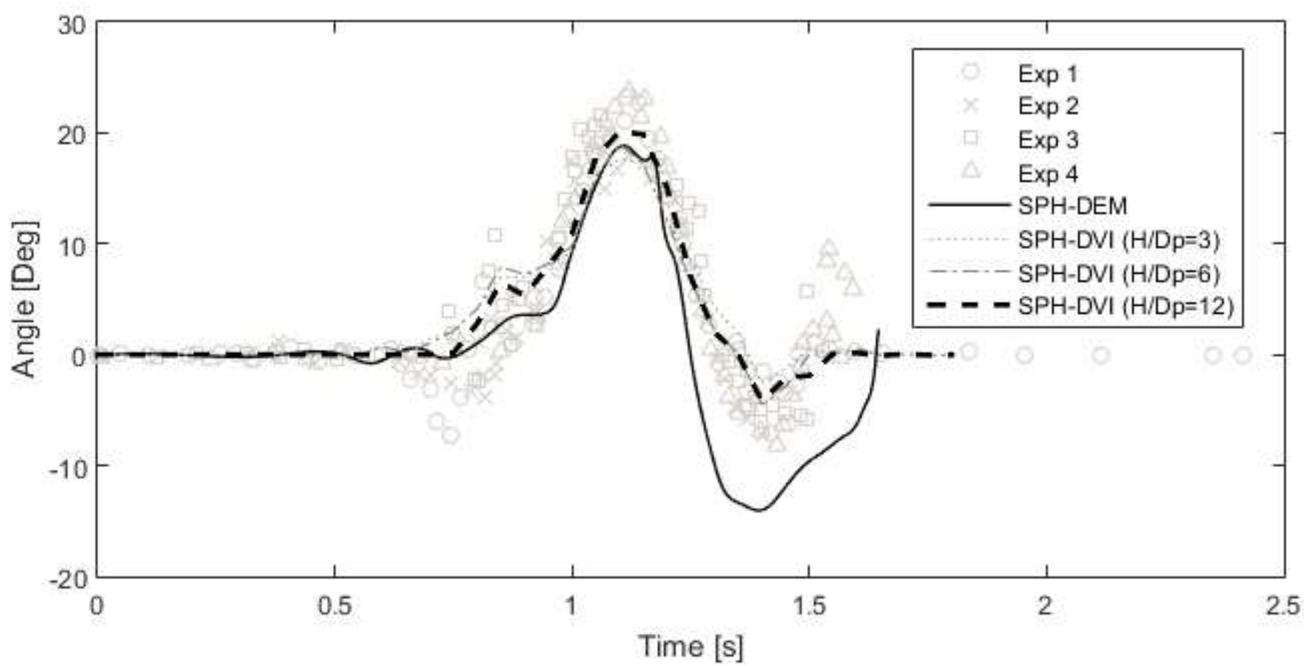
Platform experimental set up. Dimensions in mm.

Chandra and Asai, 2016



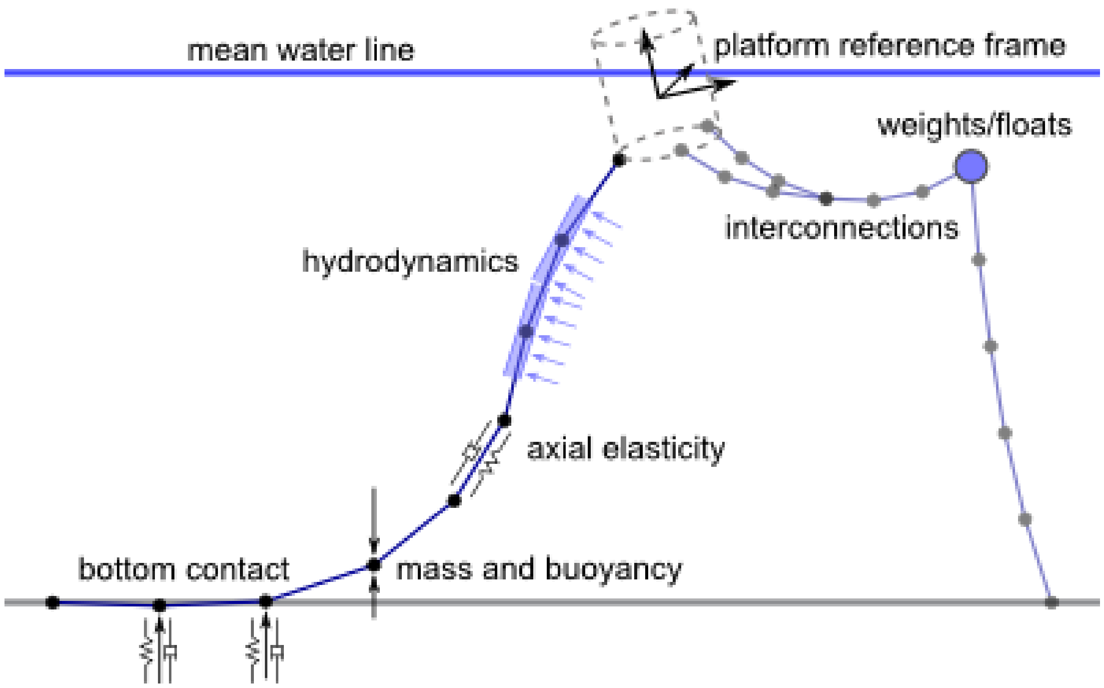


Rotation angle for h_0=300mm



Coupling with MOORDYN

MoorDyn is an open-source dynamic mooring line model that uses a lumped-mass formulation for modelling axial elasticity, hydrodynamics, and bottom contact.



http://www.matt-hall.ca/moordyn/

Coupling with MOORDYN

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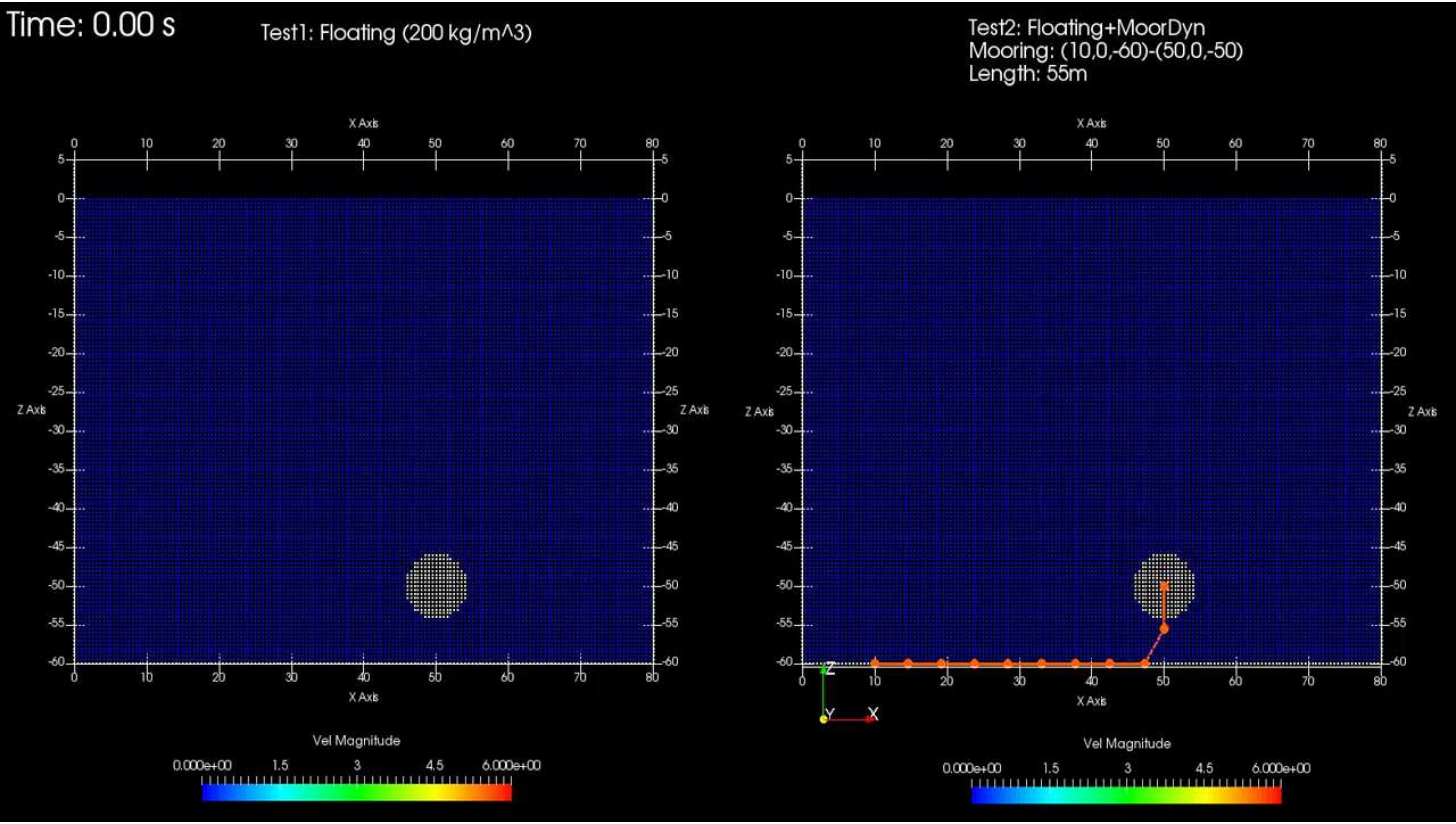
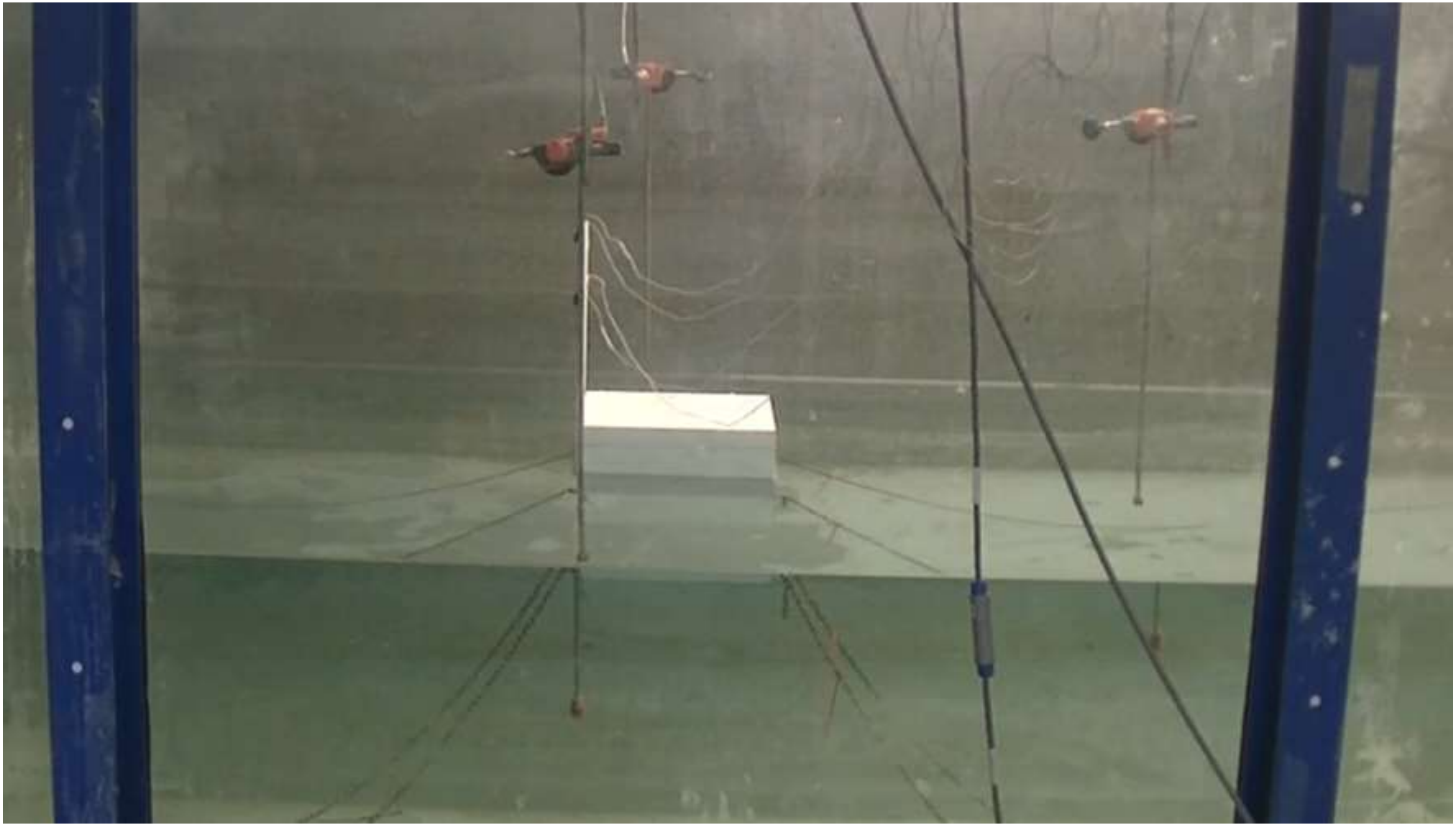


