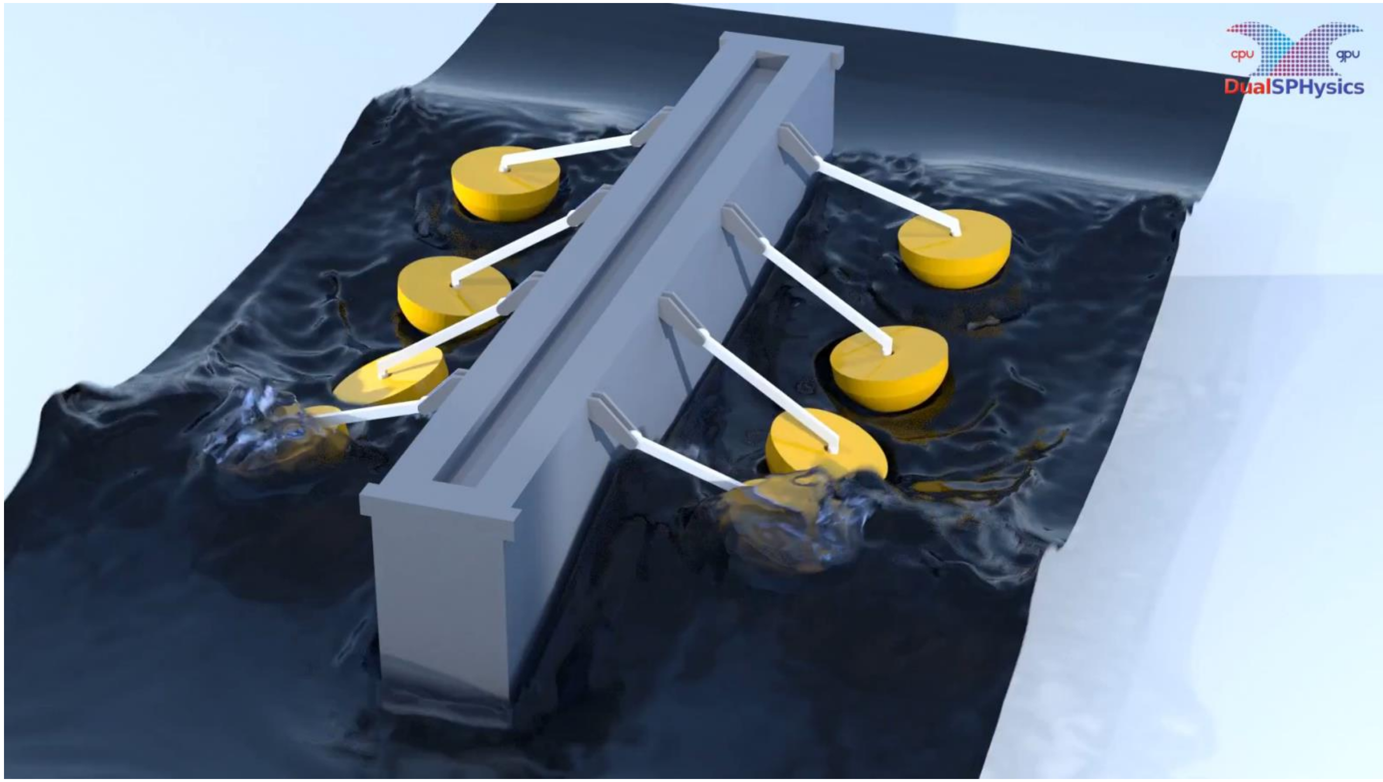
Numerical simulation of the full non-linear behaviour of Wave Energy Converters



Alejandro J. C. Crespo, M. Brito, J.M. Domínguez, R.B. Canelas, M. Hall, C. Altomare, M. Wu, V. Stratigaki, P. Troch, L. Cappietti, R.M. Ferreira, M. Gómez-Gesteira

Universidade Vigo
TÉCNICO LISBOA
UNIVERSITEIT GENT
UNIVERSITÀ DEGLI STUDI FIRENZE

OUTLINE

Objective: Numerical modelling of WECs

SPH modelling: DualSPHysics software

- Wave generation, propagation and absorption
- Wave-structure interaction
- Coupling with MoorDyn
- Coupling with Project Chrono

Application to different WECs

- Oscillating Water Column (OWC)
- Oscillating Wave Surge Converter (OWSC)
- Point absorber
- Others (WaveStar, M4)

Conclusions & Future work

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Conclusions & Future work

OBJECTIVE

MAIN OBJECTIVE:

To develop a numerical tool that helps in the design and testing of WECs
(*not only the efficiency but also the survivability*)

CHALLENGES:

NWT (Numerical Wave Tank):
How to mimic wave flumes and basins and real sea state?

FSI (Wave-structure interaction):
How to solve large deformations of fixed and floating devices under extreme wave conditions?

PTO (POWER TAKE-OFF):
How to solve numerically the mechanical constraints?

Smoothed Particle Hydrodynamics (SPH)

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, WADAM
Nemoh, WEC-SIM

TIME CONSUMING
VIOLENT FLOWS, VISCOUS FLOWS

CFD models
Approximate Navier–Stokes

Meshbased methods

VOF, OpenFoam, IH-Foam,
Fluent, Fluinco, REEF3D

Meshless methods

SPH

OUTLINE

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Conclusions & Future work

Smoothed Particle Hydrodynamics (SPH)

Navier-Stokes equations

Mass conservation

$$\frac{\mathrm{d}\rho}{\mathrm{d}t} = -\rho \nabla . \mathbf{v}$$

$$\left\langle \frac{\mathrm{d}\rho}{\mathrm{d}t} \right\rangle = \sum_j m_j \left(\mathbf{v}_i - \mathbf{v}_j \right) \cdot \nabla_i W_{ij}$$

Momentum conservation

$$\frac{\mathrm{d}\mathbf{v}}{\mathrm{d}t} = -\frac{1}{\rho} \nabla p + \mathbf{F}$$

$$\left\langle \frac{\mathrm{d}\mathbf{v}}{\mathrm{d}t} \right\rangle = \sum_j m_j \left(\frac{p_j}{\rho_j^2} + \frac{p_i}{\rho_i^2} \right) \nabla_i W_{ij}$$

Continuous notation (INTEGRALS)

Discrete notation (SUMMATIONS)

Smoothed Particle Hydrodynamics (SPH)

Navier-Stokes equations

		density		pressure
Density derivative	$\frac{d\rho}{dt}$ $\longrightarrow$	ρ	$\longrightarrow$	P
		velocity		**position**
Velocity derivative (acceleration)	$\frac{d\mathbf{v}}{dt}$ $\longrightarrow$	$\mathbf{v}$	$\longrightarrow$	$\mathbf{r}$

State equation for barotropic fluids

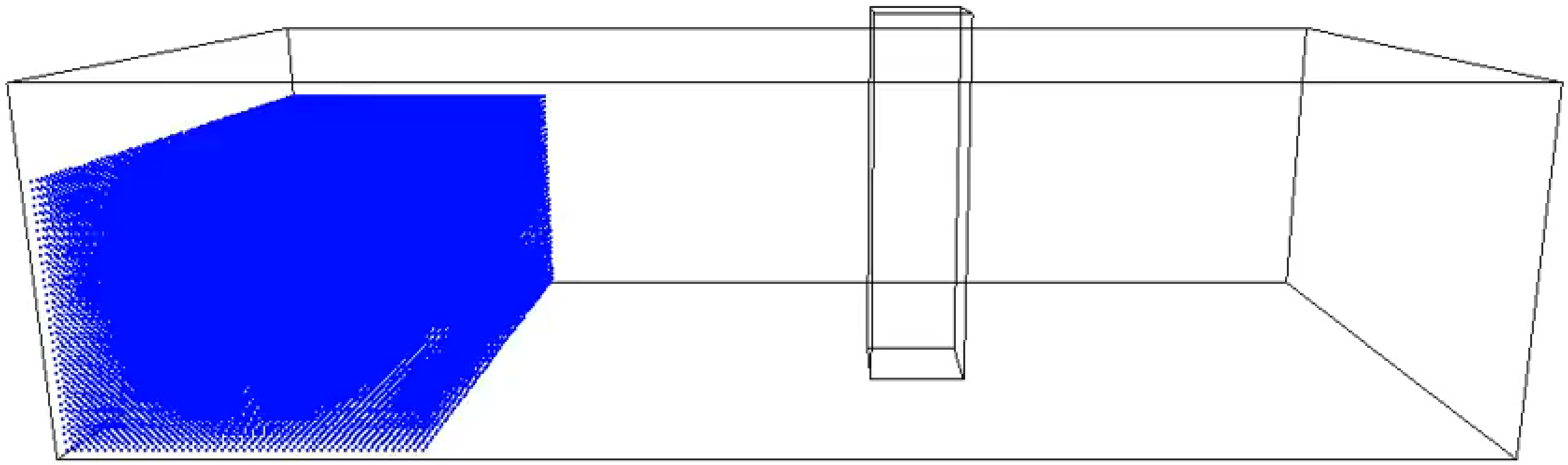
$$P = F(\rho)$$

nearly incompressible fluids **(small density variations)!**

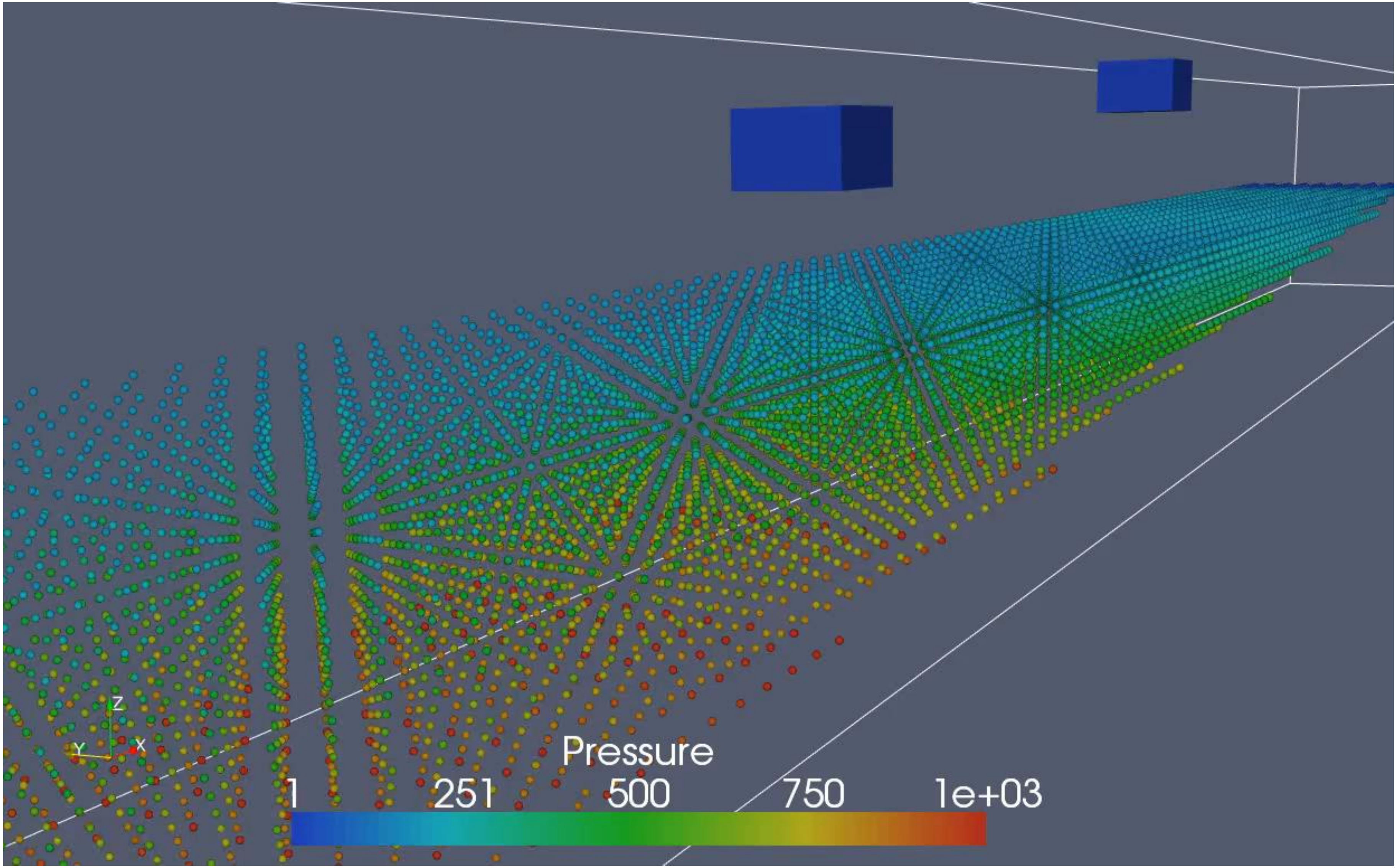
Smoothed Particle Hydrodynamics (SPH)

Navier-Stokes equations

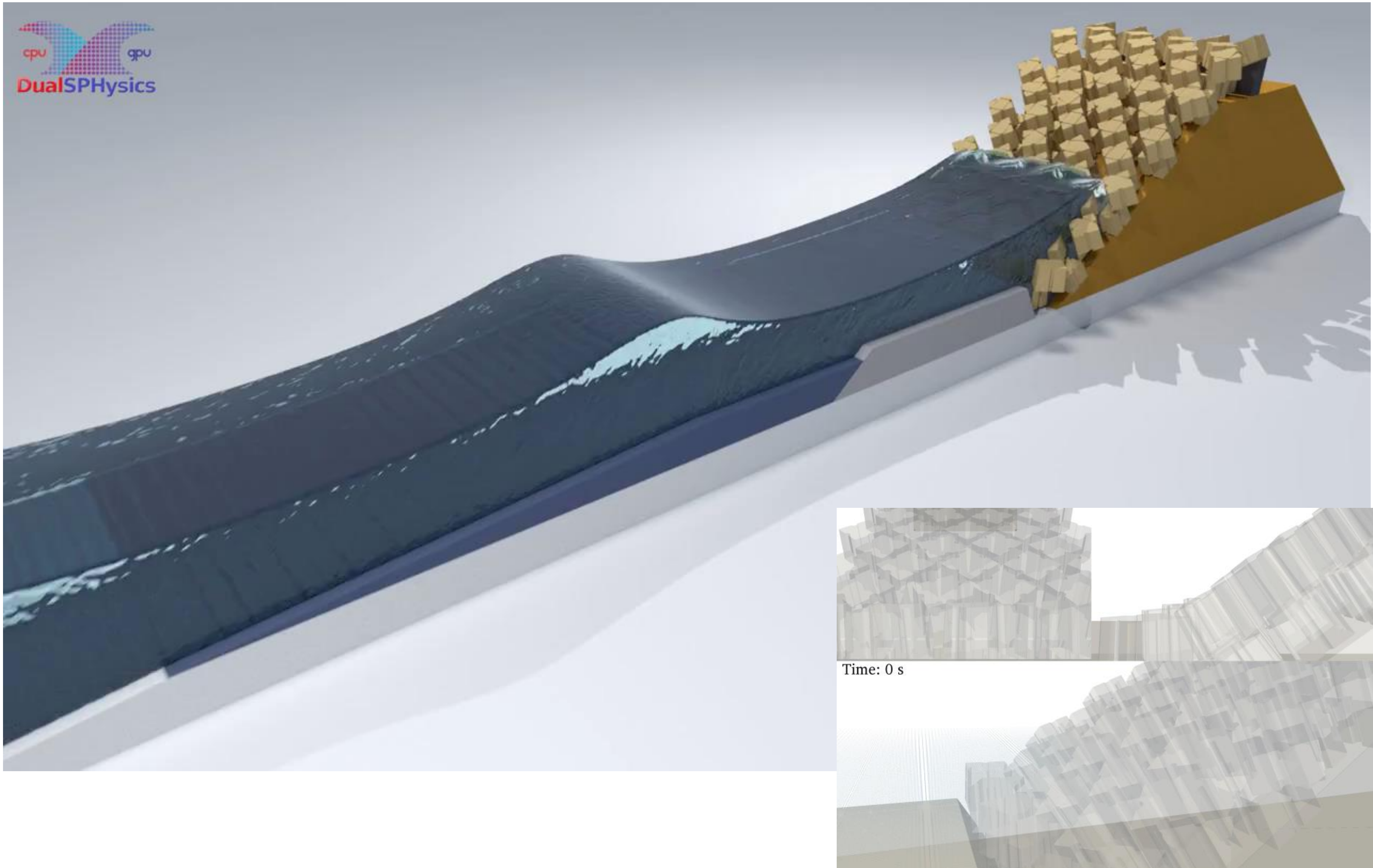
Density derivative	$\frac{\mathrm{d}\rho}{\mathrm{d}t}$	→	**density** ρ	→ **pressure** P
Velocity derivative (acceleration)	$\frac{\mathrm{d}\mathbf{v}}{\mathrm{d}t}$	→	**velocity** $\mathbf{v}$	→ **position** $\mathbf{r}$



Smoothed Particle Hydrodynamics (SPH)

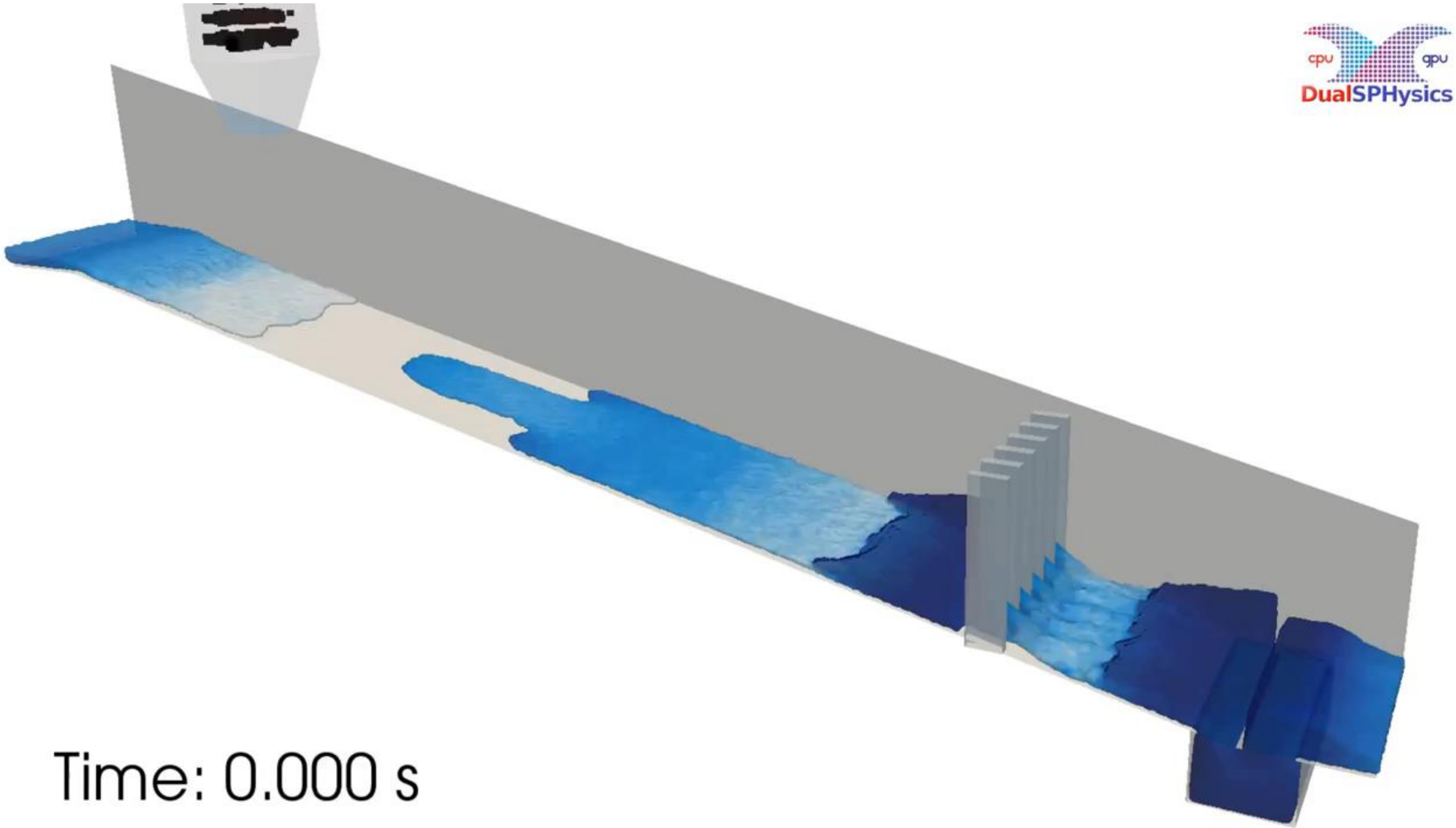


Smoothed Particle Hydrodynamics (SPH)



Smoothed Particle Hydrodynamics (SPH)

Smoothed Particle Hydrodynamics (SPH)



Smoothed Particle Hydrodynamics (SPH)

ADVANTAGES comparing with mesh-based CFD codes:

- ✓ Efficient treatment of the **large deformation** of free surfaces since there is no mesh distortion and **no need for a special treatment of the surface**
- ✓ Handling **complex geometries** and **high deformation**
- ✓ Distinguishing **between phases** due to holding material properties at each particle
- ✓ Natural incorporation of coefficient discontinuities and **singular forces**

DISADVANTAGES comparing with mesh-based CFD codes:

- ✓ There is still no unanimity to choose the best solid **boundary conditions**.
- ✓ **Turbulence treatment** is still an open field and more research is needed.
- ✓ **Time computation is expensive** comparing with other methods

DualSPHysics software

OPEN-SOURCE CODE

AVAILABLE FOR FREE

COLLABORATIVE PROJECT

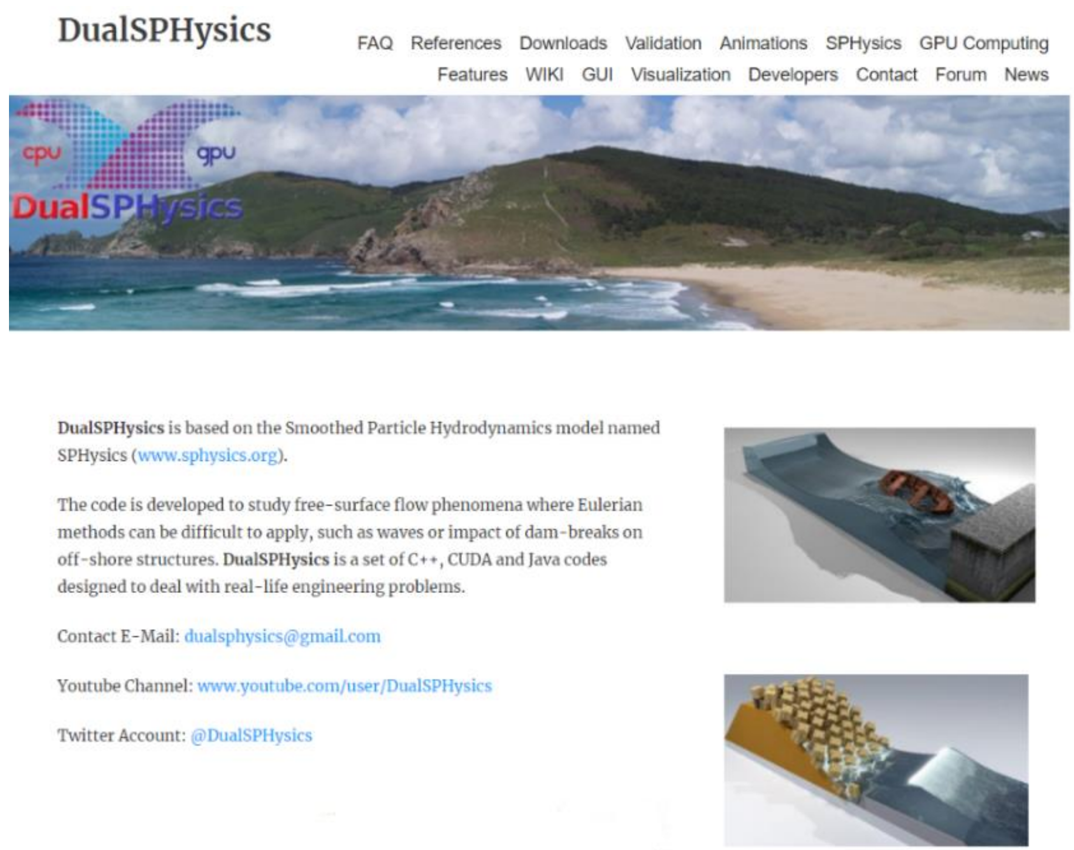
LGPL LICENSE

HIGHLY PARALLELISED

PRE- & POST-PROCESSING

APPLIED TO REAL PROBLEMS

OPEN PROJECT



www.dual.sphysics.org

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Industrial interest:
NASA JSC, BAE Systems, Volkswagen AG, McLaren Racing Ltd, Forum NOKIA, NVIDIA, AECOM, HDR Engineering, ABPmer, DLR, CFD-NUMERICS, BMT Group, Oak Ridge National Laboratory, Rainpower Norway, Shell Company, ABB, FEMTO Engineering …

Wave energy companies:
American Wave Machines, Carnegie Clean Energy Ltd, Maine Marine Composites, National Renewable Energy Laboratory in U.S.A., Atria Power Corporation Ltd., Global Hydro Energy, WavePower

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DEVELOPERS:

Universidade de Vigo, Spain
The University of Manchester, UK
Instituto Superior Tecnico, Lisbon, Portugal
Università degli studi di Parma, Italy
Flanders Hydraulics Research, Belgium
New Jersey Institute of Technology, USA

COLLABORATORS:

Universidad Politécnica de Madrid, Spain
TECNALIA. Inspiring Business, Spain
Universitat Politècnica de Catalunya
Imperial College London, UK
Universiteit Gent, Belgium
University of Salerno, Italy
New Jersey Institute of Technology, USA
Universidad de Guanajuato, Mexico

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LGPL (Lesser General Public License) can be used in **commercial** applications

Software can be incorporated into both:
- free software and
- proprietary software

