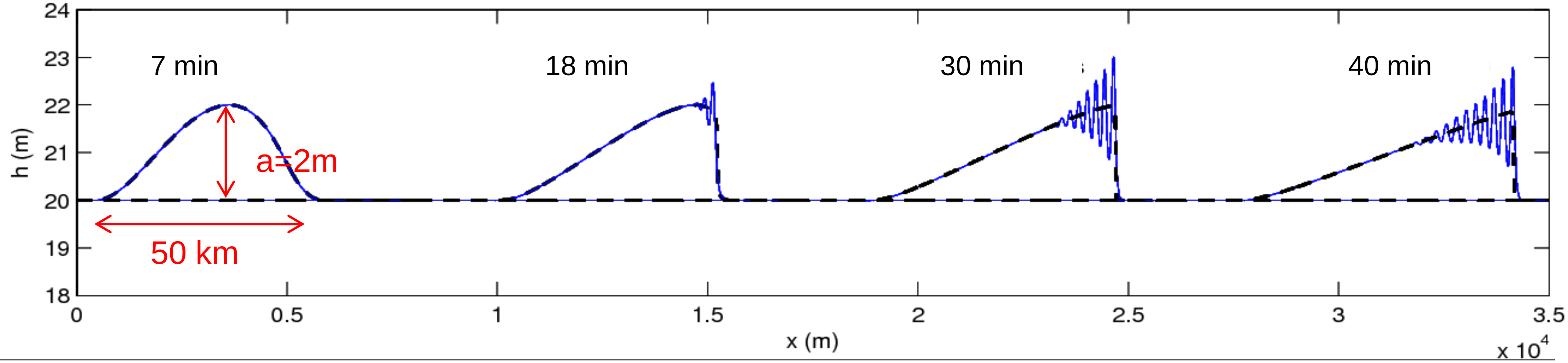
Long wave propagation and bore dynamics in coastal and estuarine environments

UNIVERSITÉ DE BORDEAUX

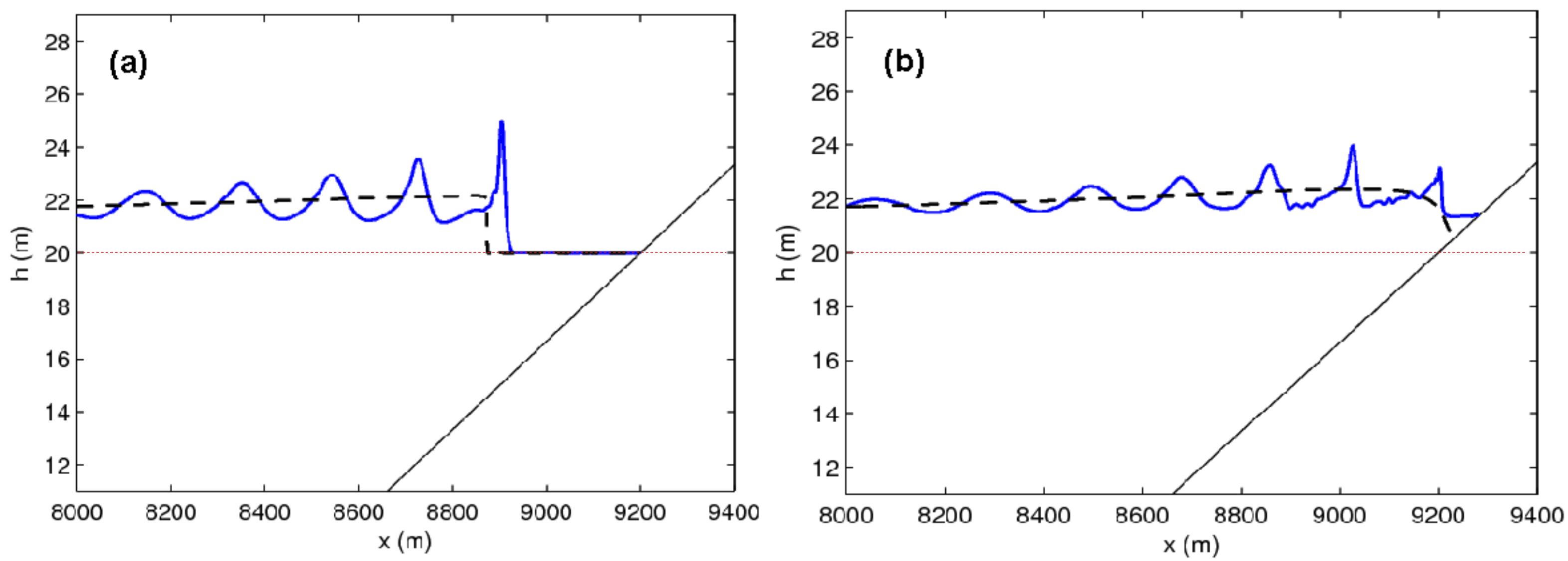
Philippe Bonneton

EPOC, METHYS team, Bordeaux Univ., CNRS

Sumatra 2004, tsunami reaching the coast of Thailand, Madsen et al. (2008)