Coupling with MOORDYN

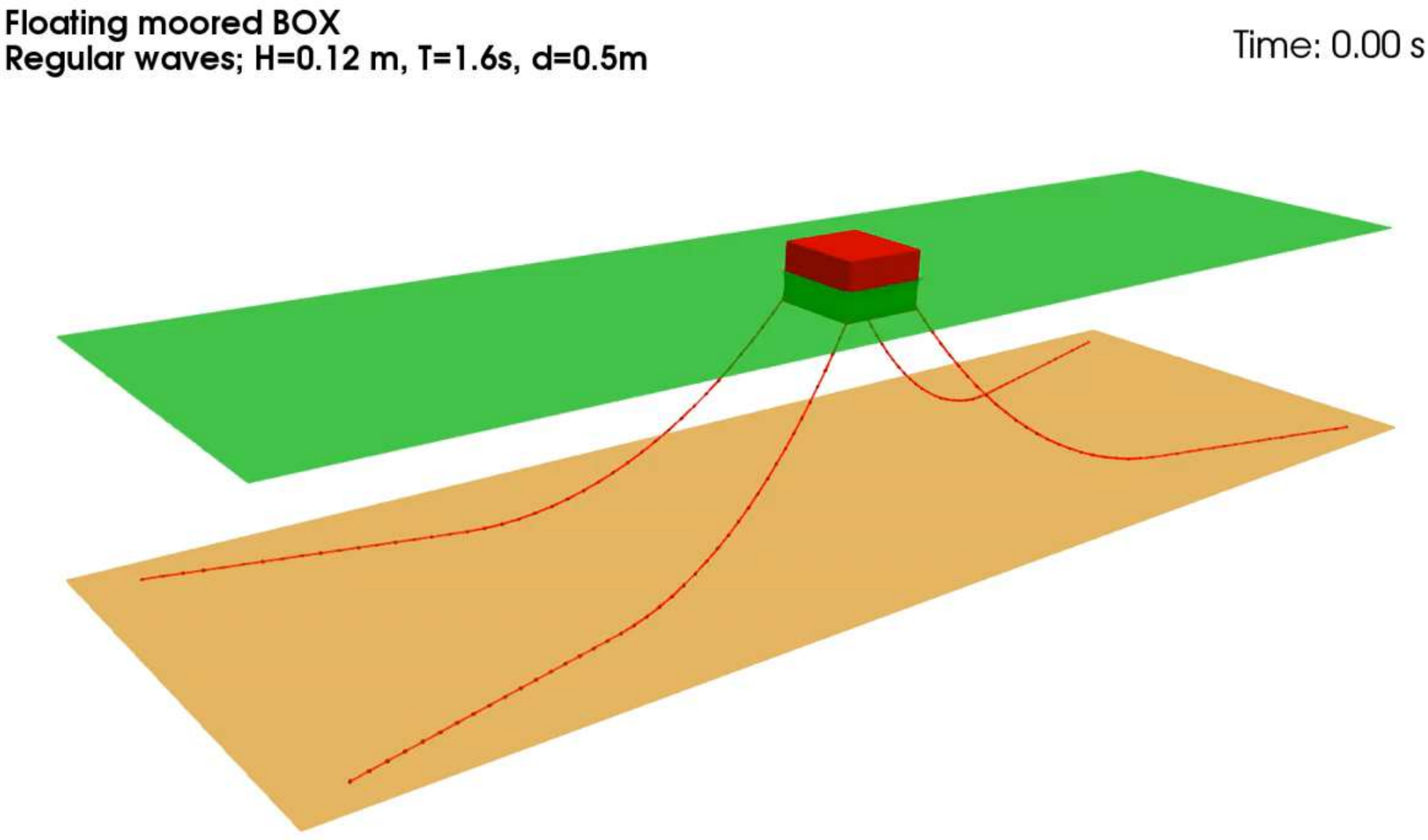
VALIDATION

EXPERIMENT IN GHENT UNIVERSITY: FLOATING BOX

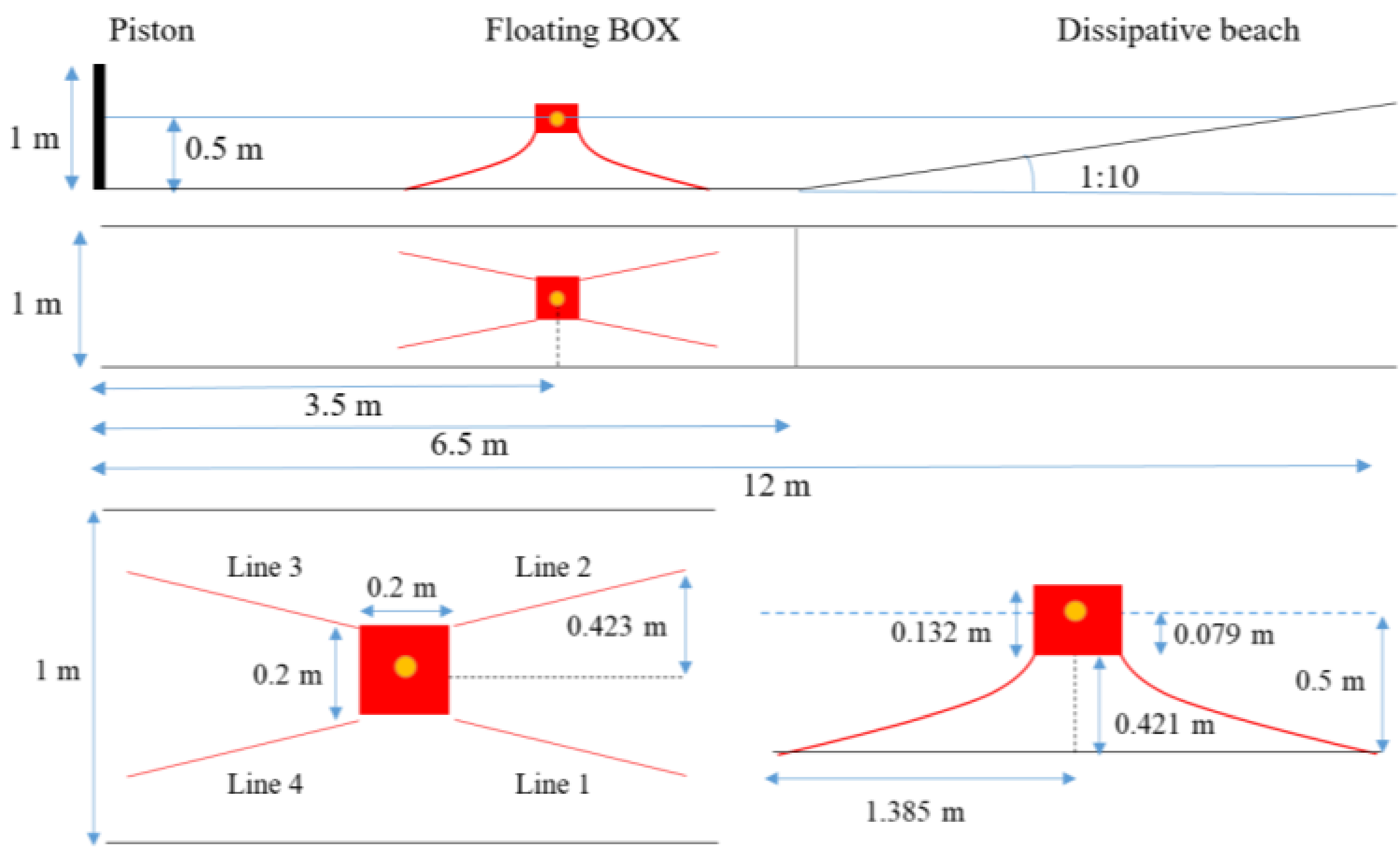


Coupling with MOORDYN

VALIDATION



Coupling with MOORDYN



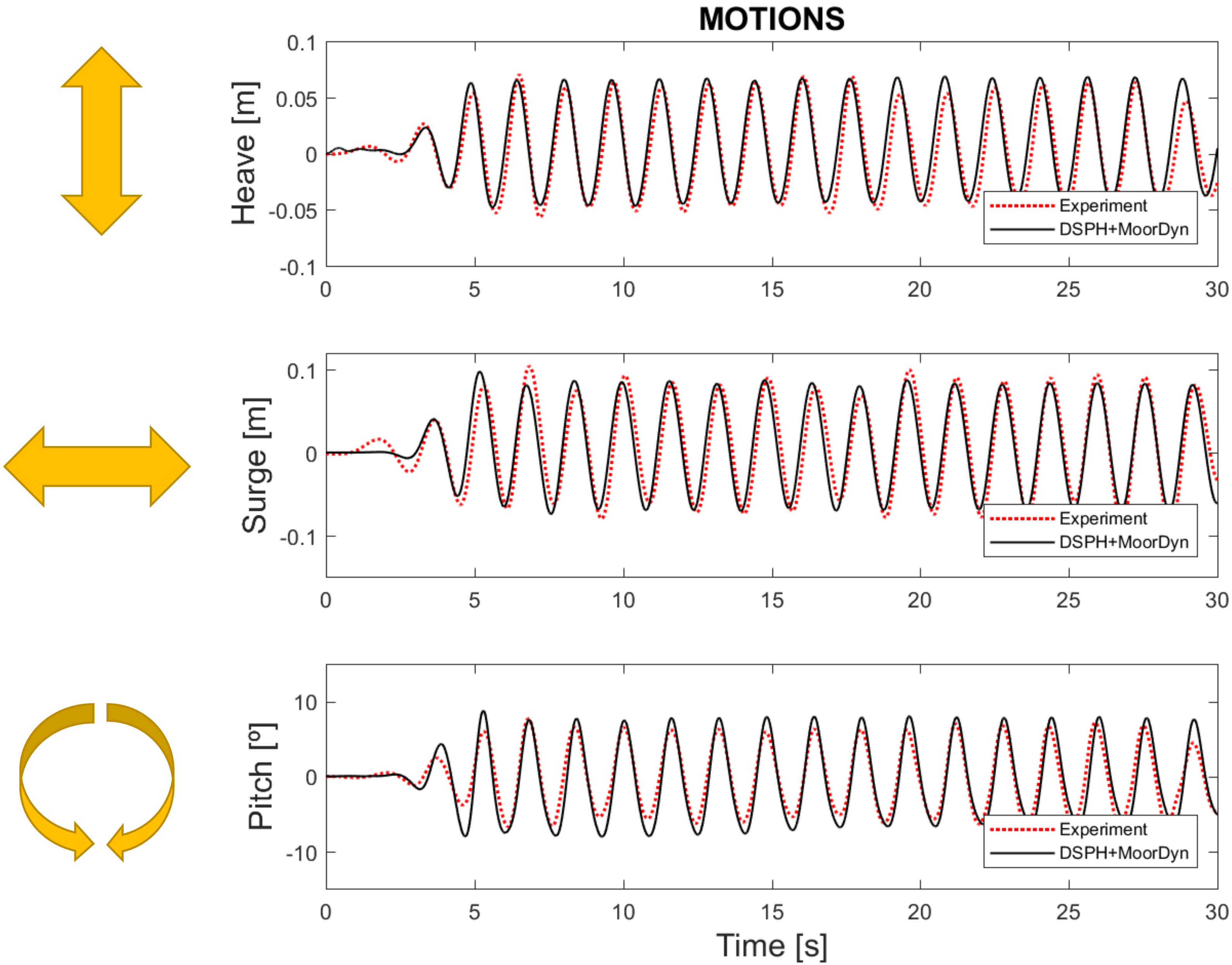
Regular waves

- H=0.12 m
- T=1.6 s
- d=0.5 m
- L=3 m

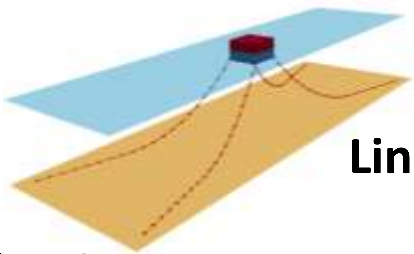
DualSPHysics	
BOX Dimensions	20 x 20 x 13.2 cm^3
BOX Weight	3 kg + 0.6 kg(extra)
BOX Centre of gravity	(0, 0, -1.26) cm
BOX Lip draught	7.86 cm