LGPL

Free Software

DualSPHysics software

OPEN-SOURCE CODE

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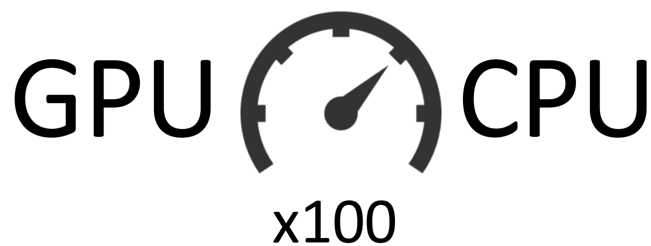
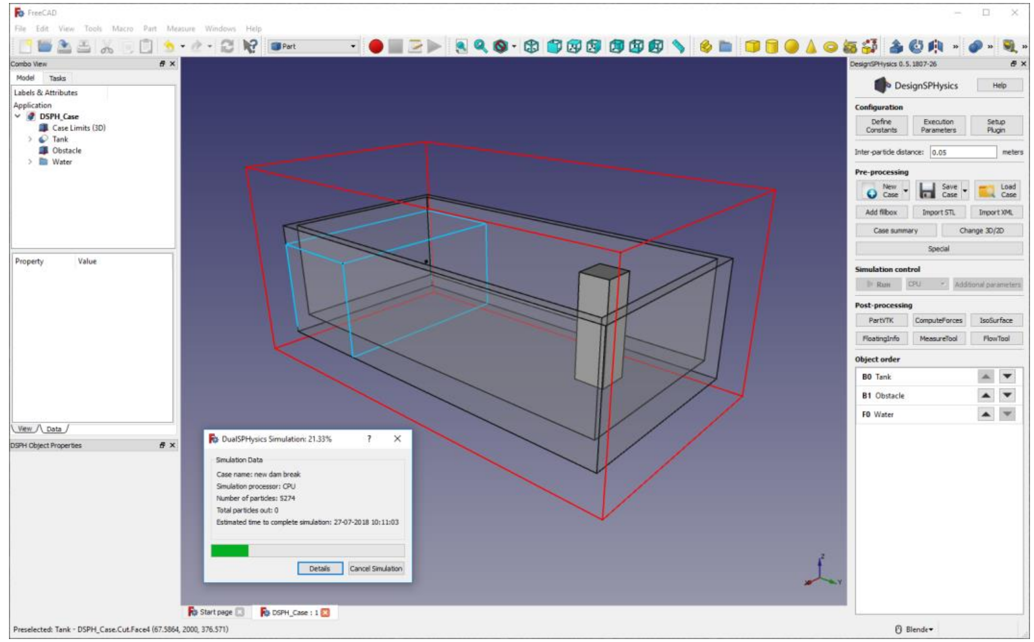


DualSPHysics software

Graphical User Interface

FreeCAD
Open Source parametric 3D CAD modeler



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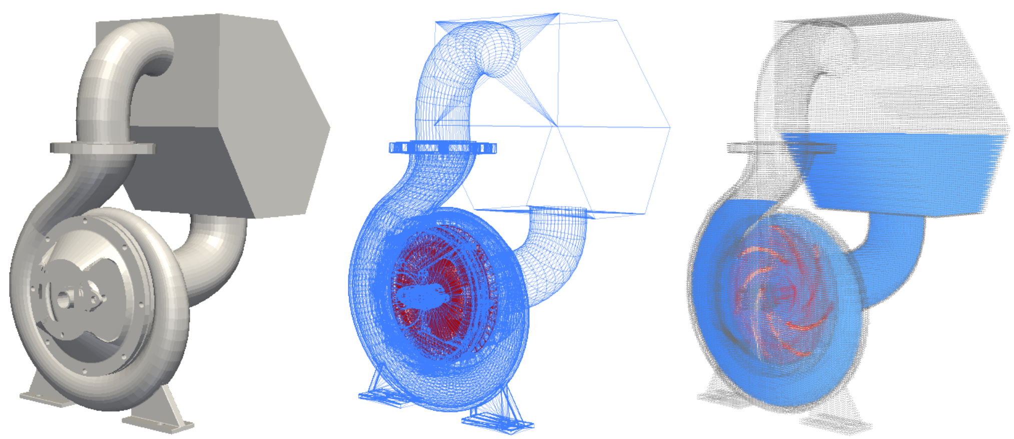

DualSPHysics software

Advanced visualisation

OPEN-SOURCE CODE

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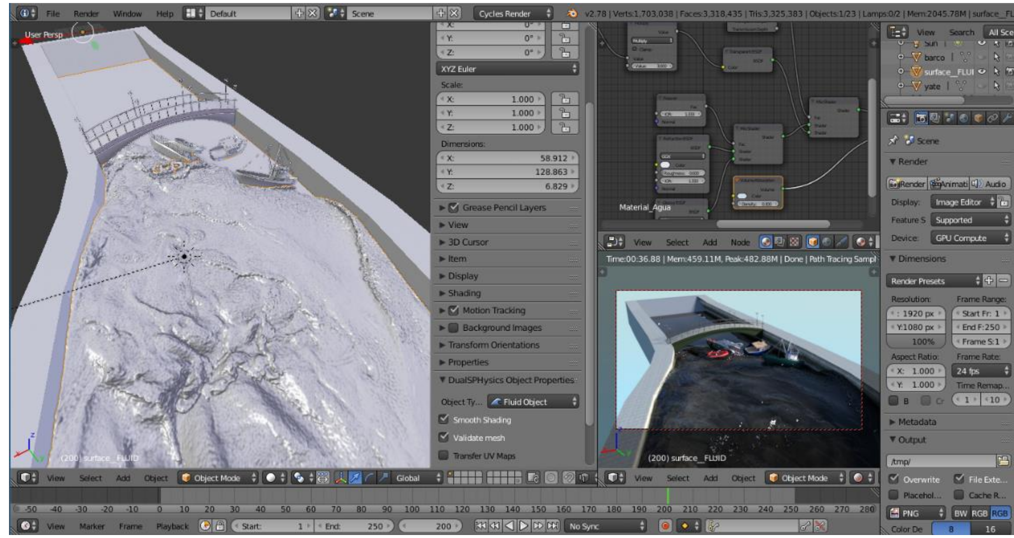

DualSPHysics software

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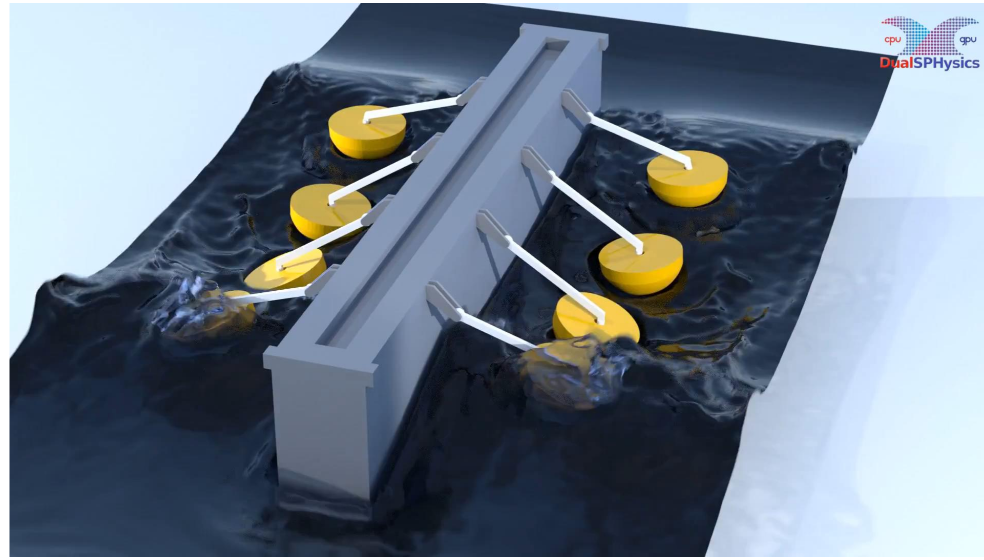

DualSPHysics software

DualSPHysics Package
http://dual.sphysics.org

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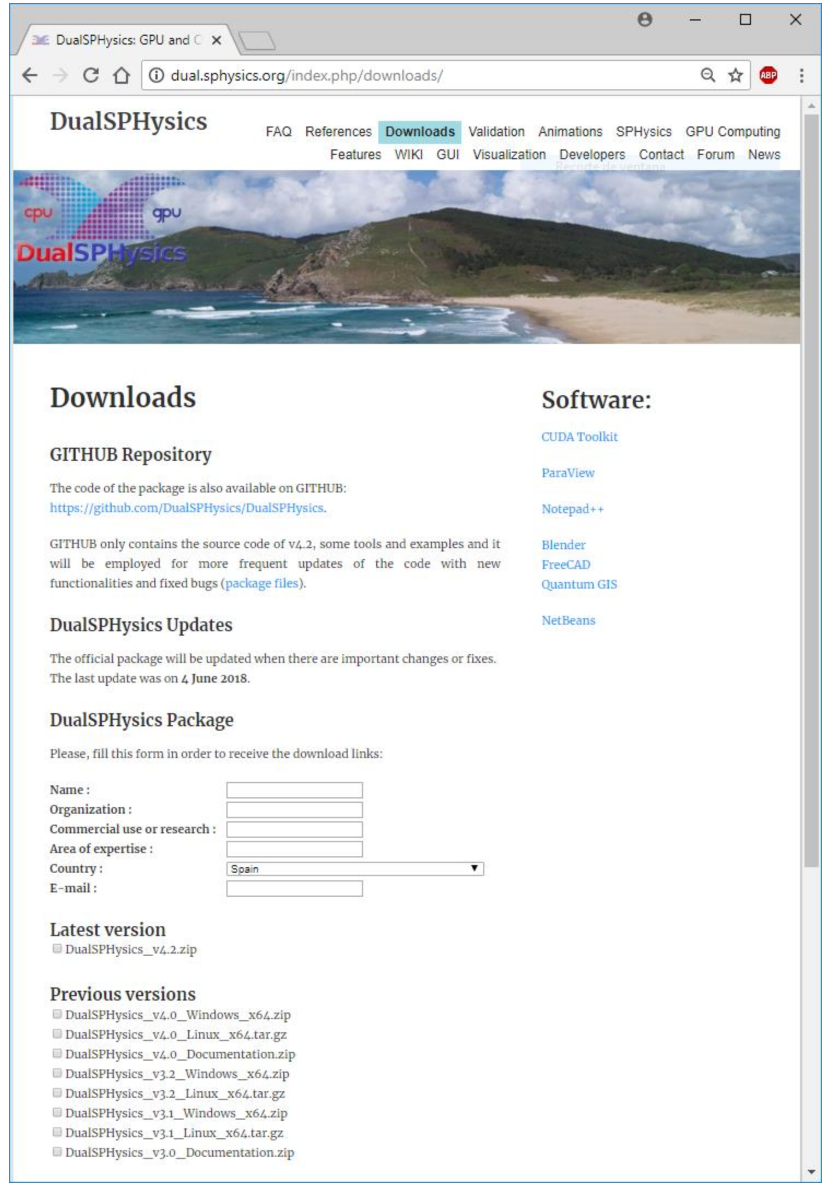

DualSPHysics software

DualSPHysics Code on GitHub

https://github.com/DualSPHysics/DualSPHysics

OPEN-SOURCE CODE

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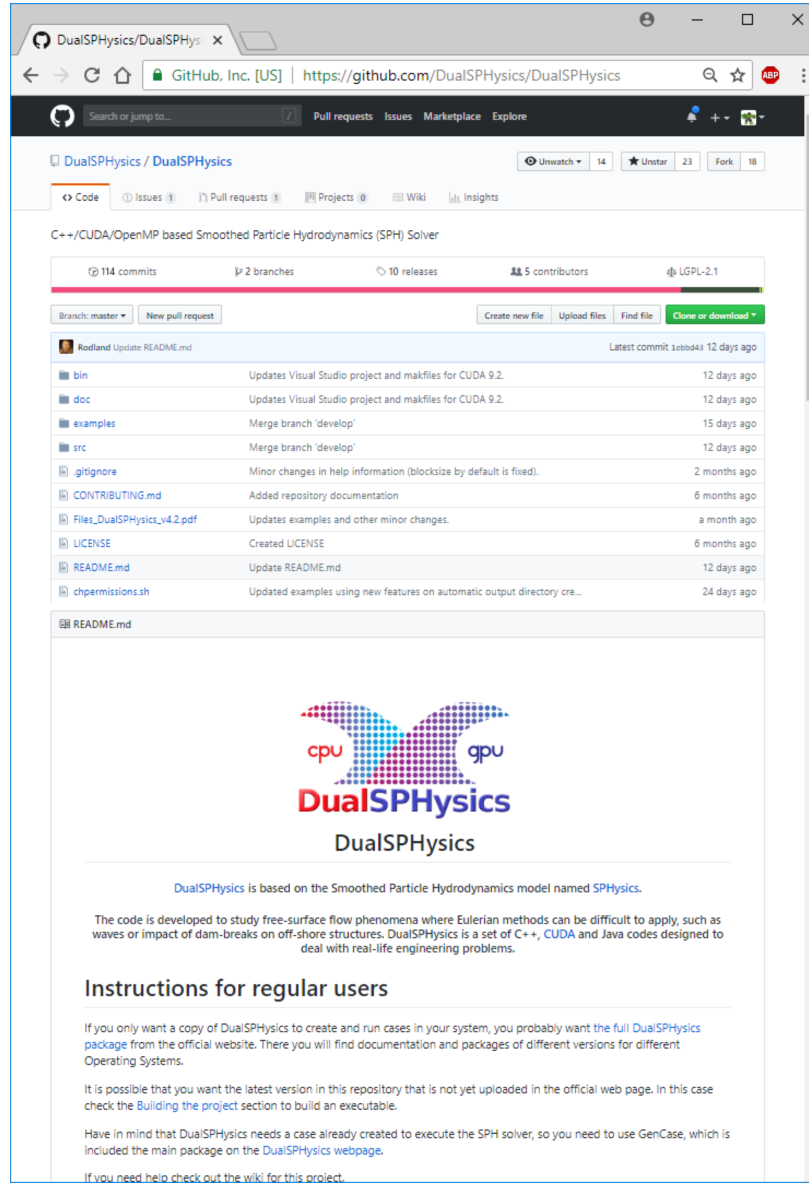
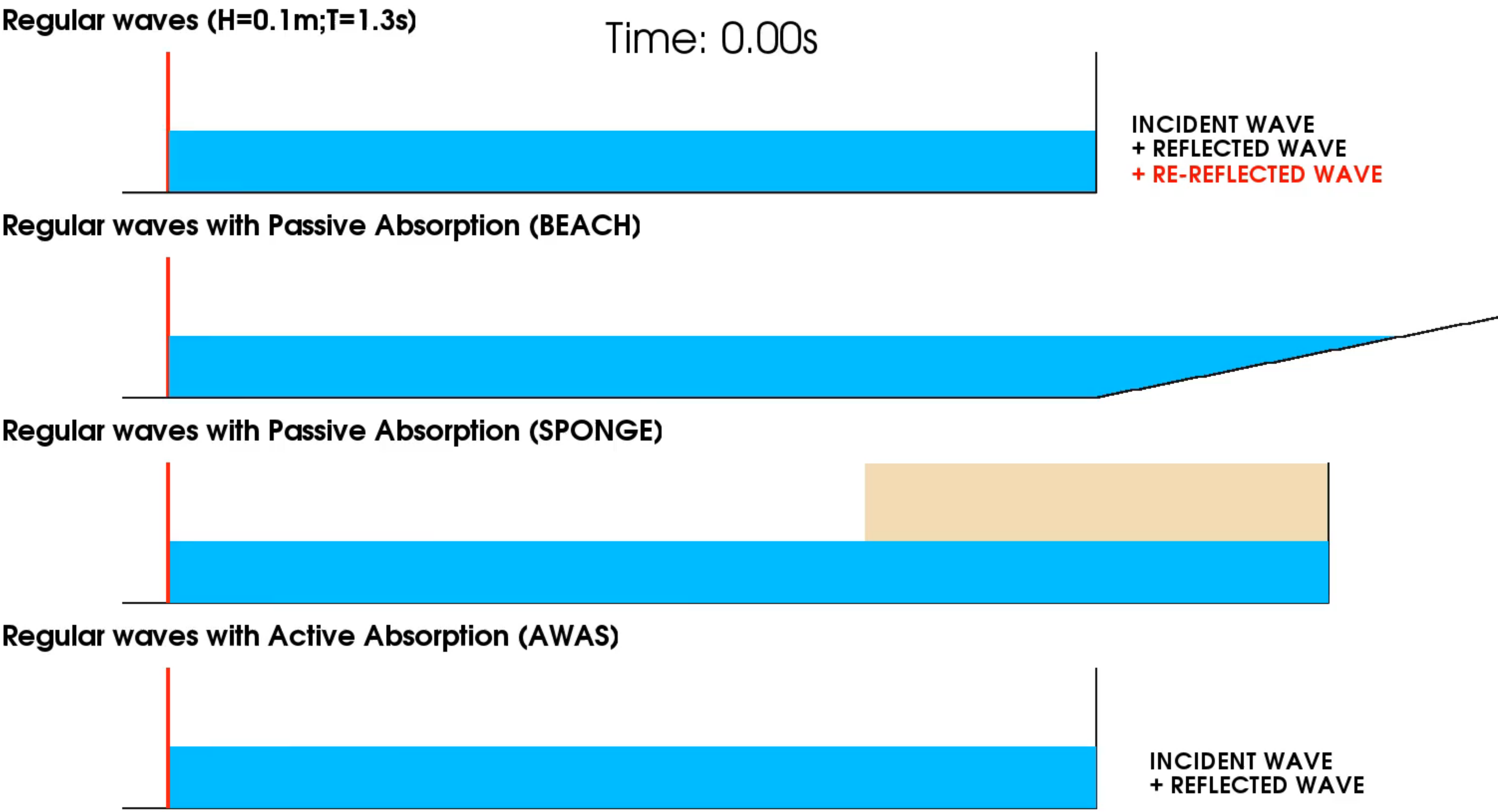


Wave propagation and absorption

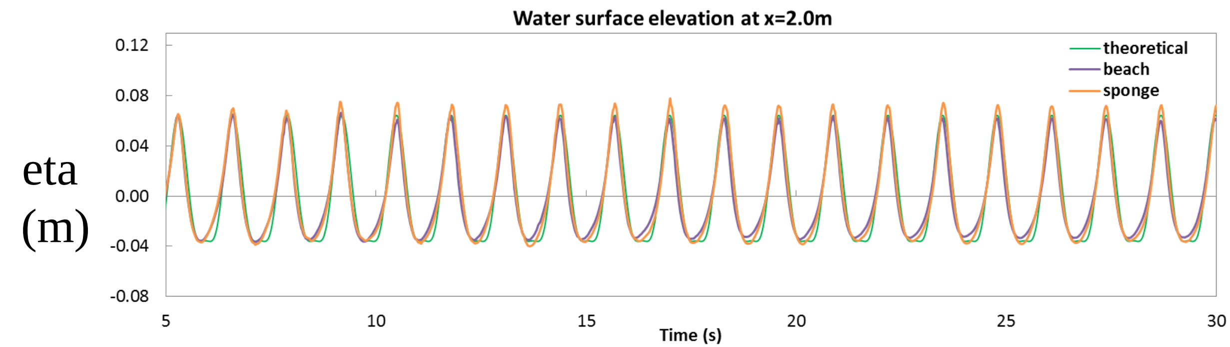
Altomare et al., 2017

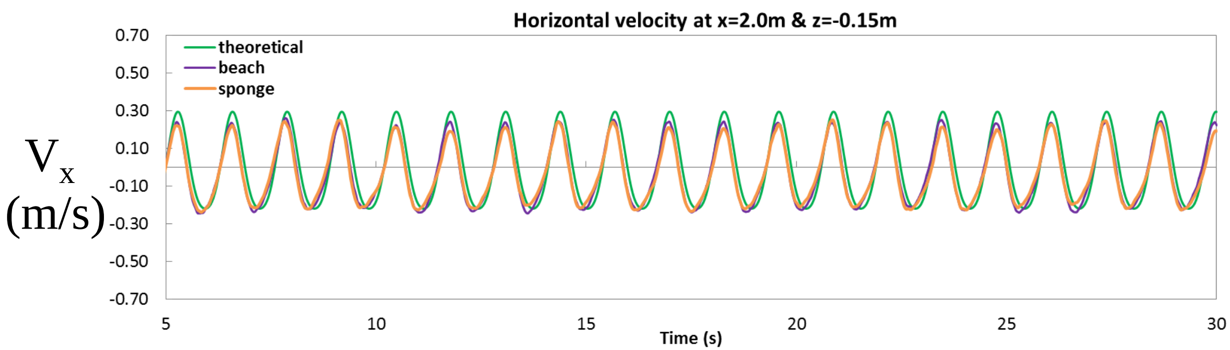


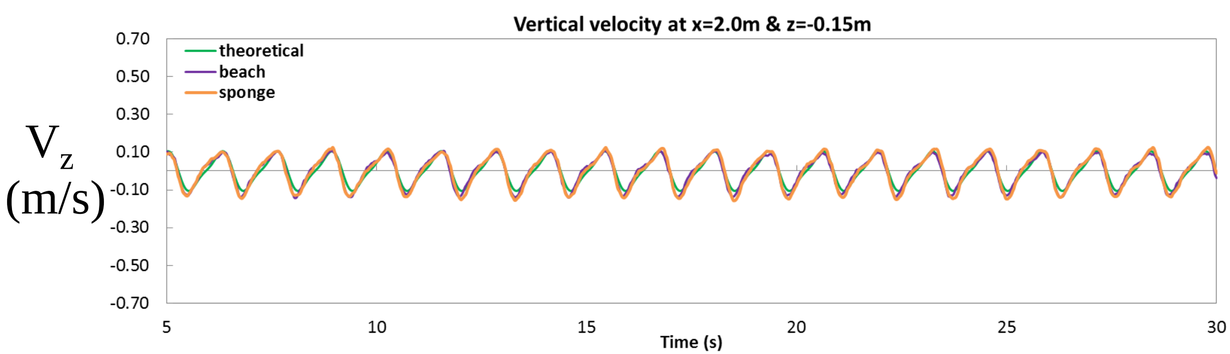
Wave propagation and absorption

Altomare et al., 2017

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





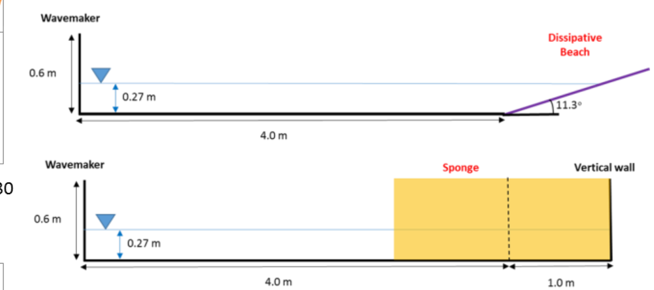


THEORY

2nd Stokes

vs

SPH



Wave-structure interaction

Interaction between waves and fixed structures: RUN-UP

DualSPHysics was validated 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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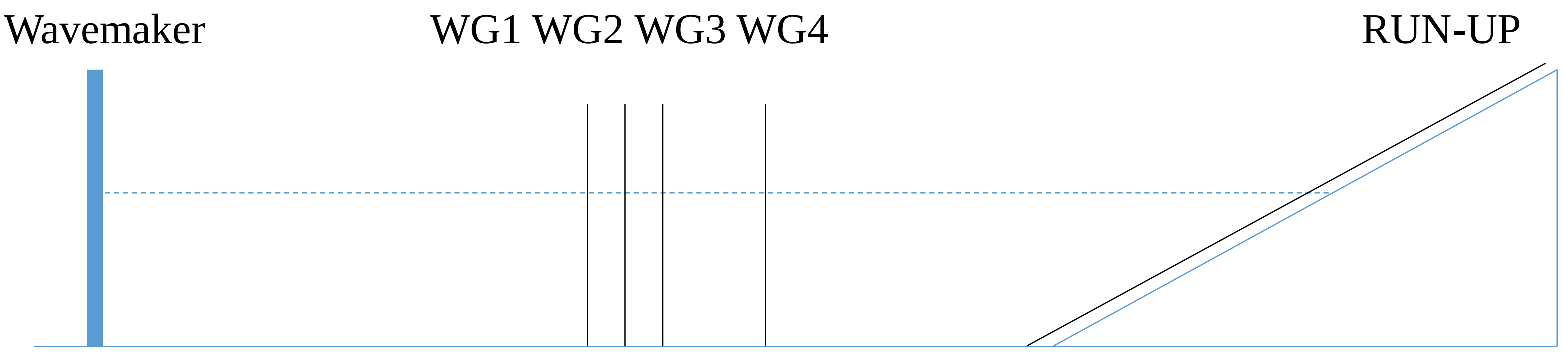
Wave-structure interaction

