THE NUMERICAL COMPUTATION OF VIOLENT LIQUID MOTION

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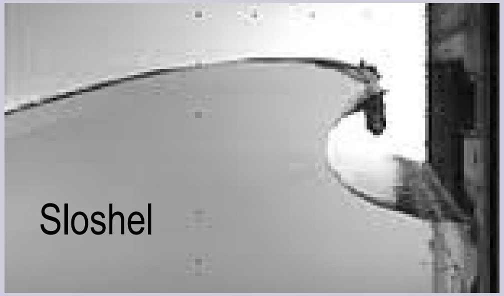
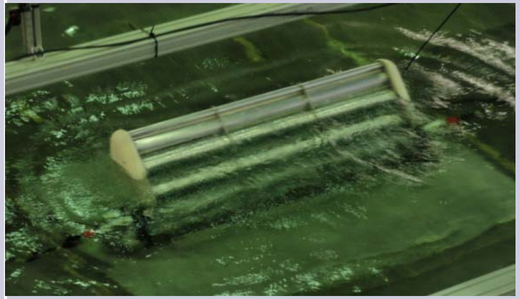
TOPICS COVERED IN TODAY'S TALK

LIQUID IMPACT ON A WALL		WAVE ENERGY CONVERTERS
		
		

COLLABORATORS

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❖Laurent Brosset (GTT)
❖Paul Christodoulides (Cyprus University of Technology)
❖Ken Doherty (Aquamarine Power Ltd.)
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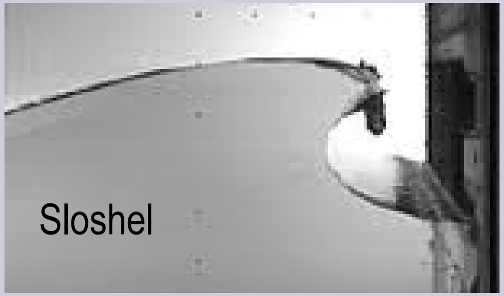
❑SFI (Science Foundation Ireland)
❑GTT (Gaz Technigaz & Transport)

PART 1

LIQUID IMPACT ON A WALL		
		
		

WAVE IMPACT AND PRESSURE LOADS

•Local phenomena involved during wave impacts are very sensitive to input conditions

•The density of bubbles, the local shape of the free surface, the local flow make the impact pressure change dramatically even for the same experimental conditions

•How does one extrapolate wave impact from model (small scale) to prototype (full scale)?

•In recent years, we have addressed the scaling issue by studying the various local phenomena present in wave impact one after the other in order

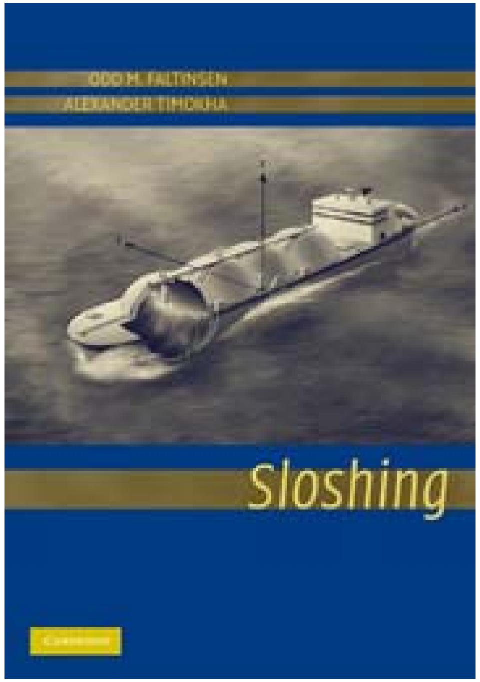
- ❑ to better understand the physics behind
- ❑ to improve the experimental modelling

GTT

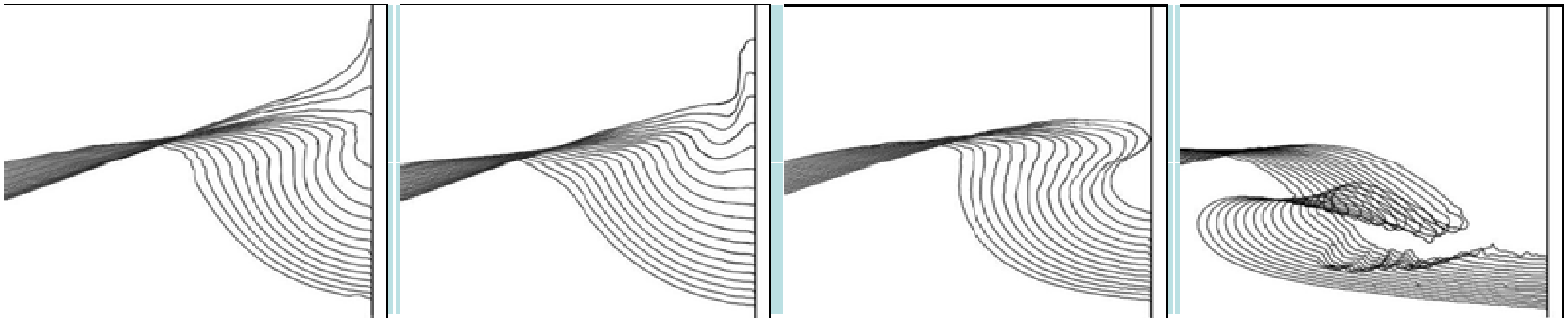
VIDEO 1 – *Experiments in Marseille (courtesy of O. Kimmoun)*

SLOSHING IN TANKS OF LIQUEFIED NATURAL GAS (LNG) CARRIERS

Heavy weather and partially loaded LNG tank resulted sloshing damage in a LNG tank – 6 months and Millions $$



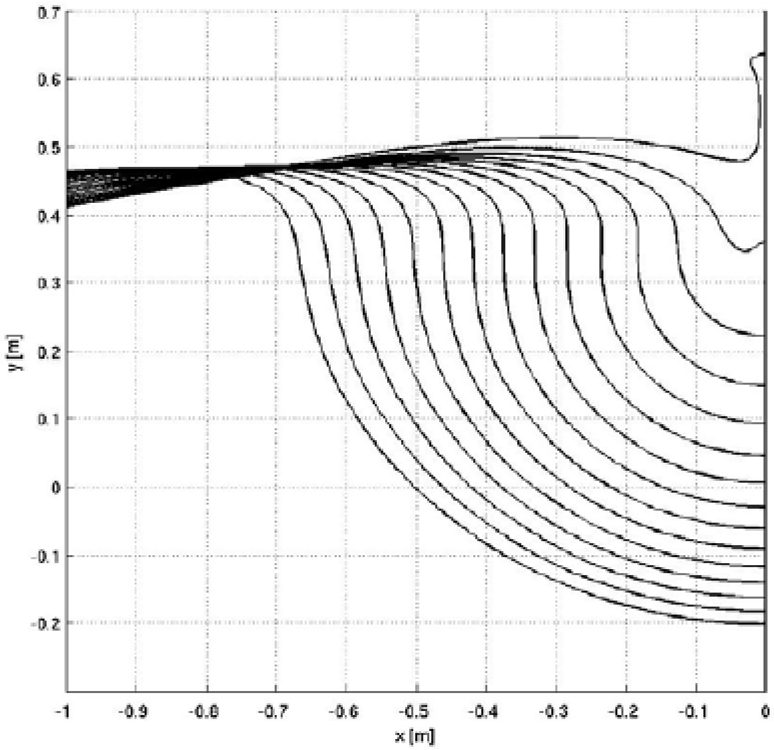
VARIOUS SCENARIOS OF WAVE IMPACT



Slosh	« Flip-through » condition with no air bubbles. The impact pressure has a single peak.	Collision of a plunging breaker with a thin air pocket	Collision of a fully developed plunging breaker with a thick air pocket

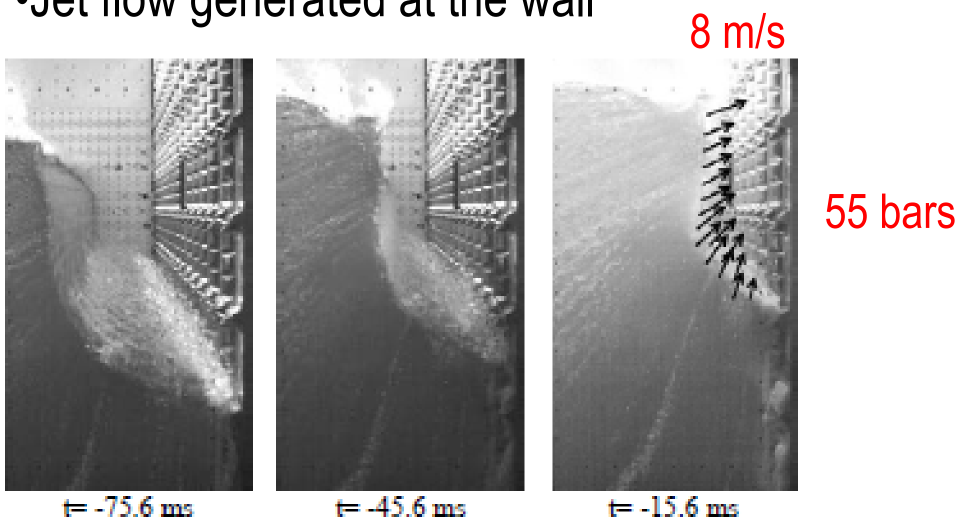
Source : Peregrine D.H. (2003), Water wave impact on walls, *Annual Review of Fluid Mechanics*

THE FLIP-THROUGH PHENOMENON



Bredmose et al. (2004), Water wave impact on walls and the role of air, *Proceedings ICCE 2004*

- Run-up of wave trough
- Forward motion of almost vertical wave front
- Jet flow generated at the wall

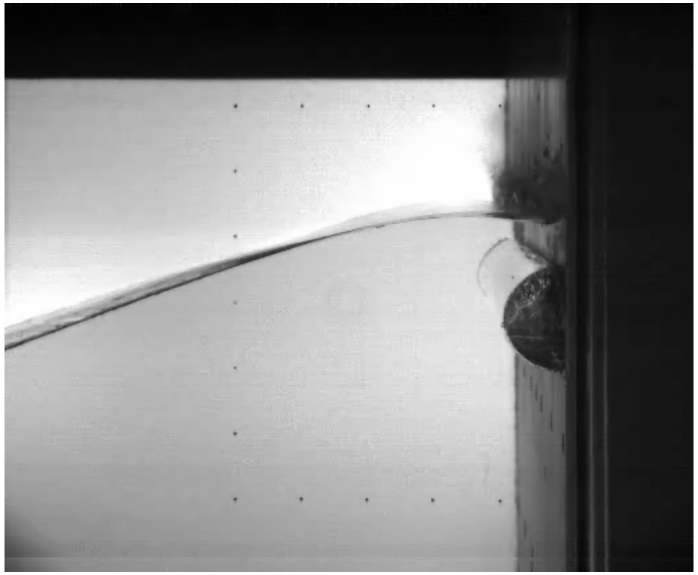


Brosset et al. (2011), A Mark III Panel Subjected to a Flip-through Wave Impact: Results from the Sloshel Project, *Proceedings ISOPE 2011*