MoorDyn	
MOORING Diameter	3.656 mm
MOORING Weight	0.607 g/cm
MOORING Length	145.5 cm
Water depth	50 cm

Coupling with MOORDYN

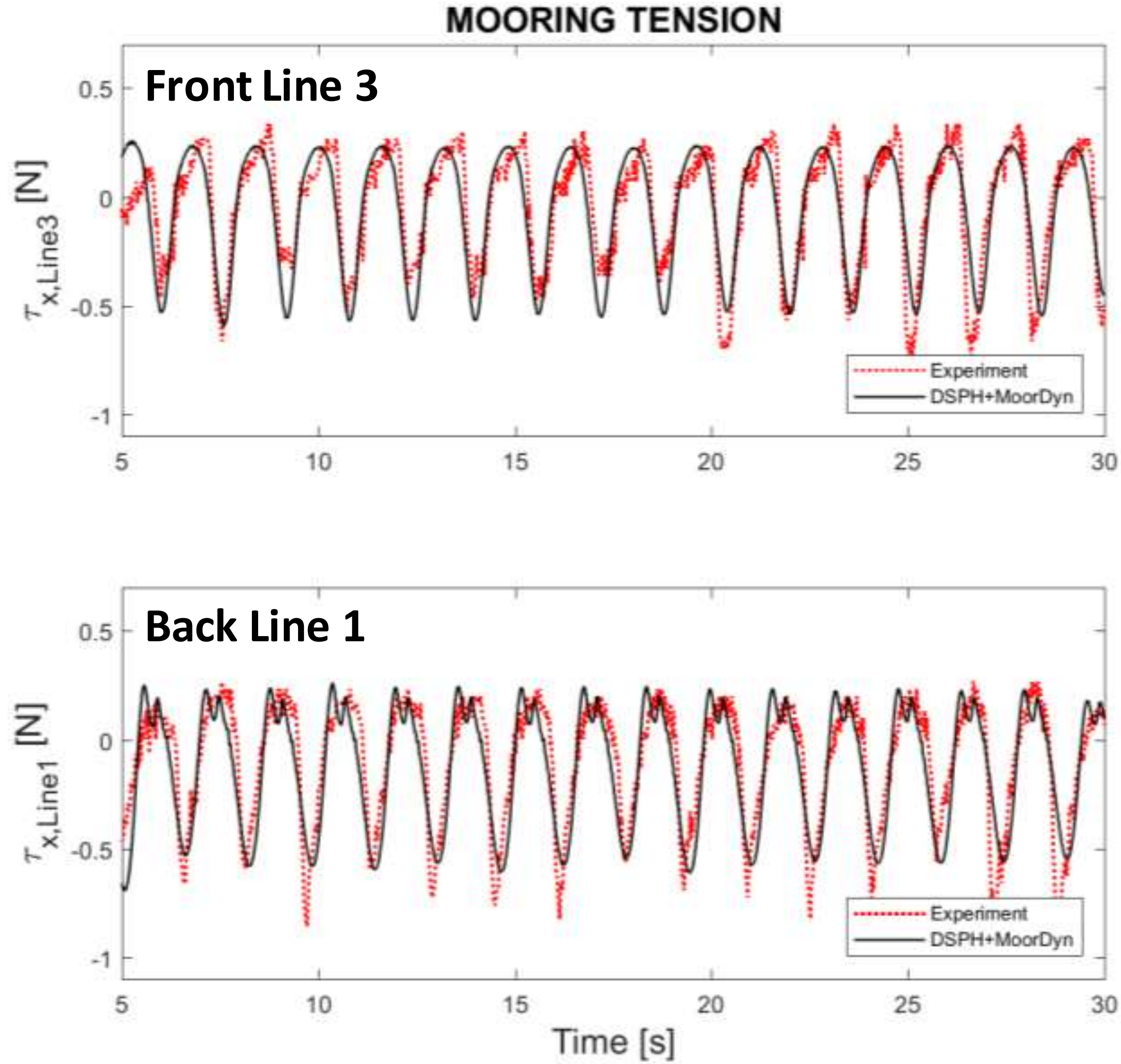


Coupling with MOORDYN



Line 1

Line 3



OUTLINE

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With Chrono
With MoorDyn

Wave Energy Converters design

Visualisation

Wave Energy Converters design

NUMERICAL MODELLING

Hydrodynamic interaction between WECs and ocean waves
is a complex high order non-linear process

FAST AND EFFICIENT
LOW AMPLITUDE MOTIONS

Linear approach
Time or frequency domain models

WAMIT

TIME CONSUMING
VIOLENT FLOWS

CFD models
Approximate Navier–Stokes

Meshbased methods

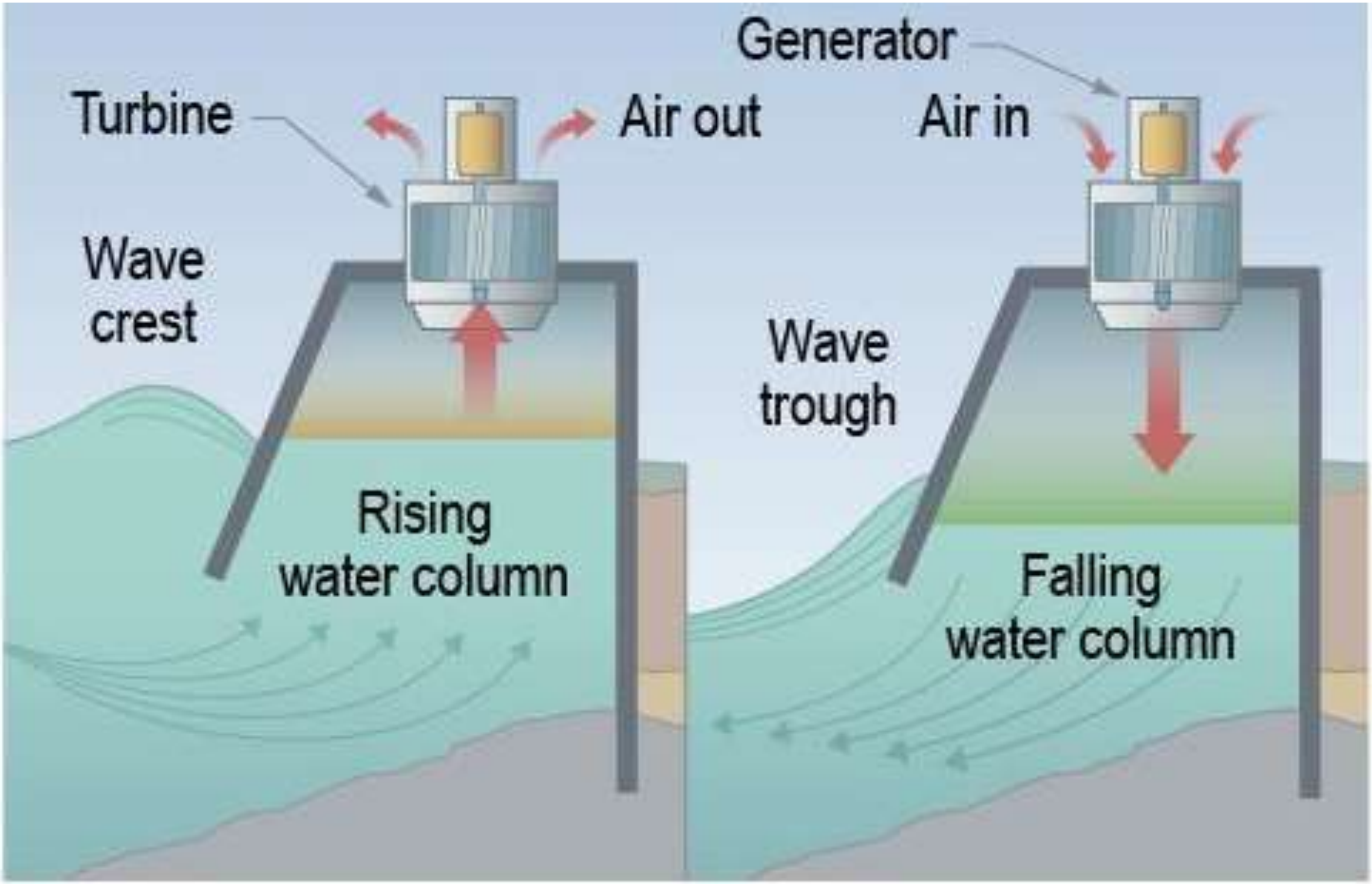
OpenFoam

Meshless methods

SPH

Wave Energy Converters design

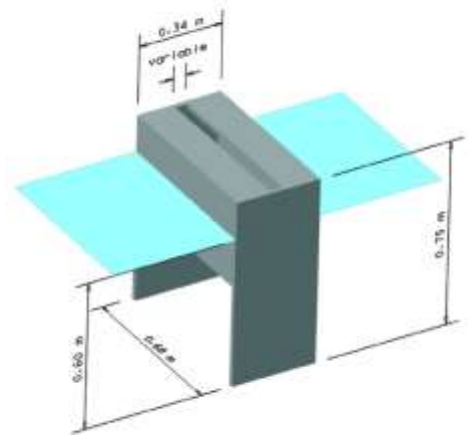
OSCILLATING WATER COLUMN



http://en.openei.org/

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).



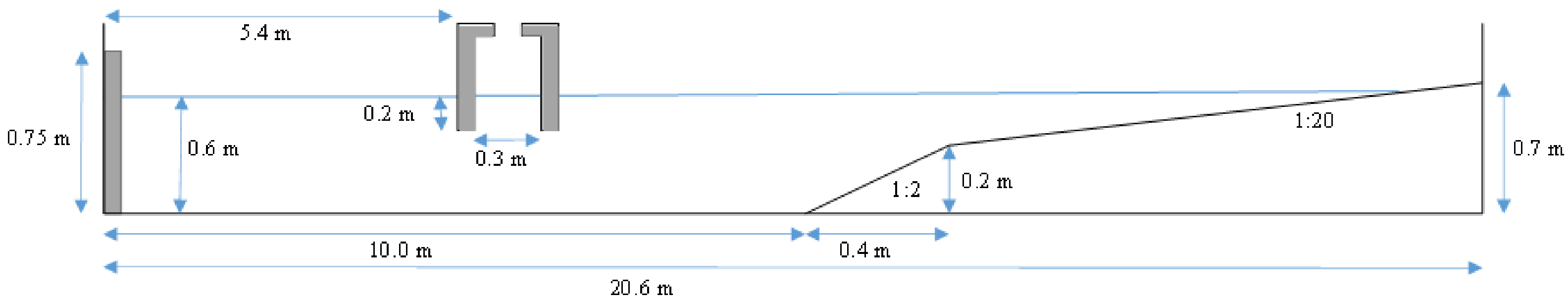
Iturrioz, A., Guanche, R., Armesto, J.A., Alves, M.A., Vidal, C., Losada, I.J. 2014. Time-domain modeling of a fixed detached oscillating water column towards a floating multi-chamber device, Ocean Engineering, 76, 65-74.