Interaction between waves and fixed structures: RUN-UP

AMOUR BLOCK DIKE

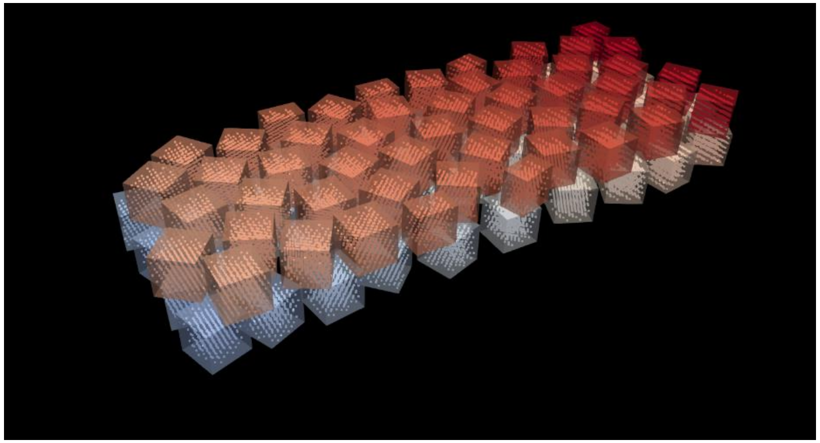


Wave-structure interaction

Interaction between waves and fixed structures: RUN-UP

AMOUR BLOCK DIKE

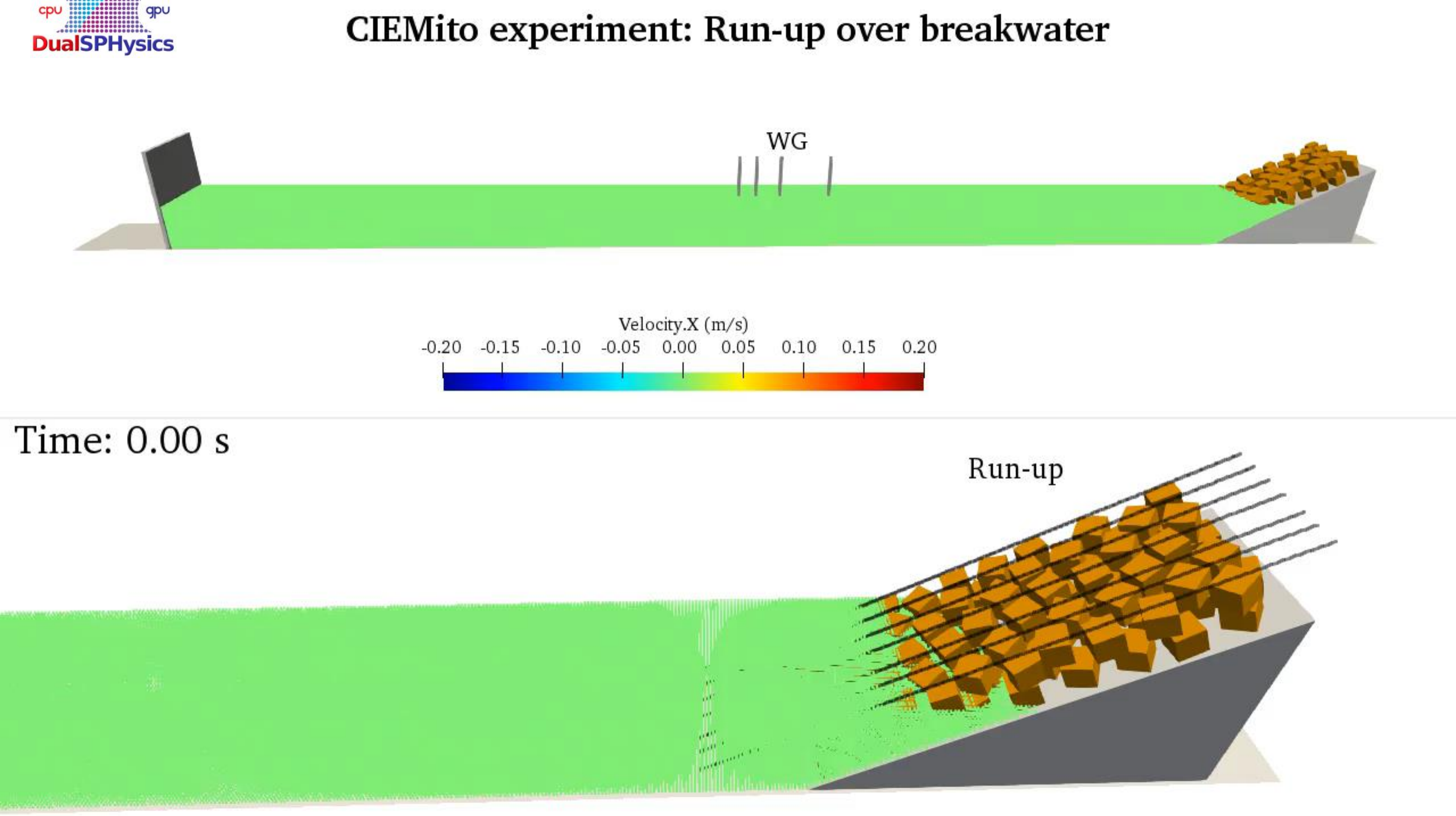
Initial particle distance: dp=0.008 m with h/dp=2.6
Wendland kernel with interaction distance of 2h
Total number of particles with depth=0.25 leads to 1,133,955
Physical time to be simulated: 20 seconds
Computational time using GeForce RTX 2080 Ti GPU card was 15.4h (160,130 steps)
Piston motion following external file (time and x-position)
Exact position of the blocks in STL file



Wave-structure interaction

Zhang et al., 2017

Interaction between waves and fixed structures: RUN-UP

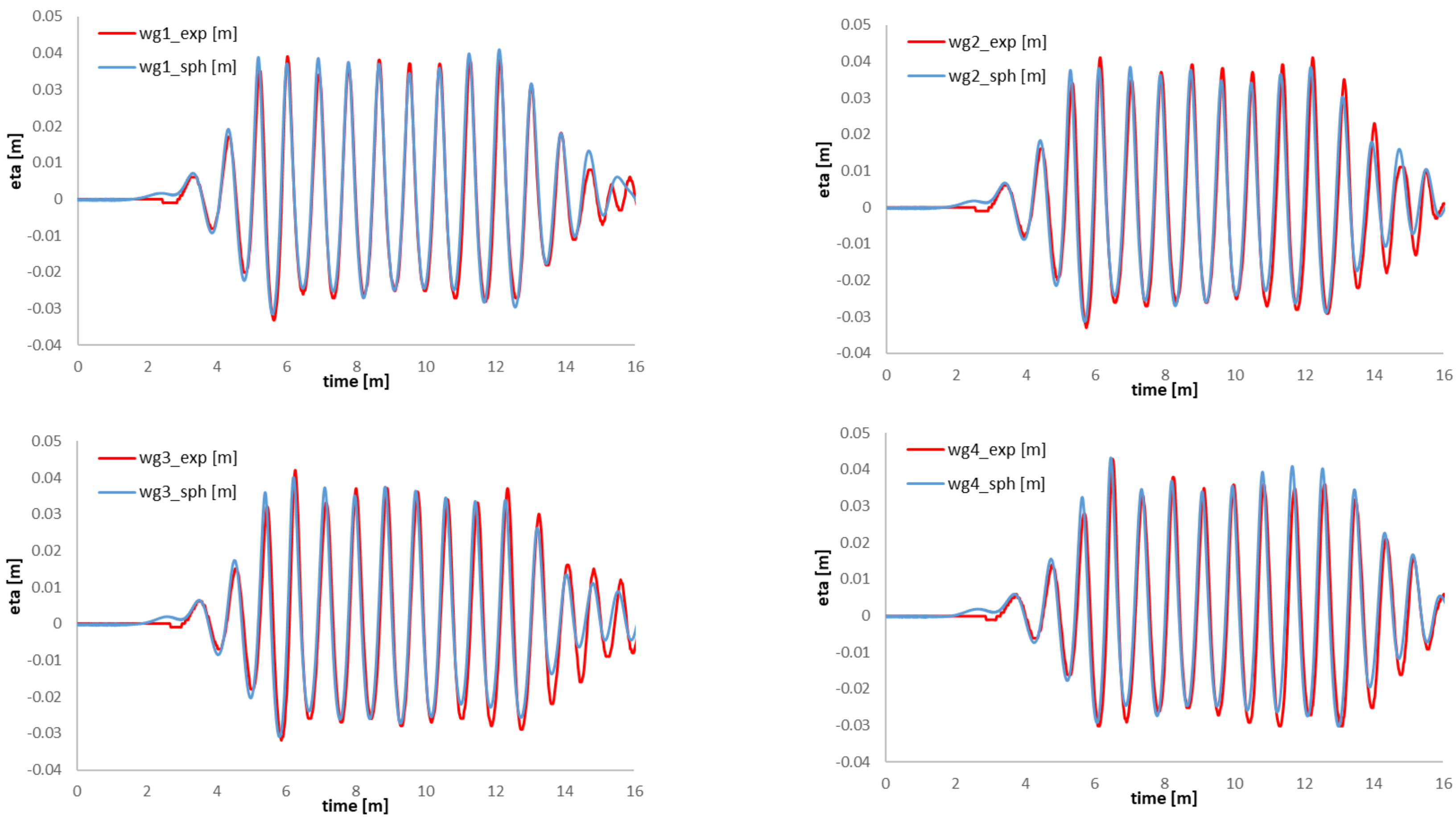


Wave-structure interaction

Zhang et al., 2017

Interaction between waves and fixed structures: RUN-UP

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



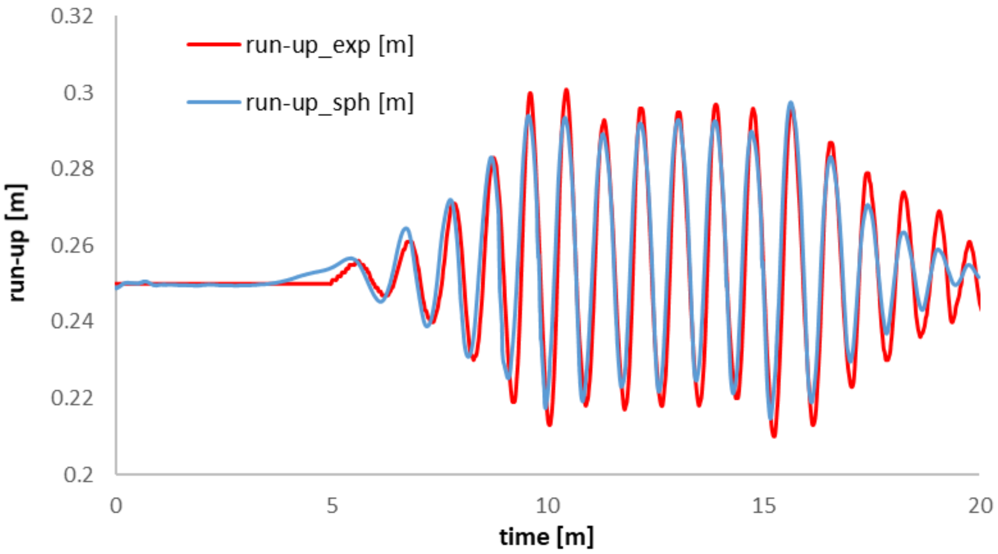
Time series of the experimental and numerical surface elevation

Zhang et al., 2017

Wave-structure interaction

Interaction between waves and fixed structures: RUN-UP

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



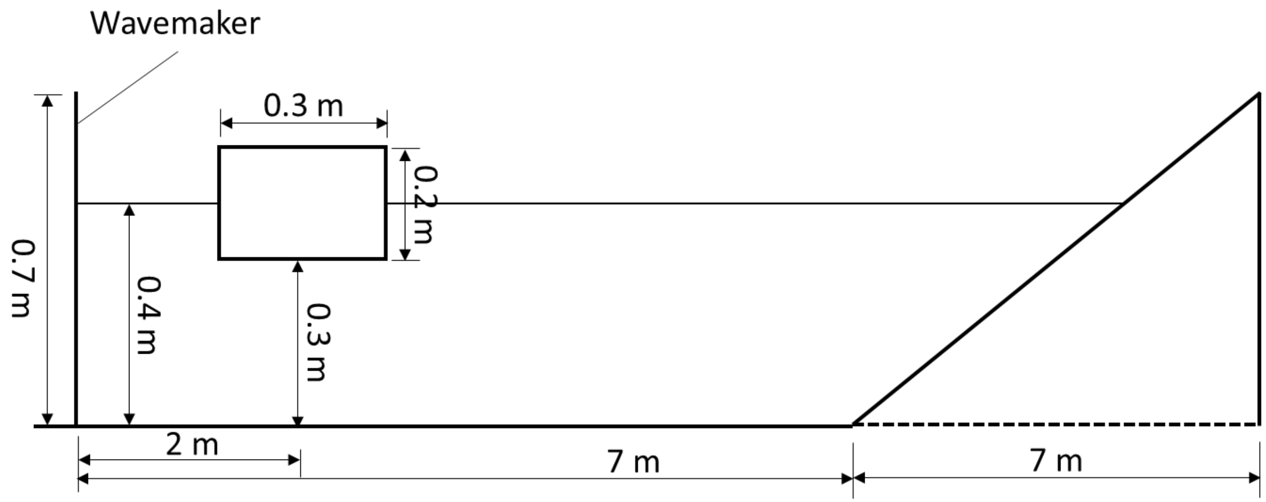
Time series of the experimental and numerical RUNUP

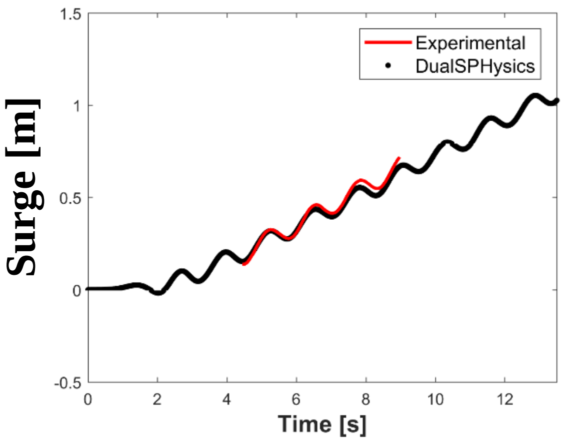
Crespo et al., 2018

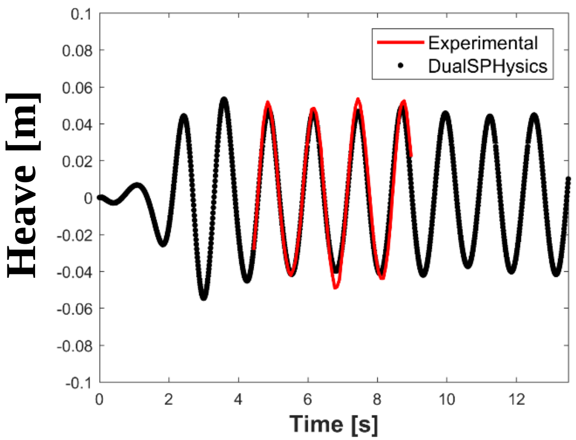
Wave-structure interaction II

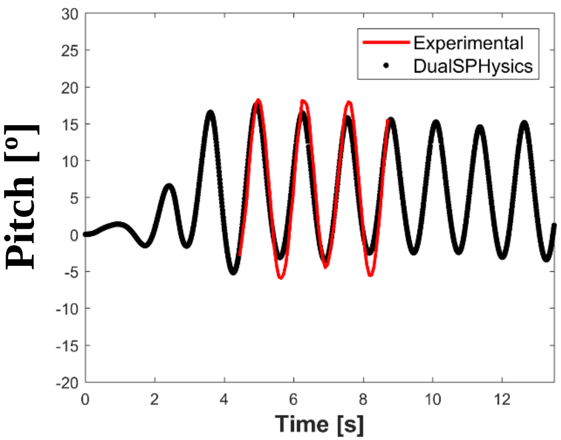
Interaction between waves and floating structures

Floating BOX subjected to REGULAR WAVES





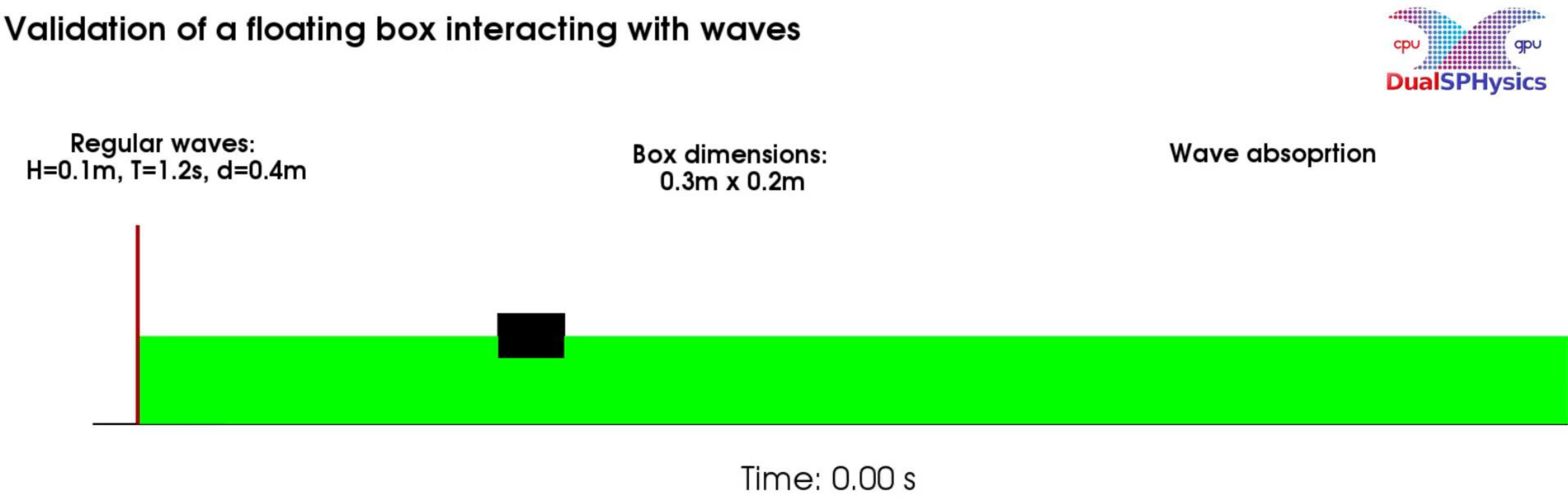


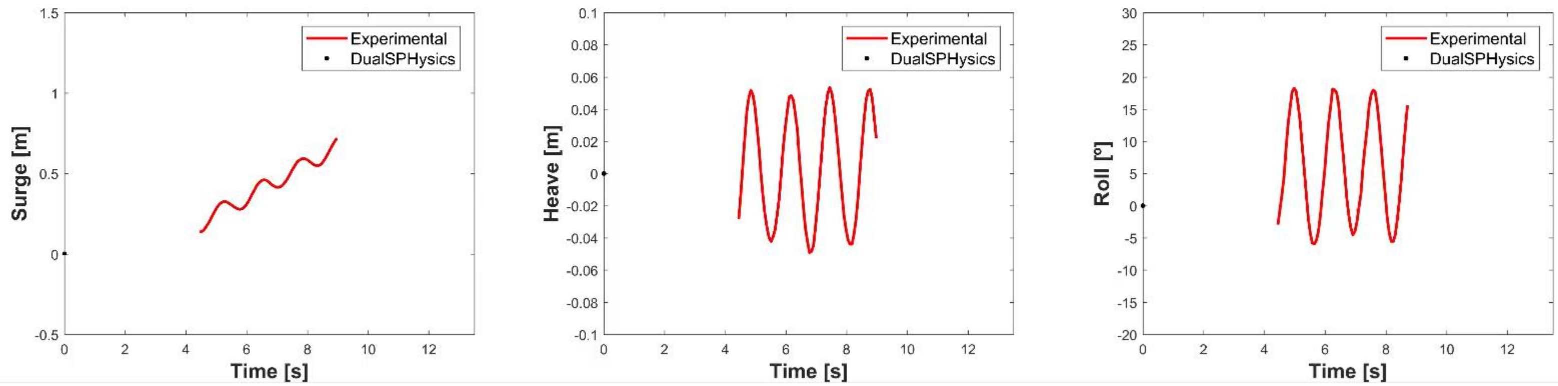


Crespo et al., 2018

Wave-structure interaction II

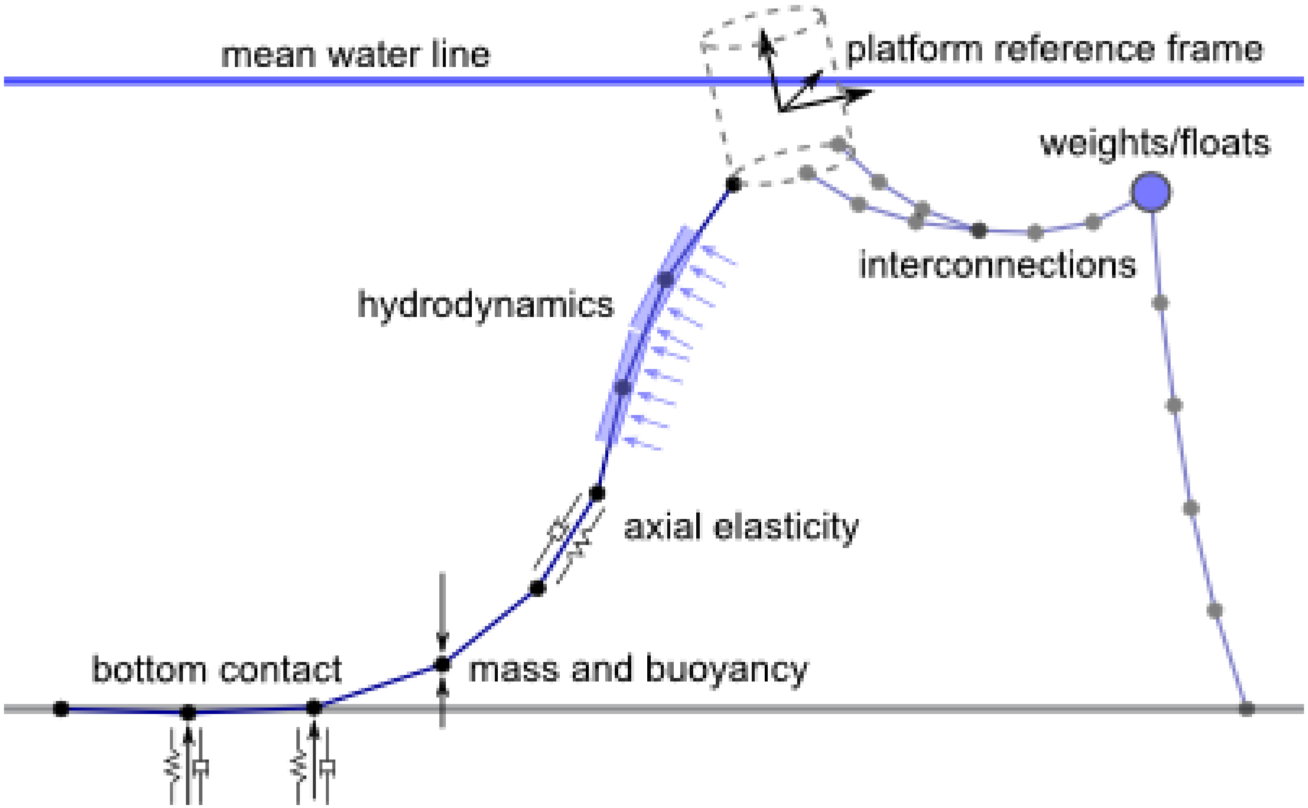
Interaction between waves and floating structures





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/

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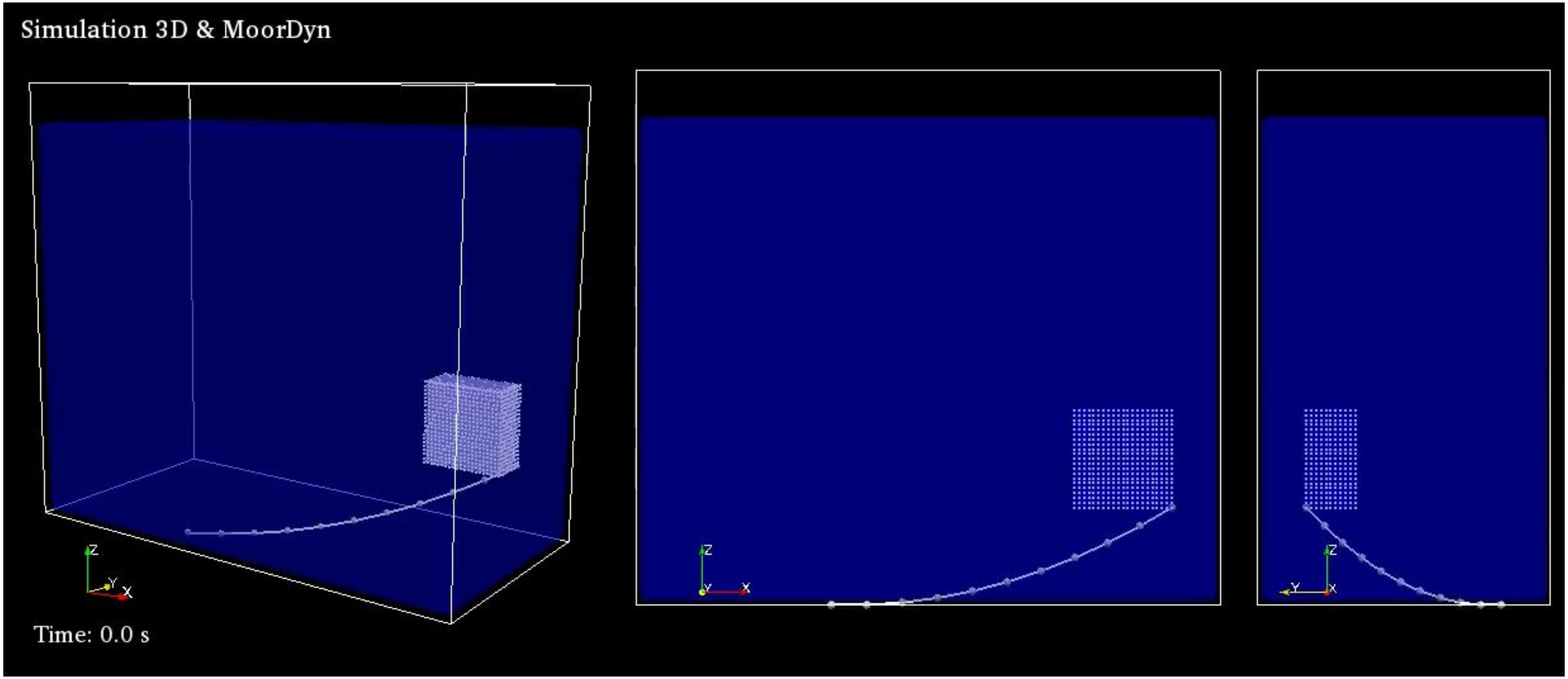
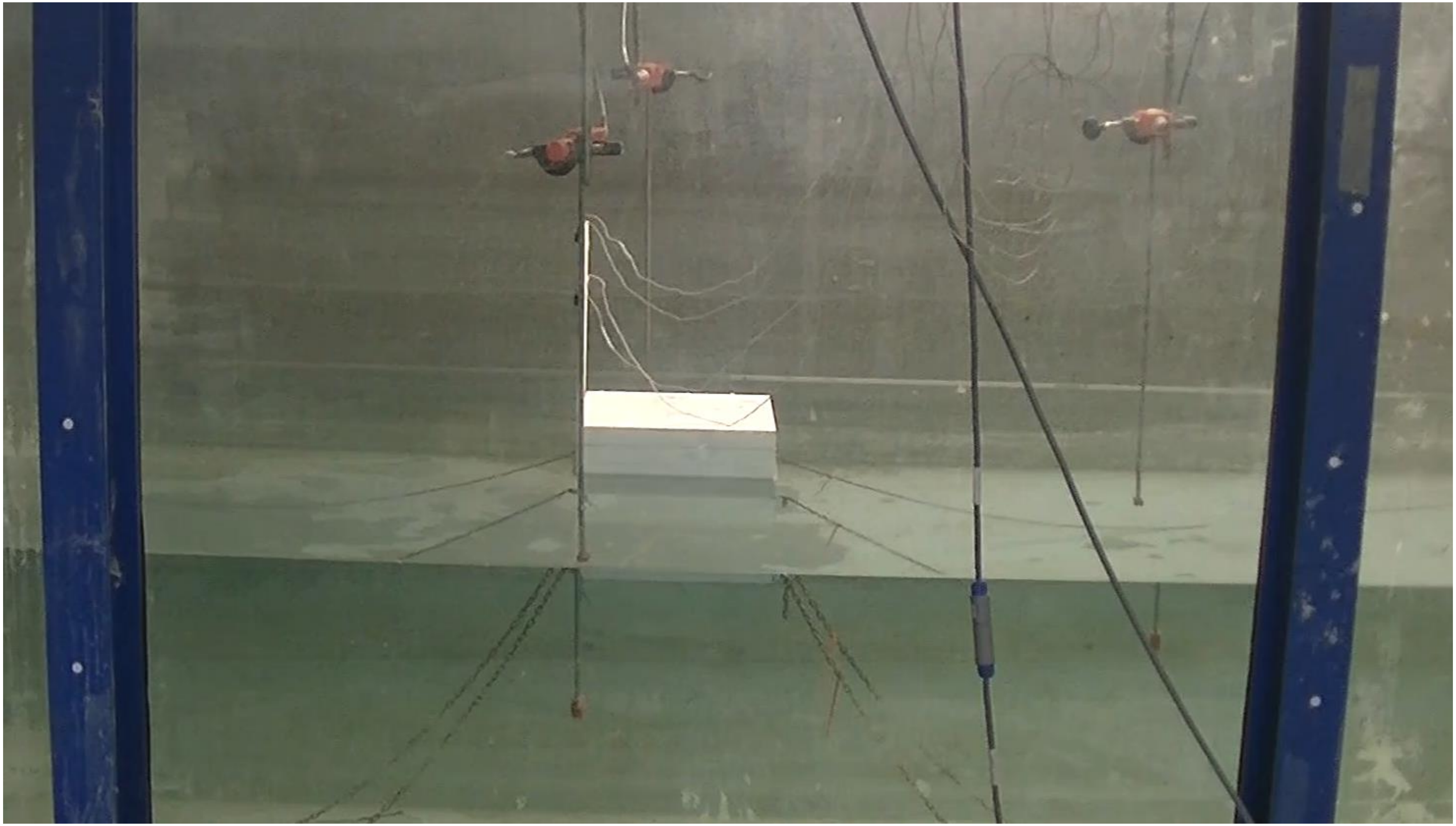