PHENOMENOLOGY OF A LIQUID IMPACT

- Global behaviour
  - Global flow governed by Froude number

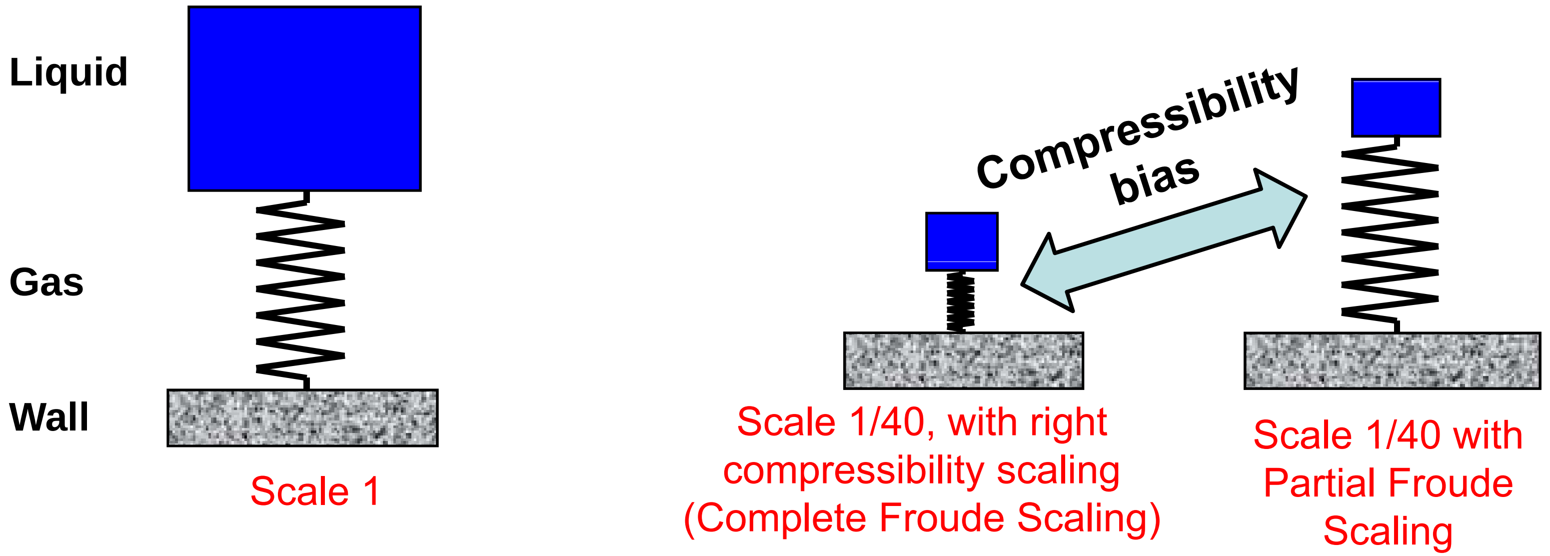
- Local behaviour
  - Escape of the gas between the liquid and the wall: momentum transfer between liquid and gas
  - Compression of the partially entrapped gas during the last stage of the impact
  - Rapid change of momentum of the liquid diverted by the obstacle
  - Possible creation of shock waves: pressure wave within the liquid and strain wave within the wall
  - Hydro-elasticity effects during the fluid-structure interaction



Braeunig et al. (2009), Phenomenological Study of Liquid Impacts through 2D Compressible Two-fluid Numerical Simulations, *Proceedings ISOPE 2009*

EXAMPLE OF BIAS INTRODUCED AT SMALL SCALE

- Locally, the impact process is not similar for similar inflow conditions
  - Gas compressibility bias: the equations of state should be scaled
  - Liquid compressibility bias: speed of sound should be scaled



- Biases are different for different impacts: no unique scaling law!

INCOMPRESSIBLE EULER EQUATIONS WITH AN INTERFACE IN PHYSICAL VARIABLES

Fluid equations:

$$\begin{aligned} u_t + uu_x + vu_y + wu_z + \frac{1}{\rho}\frac{\partial p}{\partial x} &= 0 \\ v_t + uv_x + vv_y + wv_z + \frac{1}{\rho}\frac{\partial p}{\partial y} &= 0 \\ w_t + uw_x + vw_y + ww_z + \frac{1}{\rho}\frac{\partial p}{\partial z} &= -g \\ u_x + v_y + w_z &= 0 \end{aligned}$$

(x,y,z) : spatial coordinates

u = (u,v,w) : velocity vector

p : pressure ρ : density

g : acceleration due to gravity

$h(x,y,t)$: elevation of the interface

Boundary conditions:

$$\mathbf{u}\cdot\mathbf{n} = 0$$

$$\left.\begin{aligned} h_t + uh_x + vh_y &= w \\ p &= 0 \end{aligned}\right\} \text{kinematic and dynamic conditions on the interface}$$

INVARIANCE OF INCOMPRESSIBLE EULER EQUATIONS WITH AN INTERFACE

Froude scaling $\frac{u_{fs}^2}{gD_{fs}} = \frac{u_{ms}^2}{gD_{ms}}$

fs stands for full scale, *ms* for model scale

$D_{fs} = \lambda\ D_{ms}$

$$\mathbf{u}_{fs}\left(\lambda \mathbf{x}_{ms}, \sqrt{\lambda} t_{ms}\right) = \sqrt{\lambda}\mathbf{u}_{ms}\left(\mathbf{x}_{ms}, t_{ms}\right) \qquad t_{fs} = \sqrt{\lambda} t_{ms}$$

$$\dot{\mathbf{u}}_{fs}\left(\lambda \mathbf{x}_{ms}, \sqrt{\lambda} t_{ms}\right) = \dot{\mathbf{u}}_{ms}\left(\mathbf{x}_{ms}, t_{ms}\right) \qquad p_{fs} = \lambda p_{ms}$$

TWO-FLUID COMPRESSIBLE EULER EQUATIONS WITH AN INTERFACE IN PHYSICAL VARIABLES

Fluid equations

$$\frac{\partial \rho_k}{\partial t} + \nabla \cdot (\rho_k \vec{u}_k) = 0\,,$$

$$\rho_k \left(\frac{\partial \vec{u}_k}{\partial t} + (\vec{u}_k \cdot \nabla)\, \vec{u}_k \right) + \nabla p_k = \rho_k (\vec{g} - \vec{\gamma}_e - 2\vec{\Omega} \times \vec{u}_k)\,,$$

$$\rho_k \left(\frac{\partial e_k}{\partial t} + (\vec{u}_k \cdot \nabla)\, e_k \right) + p_k \nabla \cdot \vec{u}_k = 0\,,$$

k = 1, 2

Boundary conditions

$$\vec{u}_k \cdot \vec{n} = 0$$

$$\frac{\partial f}{\partial t} = -\vec{u}_1 \cdot \nabla f = -\vec{u}_2 \cdot \nabla f\,, \quad \text{on} \quad f(x_1, x_2, x_3, t) = 0\,,$$

$$p_1 = p_2\,, \quad T_1 = T_2\,, \quad \text{on} \quad f(x_1, x_2, x_3, t) = 0\,.$$

Equation of state

$$\rho_k = \mathfrak{R}_k(p_k, e_k)\,.$$

INVARIANCE OF TWO-FLUID COMPRESSIBLE EULER EQUATIONS WITH AN INTERFACE

Froude scaling $\frac{u_{fs}^2}{gD_{fs}} = \frac{u_{ms}^2}{gD_{ms}}$ (including the speeds of sound)

$$\mathbf{u}_{fs}\left(\lambda \mathbf{x}_{ms}, \sqrt{\lambda} t_{ms}\right) = \sqrt{\lambda}\mathbf{u}_{ms}\left(\mathbf{x}_{ms}, t_{ms}\right)$$

$$\dot{\mathbf{u}}_{fs}\left(\lambda \mathbf{x}_{ms}, \sqrt{\lambda} t_{ms}\right) = \dot{\mathbf{u}}_{ms}\left(\mathbf{x}_{ms}, t_{ms}\right)$$

$$t_{fs} = \sqrt{\lambda} t_{ms}$$

Differences with the one-fluid incompressible case

$\mu = \rho_{ms} / \rho_{fs}$

$$\mathcal{R}_k^{\lambda,\mu}(p,e) = \mu \mathcal{R}_k\left(\frac{\lambda}{\mu} p, \lambda e\right)$$

$$\frac{\rho_g^{\mathrm{fs}}}{\rho_\ell^{\mathrm{fs}}} = \frac{\rho_g^{\mathrm{ms}}}{\rho_\ell^{\mathrm{ms}}}$$

⇧ Scale the equations of state

⇧ Keep the same density ratio

$p^{fs} = \lambda(\rho_{liq}{}^{fs}/\rho_{liq}{}^{ms})\, p^{ms}$

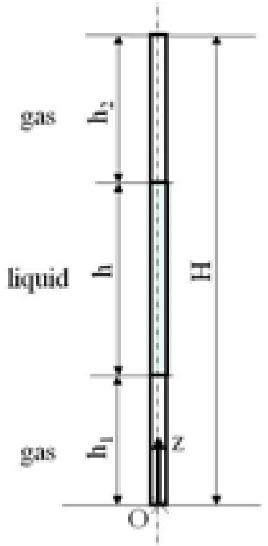
THE ROLE OF NUMERICAL STUDIES

- For sloshing inside the tank of a LNG carrier or for the motion of a wave energy converter, numerical simulations can provide impressive results but the question remains of how relevant these results are when it comes to determining impact pressures !

- The numerical models are too simplified to reproduce the high variability of the measured pressures. NOT POSSIBLE FOR THE TIME BEING TO SIMULATE ACCURATELY BOTH GLOBAL AND LOCAL EFFECTS ! (see ISOPE 2009 Numerical Benchmark)

- However, numerical studies can be quite useful to perform sensitivity analyses in idealized problems (see ISOPE 2010 Numerical Benchmark)

COMPARATIVE NUMERICAL STUDY (2010)



Length	(m)
H	15
h	8
h_1	2
h_2	5

Organizers: GTT and UCD
(*compressible bi-fluid software was required)*

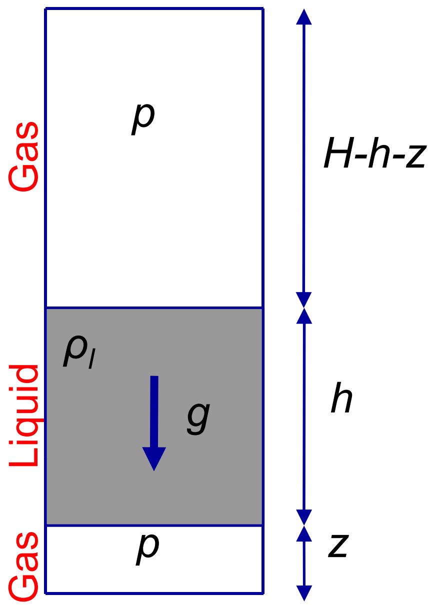
1D case

LNG = Liquefied Natural Gas
NG = Natural Gas

Participants
ANSYS
Principia
ENS-Cachan
Hydrocean
Bureau Veritas
Lloyd's Register
Force

Case #	*Scale*	*Liquid*	*Gas*
1	1:1	LNG	NG
2	1:40	LNG	NG
3	1:40	Water	Air
4	1:40	Water	SF_6+N_2
5	1:40	*1:40-scaled LNG*	*1:40-scaled NG*