Wave Energy Converters design

Crespo et al., 2017

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)

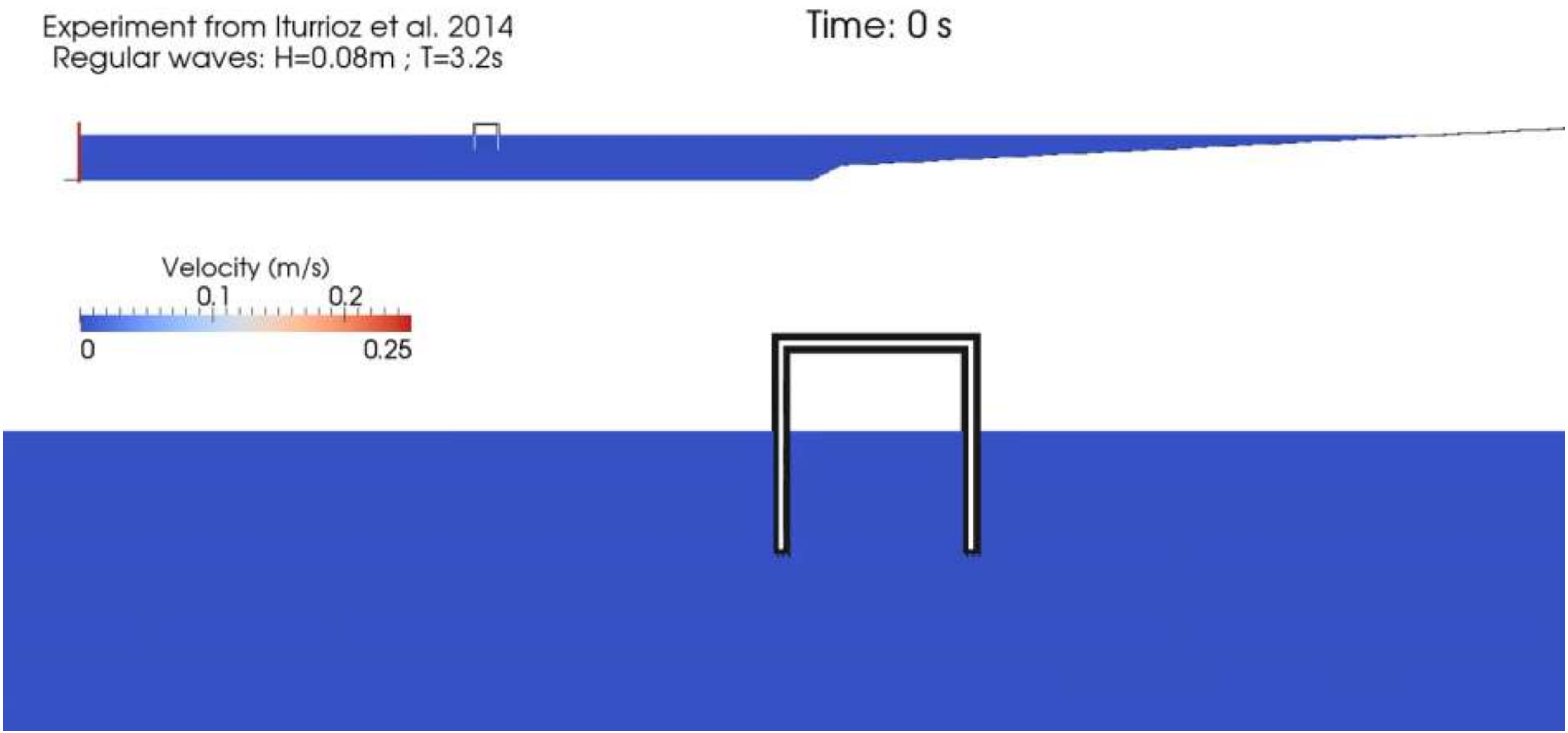
Height (H)	Period (T)	Depth (d)	Wavelength (L)	Relative depth (d/L)	Wave order
0.08 m	3.2 s	0.6 m	7.46 m	0.08	Stokes 2nd order

Iturrioz, A., Guanche, R., Armesto, J.A., Alves, M.A., Vidal, C., Losada, I.J. 2014. Time-domain modeling of a fixed detached oscillating water column towards a floating multi-chamber device, Ocean Engineering, 76, 65-74.

Wave Energy Converters design

Crespo et al., 2017

EXPERIMENT IN IH-CANTABRIA

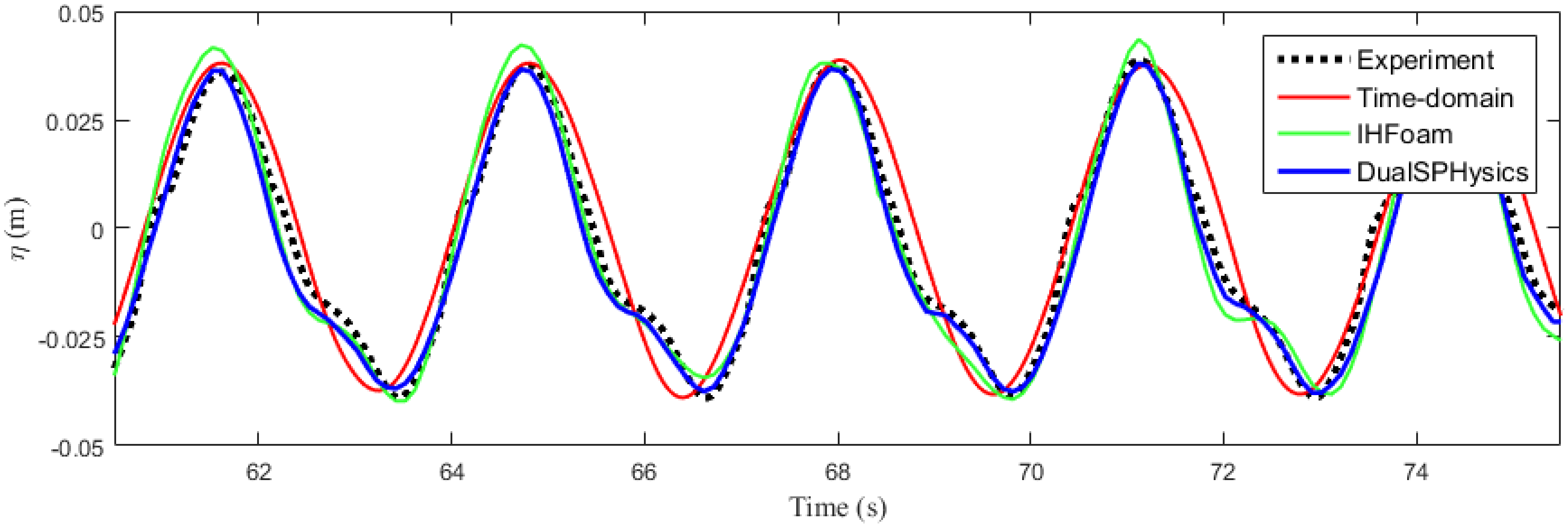


Wave Energy Converters design

Crespo et al., 2017

EXPERIMENT IN IH-CANTABRIA

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

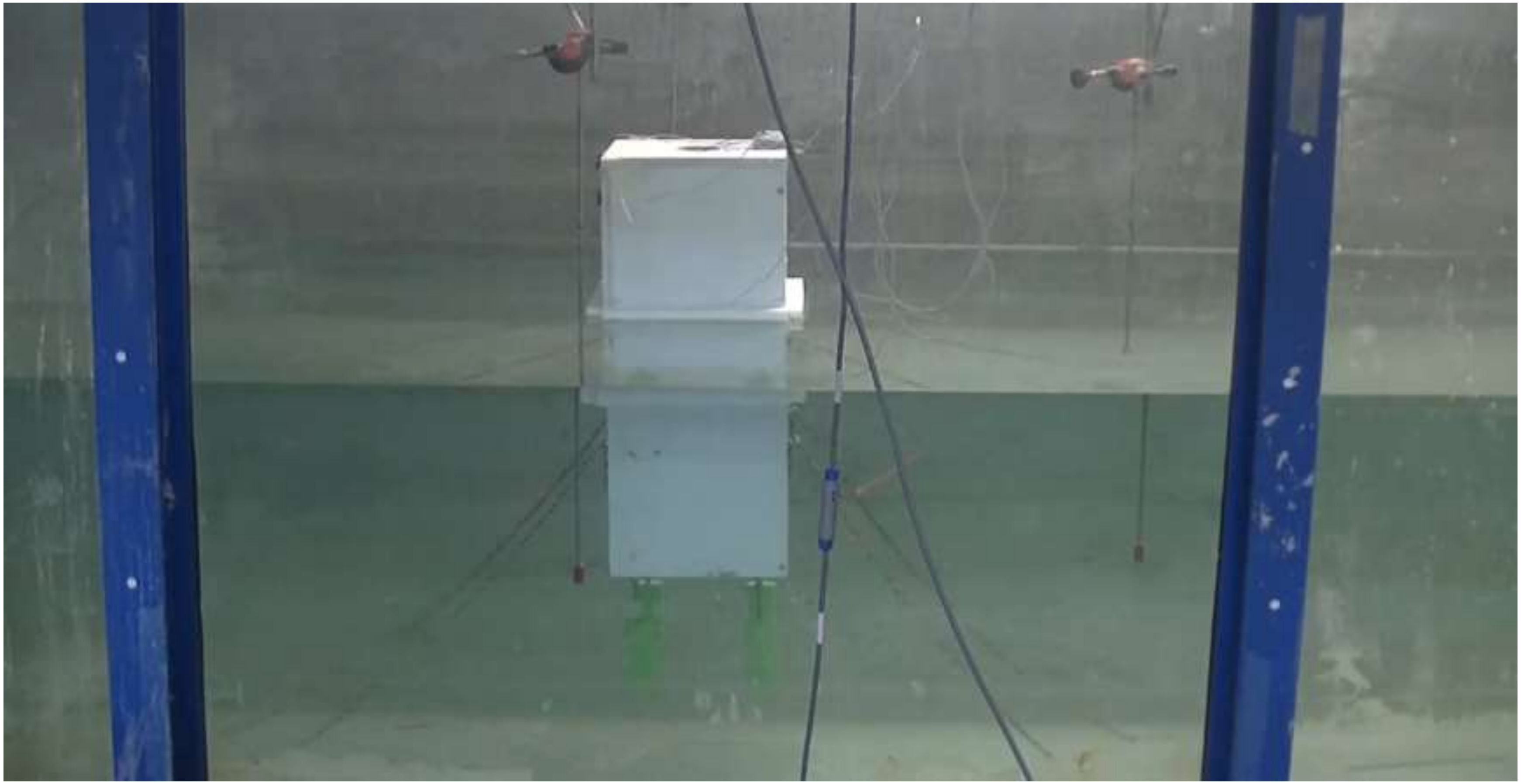


Elevation inside the chamber:
Experiment vs Time-domain vs IHFoam vs DualSPHysics