http://www.matt-hall.ca/moordyn/

Crespo et al., 2018

Coupling with MoorDyn

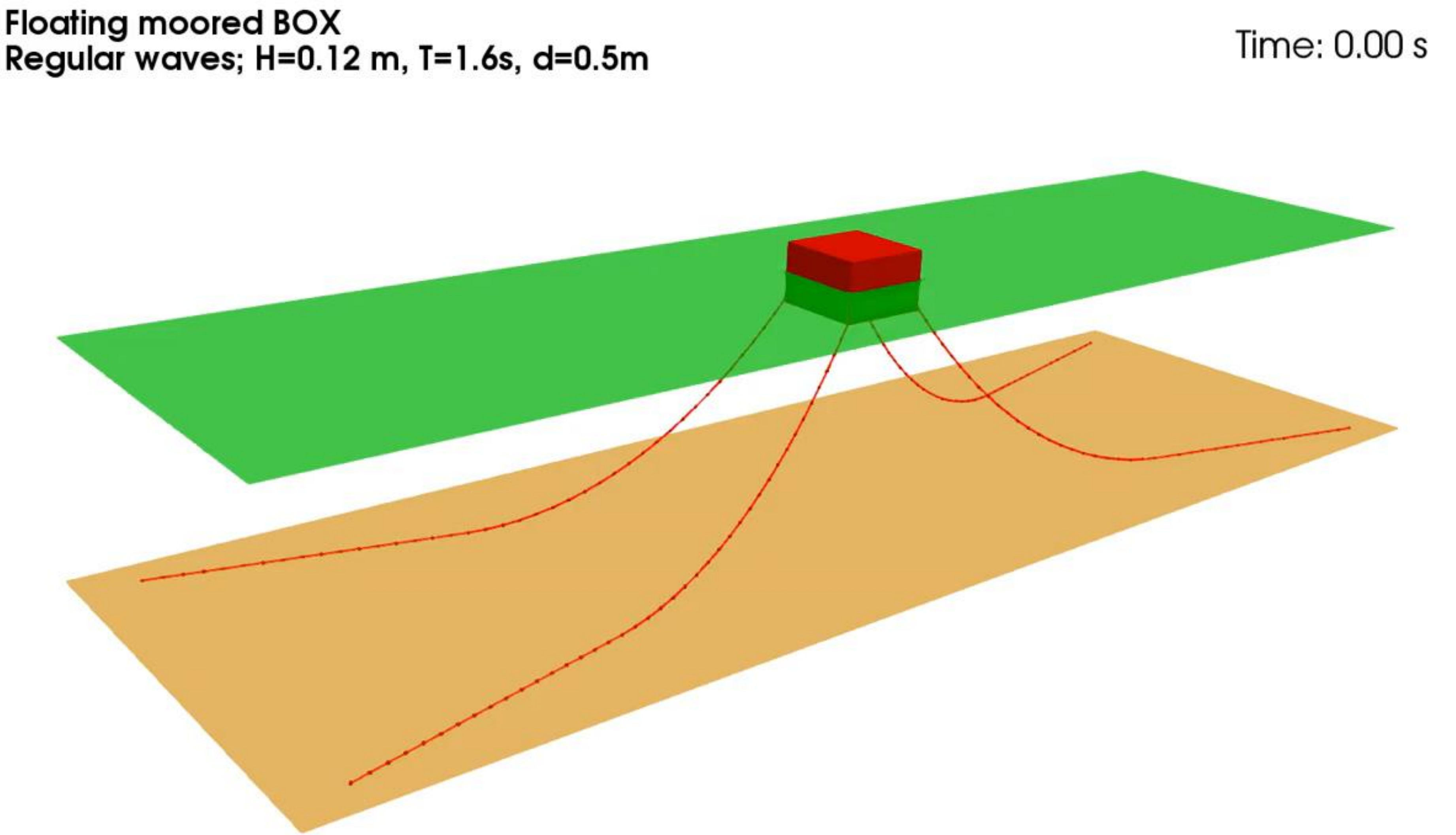
VALIDATION: EXPERIMENTS IN GHENT UNIVERSITY



Coupling with MoorDyn

Crespo et al., 2018

VALIDATION: EXPERIMENTS IN GHENT UNIVERSITY



Coupling with MoorDyn

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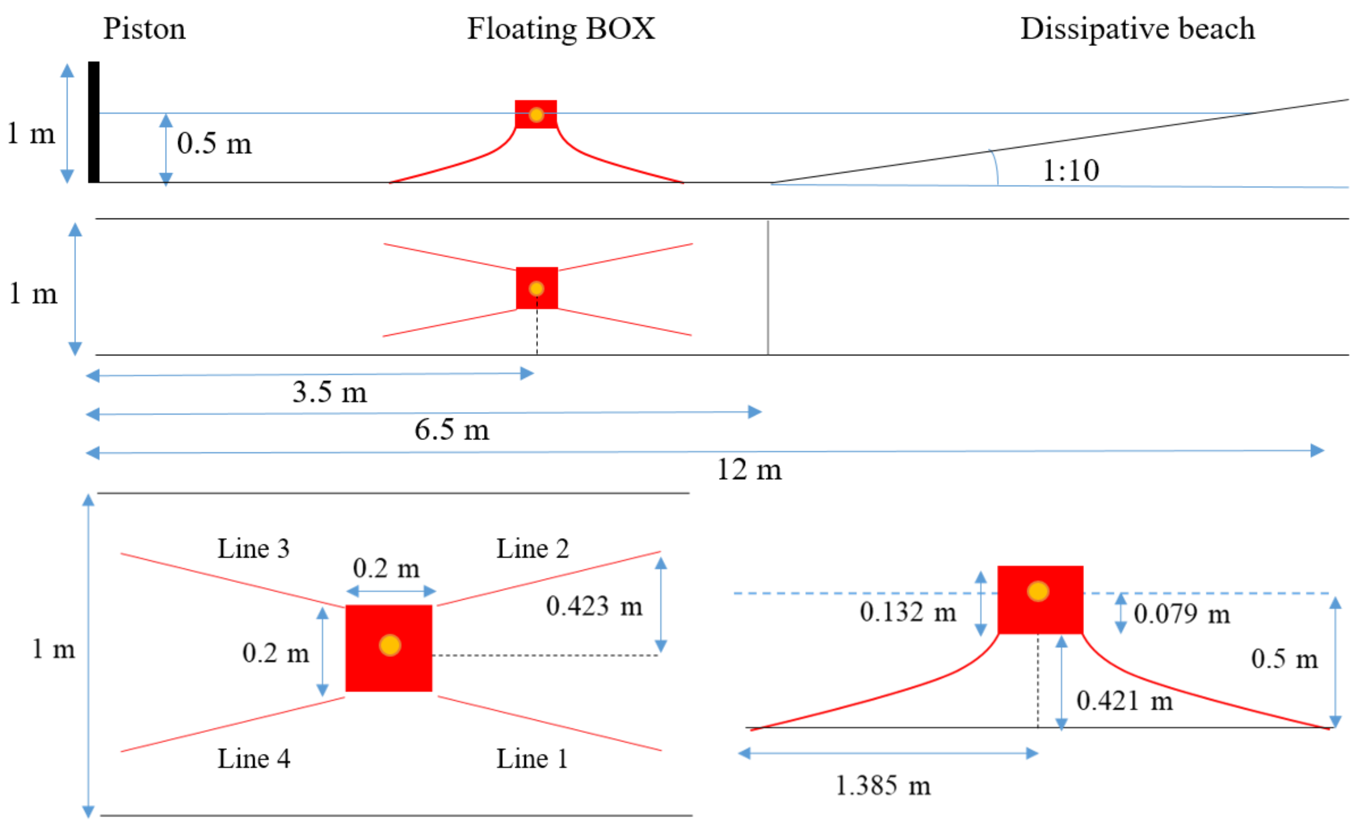


Regular waves

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

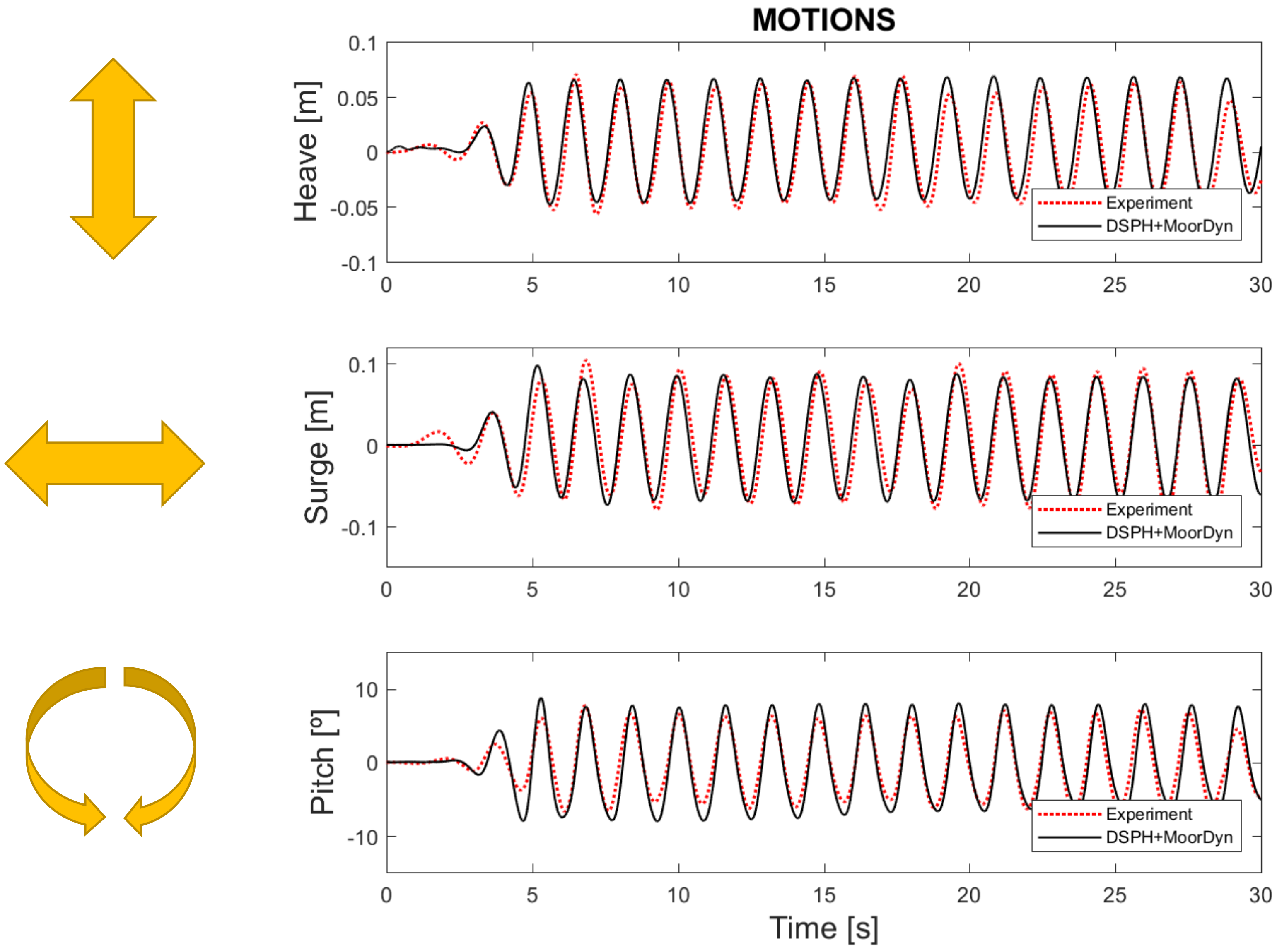
DualSPHysics	
BOX Dimensions	20 x 20 x 13.2 cm^3
BOX Weight	3 kg + 0.6 kg(extra)
BOX Centre of gravity	(0, 0, -1.26) cm
BOX Lip draught	7.86 cm

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

Coupling with MoorDyn

Crespo et al., 2018

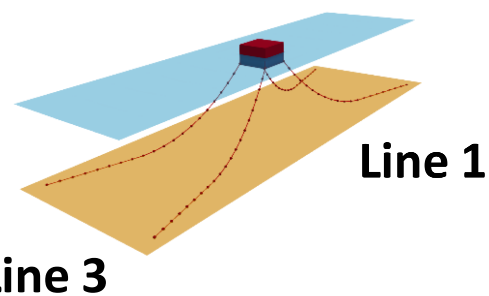
VALIDATION: EXPERIMENTS IN GHENT UNIVERSITY

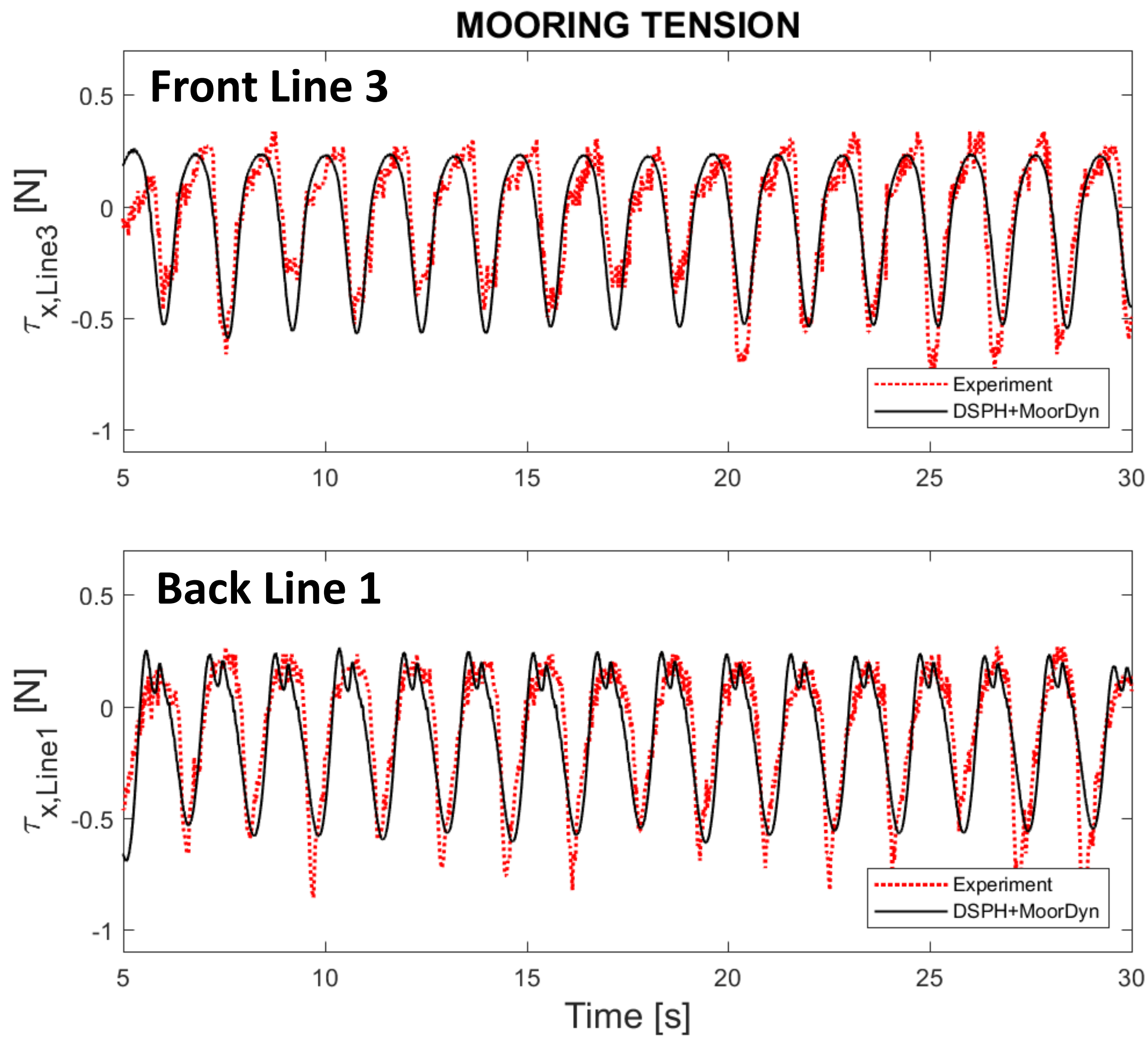


Crespo et al., 2018

Coupling with MoorDyn

VALIDATION: EXPERIMENTS IN GHENT UNIVERSITY

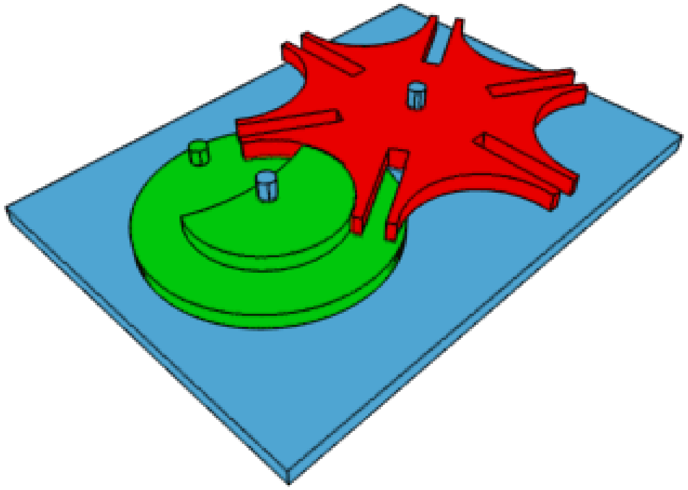




Canelas et al., 2018

Coupling with Project Chrono

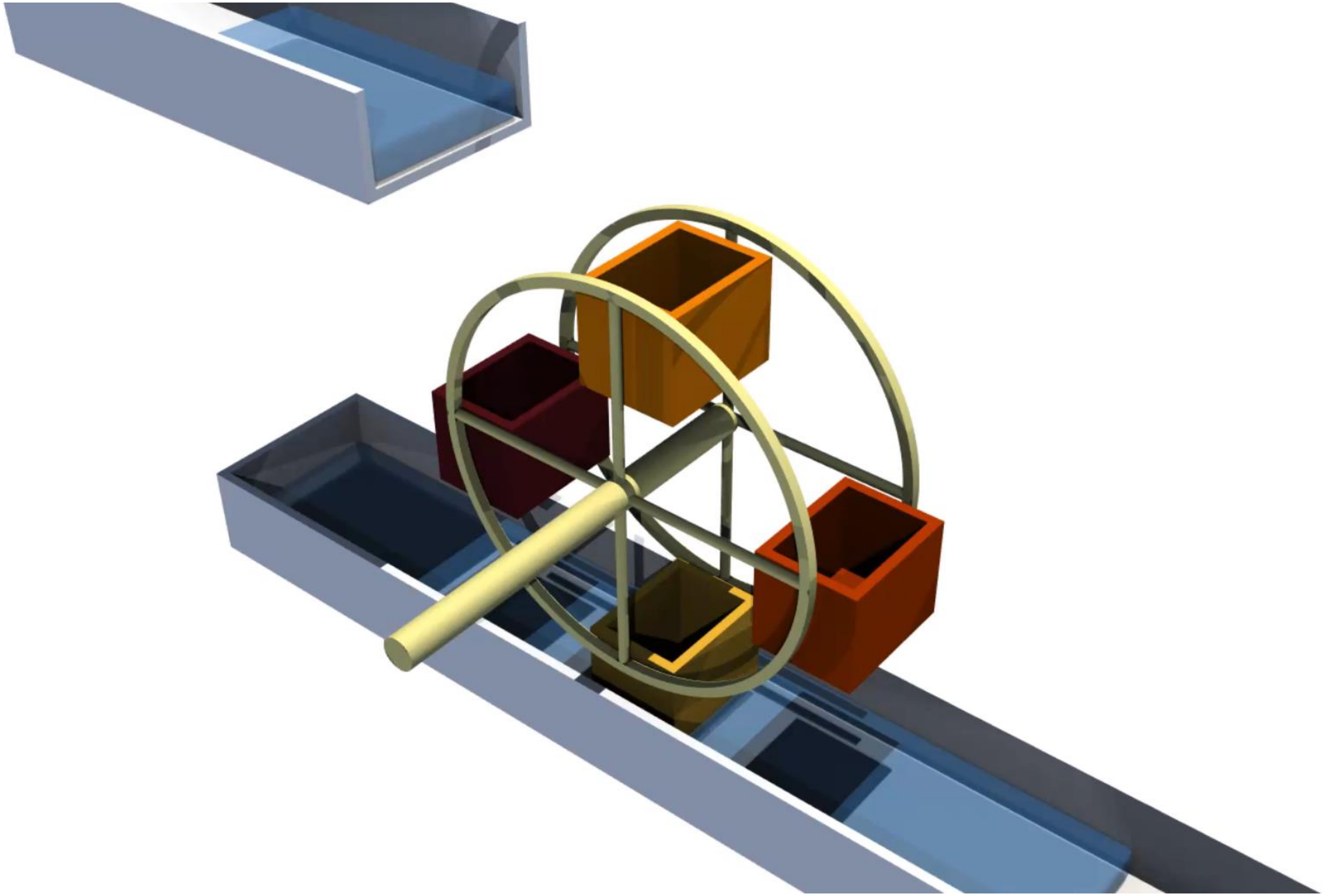
Project Chrono is an open-source **multi-physics** simulation engine