1D SURROGATE MODEL OF AIR-POCKET IMPACT

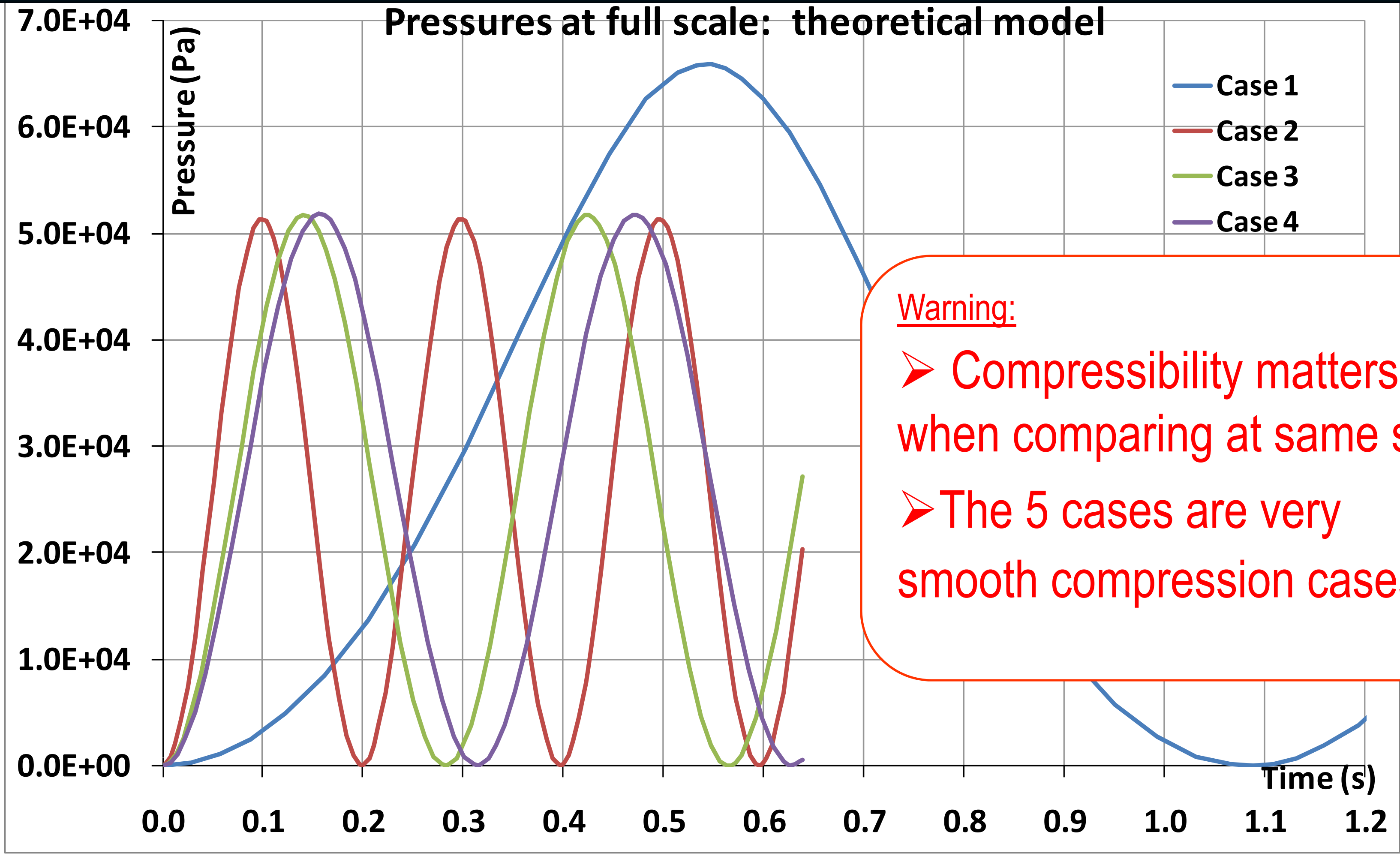


- Piston model
  - Perfect gas $$p = \rho R T$$
  - Adiabatic process $$p\left(\frac{1}{\rho}\right)^{\gamma} = constant$$

Initial conditions: $p=p_0$, $z(0)=h_1$, $\dot{z}(0) = 0$

$$\ddot{z}(t) = -g - \frac{p_0}{\rho_l h}\left(\left(\frac{h_2}{H-h-z}\right)^{\gamma} - \left(\frac{h_1}{z}\right)^{\gamma}\right)$$

THEORY : PRESSURES IN TIME DOMAIN



Warning:

- Compressibility matters, when comparing at same scale
- The 5 cases are very smooth compression cases

Pressures and times are Froude-scaled for cases 2, 3, 4, 5 with $\lambda = 40$, ^{fs} = full scale, ^{ms} = model scale

$p^{fs} = \lambda \, (\rho_{liq}^{fs}/\rho_{liq}^{ms}) \, p^{ms}$ $\quad t^{fs} = \sqrt{\lambda} \, t^{ms}$

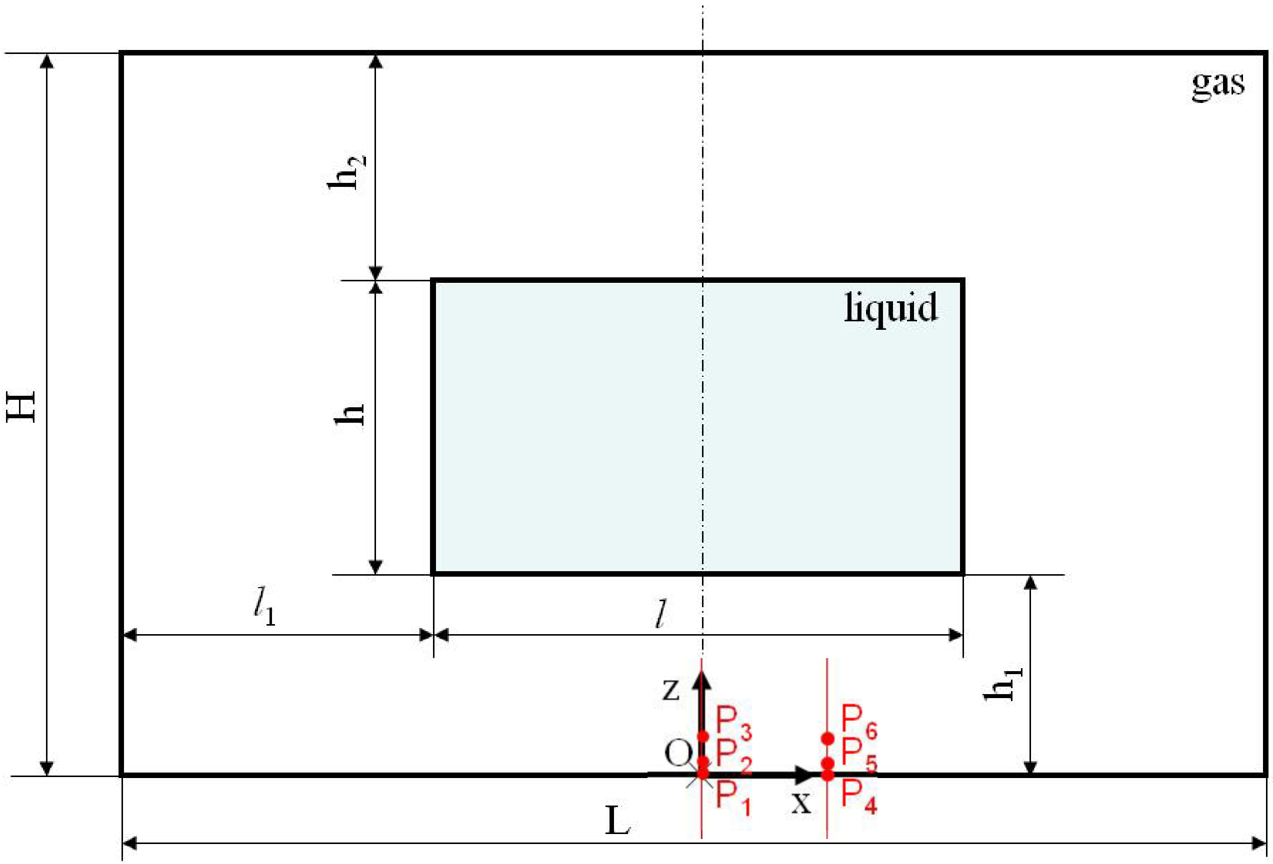
CONCLUSIONS FOR THE 1D CASE

- ❑ The different numerical methods are able to simulate adequately a simple smooth compression of a gas pocket without escape of gas
- ❑ Very good agreement on the maximum pressure

- ❑ For all methods :
  - ➢ Complete Froude Scaling (CFS) works (same result for cases 1 & 5)
  - ➢ Partial Froude Scaling (PFS) generates a bias

COMPARATIVE NUMERICAL STUDY (2010)

VIDEO 2 – *ENS-Cachan code*



2D case

Length	(m)
H	15
h	8
h_1	2
h_2	5
L	20
l	10
l_1	5

COMPARATIVE NUMERICAL STUDY (2010) – 2D CASE

Case #	*Scale*	*Liquid*	*Gas*
6	1:1	LNG	NG
7	1:40	LNG	NG
8	1:40	Water	Air
9	1:40	Water	SF_6+N_2
10	1:40	*1:40-scaled LNG*	*1:40-scaled NG*

Participants	***Software***	***Method***	***6***	***7***	***8***	***9***	***10***
ANSYS	Fluent	Finite Volume/VOF	X	X	X	X	X
Principia	LS-DYNA	FEM Euler/Lagrange	X	X	X	X	X
ENS-Cachan	Flux-IC	Finite Volume/NIP	X	X	X	X	X
Lloyds Register	OpenFOAM	Finite Volume/VOF	X	X	X	X	X
Force	Comflow	Finite Volume/VOF	X	X	X	X	X
UoSFSI	in House	Finite Differences/VOF	X	X		X	

THE ENS-CACHAN CODE

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A totally Eulerian finite volume solver for multi-material fluid flows

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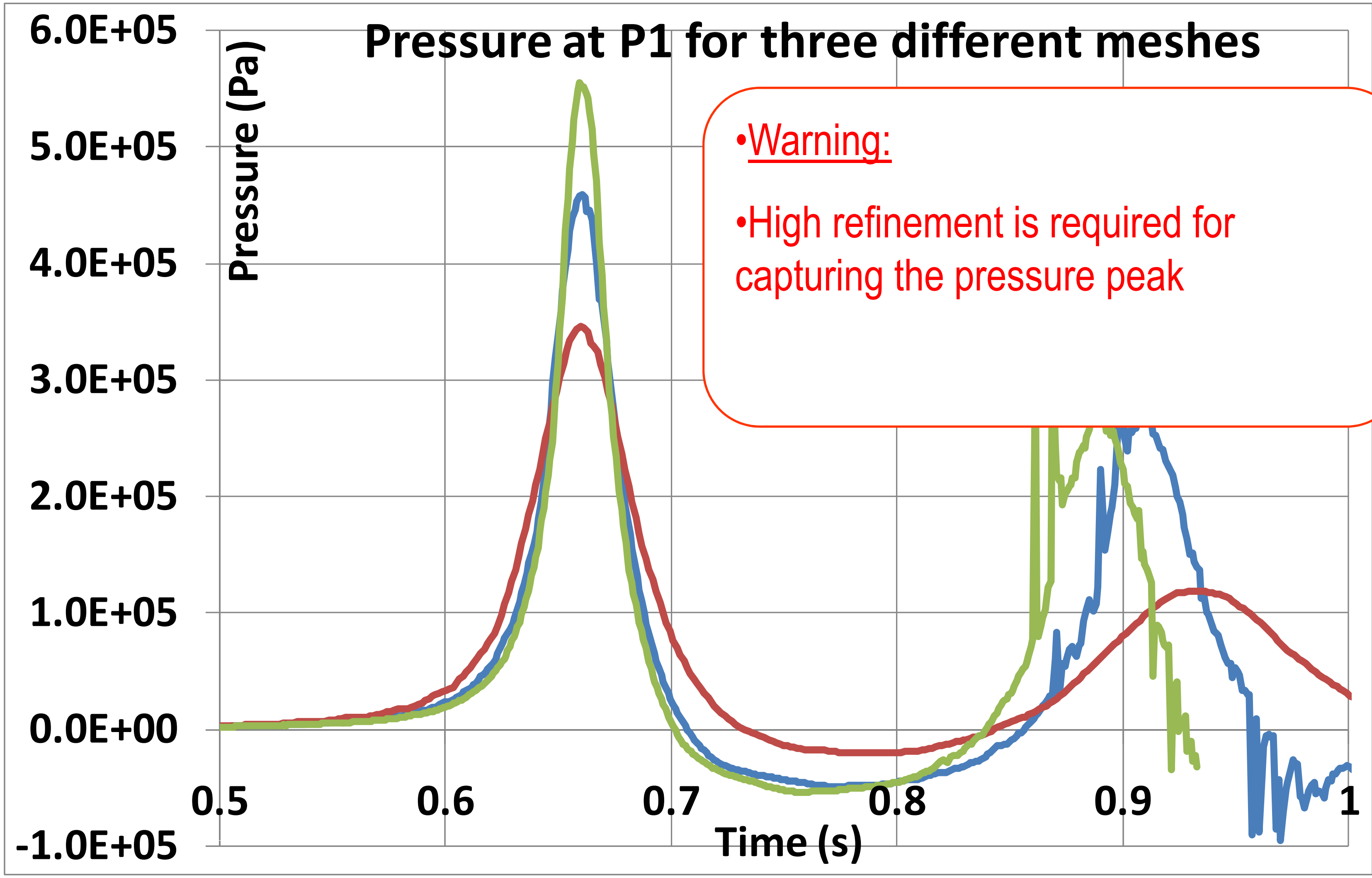
Finite volume method