Wave Energy Converters design

OFFSHORE FLOATING OWC IN THE OPEN SEA

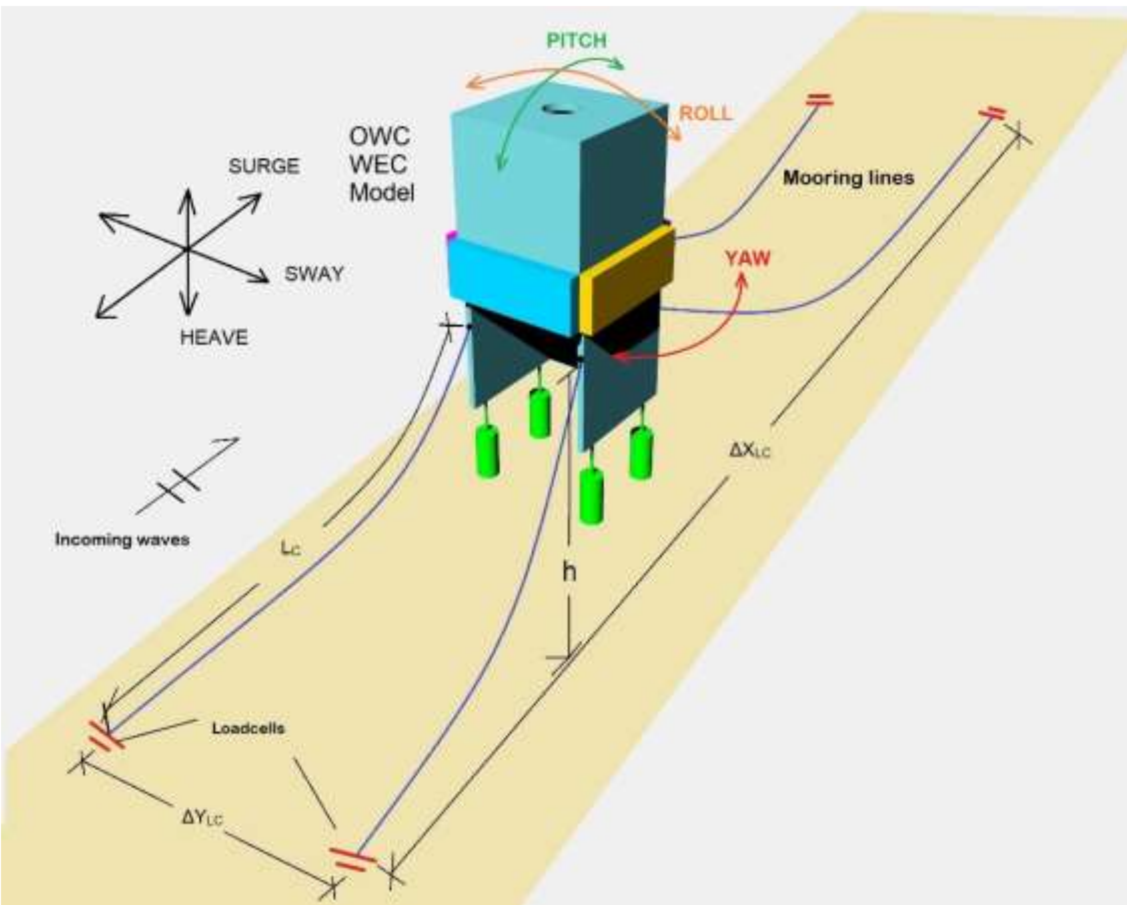
EXPERIMENT IN GHENT UNIVERSITY: OFFSHORE OWC

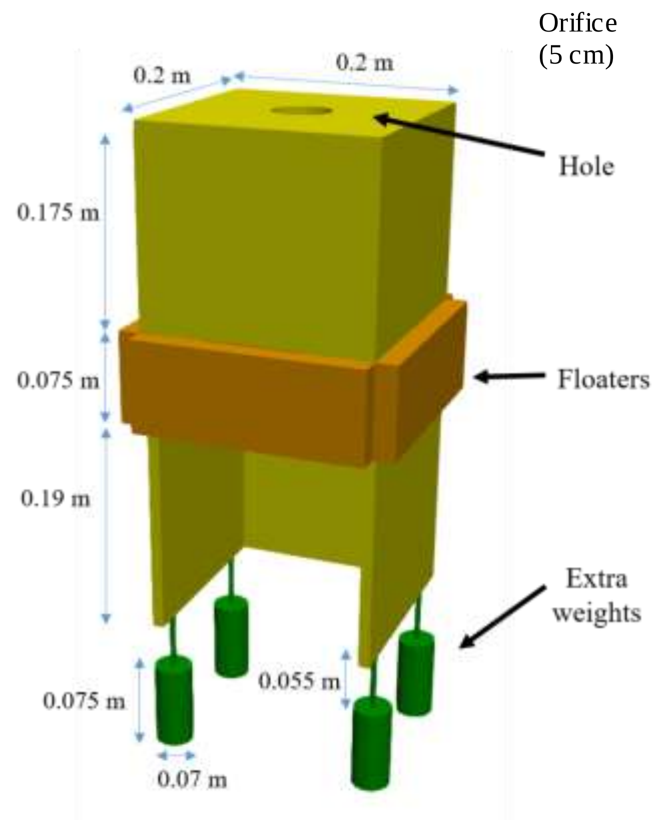


Wave Energy Converters design

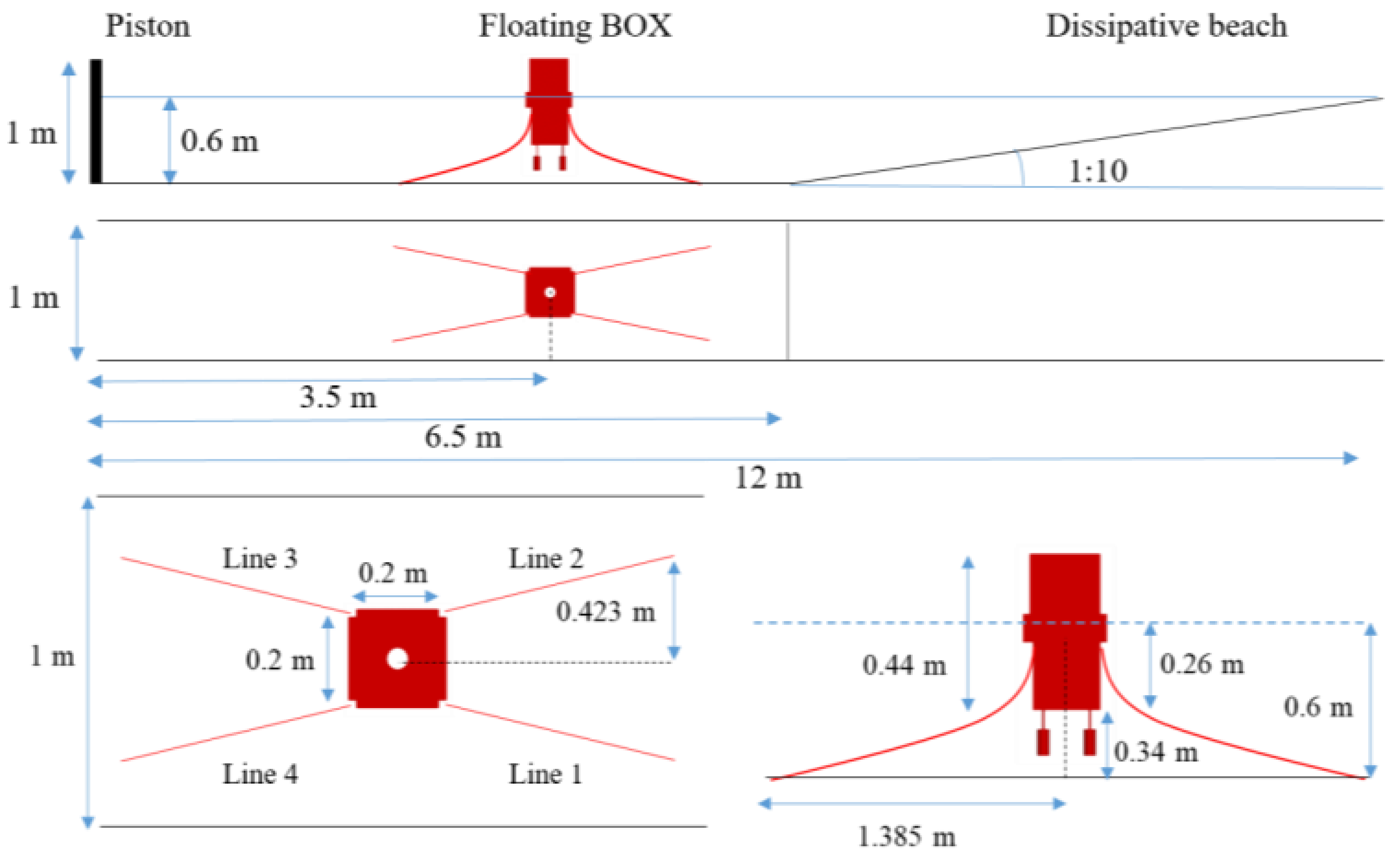
OFFSHORE FLOATING OWC IN THE OPEN SEA

OWC with different materials but total MASS is 2.593 kg
SPH particles of density 578 kg/m^3





Wave Energy Converters design



Regular waves

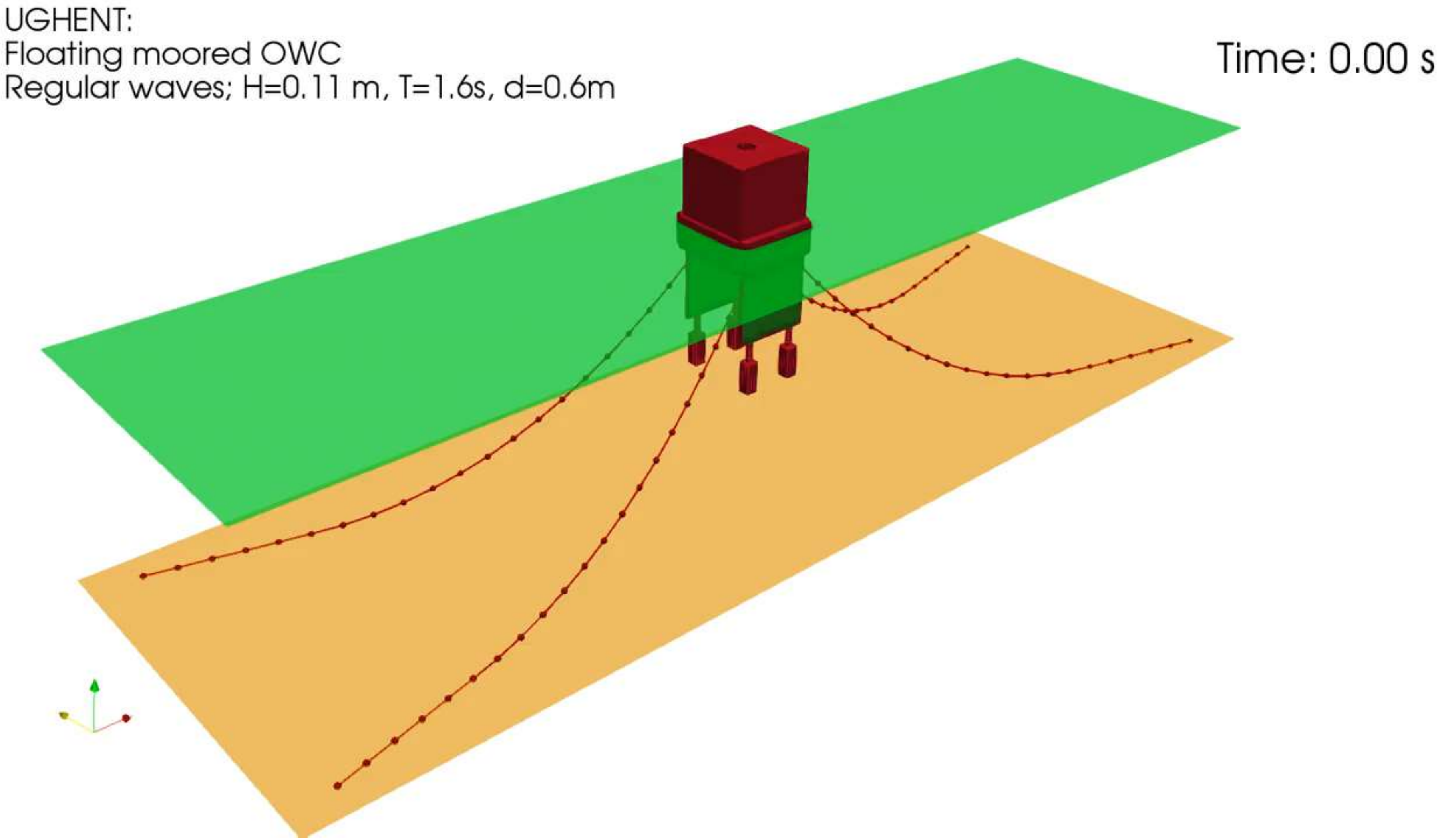
- H=0.11 m
- T=1.6 s
- d=0.6 m
- L=3.27 m