- Wide set of joints: spherical, revolute joint, prismatic, glyph, etc.
- Unilateral constraints
- Exact Coulomb friction model, for precise stick-slip of bodies
- **Springs and dampers, even with non-linear features**

http://projectchrono.org

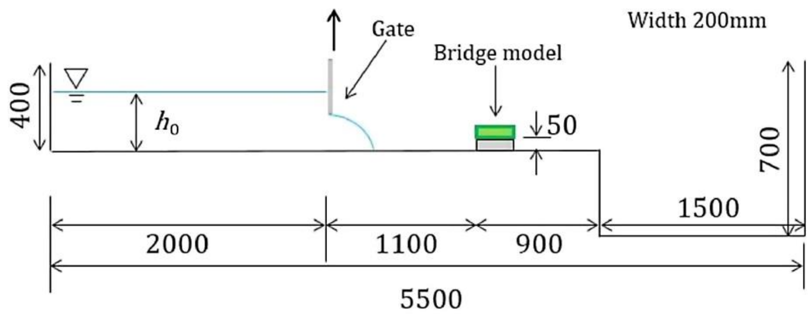
Coupling with Project Chrono

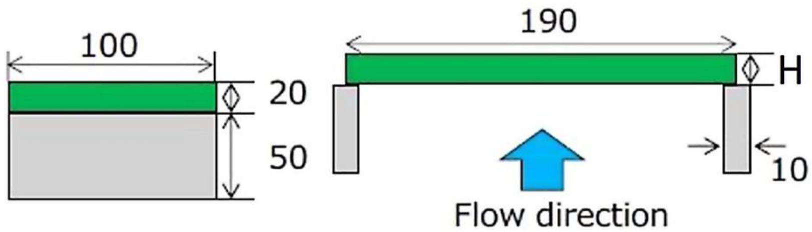


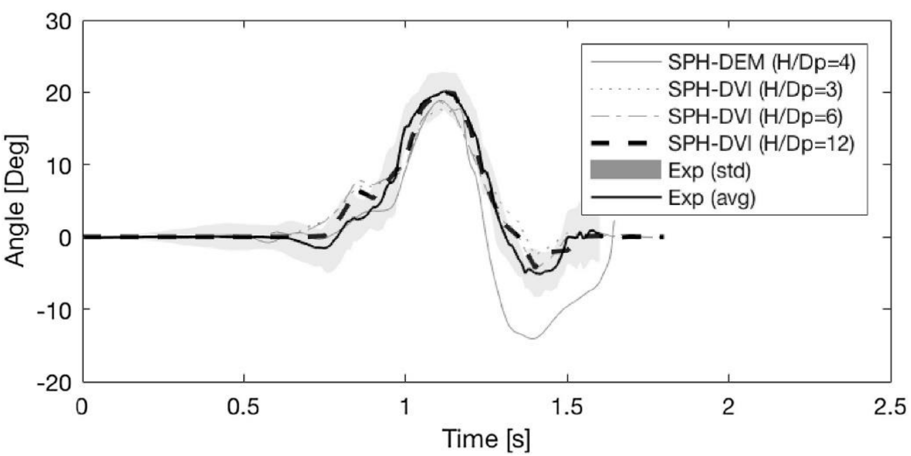
Coupling with Project Chrono

Canelas et al., 2018

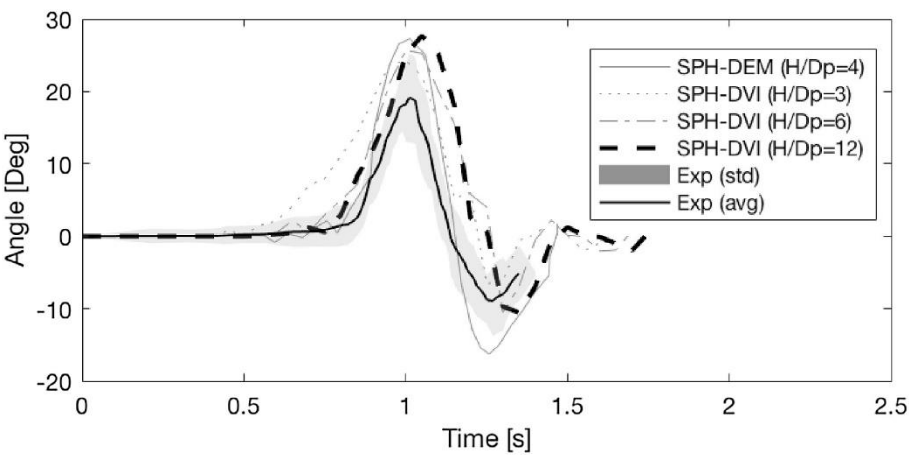
VALIDATION: Chandra and Asai, 2016







Rotation angle for h_0=300mm



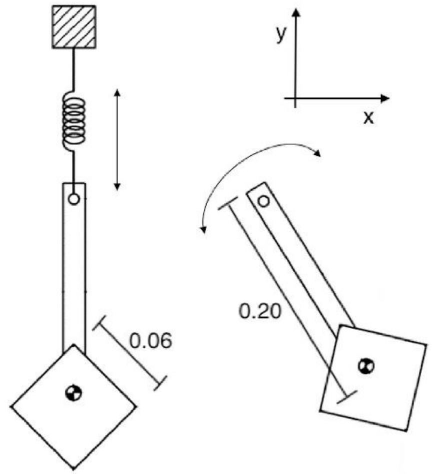
Rotation angle for h_0=350mm

Coupling with Project Chrono

Canelas et al., 2018

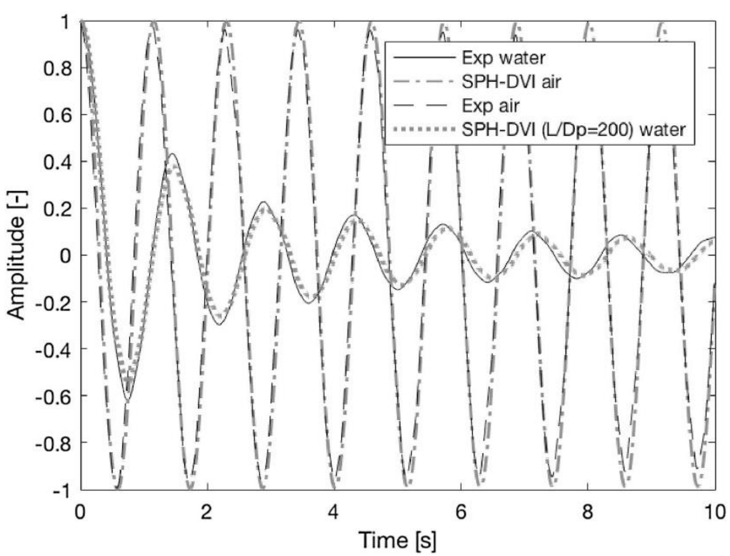
VALIDATION

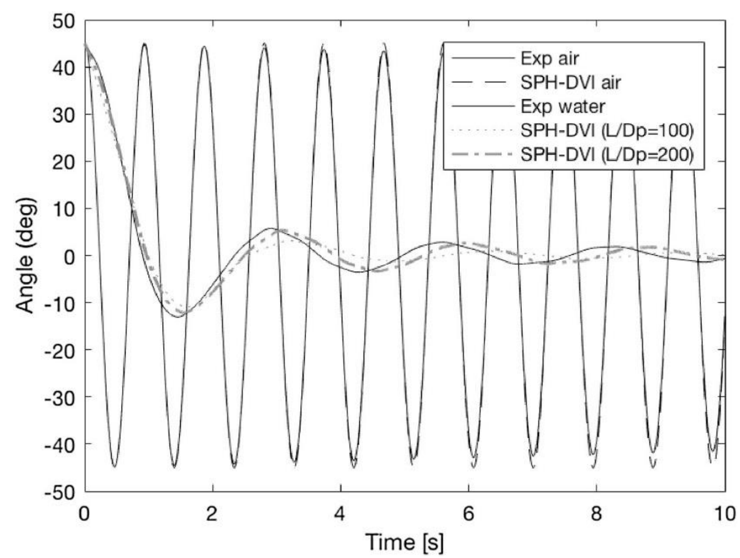
Spring pendulum



Gravity pendulum

Comparison between numerical and experimental rotation angle of **spring pendulum** in air and water and **gravity pendulum** in air and water





OUTLINE

Objective: Numerical modelling of WECs

SPH modelling: DualSPHysics software

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- Coupling with Project Chrono

Application to different WECs

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- Oscillating Wave Surge Converter (OWSC)
- Point absorber
- Others (WaveStar, M4)

Conclusions & Future work

Oscillating Water Column (OWC)

OFFSHORE **FLOATING MOORED** OWC

EsflOWC

Efficiency and survivability of floating Oscillating Water Column Wave Energy Converters moored to the seabed

GHENT UNIVERSITY (COORDINATOR), BELGIUM

UNIVERSIDADE DE VIGO, SPAIN

IST - UNIVERSIDADE DE LISBOA, PORTUGAL

THE UNIVERSITY OF MANCHESTER, UNITED KINGDOM

UNIVERSITÀ DEGLI STUDI FIRENZE, ITALY

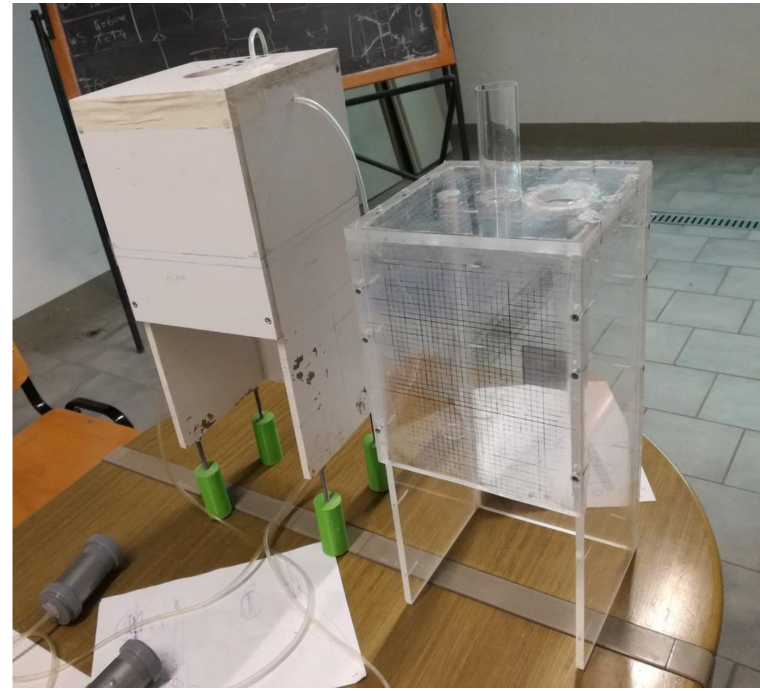
Universida de Vigo | TÉCNICO LISBOA | GHENT UNIVERSITY | MANCHESTER 1824 The University of Manchester | UNIVERSITÀ DEGLI STUDI FIRENZE

A MARINET2 TRANSNATIONAL ACCESS PROJECT (EU H2020 PROGRAMME UNDER GRANT AGREEMENT NO 731084)
SUPPORTED ALSO BY THE RESEARCH FOUNDATION FLANDERS (FWO), BELGIUM - FWO.OPR.2.0 - FWO RESEARCH PROJECT NO. 3G029114

INFRASTRUCTURES: LABIMA-UNIFI, WAVE-CURRENT FLUME (WCF)
AND COASTAL ENGINEERING RESEARCH GROUP OF GHENT UNIVERSITY, LARGE WAVE FLUME

fwo Fonds Wetenschappelijk Onderzoek Vlaanderen Opening new horizons | HORIZON 2020 | MaRINET2 Marine Renewables Infrastructure Network for Enhancing Energy Technologies

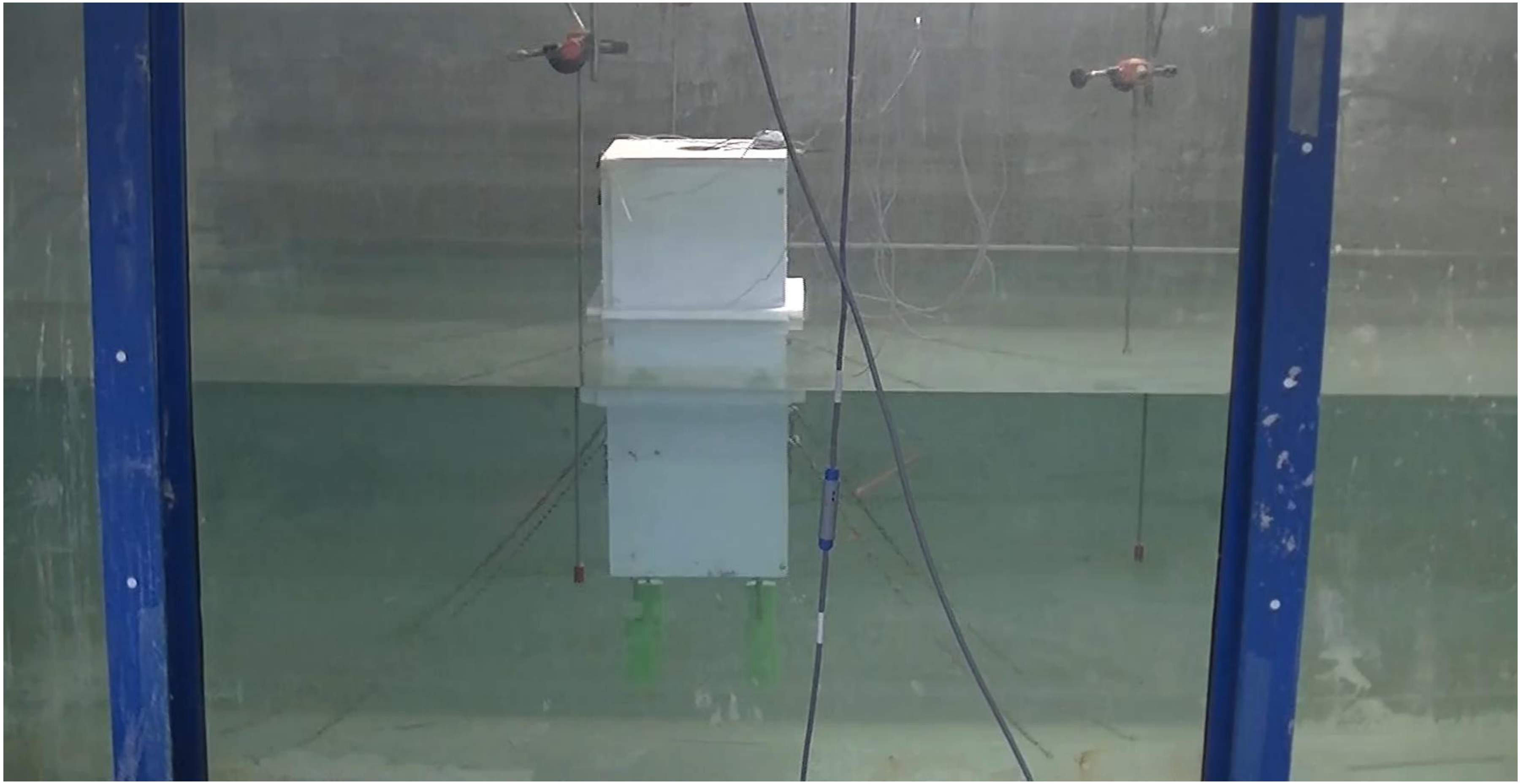
MaRINET2



Oscillating Water Column (OWC)

Floating and moored OWC

EXPERIMENT IN GENT UNIVERSITY: FLOATING MOORED OWC

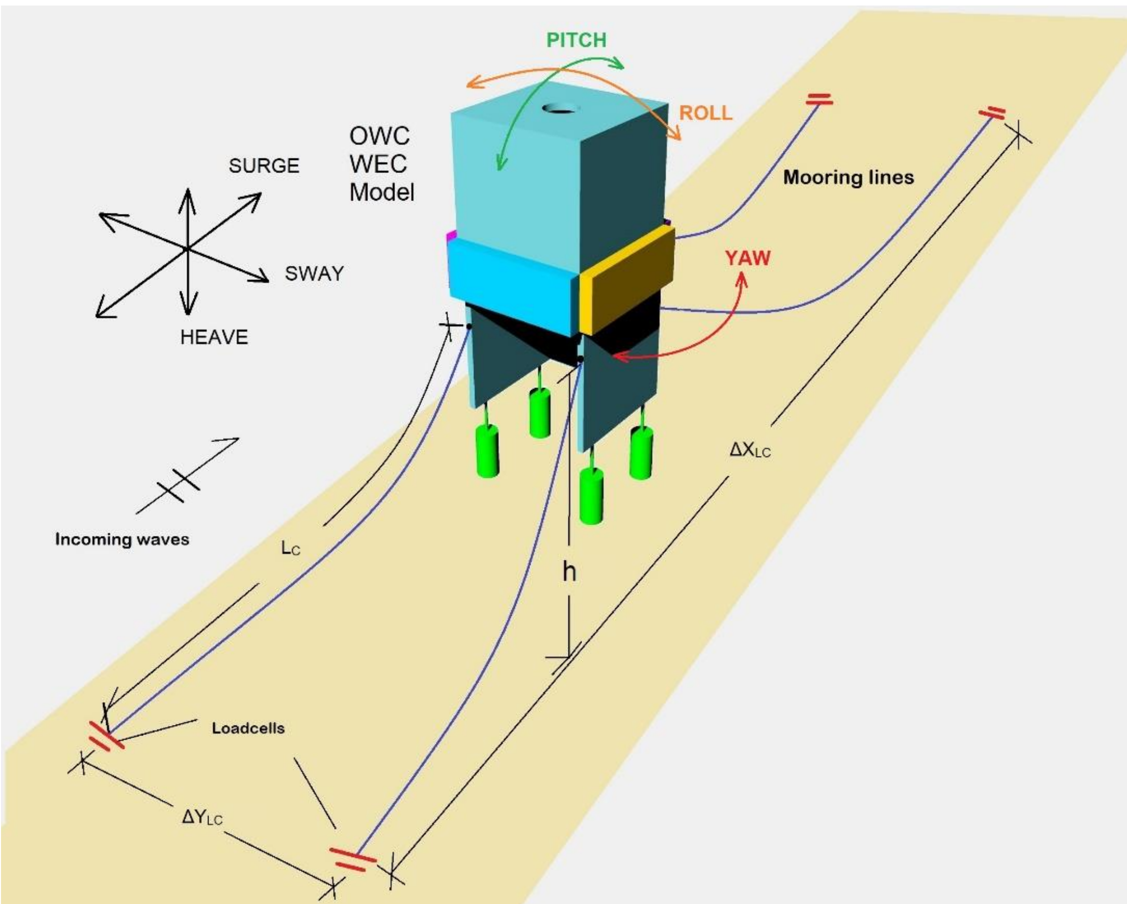


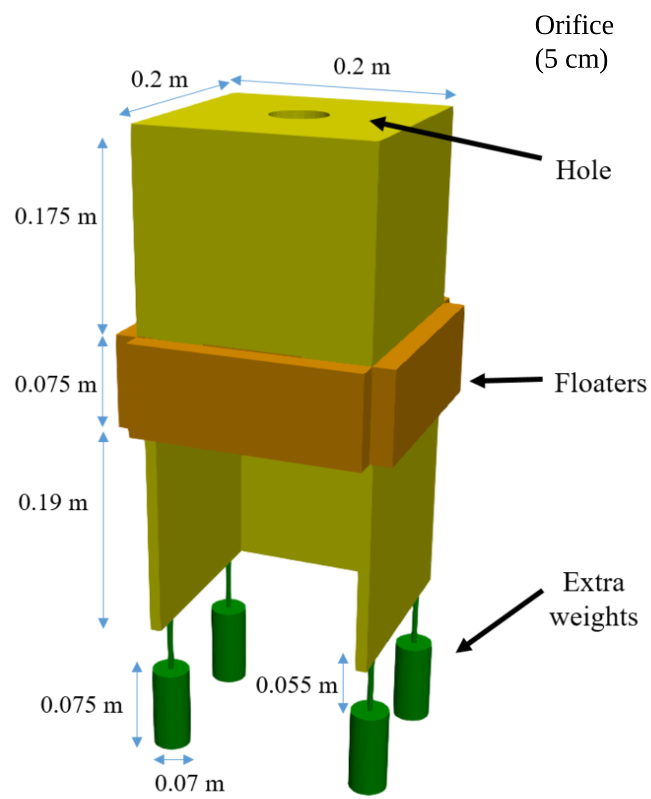
Crespo et al., 2018

Oscillating Water Column (OWC)

Floating and moored OWC

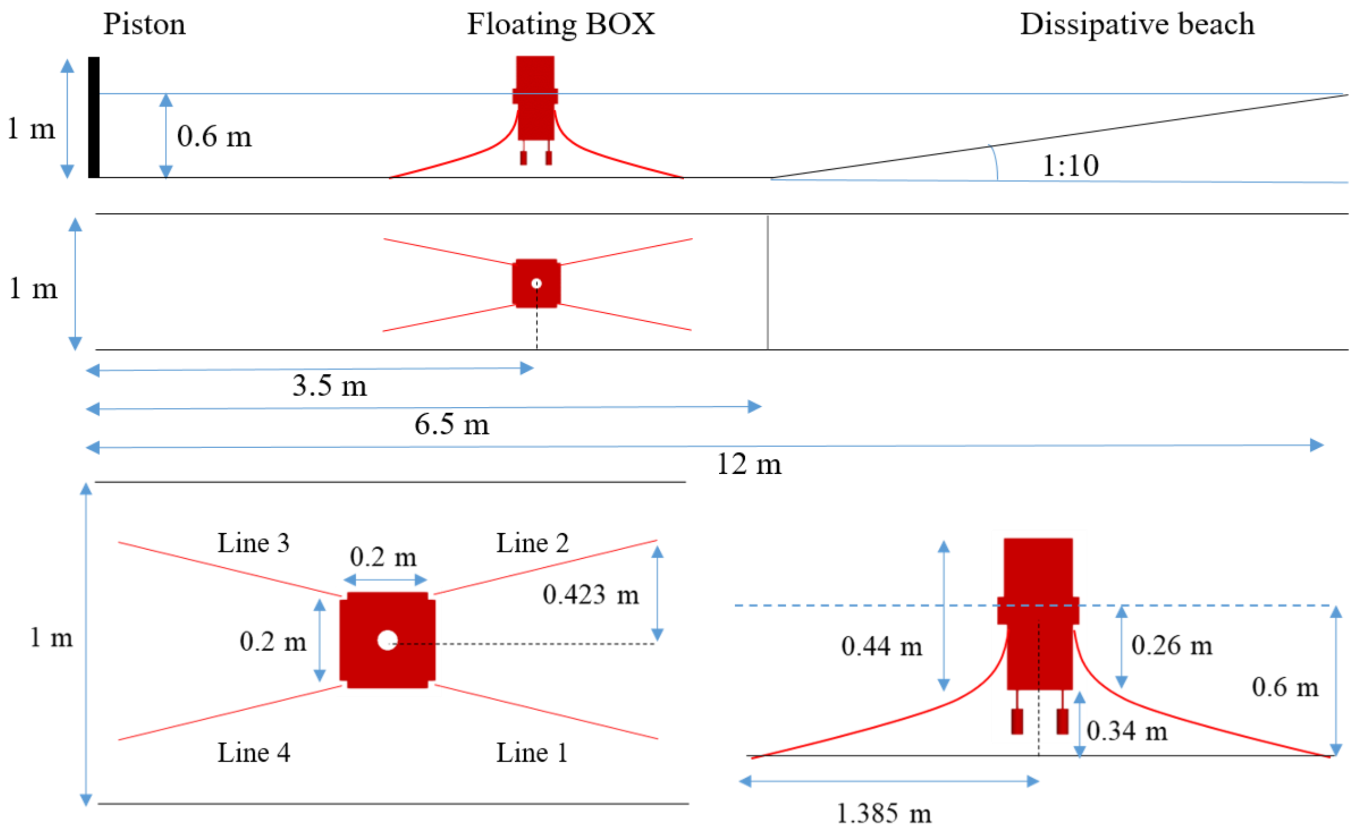
OWC with different materials but total MASS is 2.593 kg
SPH particles of density 578 kg/m^3





Oscillating Water Column (OWC)

Floating and moored OWC



Regular waves

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

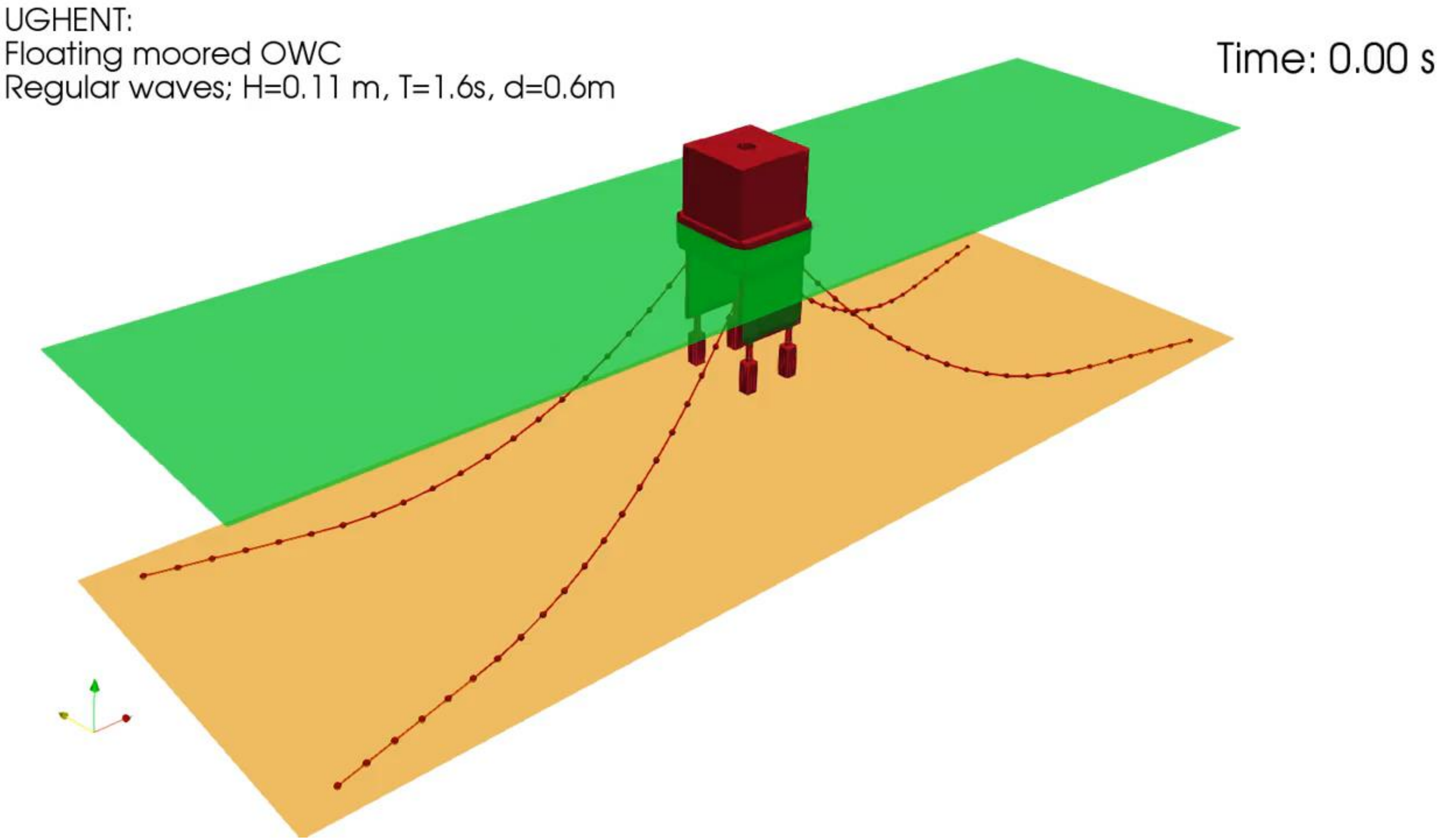
DualSPHysics	
OWC Dimensions	20 x 20 x 44 cm^3
OWC Weight	2.593 kg
OWC Centre of gravity	(-0.91, 0, -10.8) cm

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

Crespo et al., 2018

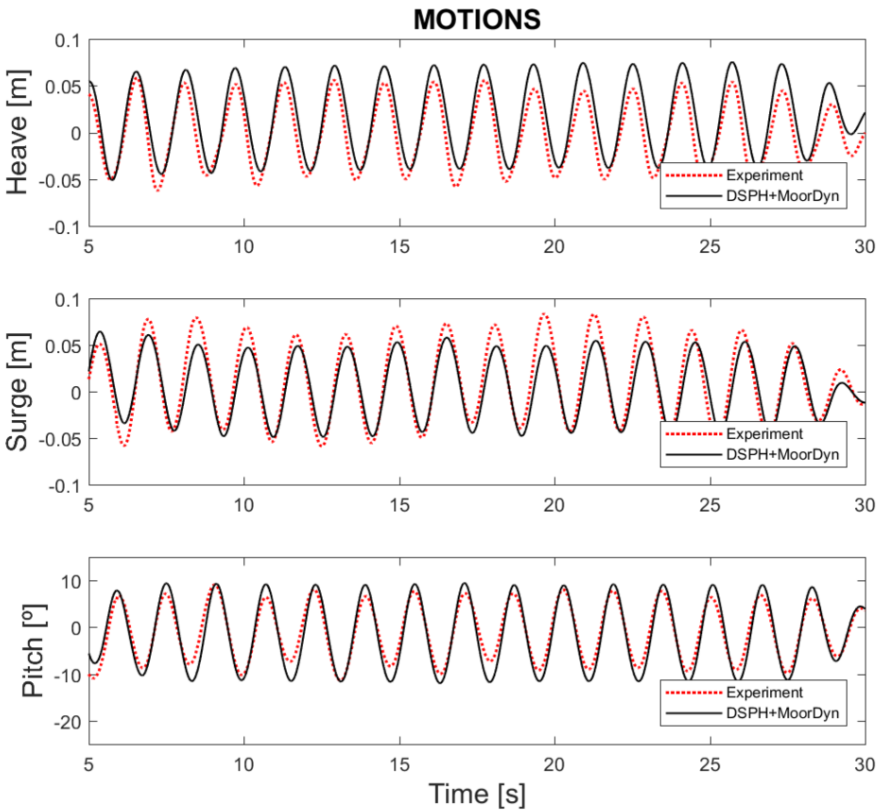
Oscillating Water Column (OWC)