A B S T R A C T

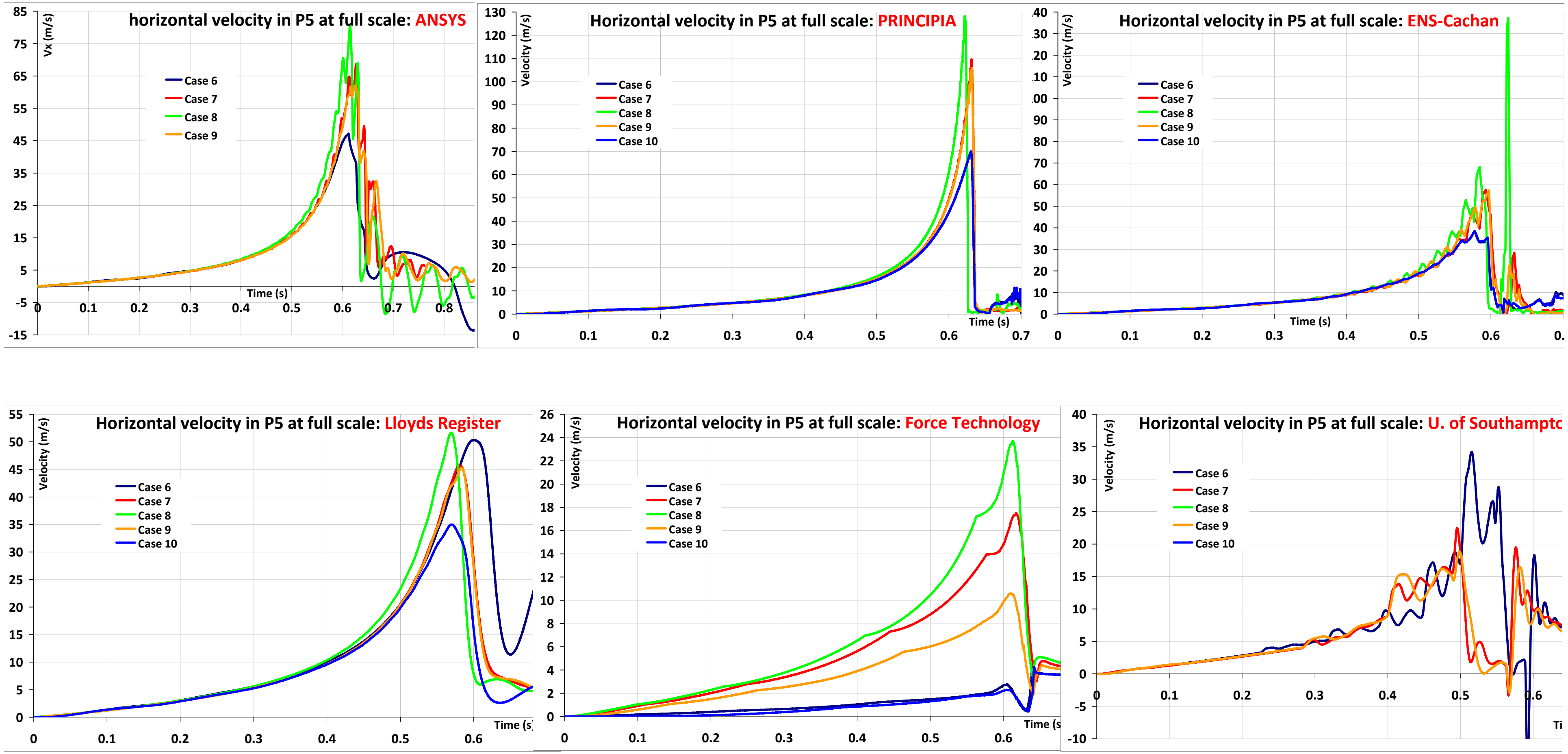
The purpose of this work is to present a new numerical scheme for multi-material fluid flows in dimension $d \geqslant 1$. It is a totally Eulerian conservative scheme that allows to compute sharp interfaces between non-miscible fluids. The underlying flux scheme in single material cells is the so-called FVCF scheme, whereas interface reconstruction and directional splitting is used in multi-material cells. One of the novelty of our approach is the introduction of the concept of "condensate" which allows to handle mixed cells containing two or more materials. Moreover, it has been designed to allow free sliding of materials on each others, thanks to a material volume centered computation of variables in mixed cells.

ENS-CACHAN : MESH SENSITIVITY FOR CASE 6 (SCALE 1:1)



- Warning:
- High refinement is required for capturing the pressure peak

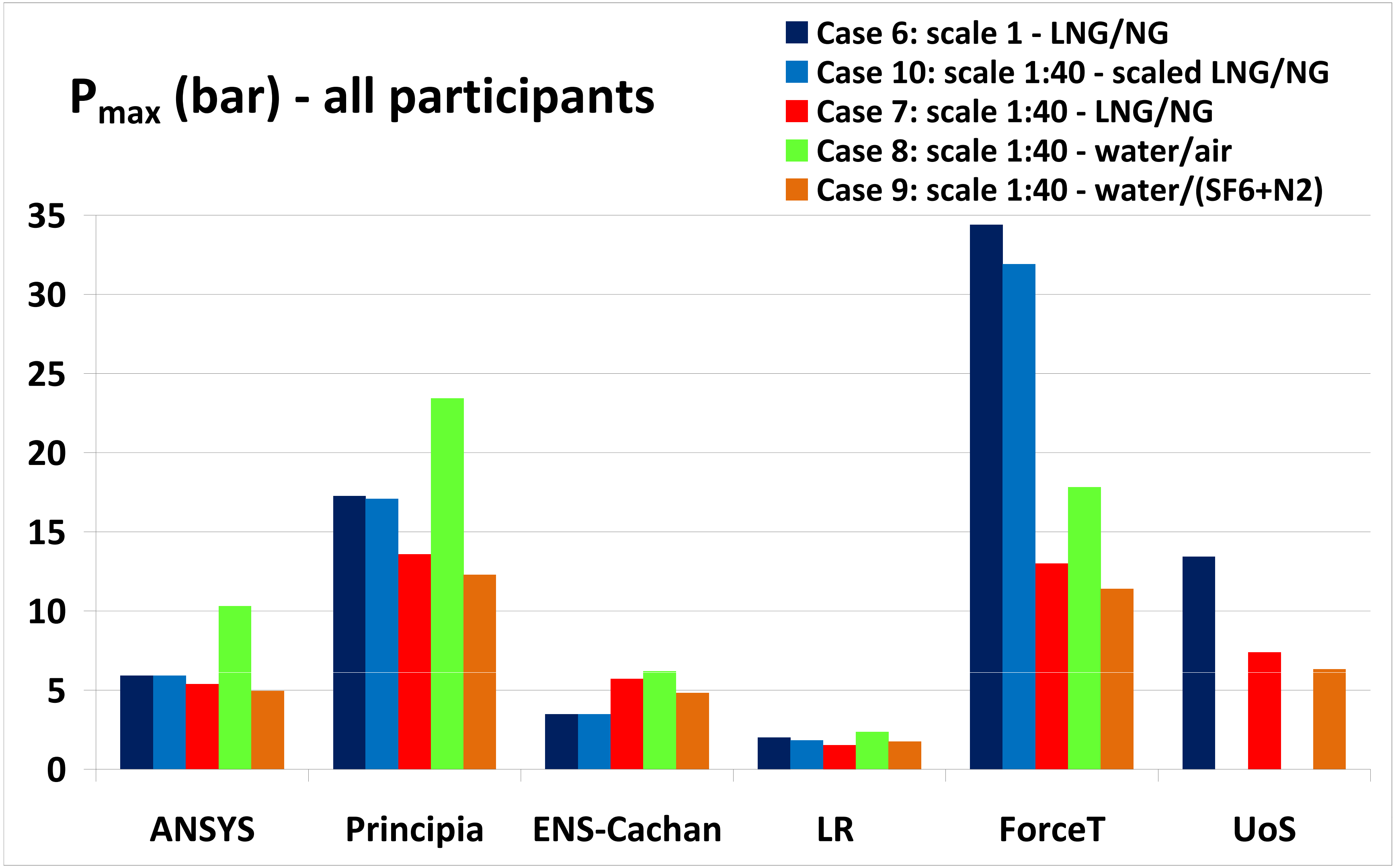
HORIZONTAL TIME SERIES AT P_5 : ALL PARTICIPANTS



Velocities and times are Froude-scaled for cases 7, 8, 9, 10

$V^{fs} = \sqrt{\lambda}.V^{ms}$, $t^{fs} = \sqrt{\lambda}.t^{ms}$ with $\lambda = 40$, ^{fs} = full scale, ^{ms} = model scale

MAXIMUM PRESSURE AT P_1 : ALL PARTICIPANTS



COMPARATIVE NUMERICAL STUDY (2010) – 2D CASE

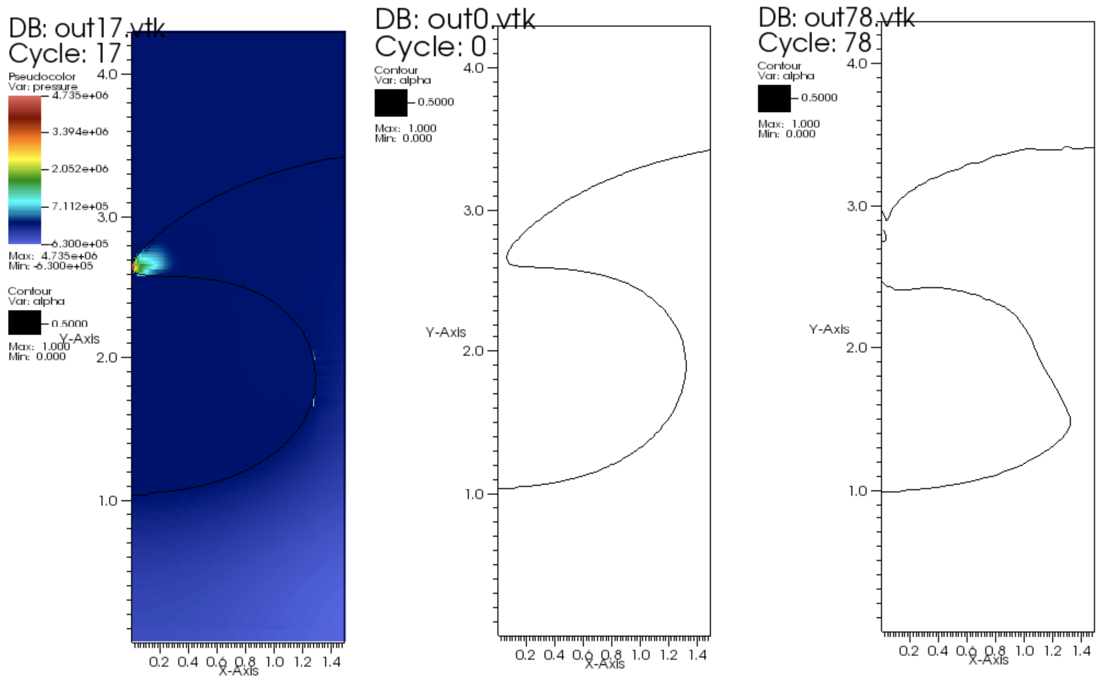
- Absolute values for V_{max} and P_{max} are very scattered
- The meshes are not refined enough to capture sharp peak pressures
- After some work on the models, results should be much less scattered (work in progress)
- Such a simple test should be passed adequately before attempting to calculate more complex impacts
- For all methods, whether relevant or not :
  - Complete Froude Scaling (CFS) is satisfied
  - Partial Froude Scaling generates a bias