DualSPHysics	
OWC Dimensions	20 x 20 x 44 cm^3
OWC Weight	2.593 kg
OWC Centre of gravity	(-0.91, 0, -10.8) cm

MoorDyn	
MOORING Diameter	3.656 mm
MOORING Weight	0.607 g/cm
MOORING Length	145.5 cm
Water depth	50 cm

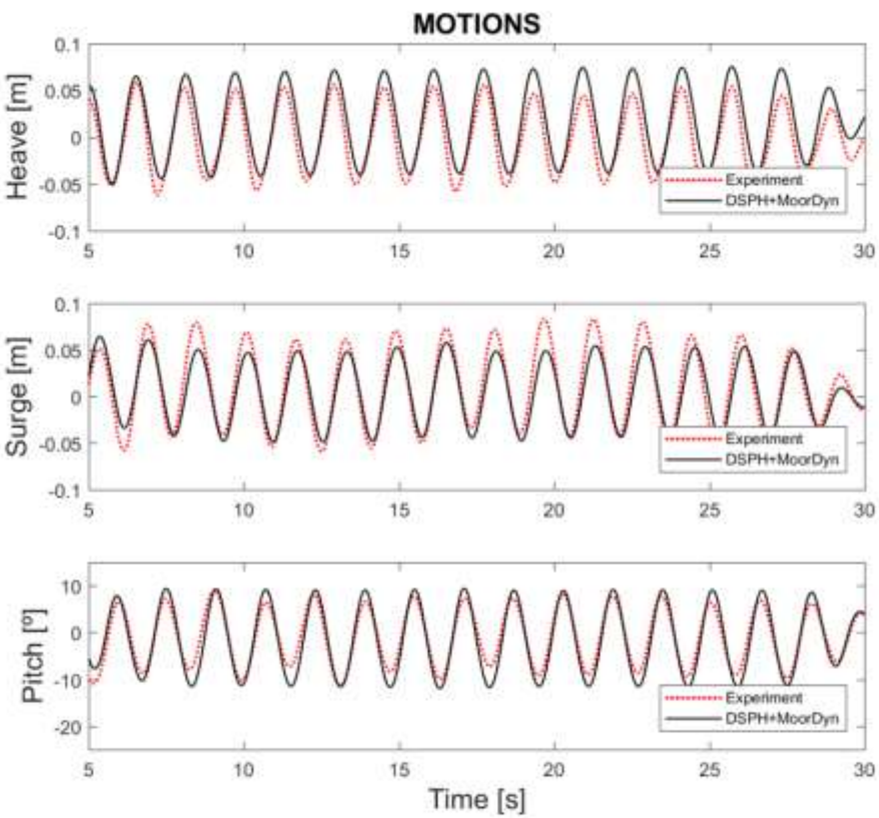
Wave Energy Converters design

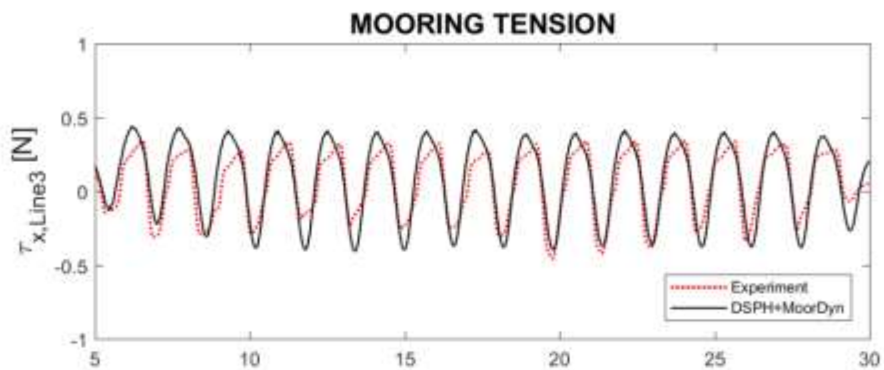
OFFSHORE FLOATING OWC IN THE OPEN SEA



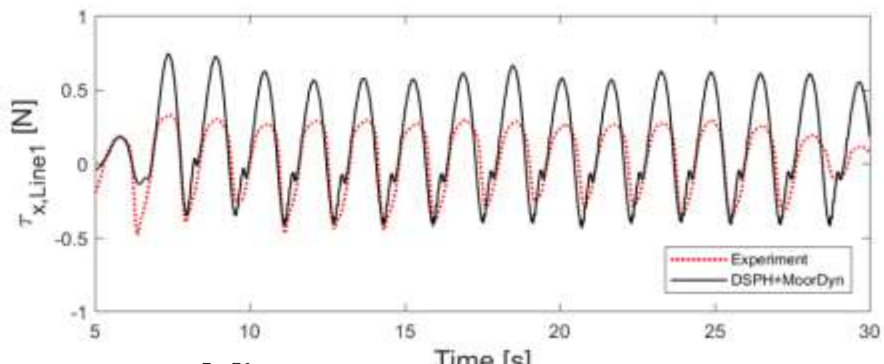
Wave Energy Converters design

OFFSHORE FLOATING OWC IN THE OPEN SEA

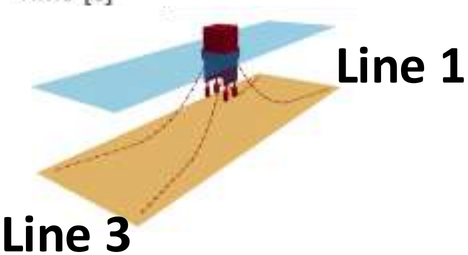




Front line



Back line



Wave Energy Converters design

OFFSHORE FLOATING OWC IN THE OPEN SEA

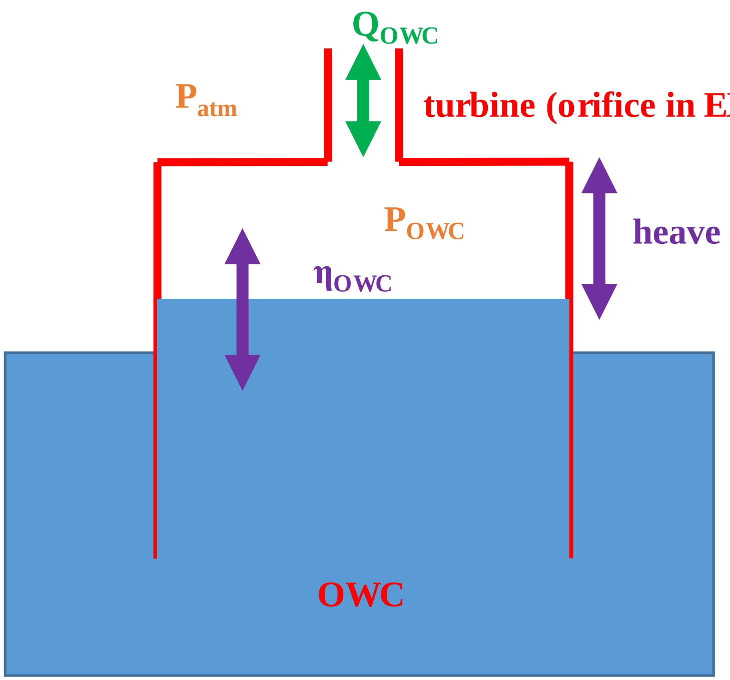
ENERGY CONVERSION

AIR FLUX TROUGH THE TURBINE

PRESSURE DIFFERENCE OF AIR INSIDE AND OUTSIDE OWC

CHANGES IN AIR VOLUME INSIDE OWC

RELATIVE MOTION BETWEEN HEAVE AND WATER ELEVATION INSIDE OWC

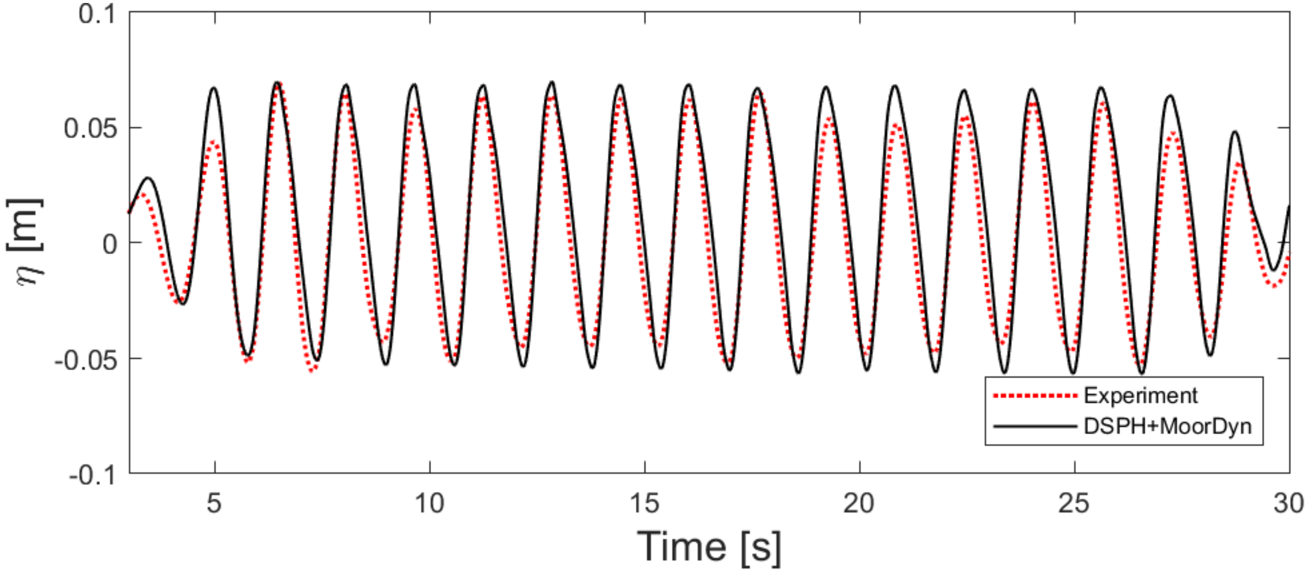


heave - η_{OWC}

Wave Energy Converters design

OFFSHORE FLOATING OWC IN THE OPEN SEA

η_{OWC}



RELATIVE MOTION BETWEEN HEAVE AND WATER ELEVATION INSIDE OWC

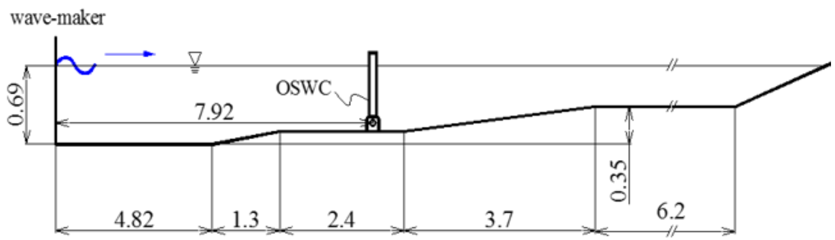