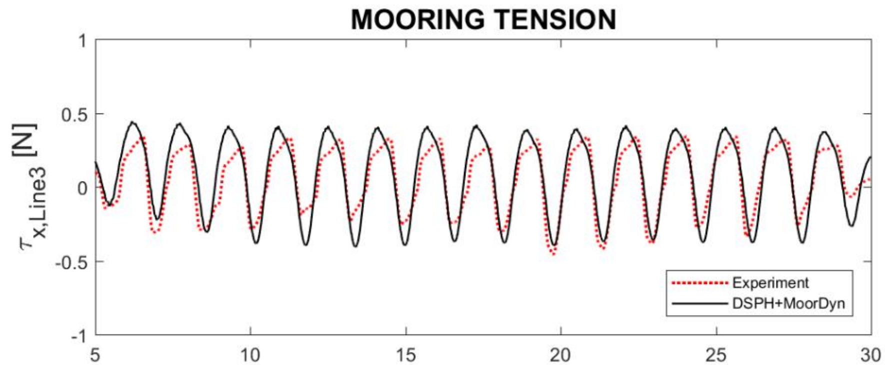
Floating and moored OWC



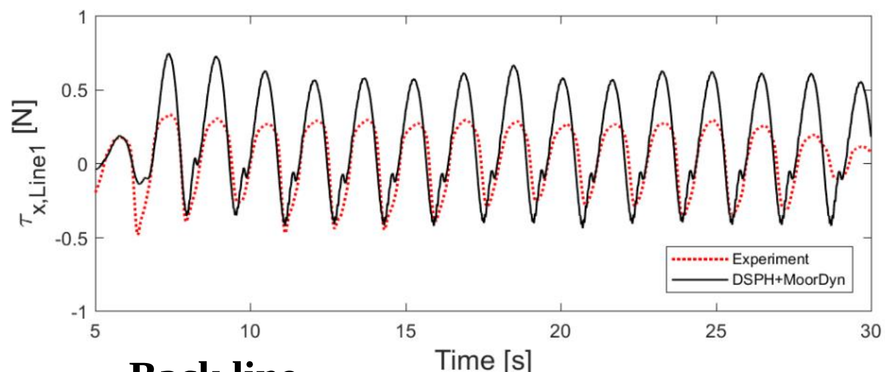
Oscillating Water Column (OWC)

Floating and moored OWC

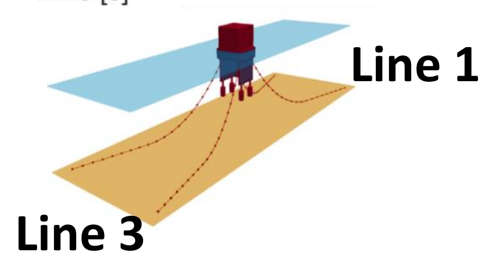




Front line



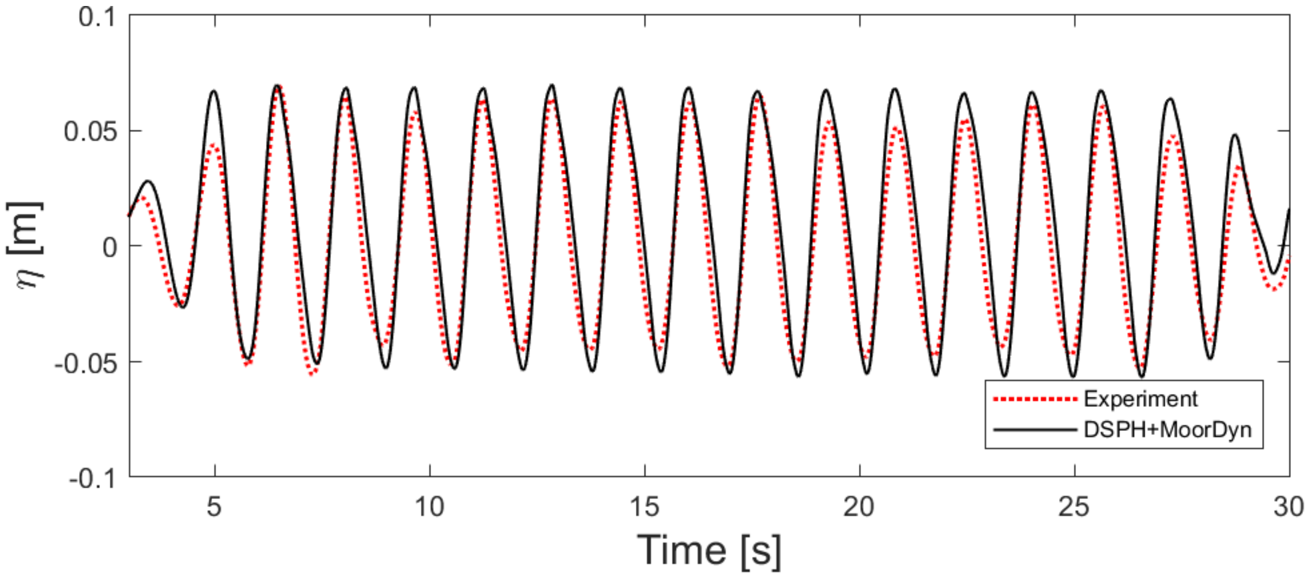
Back line



Oscillating Water Column (OWC)

Floating and moored OWC

η_{OWC}



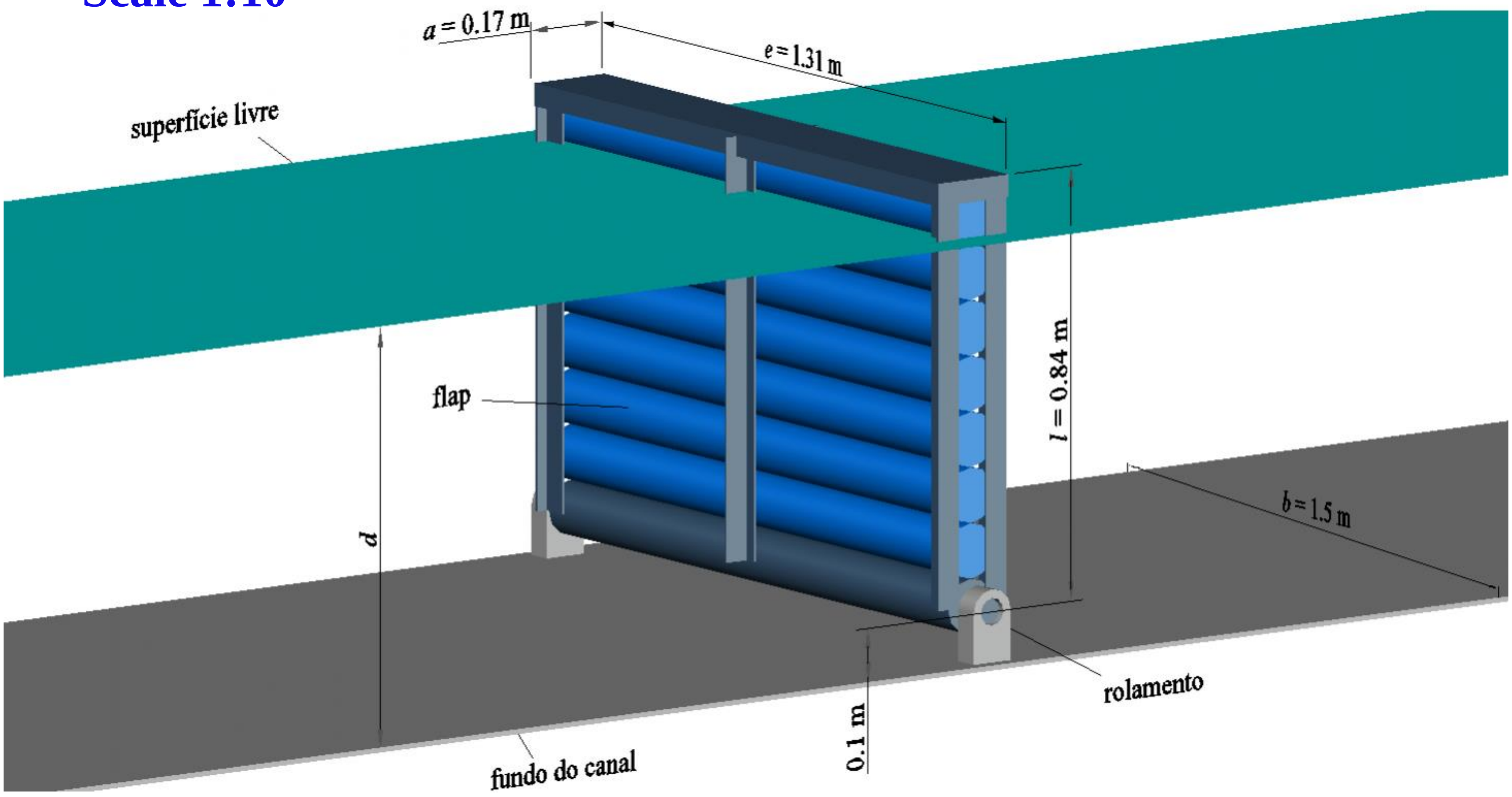
RELATIVE MOTION BETWEEN HEAVE AND WATER ELEVATION INSIDE OWC

heave - η_{OWC}

Oscillating Wave Surge Converter (OWSC)

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

Scale 1:10

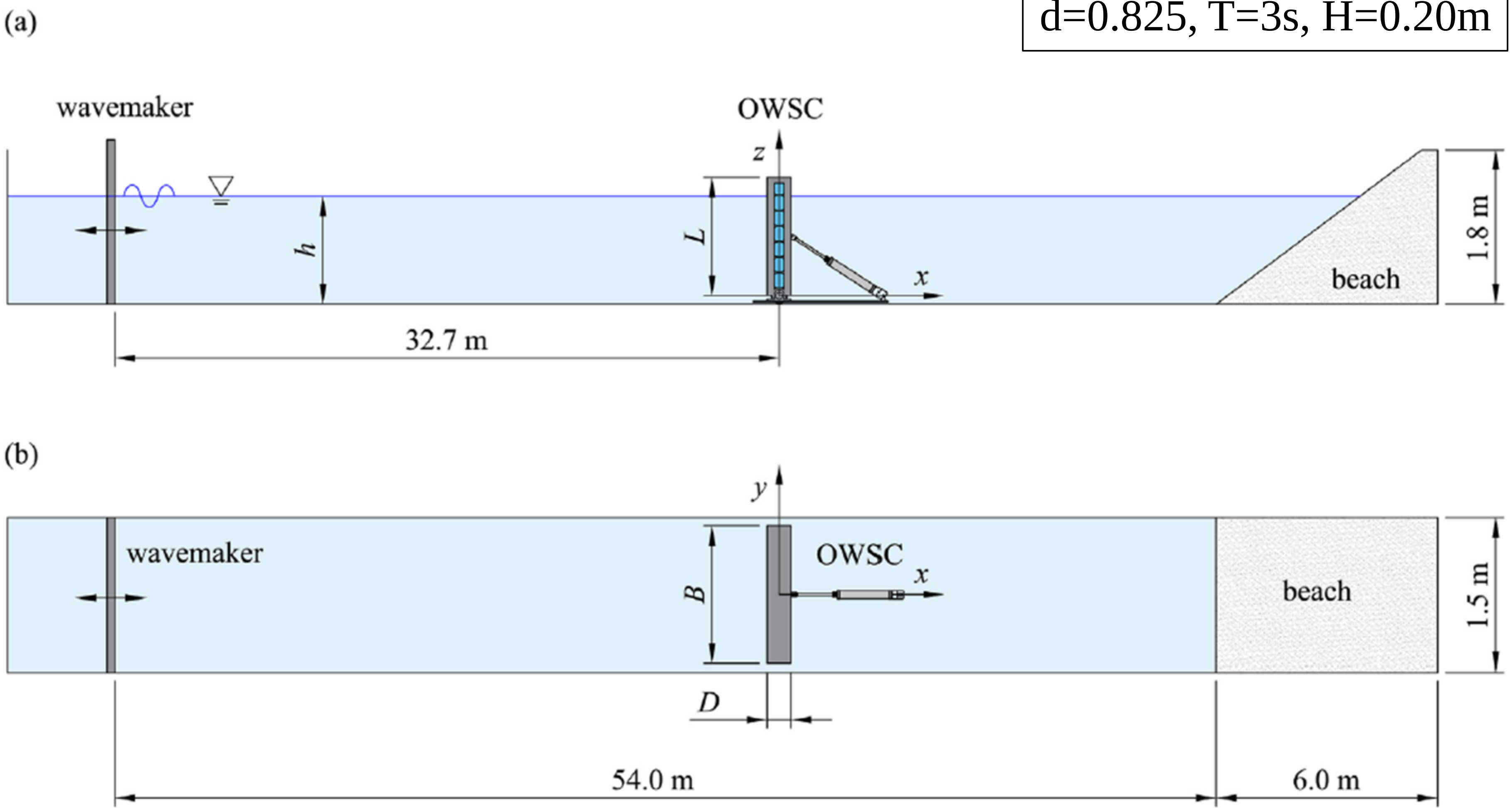


Brito et al., 2019

Oscillating Wave Surge Converter (OWSC)

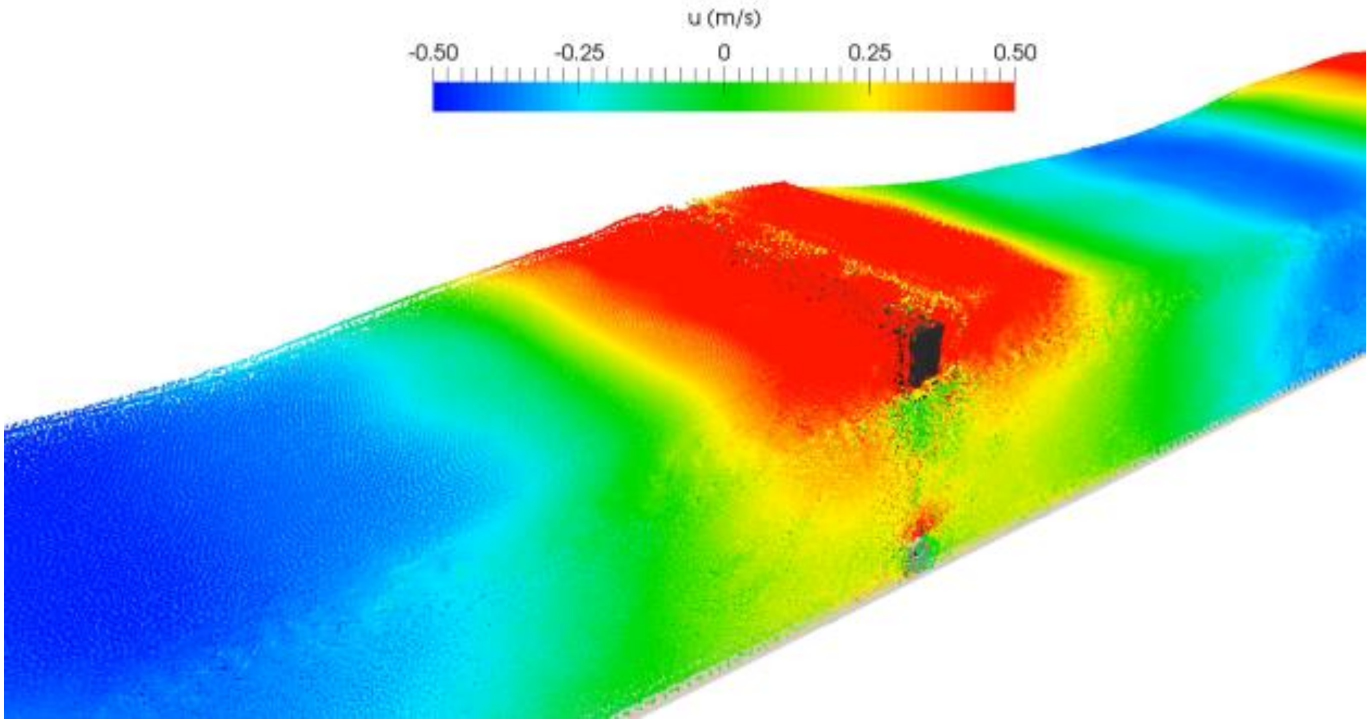
Experimental set up at the Marine Research Group's hydraulics laboratory at Queen's University Belfast.

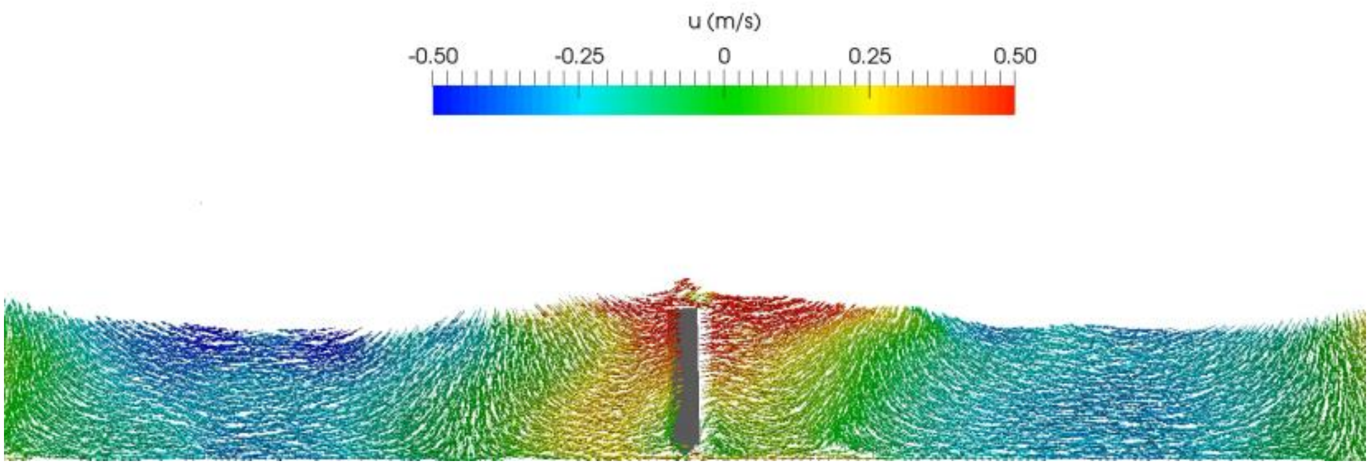
Regular waves:
d=0.825, T=2s, H=0.15m
d=0.825, T=2s, H=0.25m
d=0.825, T=3s, H=0.20m



Oscillating Wave Surge Converter (OWSC)

Brito et al., 2019

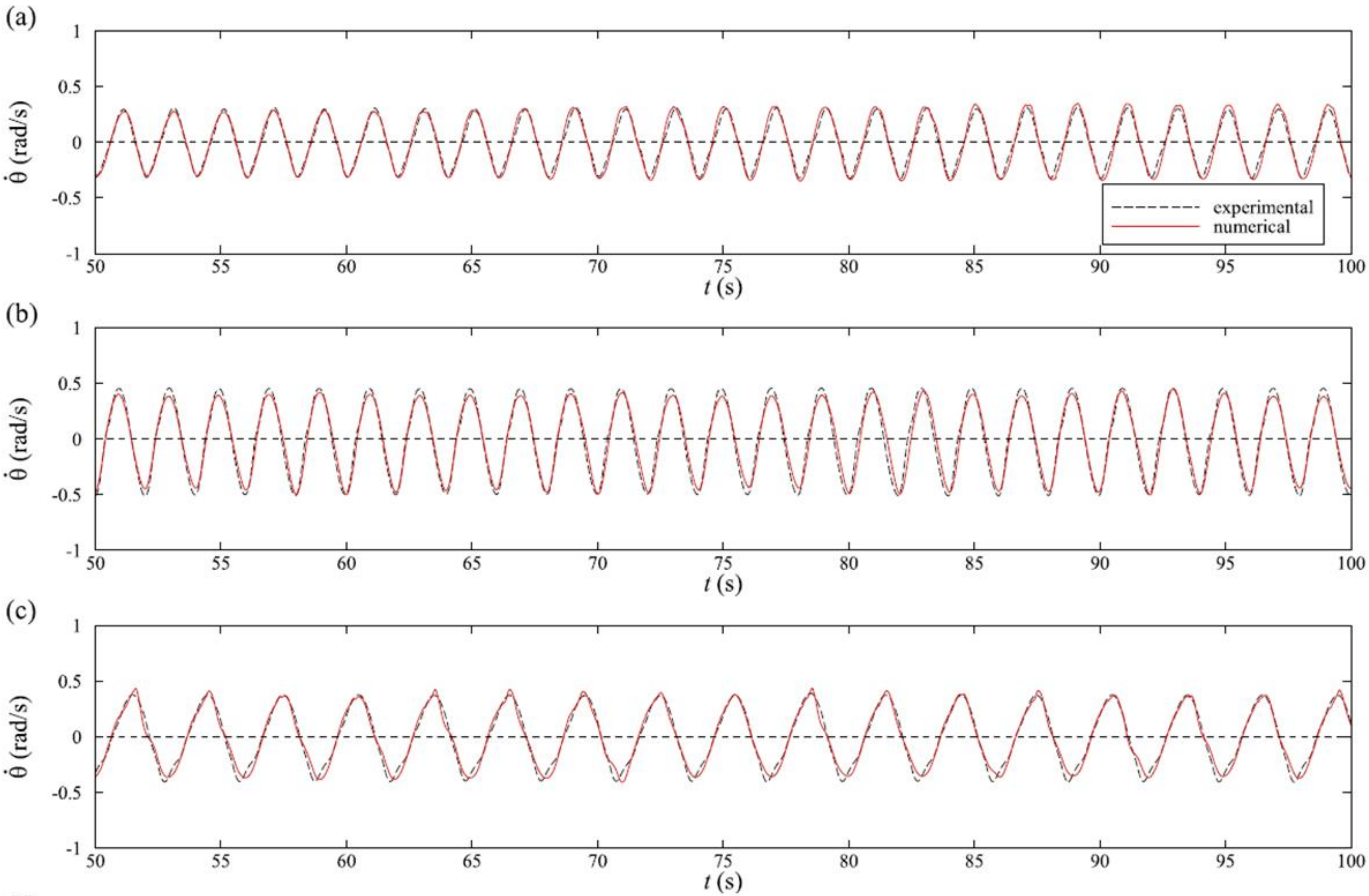




Oscillating Wave Surge Converter (OWSC)

VALIDATION:

Numerical and **experimental** time series of angular velocity of the flap



T=2s
H=0.15m

T=2s
H=0.25m

T=3s
H=0.20m

Oscillating Wave Surge Converter (OWSC)

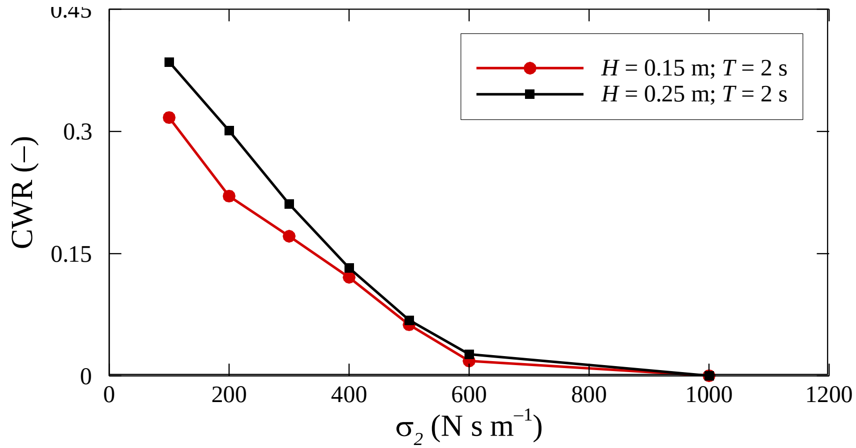
Brito et al., 2019

Influence of the PTO system

CWR: capture width ratio

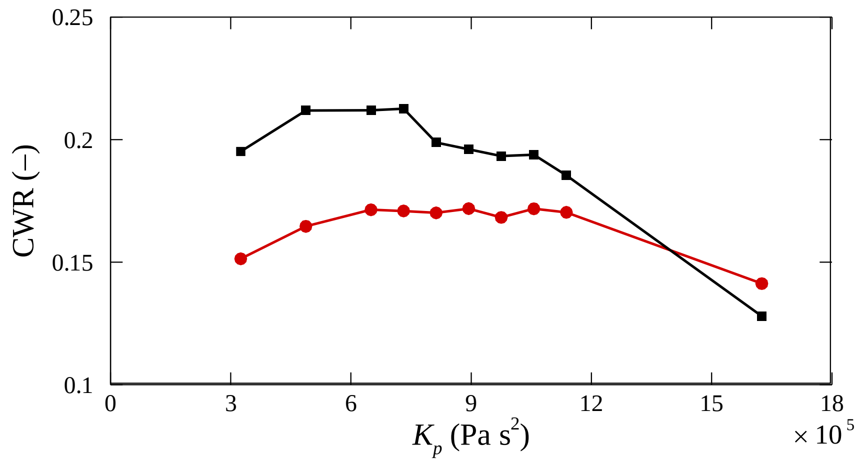
$$F_f^{smooth}(t) = \sigma_0 z_d(t) + \sigma_1 \dot{z}_d(t) + \sigma_2 \dot{x}(t)$$