BACK TO WAVE IMPACT

- Strategy used to compute wave impact : couple potential flow solver with two-fluid compressible flow solver

- Potential flow solver computes the wave all the way to overturning (Fochesato & Dias 2006)

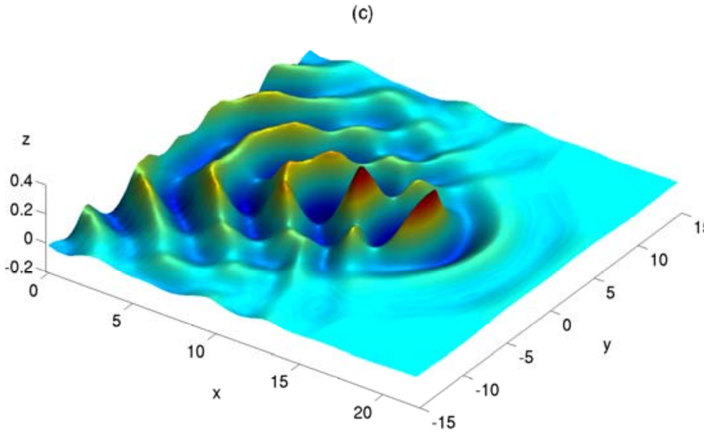
- Two-fluid (gas + liquid) compressible flow solver computes the liquid impact on the wall



work in progress

THE FULLY NONLINEAR POTENTIAL FLOW SOLVER

VIDEO 5 – *Experiments in Nantes*



PROCEEDINGS OF THE ROYAL SOCIETY A

Proc. R. Soc. A (2006) **462**, 2715–2735
doi:10.1098/rspa.2006.1706
Published online 5 April 2006

A fast method for nonlinear three-dimensional free-surface waves

By Christophe Fochesato and Frédéric Dias*

- Evidence of directional wave focusing in a « numerical » wave tank (Fochesato, Grilli, Dias, Wave Motion, 2007)
- High-order three-dimensional boundary element method combined with mixed Eulerian–Lagrangian time updating, based on second-order explicit Taylor expansions with adaptive time-steps
- Accelerated by the Fast Multipole Algorithm

OCEAN WAVE ENERGY : AN ASSET

		WAVE ENERGY CONVERSION
		
		

WAVE ENERGY CONVERSION

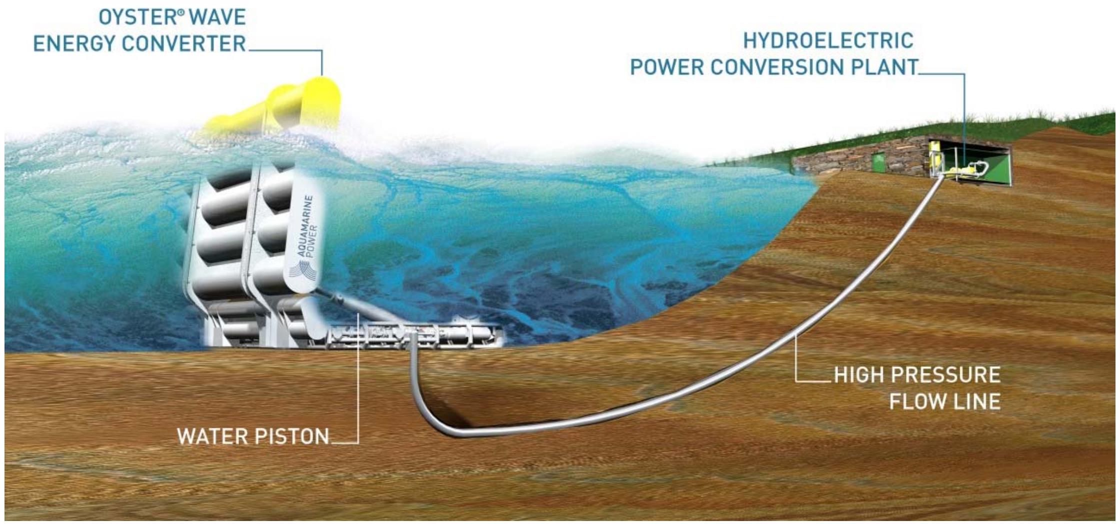
Aquamarine Power is a technology company that has developed a product called Oyster which produces electricity from ocean wave energy.

UCD and Aquamarine Power are collaborating to deliver the next-generation Oyster 800.

OYSTER TECHNOLOGY

- Large mechanical ‘flap’ moves back and forth with motion of waves
- Two hydraulic pistons pump high pressure water via pipeline to shore
- Conventional hydroelectric generator located onshore
- Secured to seabed at depths of 8 – 16m
- Located near shore, typically 500 – 800m from shoreline

VIDEO 7



AQUAMARINE POWER

OYSTER
PROJECT MILESTONES

- **Oyster 1 Project** – 315kW demonstrator successfully installed and grid-connected at European Marine Energy Centre (EMEC) in Orkney, October 2009 – Spring 2011 (finished)
- **Oyster 2 Project** – 2.4MW project (3 Oyster 800 WEC) – on schedule for 2011(1 Oyster 800 installed) / 2012 (two more to be installed)
- **Oyster 3 Project** – 10MW development on track – commissioning 2013 or 2014
- First commercial wave farm off the west coast of Ireland (Westwave project) – 2015

AQUAMARINE POWER

WHAT DOES MATHEMATICS BRING ?

High end computational modeling for wave energy systems

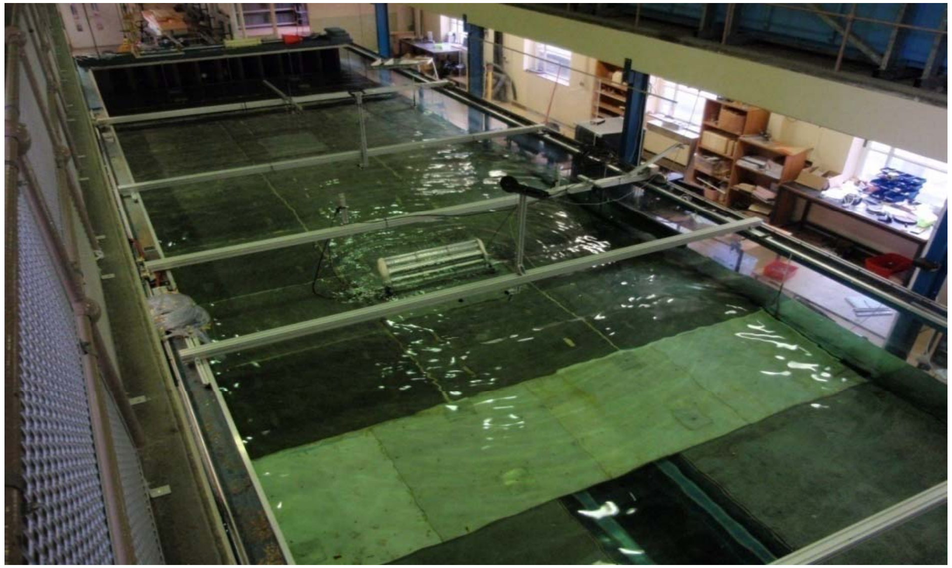
1. Wave impact and pressure loads on a single Wave Energy Converter
2. Optimal device spacing for an array of Wave Energy Converters
3. Preferred geographical locations for near shore Wave Energy Converter sites in Ireland
4. Biofouling (biological growth on surfaces in contact with water)

SURVIVABILITY

Scale effects in experiments at small scale

- One of the most commonly acknowledged difficulties of conducting experiments with Wave Energy Converters : presence of scale effects (Reynolds much larger at full scale than at small scale – for example, at scale 1/40, viscous forces on the model are multiplied by a factor 253 if only Froude scaling is satisfied)

- This makes mathematical and numerical modelling a particularly valuable tool in the development of Wave Energy Converters



Experiments performed at Queen's University Belfast

WHICH TOOLS ?

High end computational modeling for wave energy systems

Wave impact and pressure loads on a single Wave Energy Converter

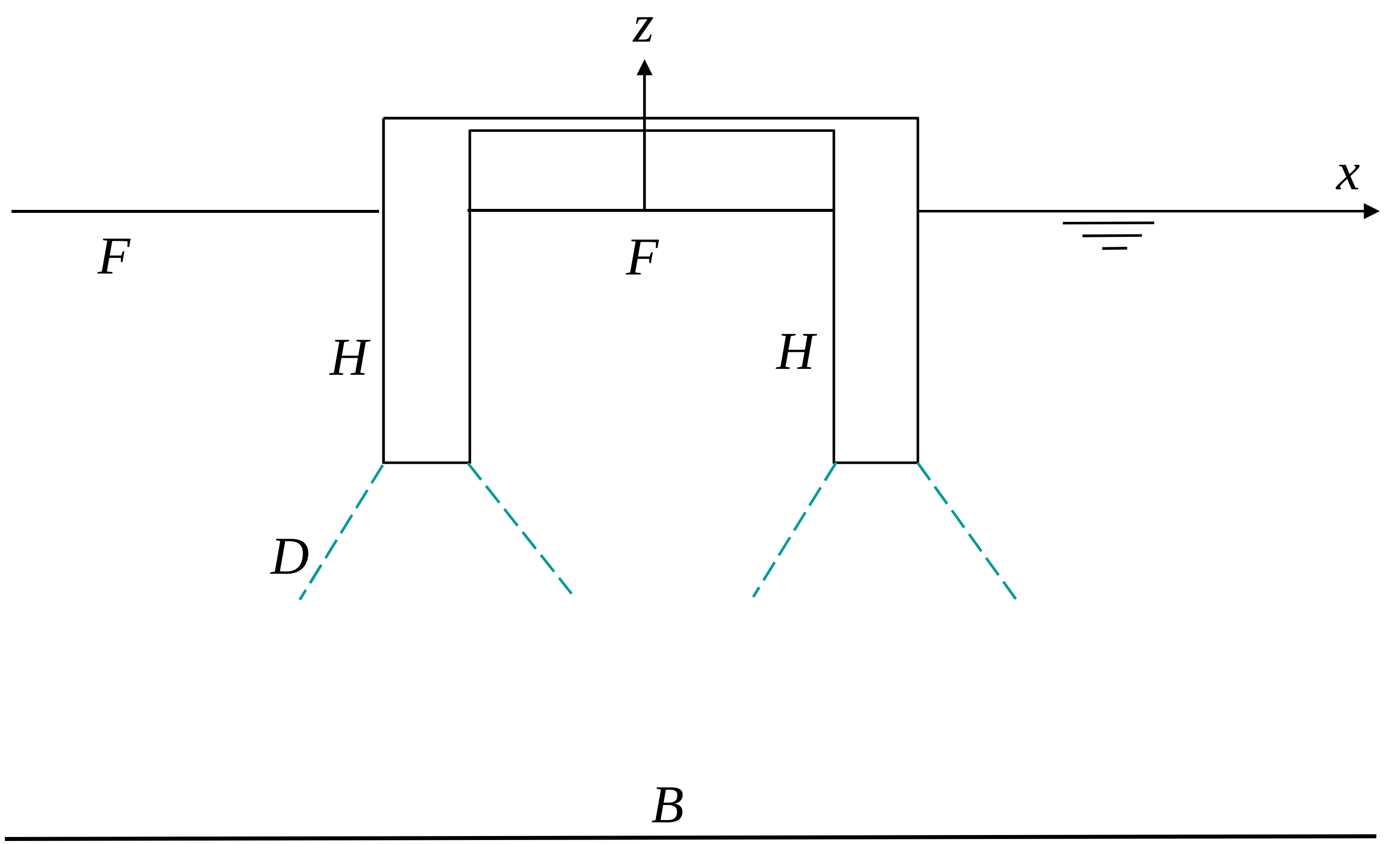
Fully nonlinear potential flow solver (for example WSIM – Boundary Element Method) combined with a Navier-Stokes solver (for example OpenFOAM – vortex shedding at the edges of the flap)