heave - η_{OWC}

Wave Energy Converters design

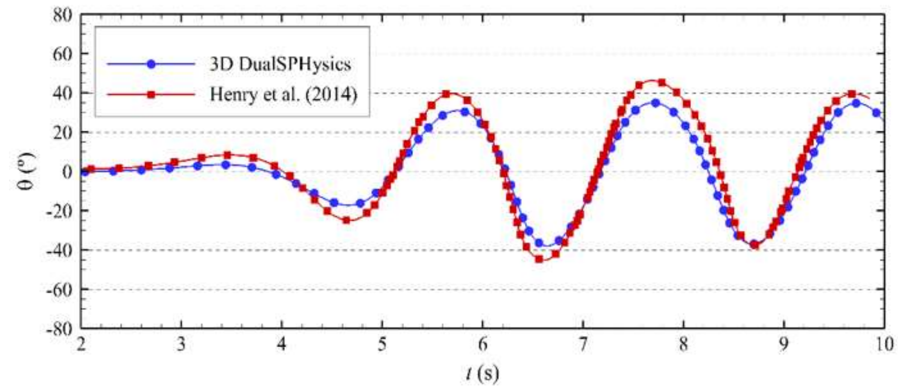
Brito et al., 2017

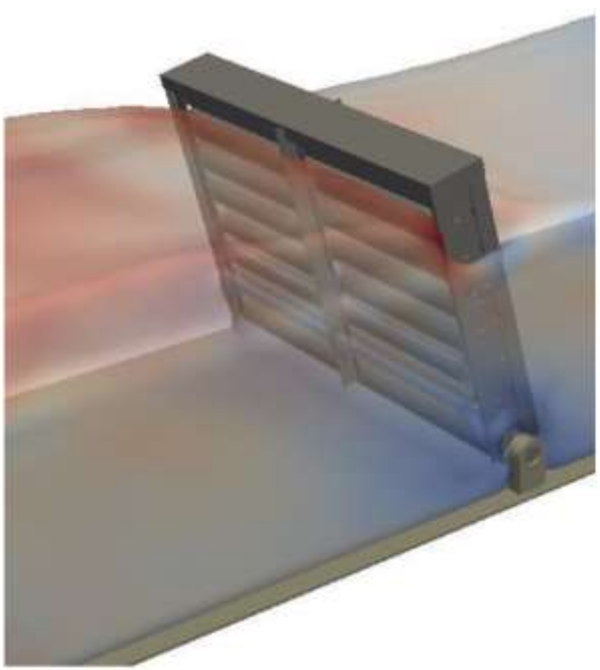
Coupling with CHRONO

Application to Wave Energy Converters – Wave roller



Experimental set up at the Marine Research Group's hydraulics laboratory at Queen's University Belfast.



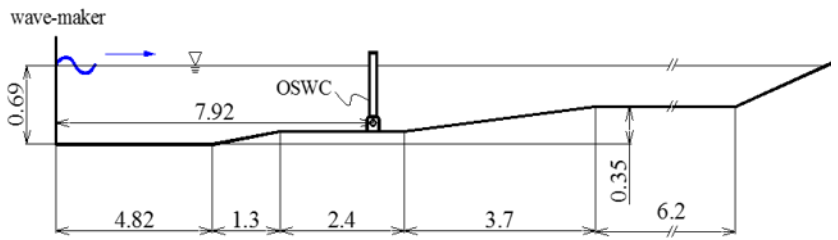


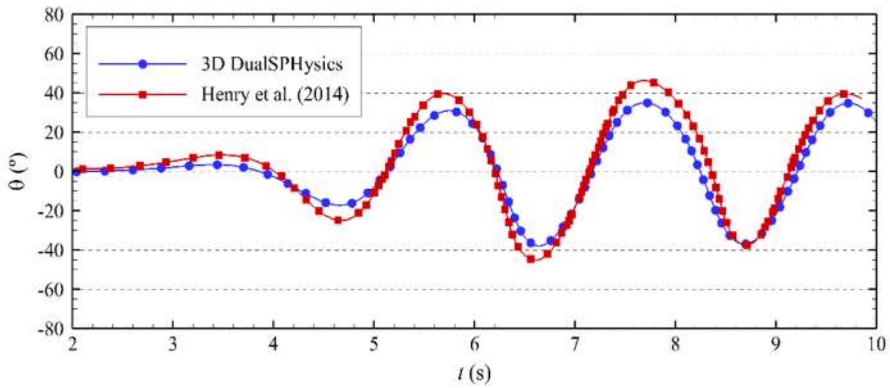
Wave Energy Converters design

Brito et al., 2017

Coupling with CHRONO

Application to Wave Energy Converters – Wave roller





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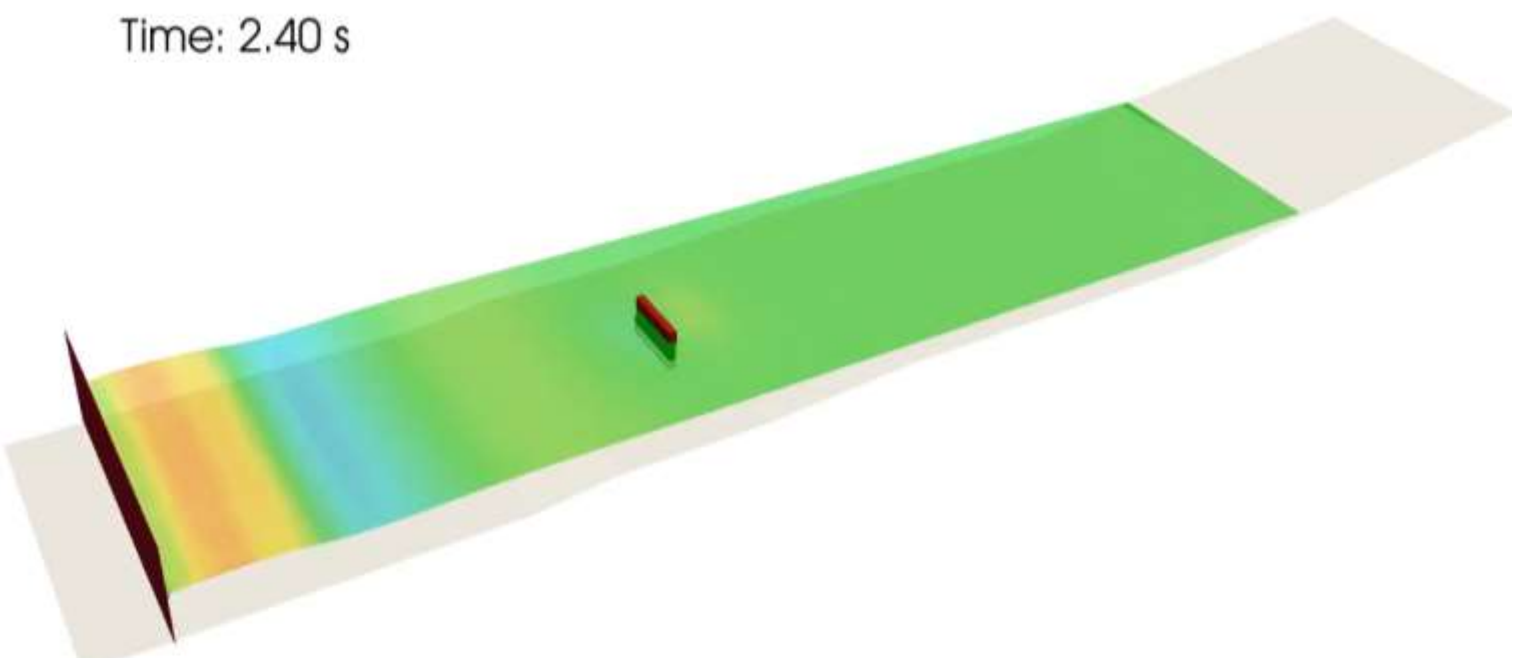
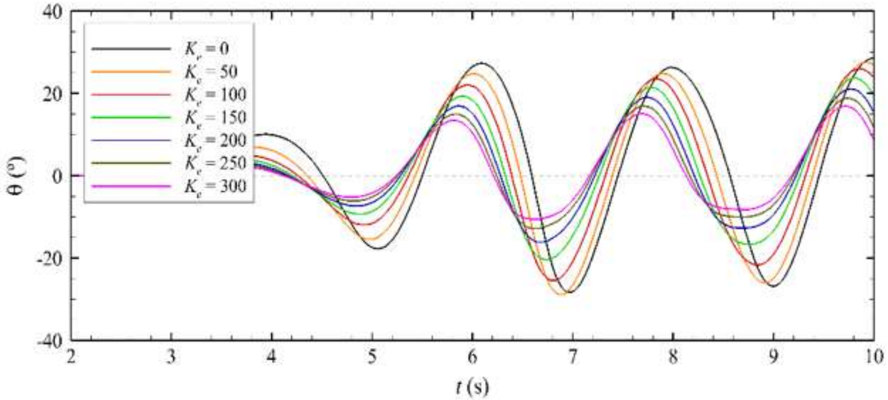
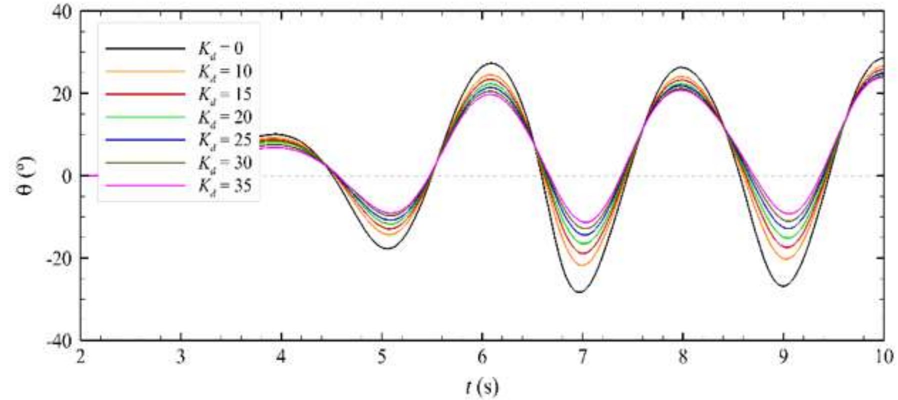


Wave Energy Converters design

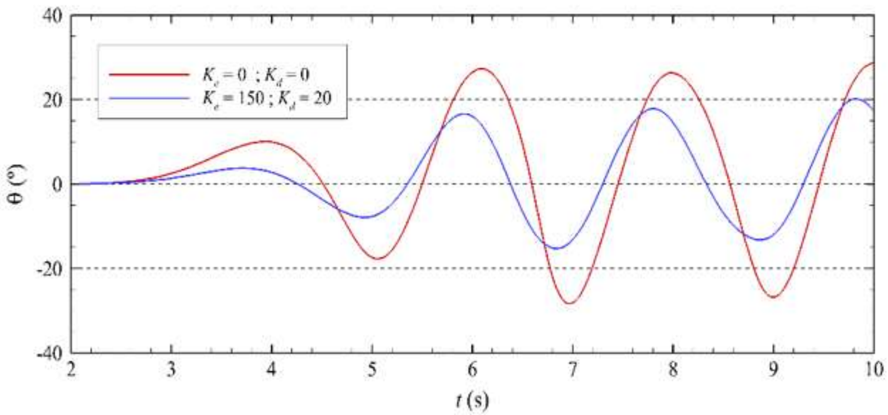
Coupling with CHRONO

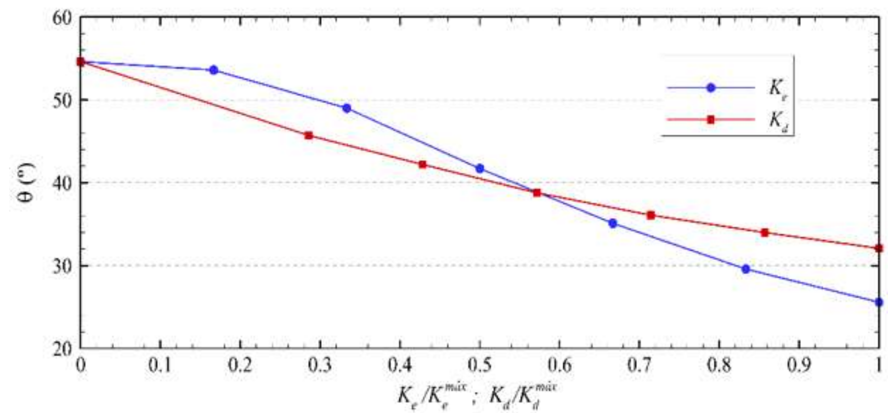
Application to Wave Energy Converters – Wave roller





Introducing different values of the elastic coefficient (K_e) and the damping coefficient (K_d), we can go beyond the current experiments.