Viscous friction coefficient



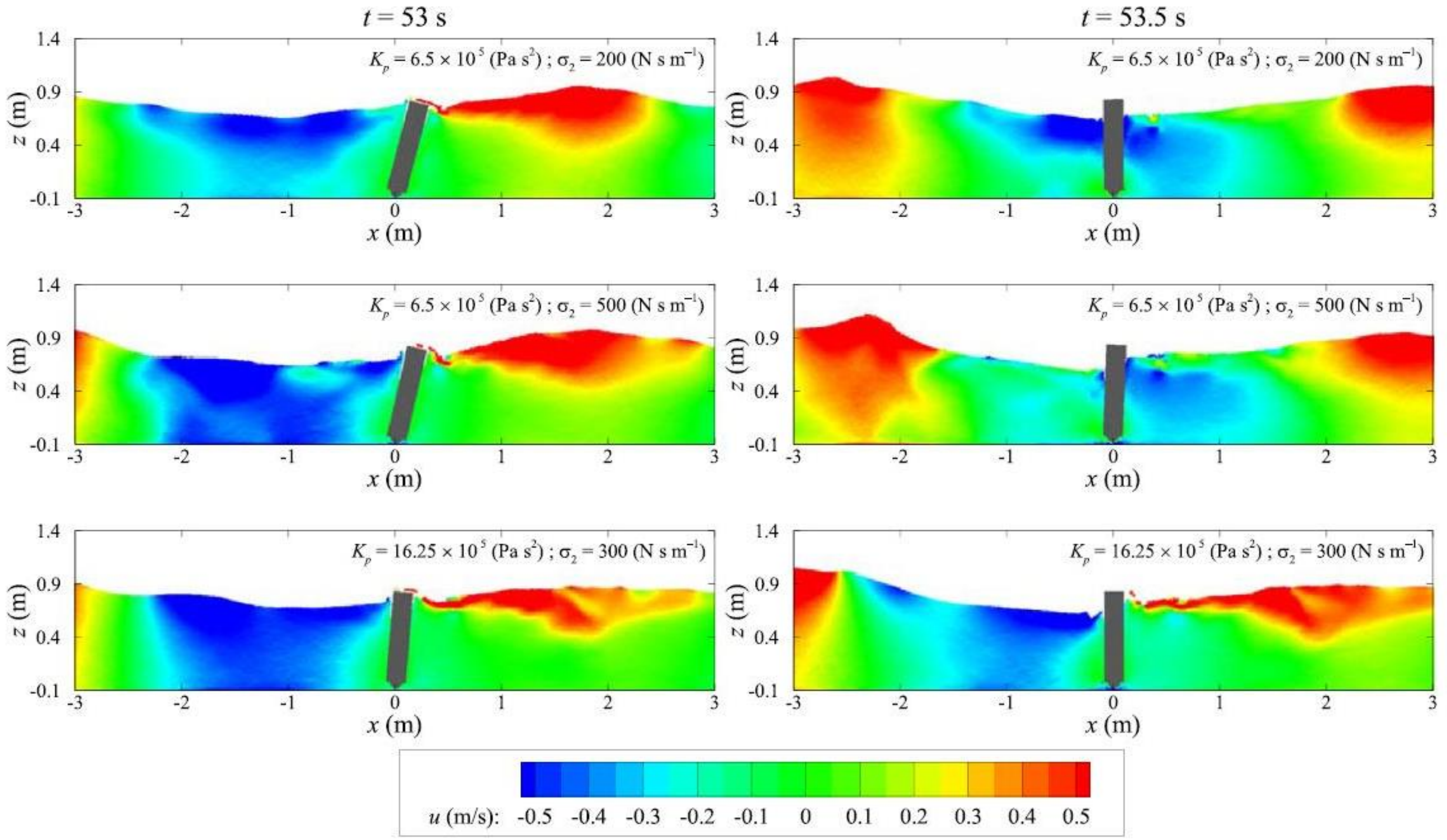
$$F_p^{smooth}(t) = \left[K_p \dot{x}(t)^2 + I_p \ddot{x}(t) \right] A$$

Pressure loss coefficient



Oscillating Wave Surge Converter (OWSC)

Influence of the PTO system

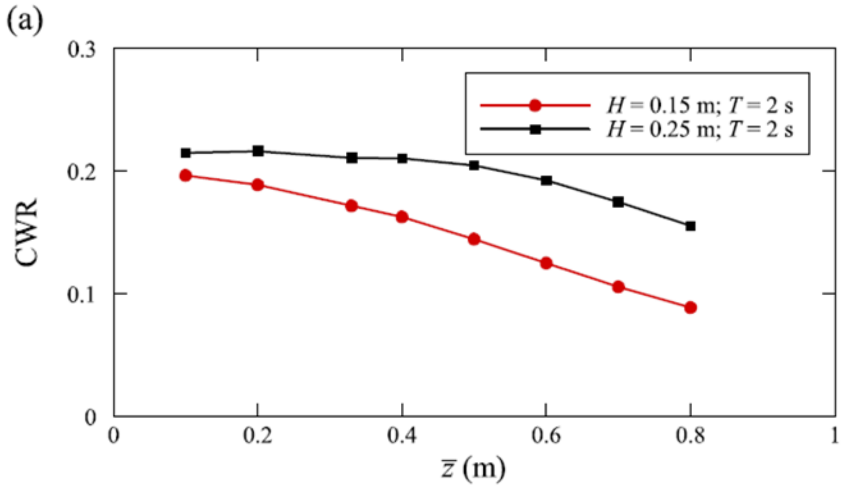


Oscillating Wave Surge Converter (OWSC)

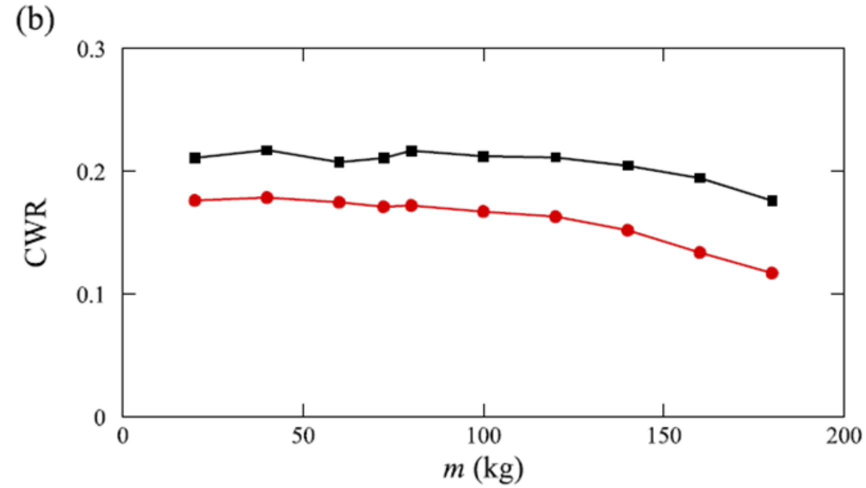
Brito et al., 2019

Influence of flap inertia

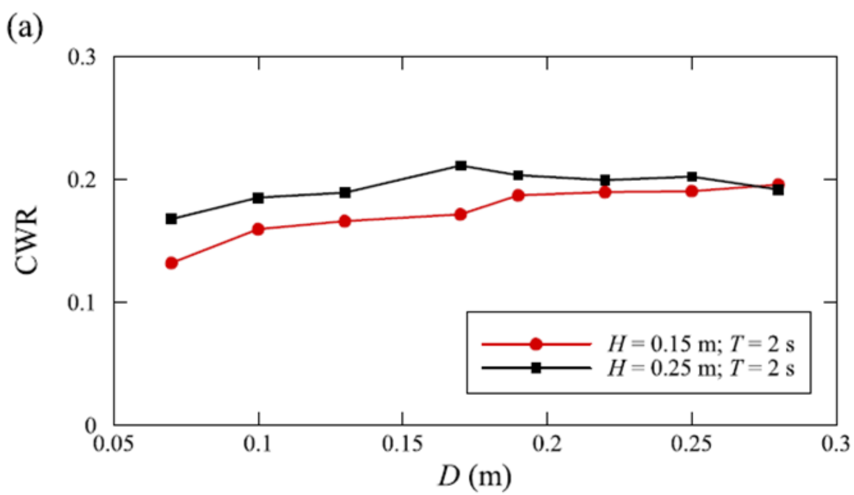
CWR: capture width ratio



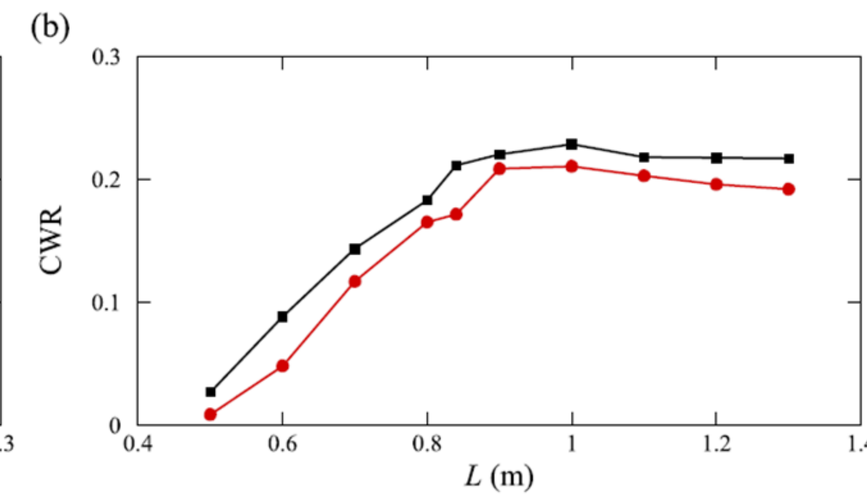
CENTER OF MASS



MASS



THICKNESS



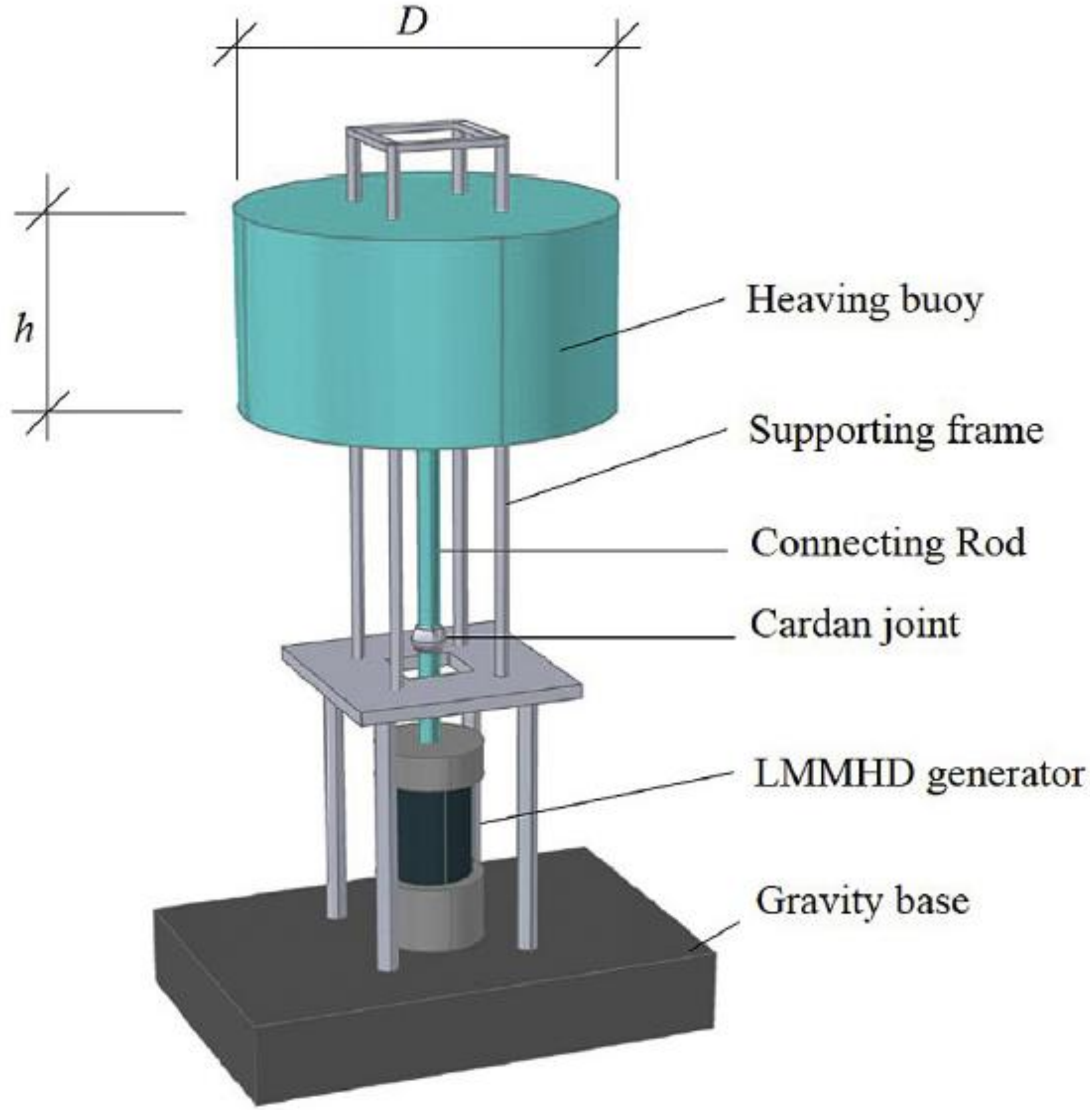
HEIGHT

Point absorber (only heave motion)

F_{PTO}=**k**·z+**c**·vel.z

k: stiffness

c: damping



Point absorber (only heave motion)

Zang Z, Zhang Q, Qi Y, Fu X, 2018. Hydrodynamic responses and efficiency analyses of a heaving-buoy wave energy converter with PTO damping in regular and irregular waves. Renewable Energy, 116: 527-542

PTO is modelled as a linear damper

$$F_{PTO}=\mathbf{c}\cdot vel.z$$

Buoy: cylinder with only-heave motion:

Diameter D=0.5 m

Mass M=21.6 kg

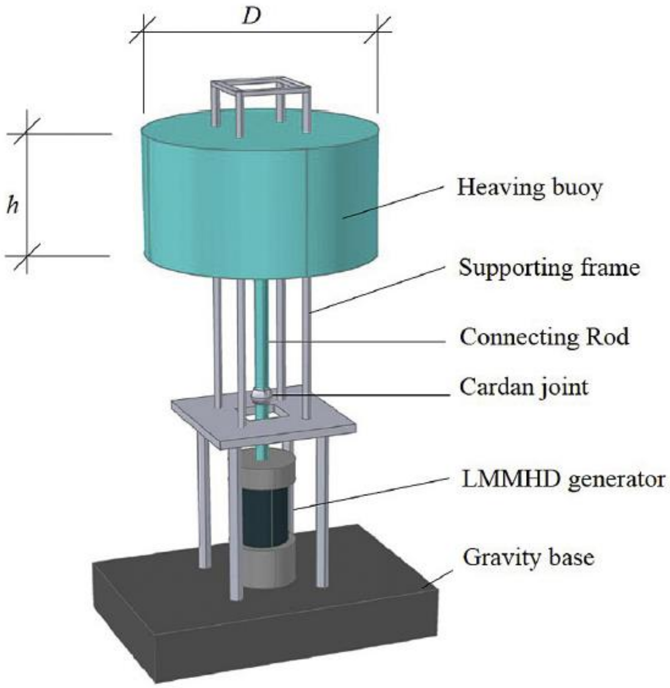
Draft B=0.11 m

Regular waves:

H=0.16 m, T=1.5 s, d=1.1 m

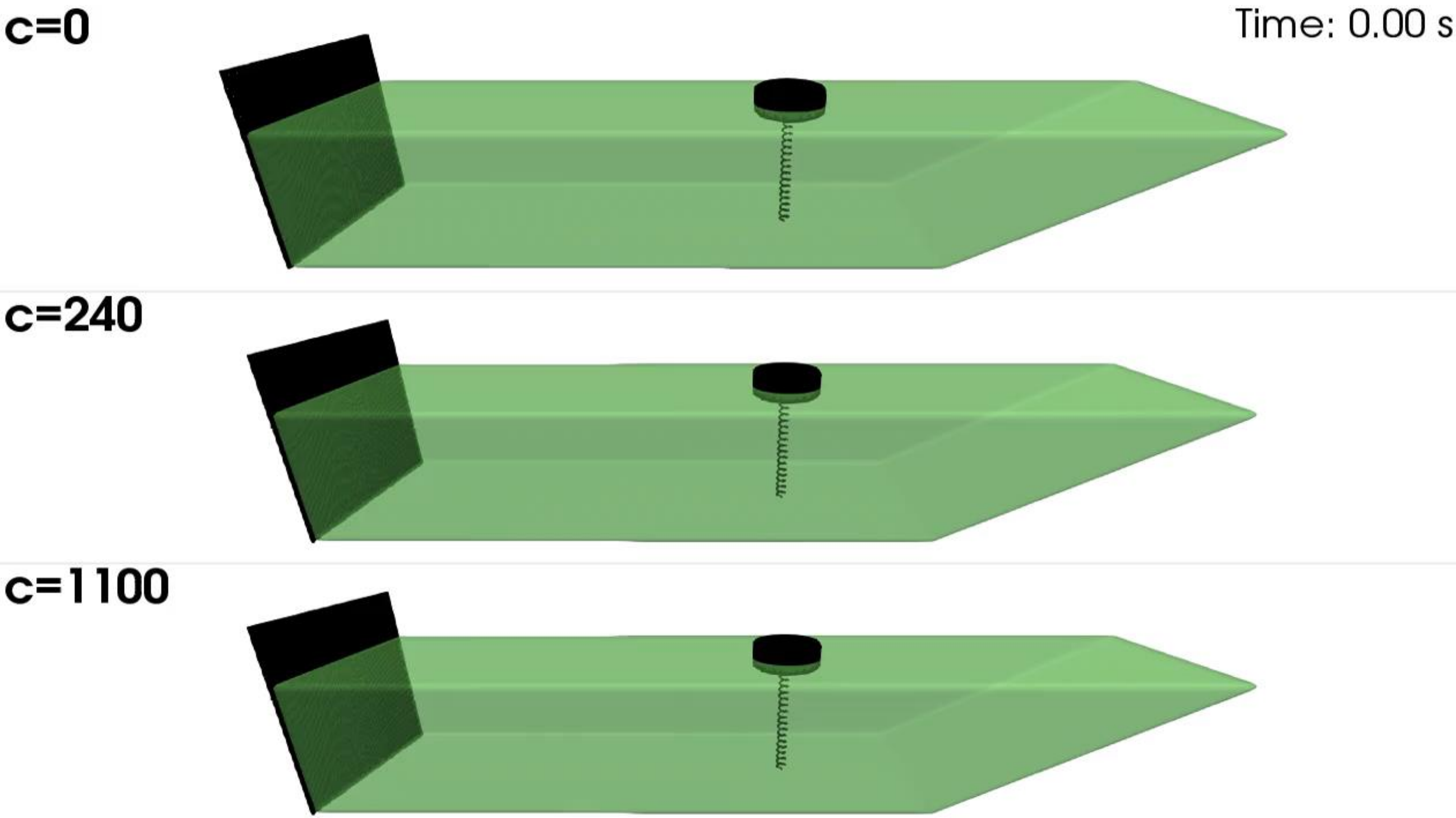
Linear damper with CHRONO:

rest_length=0.99 m, k(stiffness)=0



Point absorber (only heave motion)

Regular waves: H=0.16 m, T=1.5 s, d=1.1 m
Spring-damper with CHRONO: rest_length=0.99 m, k=0



Point absorber (only heave motion)

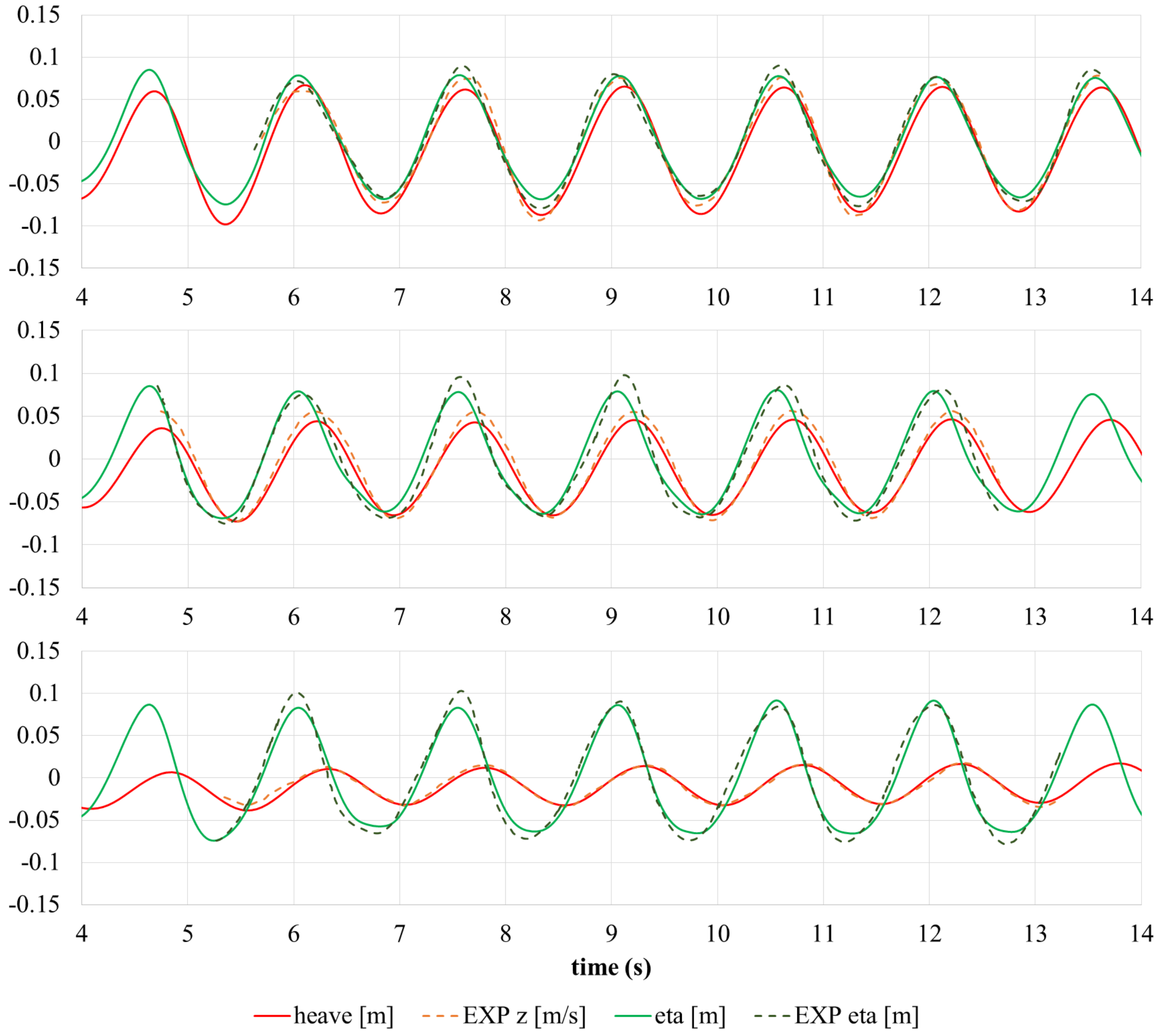
VALIDATION

Regular waves: H=0.16 m, T=1.5 s, d=1.1 m
Spring-damper with CHRONO: rest_length=0.99 m, k=0

c=0

c=240

c=1100



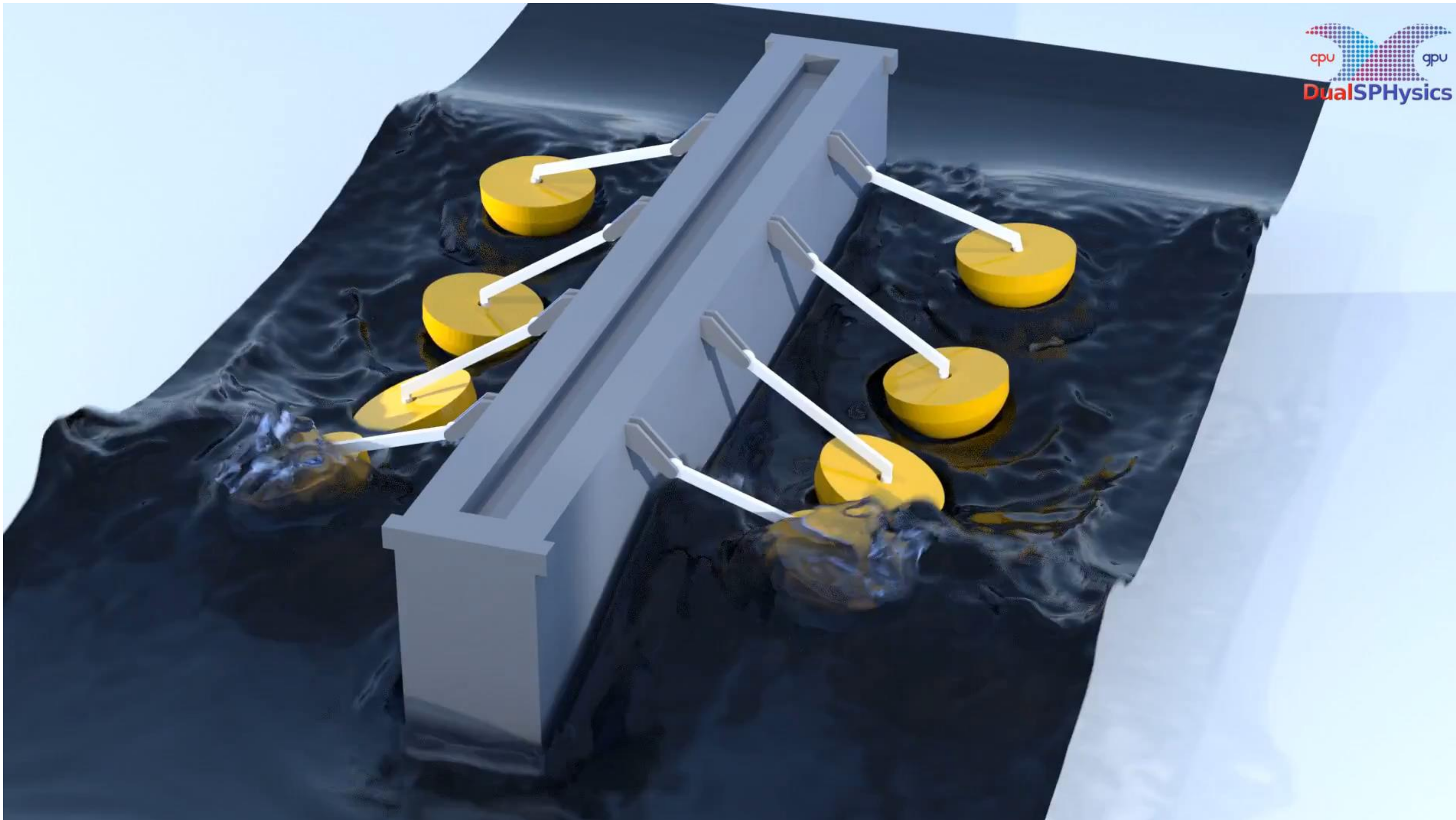
WaveStar

Revolute and spherical joints on the articulated arms and buoys.

WaveStar

Canelas et al., 2018

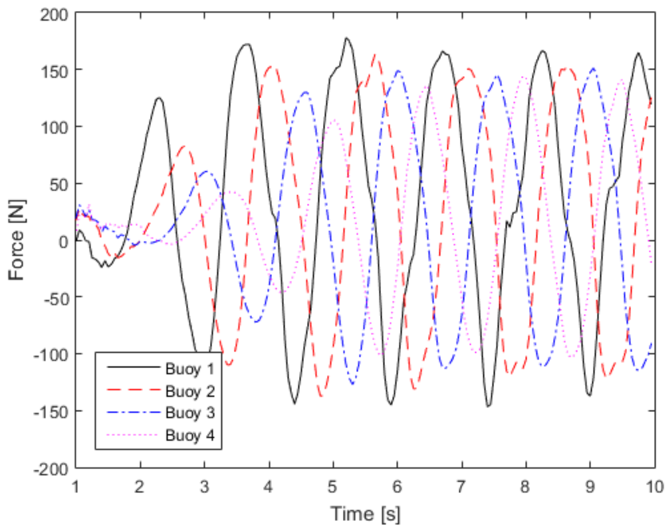
Revolute and spherical joints on the articulated arms and buoys.