Alternative approach (dissipative surfaces)

Oyster 800 prototype is equipped with a number of pressure sensors

Fairly perfect fluid (joint work with X.B. Chen – Bureau Veritas)

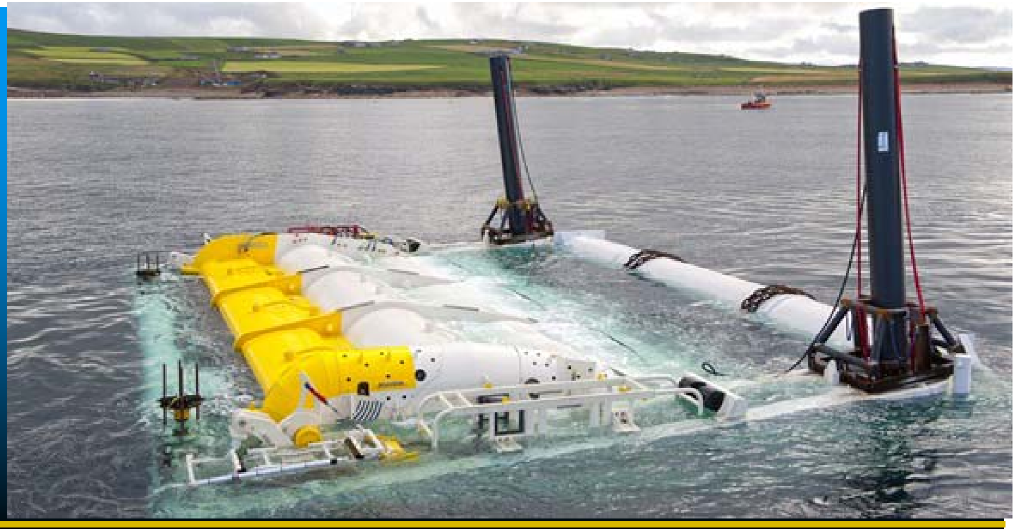
Fluid domain with a body and dissipative surfaces



AQUAMARINE POWER

WHICH TOOLS ?

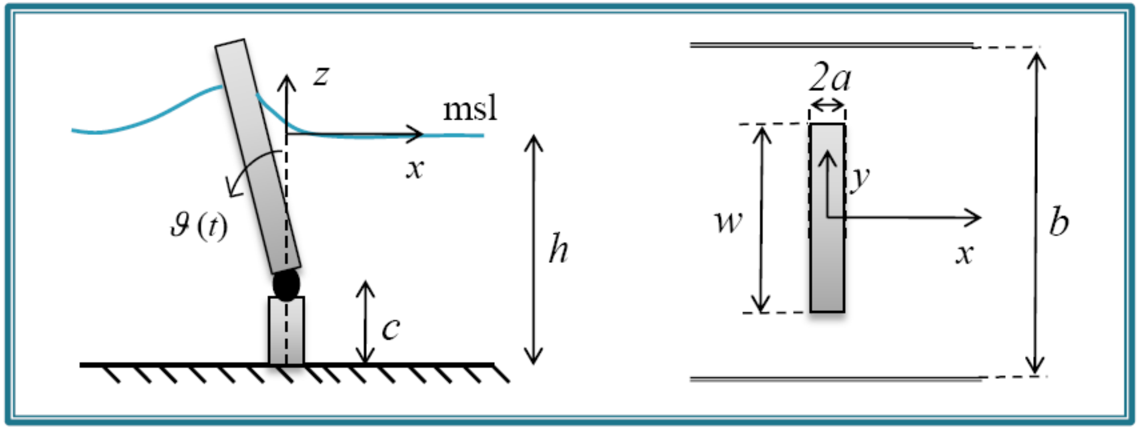
High end computational modeling for wave energy systems



Optimal device spacing for an array of Wave Energy Converters

Analytical approach for the time being

3D LINEAR THEORY



Assume fluid is inviscid, flow is irrotational

POTENTIAL FLOW THEORY: $\nabla^2\Phi = 0$

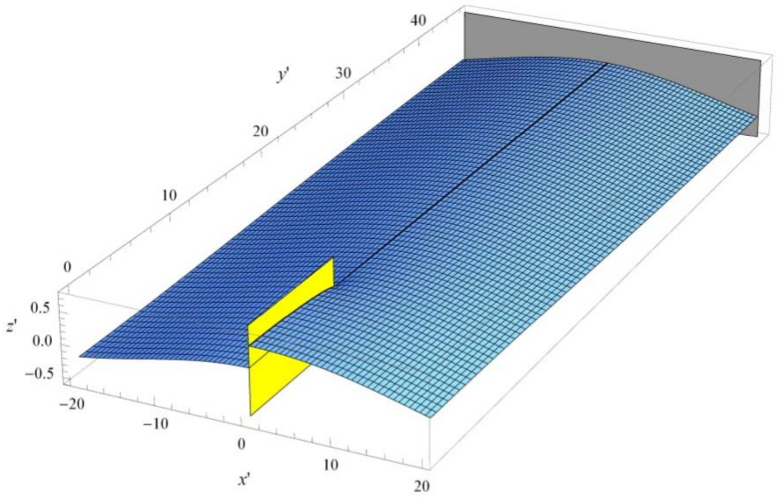
Wave train incident upon a moving structure

$$\Phi(x,y,z,t) = \Phi^S(x,y,z,t) + \Phi^R(x,y,z,t)$$

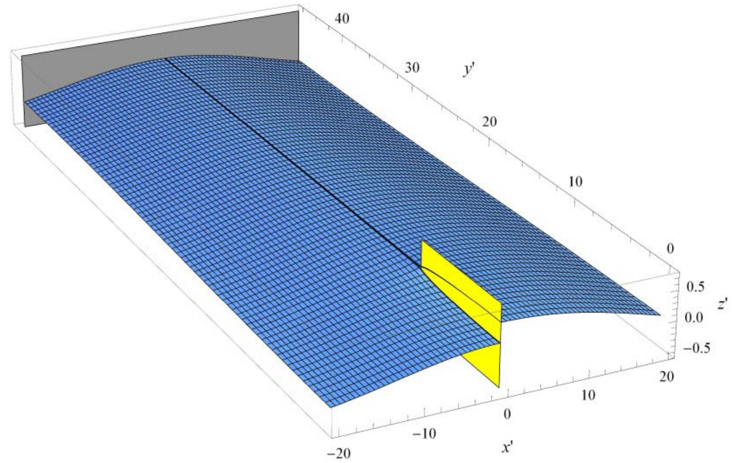
Scattered waves — Radiated waves

T = 7 s

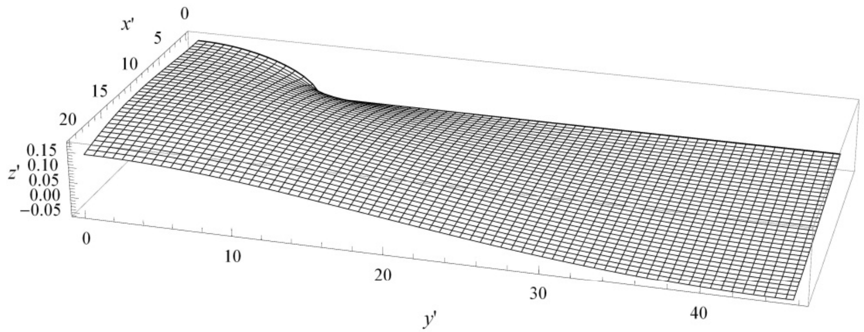
Free-surface elevation front side



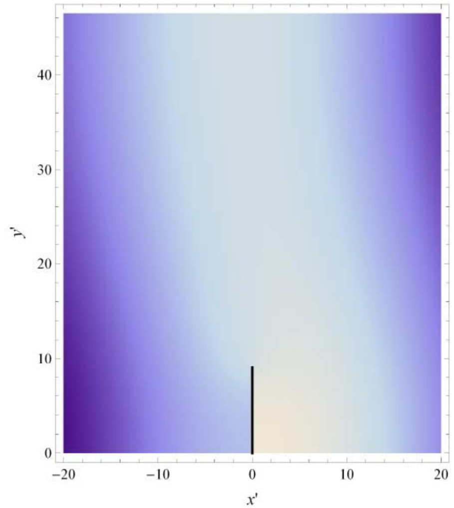
Free-surface elevation back side



Reflected waves



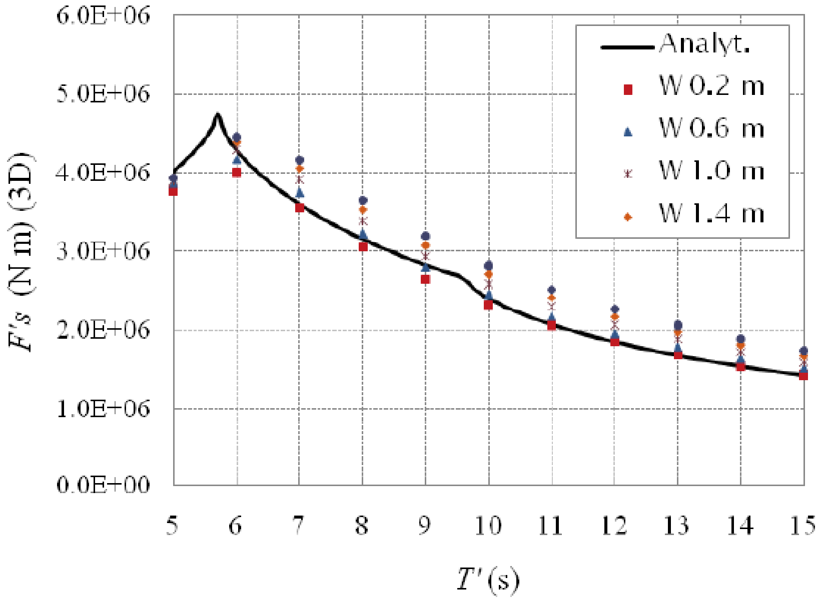
Free-surface density plot



PRELIMINARY WORK ON ARRAYS OF FLAPS

3D LINEAR THEORY

Scattering problem – Validation



OWSC width	18 m
Dist. btm-hinge	1.5 m
Water depth	10.9 m
Ampl. inc. wave	0.3 m

- Comparison with numerical model (WAMIT data by J. van't Hoff) very satisfactory (time mesh should be refined)
- Thin-plate approximation validated (good also for thicker plate)