OUTLINE

Validations and applications

I. Dam break

II. Wave generation and absorption

II. Wave-structure interaction

III. Floating bodies

IV. Solid interactions

Coupling with other libraries

With SWASH

With Chrono

With MoorDyn

Wave Energy Converters design

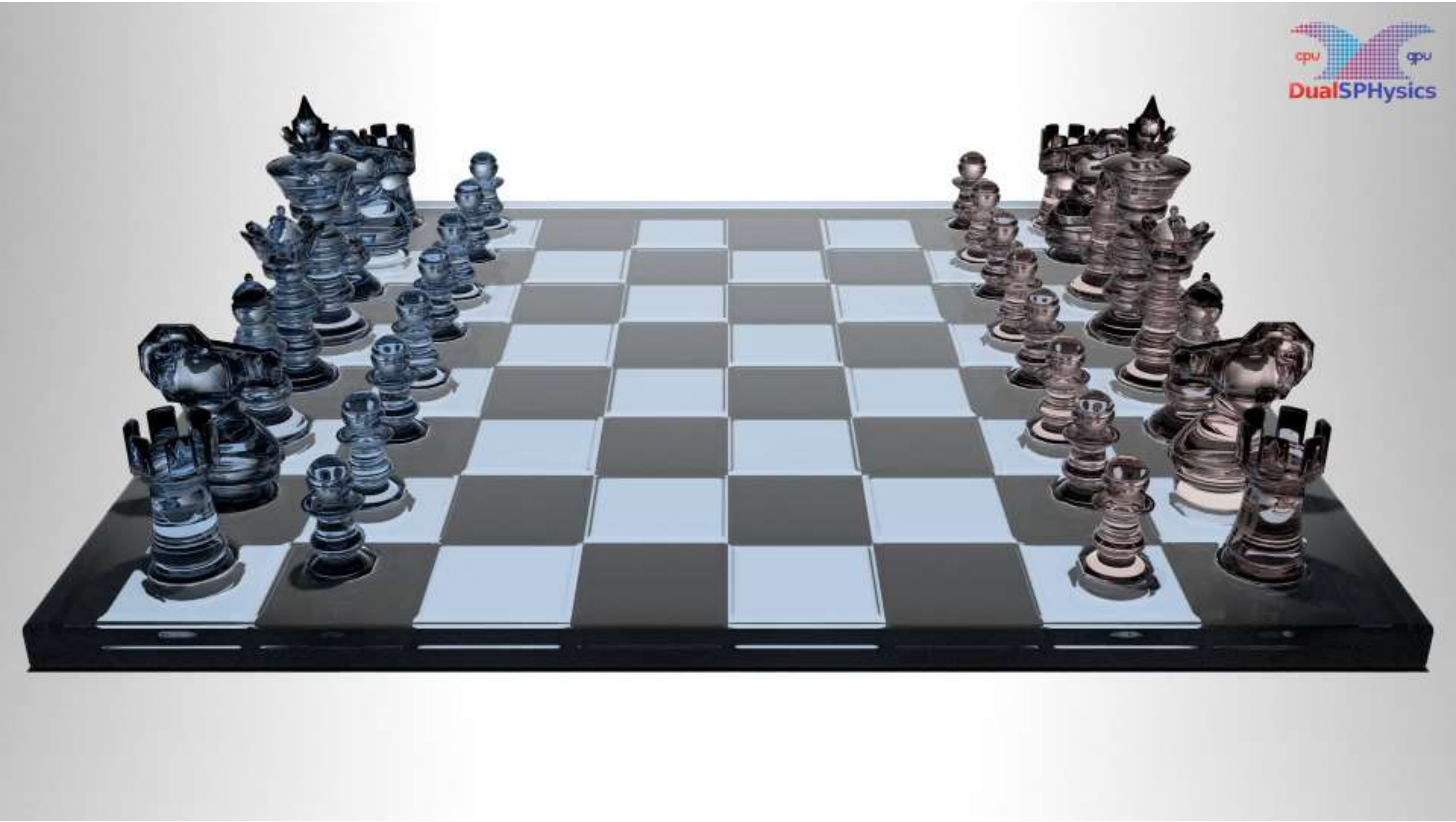
Visualisation

Visualisation

Film industry has been using SPH and to create fluid effects

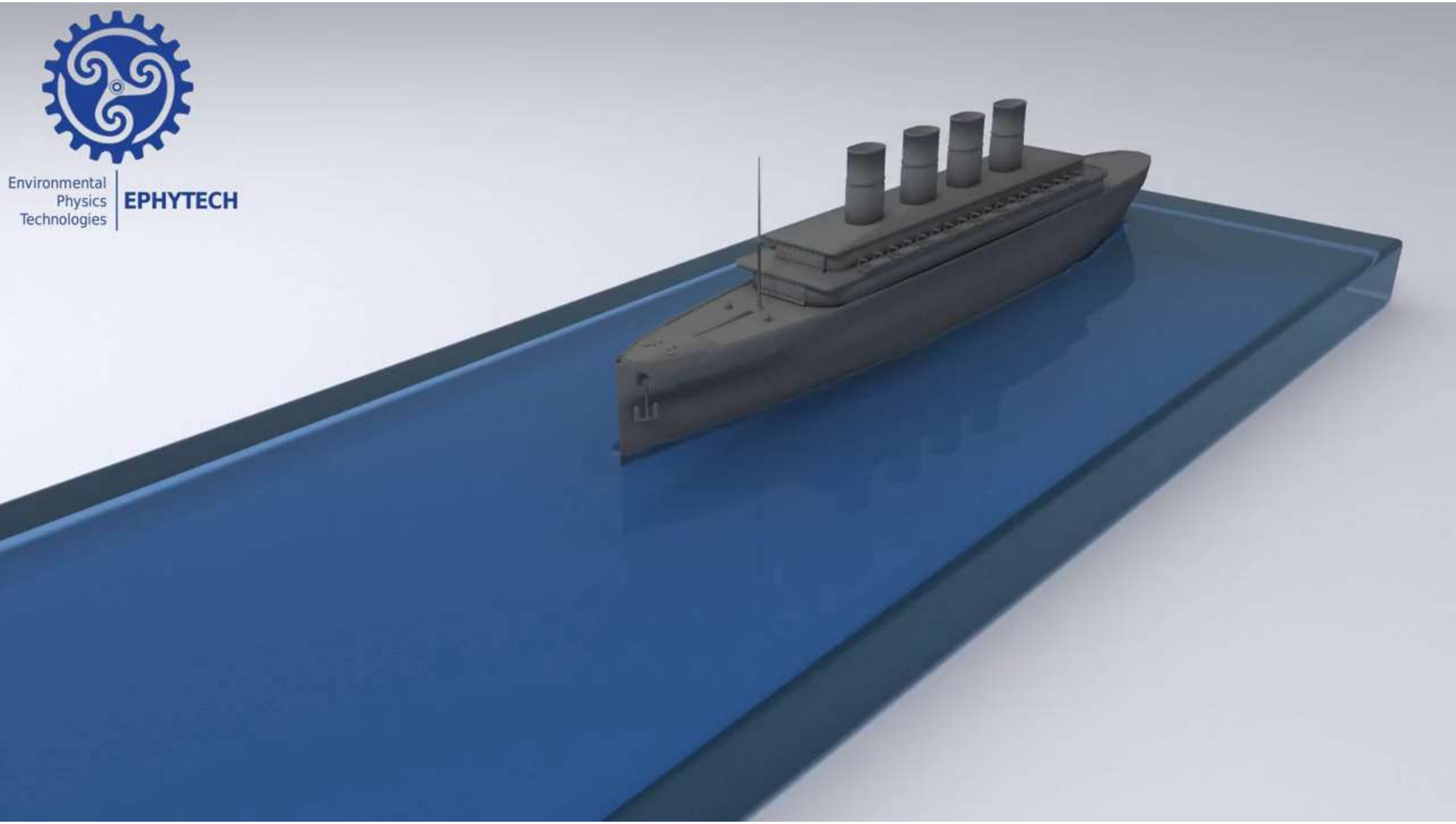
Visualisation

Visualisation



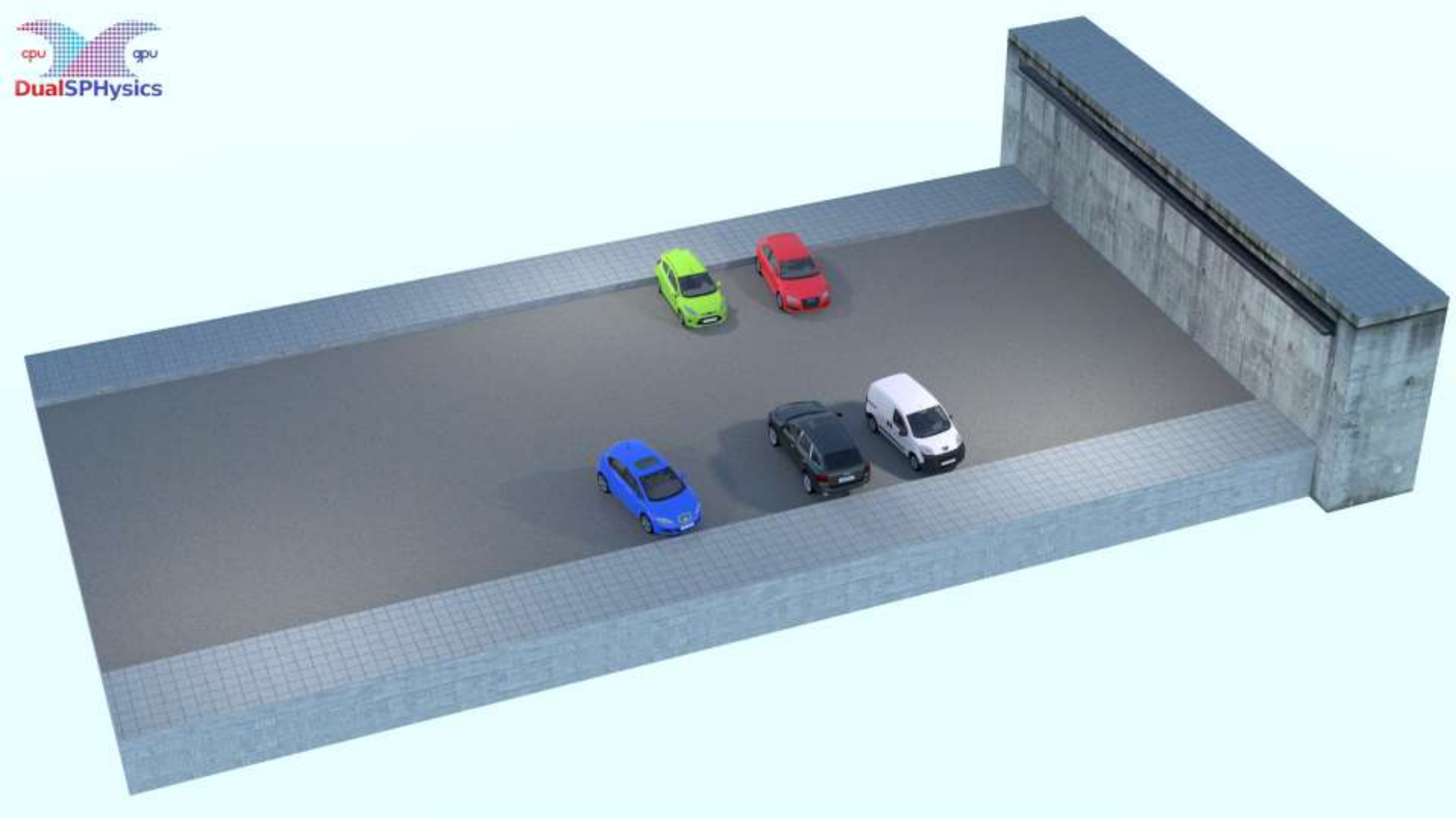
Visualisation

Visualisation



Visualisation

Visualisation



Visualisation

Visualisation

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THANKS FOR YOUR ATTENTION