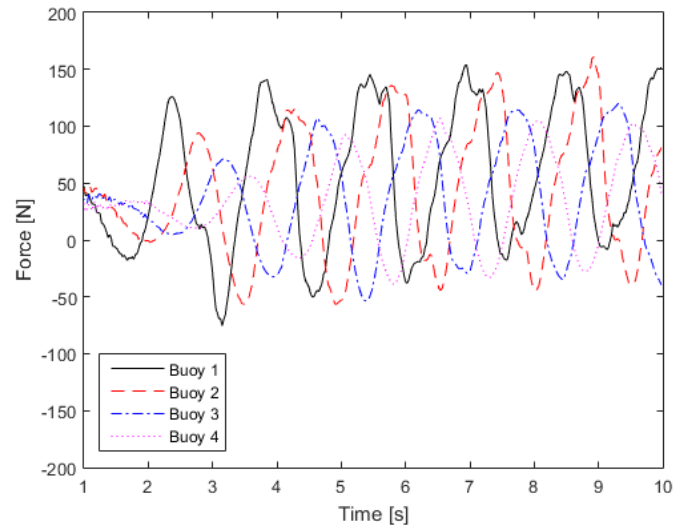


Canelas et al., 2018

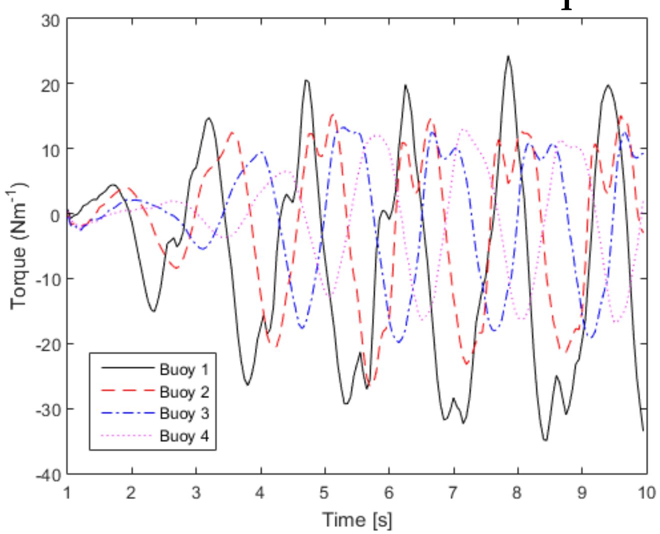
WaveStar

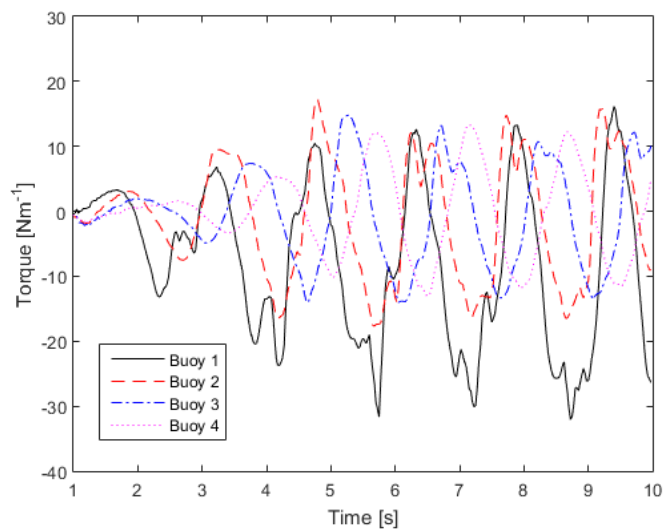
Forces on the buoy link





Torque on the buoy link





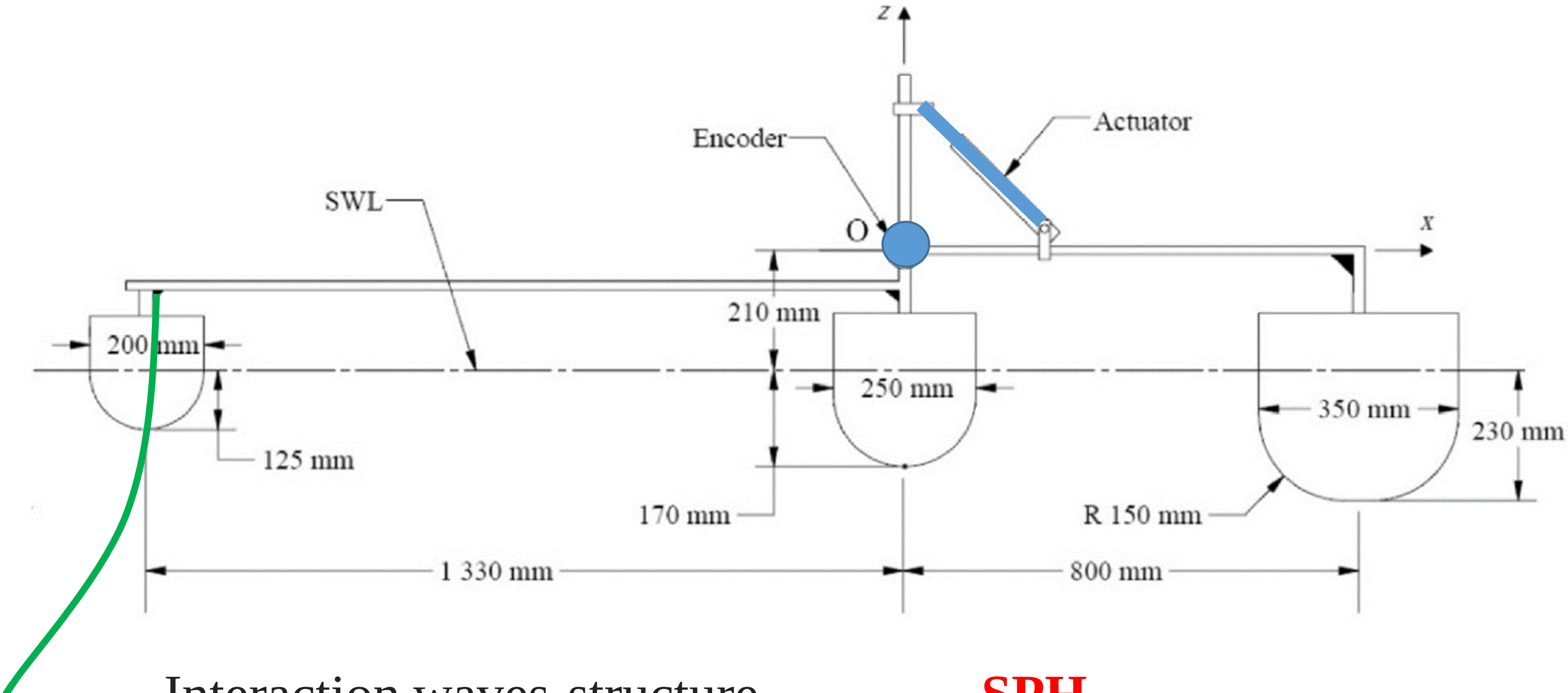
Without PTO
k=0, c=0

With PTO
k=2500, c=500

Multi-floater M4

M4 is a moored three-float line absorber WEC

Stansby P, Carpintero-Moreno E, Stallard T, 2017. Large capacity multi-float configurations for the wave energyconverter M4 using a time-domain linear diffraction model. Applied Ocean Research, 68: 53-64.

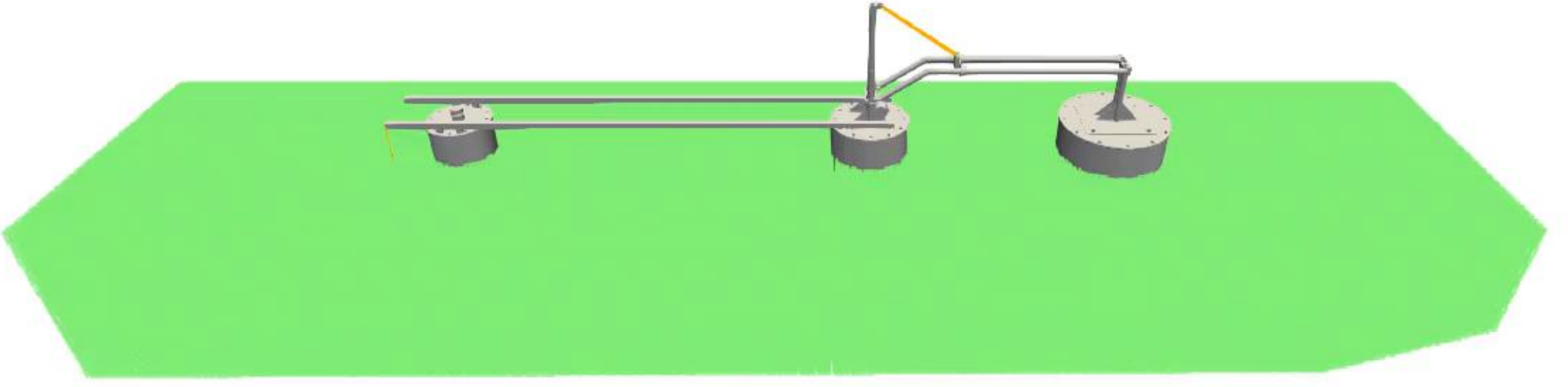


Interaction waves-structure **SPH**
Mechanical constraint “hinge” **CHRONO**
Pneumatic actuator or damper **CHRONO**
Mooring line **MOORDYN**

Multi-floater M4

M4 is patented and has been supported by:

- EPSRC Supergen Marine Challenge grant Step WEC (EP/K012487/1) provided by the UK government
- The Energy Sustainability Conacyt-SENER fund provided by the Mexican government
- The EU Marinet2 Transnational Access programme (project M4WW)



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- Point absorber
- Others (WaveStar, M4)

Conclusions & Future work

Conclusions & Future work

- ✓ DualSPHysics code has been **validated with experimental data** to prove the capability to simulate wave-structure interactions (fixed and floating structures).

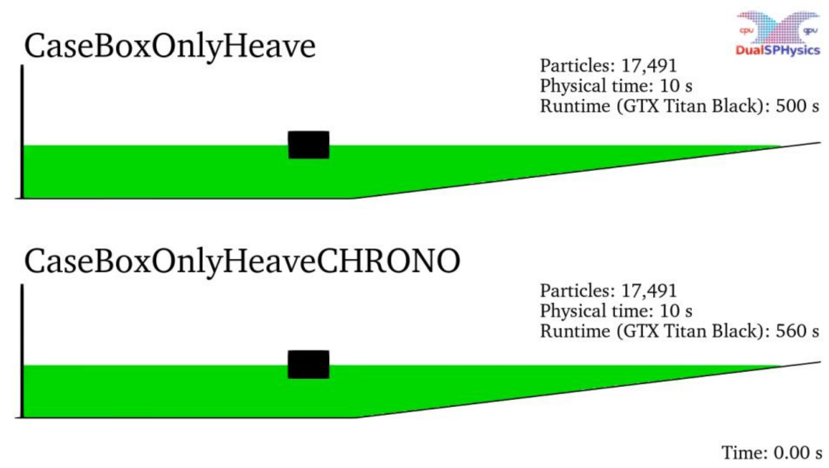
- ✓ DualSPHysics is **successfully coupled with the other models:**
  - ✓ MoorDyn to simulate mooring lines
  - ✓ Project Chrono to simulate the behaviour of PTO

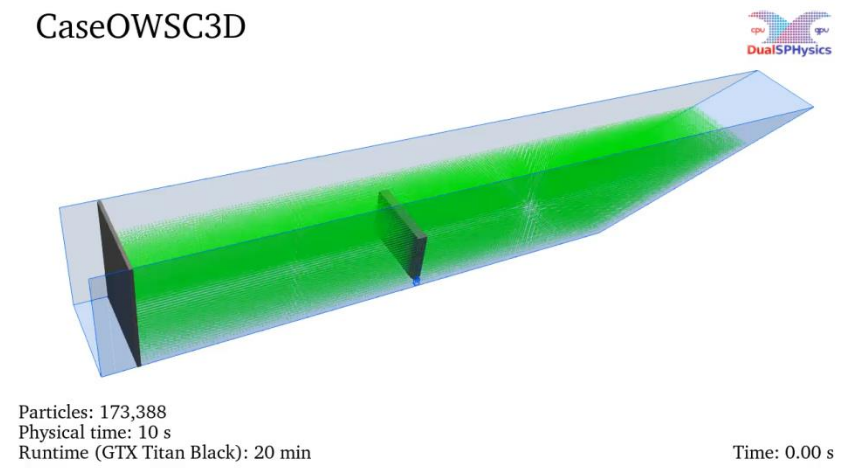
- ✓ It can be used to study not only the **efficiency** of WECs but also **the survivability under extreme waves** (high energetic sea states).

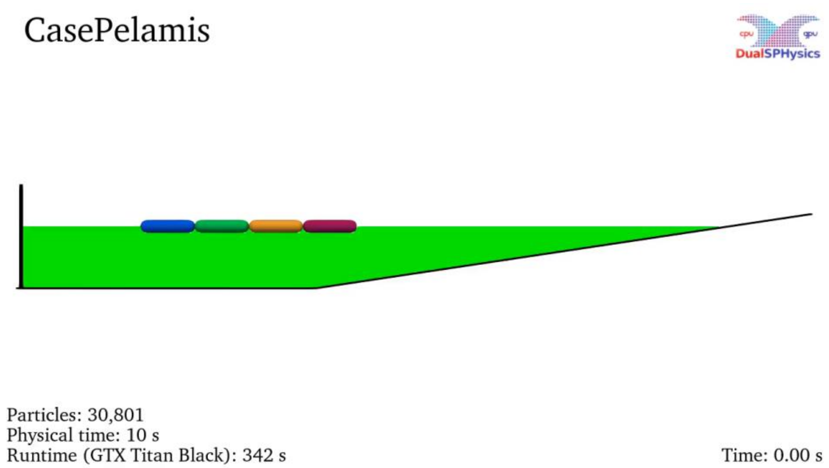
- ✓ Source code and examples are **available in DualSPHysics v4.4**

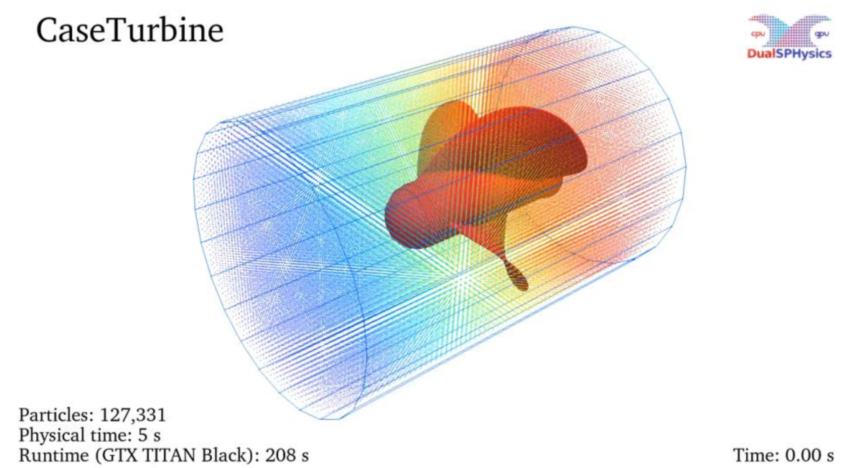
Conclusions & Future work

SOURCE CODE AND EXAMPLE IN DUALSPHYSICS V4.4









https://dual.sphysics.org/

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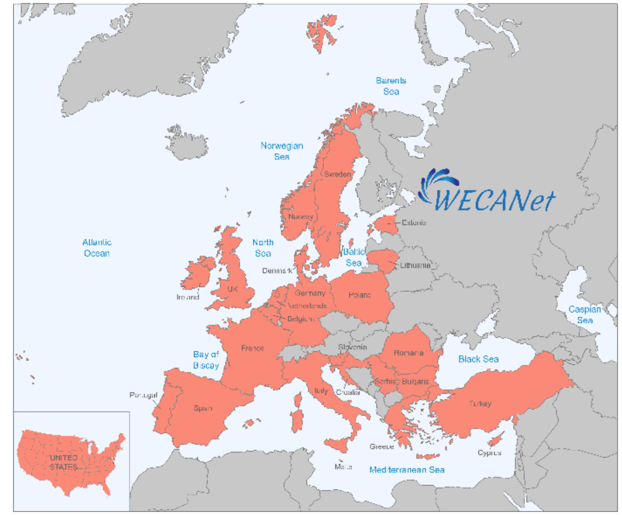
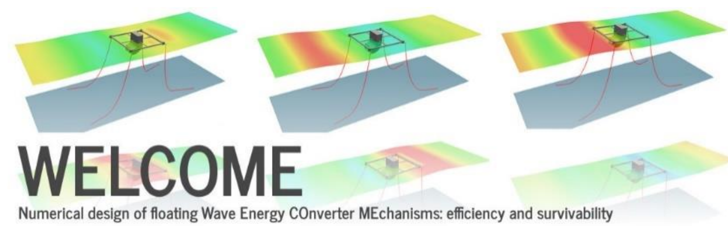
- Crespo AJC, Hall M, Domínguez JM, Altomare C, Wu M, Verbrugghe T, Stratigaki V, Troch P, Gómez-Gesteira M. 2018. Floating moored oscillating water column with meshless SPH method. In: 37th International Conference on Ocean, Offshore and Artic Engineering, Madrid, Spain, OMAE2018-77313
- Brito M, Canelas RB, García-Feal O, Domínguez JM, Crespo AJC, Ferreira RML, Neves MG, Teixeira L. 2019. A numerical tool for modelling oscillating wave surge converter with nonlinear mechanical constraints. Renewable Energy, 146: 2024-2043.

ACKNOWLEDGEMENTS

COST Action CA17105, COST Association
WECANet: A pan-European Network for Marine Renewable Energy

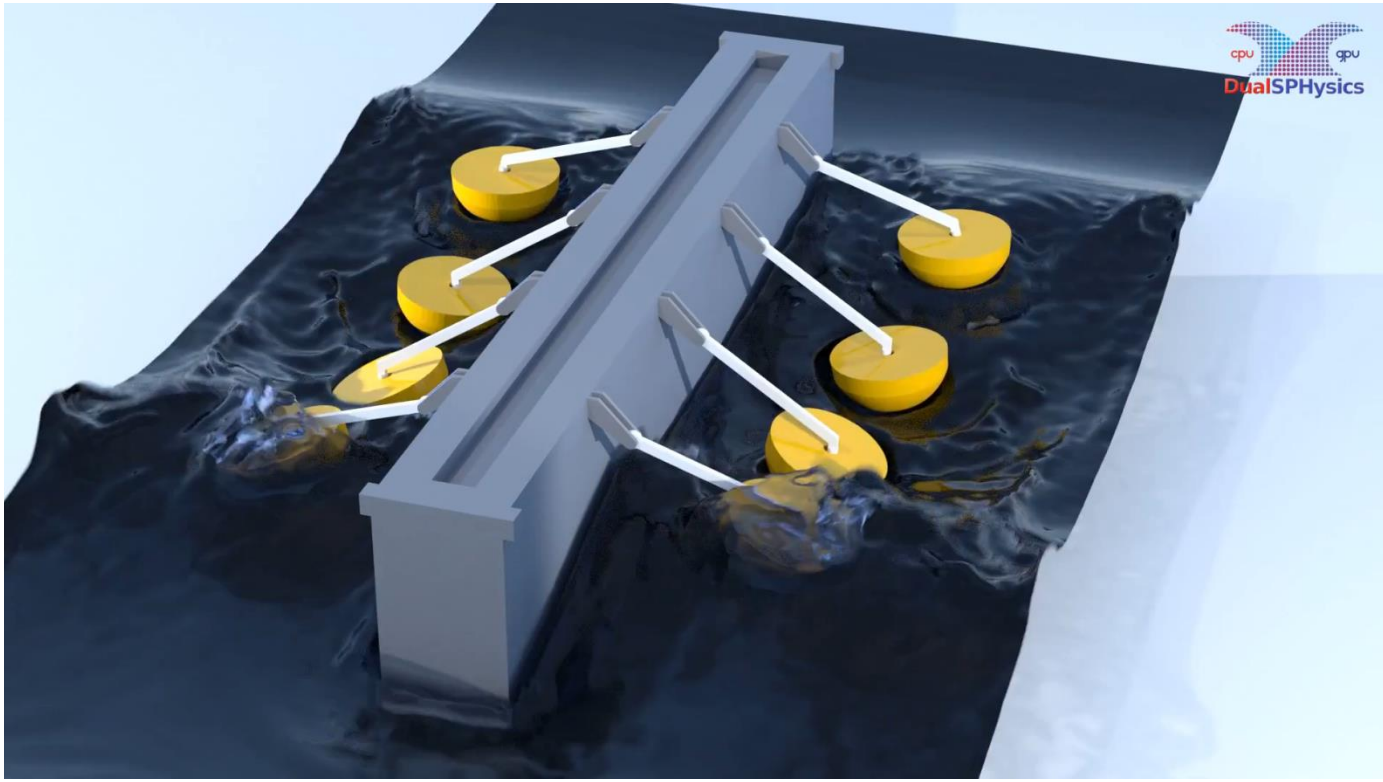


SPANISH GOVERNMENT. RETOS 2016
WELCOME: Numerical design of floating Wave Energy COnverter MEchanisms: efficiency and survivability



MARINET2
EsflOWC: Efficiency and survivability of floating OWC moored to the seabed

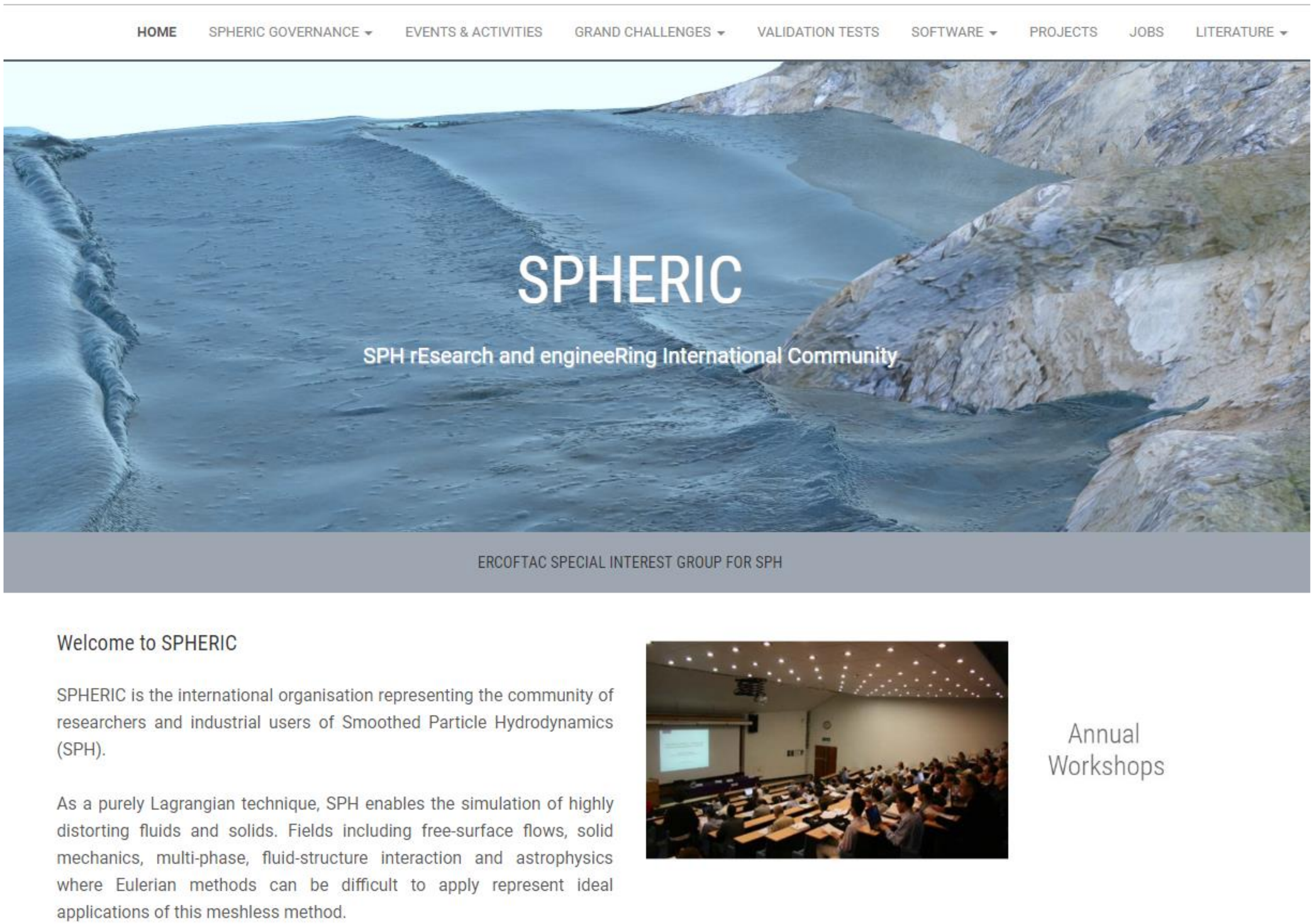
Thanks a lot for your attention



Grazie per la vostra attenzione

MORE…

SPHERIC organisation



http://spheric-sph.org/

MORE…

SPHERIC organisation

SPHERIC is the international organisation representing the community of researchers and industrial users of Smoothed Particle Hydrodynamics (SPH)
UNIVERSIDADE DE VIGO is member of SPHERIC since 2006

Objectives of SPHERIC

To develop the fundamental basis of SPH.
To discuss current and new concepts.
To foster communication between industry and academia.
To communicate experience in the application of the technology.
To investigate accelerating simulations and visualisation.
To provide access to existing software and methods.
To define benchmark test cases.
To identify future needs of SPH.

SPHERIC STEERING COMMITTEE:

Prof. Moncho Gómez Gesteira (2006-2013)
Dr Alejandro J. C. Crespo (2014-TODAY) *WEBMASTER*

http://spheric-sph.org/

MORE…

DualSPHysics Users Workshop

1st DualSPHysics Users Workshop, University of Manchester, U.K., 8-9 September 2015
2nd DualSPHysics Users Workshop, University of Manchester, U.K., 6-7 December 2016
3rd DualSPHysics Users Workshop, University of Parma, Italy, 13-15 November 2017
4th DualSPHysics Users Workshop, Instituto Superior Técnico, Lisboa, 22-24 October 2018

5th DualSPHysics Users Workshop, Universitat Politècnica de Catalunya, Barcelona, 2020