Analytical theory for Oyster

3D LINEAR THEORY

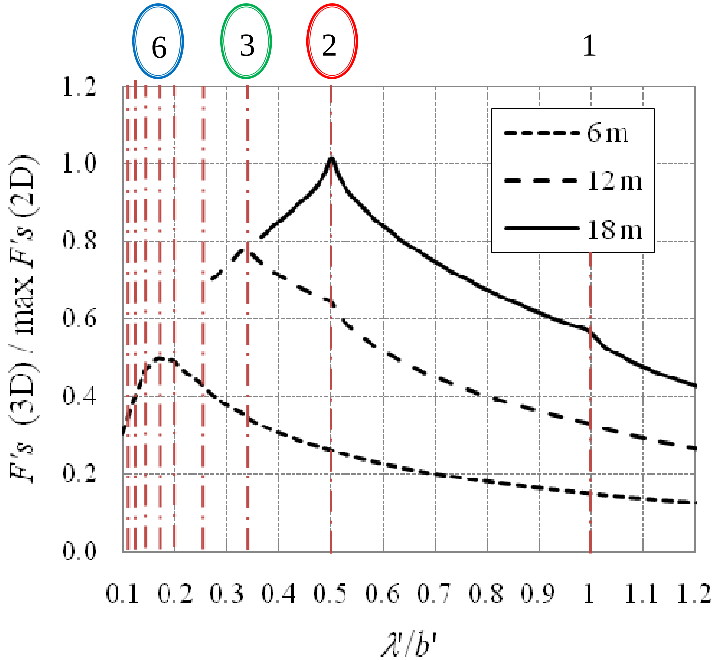
Scattering problem - Discussion

For a given modal order m, the modal interaction factor is max when

$$w = w_m = \frac{b}{2m}$$

RESONANT WIDTH FOR MODE m

Mode	Resonant width (m)	
1	45.8	(too large!)
2	22.9	18 m Oyster (modes 2–3)
3	15.27	12 m Oyster (modes 3–4)
4	11.45	
5	9.16	
6	7.6	6 m Oyster



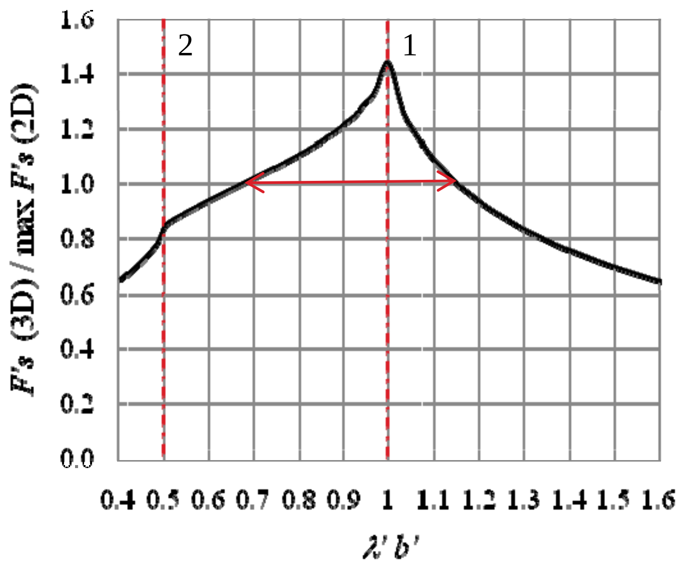
Analytical theory for Oyster

3D LINEAR THEORY

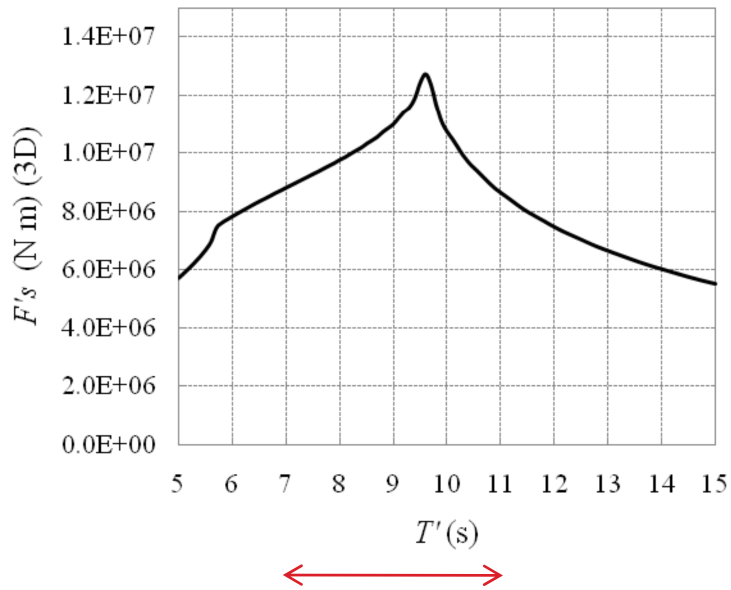
Scattering problem - Discussion

An optimum width (in this channel!) for which the Oyster interacts mostly with the first two sloshing modes:

$$w_{opt} \approx (46 + 23)/2 \text{ m} \approx 34 \text{ m}$$



Constructive interference of sloshing waves increases the 3D performance

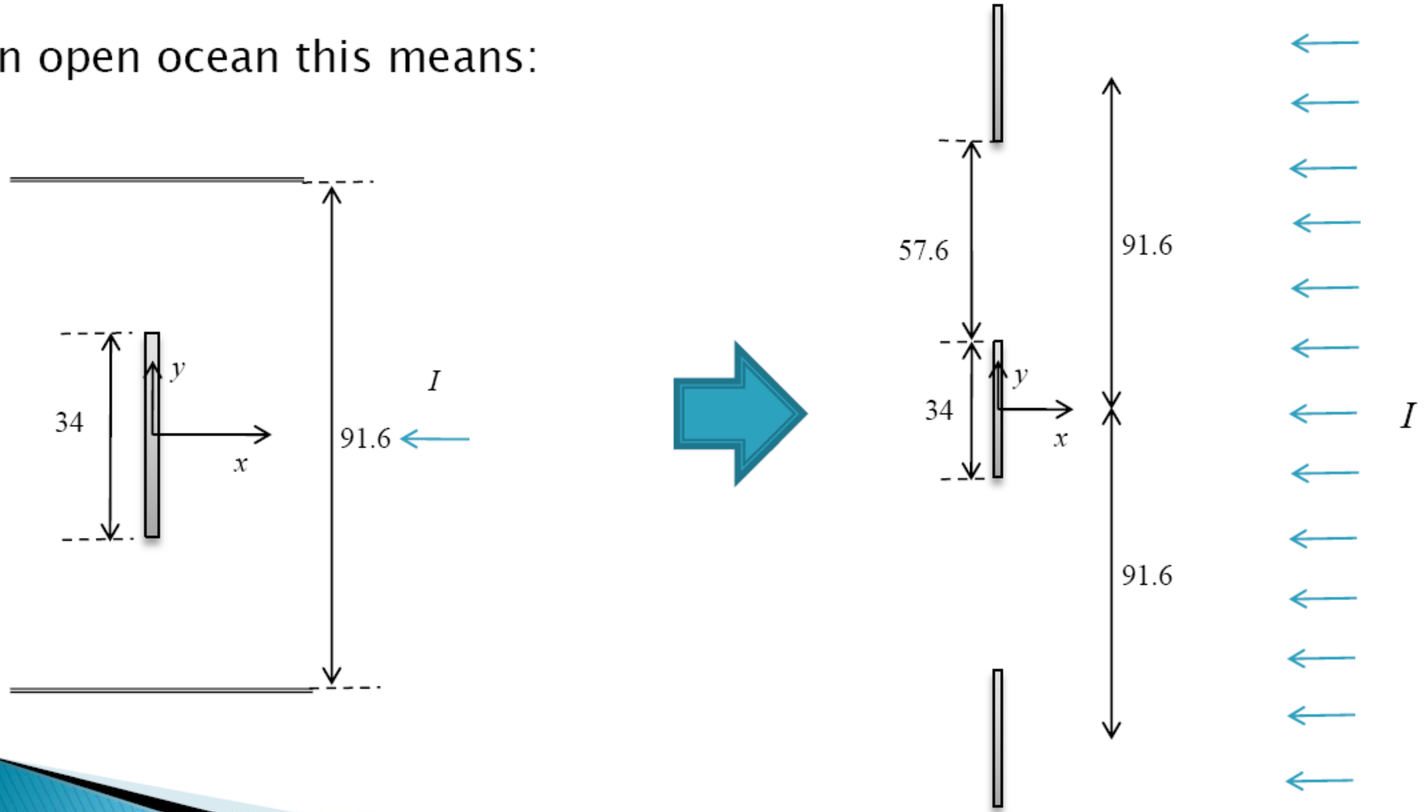


Large range of periods (7 s-11 s) for which the torque is close to max value

3D LINEAR THEORY

Scattering problem – Discussion

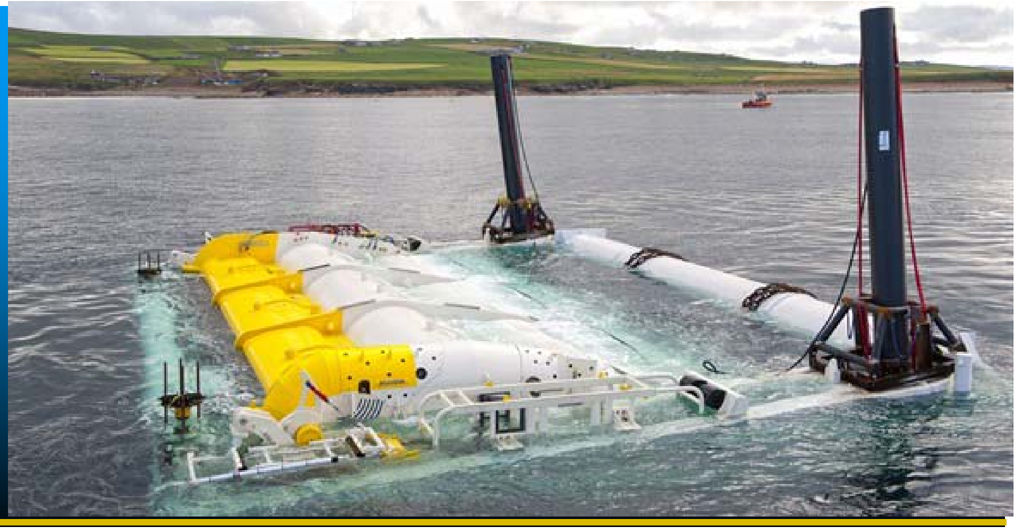
In open ocean this means:



AQUAMARINE POWER

WHICH TOOLS ?

High end computational modeling for wave energy systems



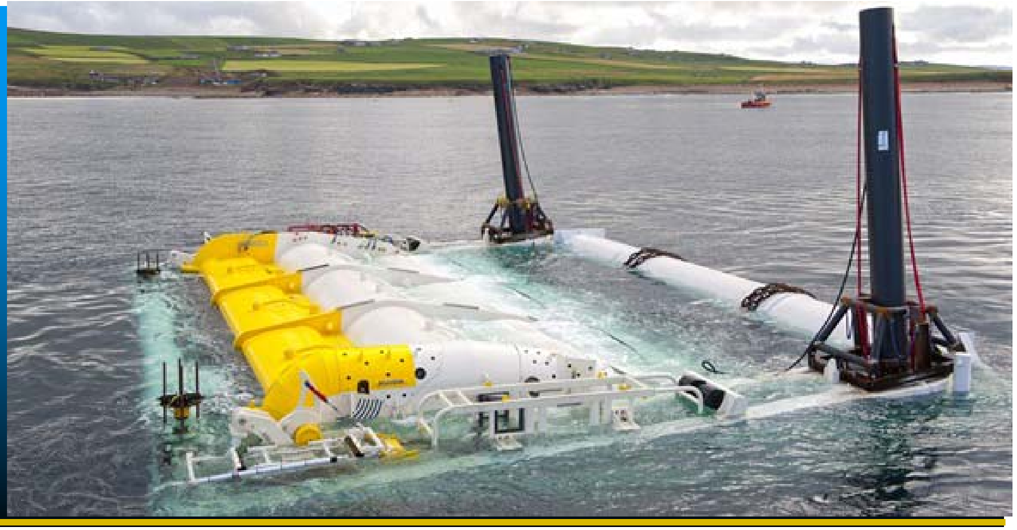
Preferred geographical locations for near shore Wave Energy Converter sites in Ireland

Variety of spectral wave models available to scientists and engineers, including SWAN and WAVEWATCH III™ (one solves the random phase spectral action density balance equation for wavenumber-direction spectra). Is it enough for wave prediction or is it necessary to couple such spectral wave models with shallow-water type models in very shallow water?

AQUAMARINE POWER

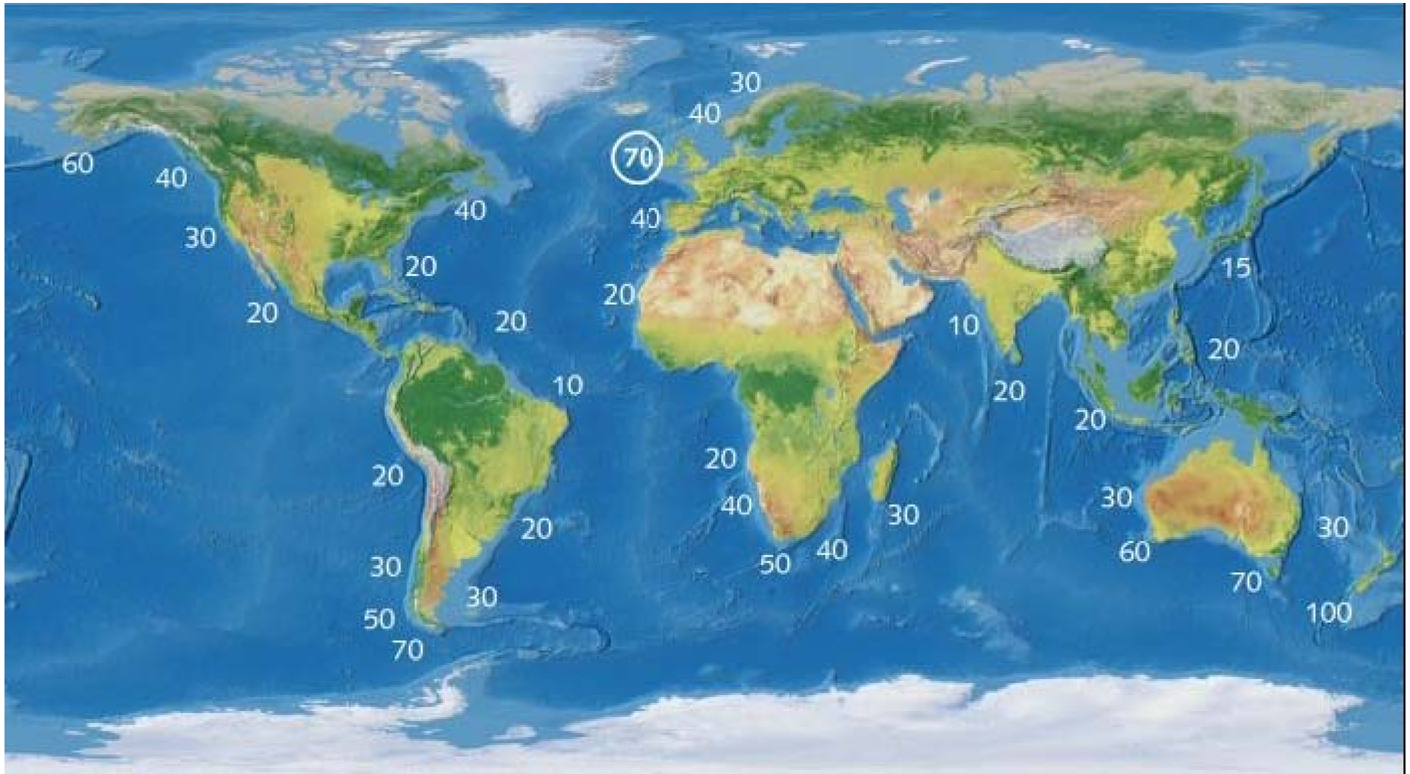
WHICH TOOLS ?

High end computational modeling for wave energy systems



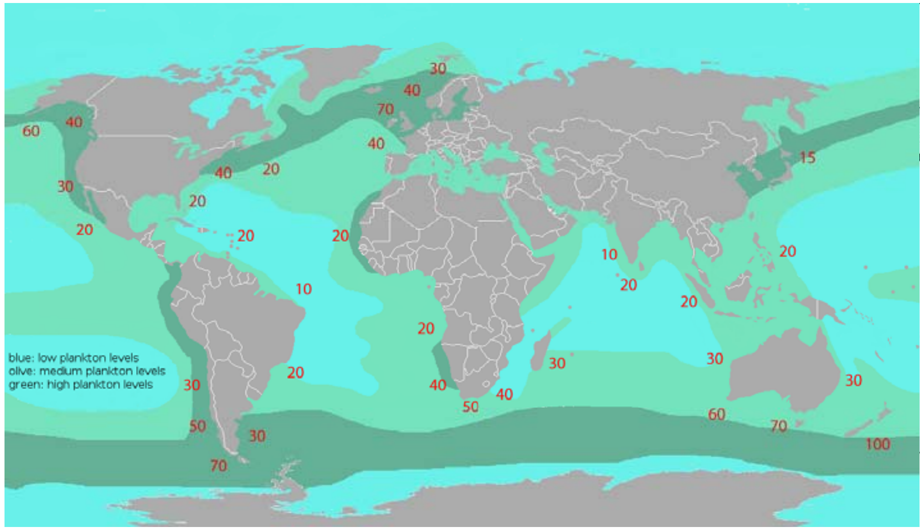
Biofouling (biological growth on surfaces in contact with water)

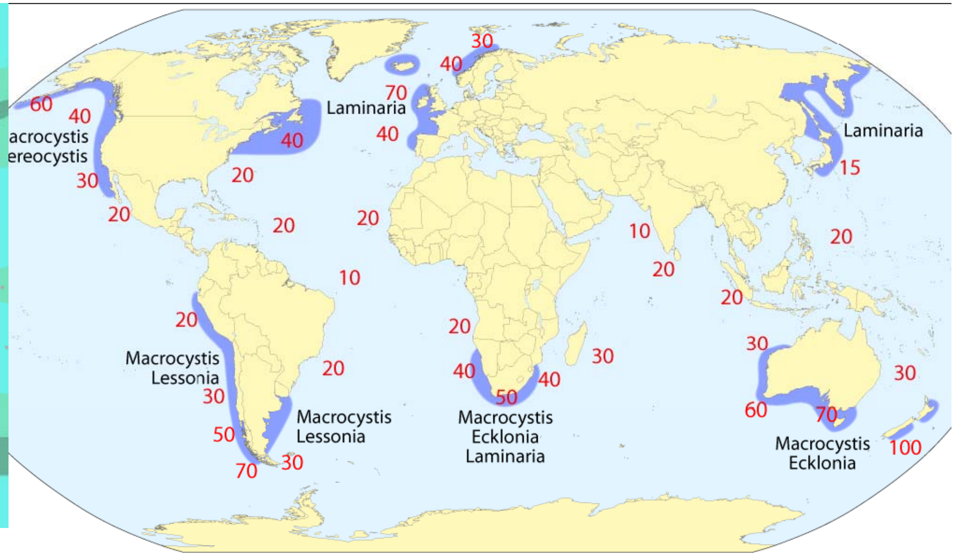
WAVE POTENTIAL AROUND THE WORLD



Numbers show the available power in kW/m (Source : World Energy Council)

WAVE POTENTIAL + PLANKTON AND KELP DISTRIBUTIONS





Source : Kelp data : Kelp forest ecosystems - biodiversity, stability, resilience and future, Robert S. Steneck, Michael H. Graham et al.

Temperate Shelf and Seas

seasonal variability + freshwater influx from coastal streams and tidal action

+ very heterogeneous habitats

= high diversity of organisms: algae, invertebrate, fish, marine mammals,...

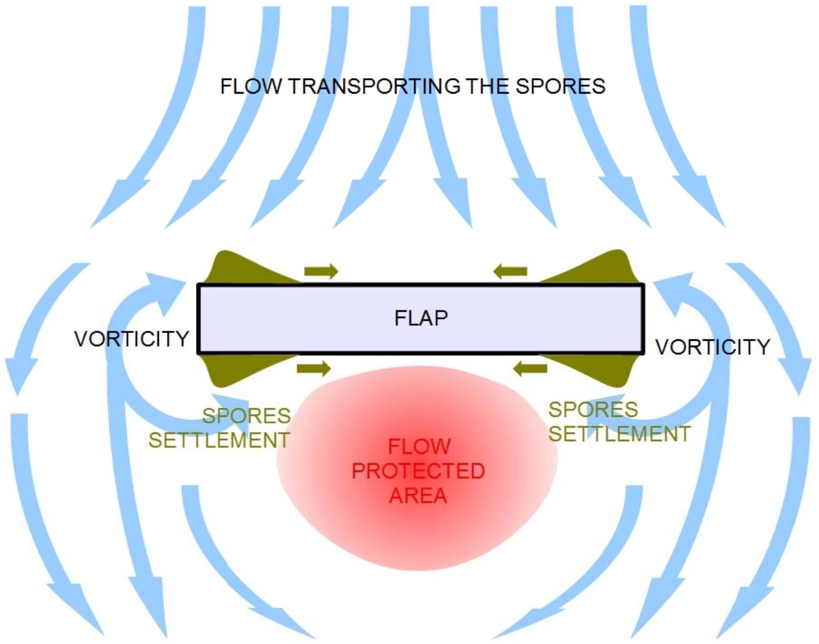
BIOFOULING MUST BE CONSIDERED SERIOUSLY

A tidal device which spent one year in water on Ouessant island in Britanny ...

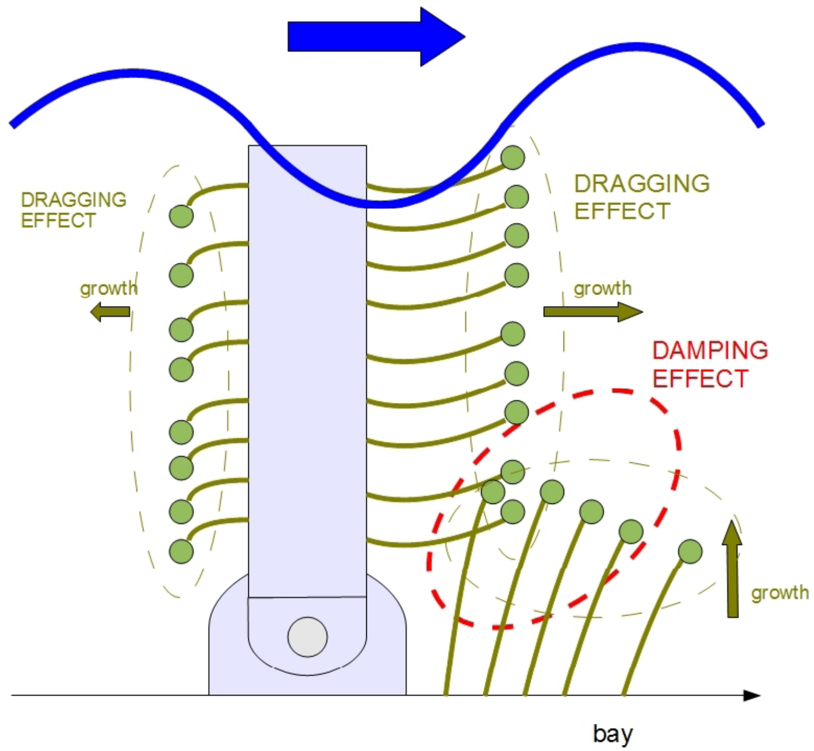
Modeling of growth done in collaboration with E. Reynaud (biologist at UCD) and C. Pinck

work in progress

EXPECTED SETTLEMENT ON THE FLAP



Some indications obtained from videos during cleaning operations



Mechanical effects on the flap

CONCLUDING REMARKS

Flaps might be simple devices from the engineering point of view. But they are really challenging from the fluid mechanics and numerical simulation points of view

- Intermediate water depth (kh of order unity)
- 3D problem
- Neither laminar flow nor potential flow (vortex shedding)
- Moving solid boundary (large motion) + free surface
- Intermediate size structure (no simplification)
- Nonlinear waves
- Coupling with biological growth

THANK YOU FOR YOUR ATTENTION

Howth, Ireland