Tissier , Bonneton et al., JCR2011



Long waves and non-hydrostatic processes

Tsunamis

2011 great Tohoku tsunami; Naka river at Hitachinaka city

Tidal waves

→ tidal bores

Tidal bore, Bonneton et al. 2011

Long waves and non-hydrostatic processes

Nearshore wind waves

- Understanding of non-hydrostatic phenomena and breaking
- Development of efficient long-wave modelling approaches

❑ long wave modelling

- Eric Barthélémy — LEGI, Grenoble
- Rodrigo Cienfuegos — PUC, Santiago de Chile
- Marion Tissier — TU Delft
- David Lannes — ENS, Paris
- Fabien Marche — I3M, Montpellier
- Mario Ricchiuto — INRIA, Bordeaux

❑ Nha Trang project / MOST — Vietnam / France

- Nguyen Trung Viet
  → Water Resources University
- Dinh Van Uu,
  → Hanoi University of Science
- Rafael Almar, J-P. Lefebvre
  → IRD, France
- Natalie Bonneton, Philippe Bonneton
  → EPOC, France

Outline

- ❑ **Introduction**
- ❑ **Observation of non-hydrostatic processes**
  - → tidal wave propagation and tidal bore formation
- ❑ **Non-hydrostatic modelling**
  - Theoretical background
  - A new approach
  - Validations
- ❑ **Conclusion and perspectives**

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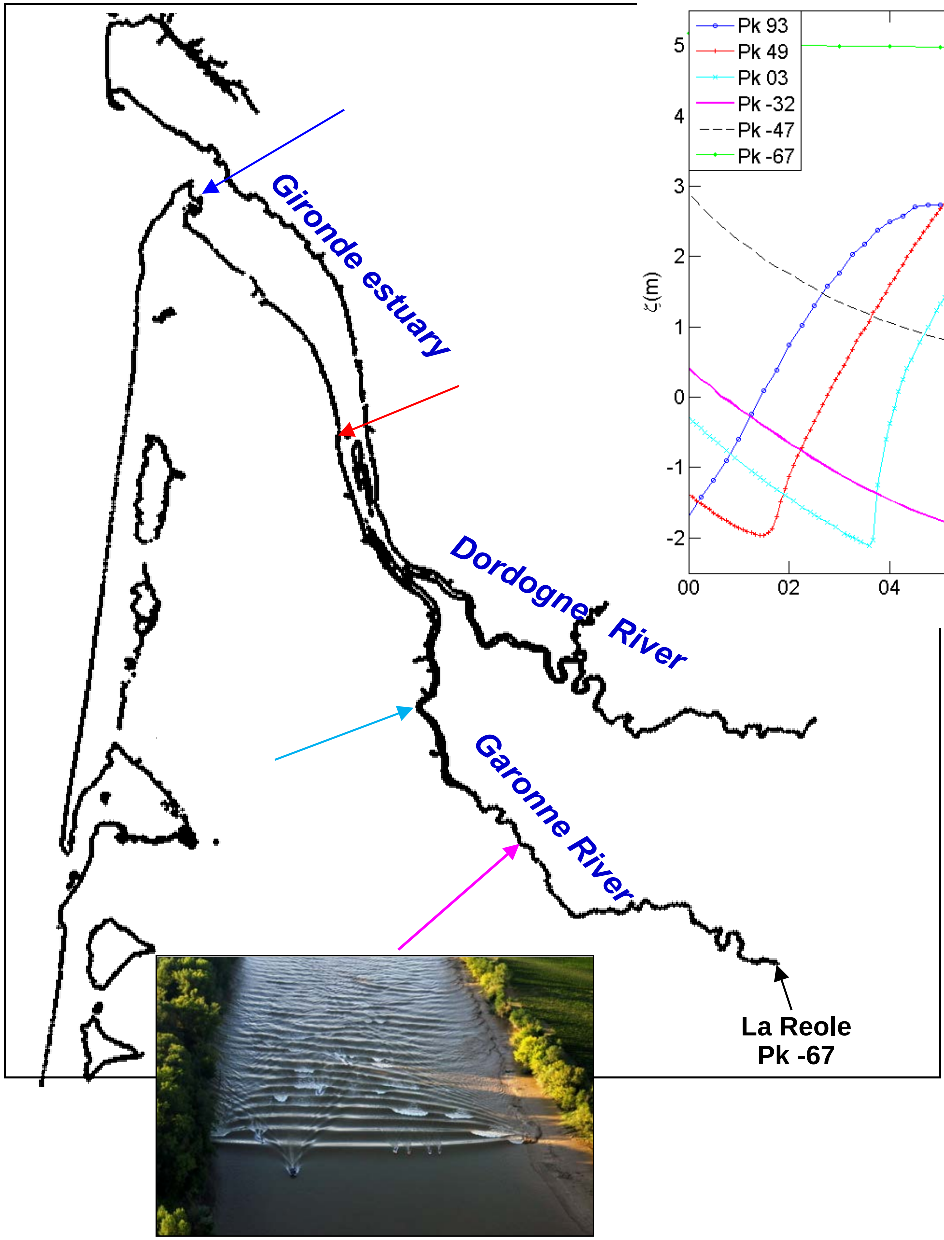
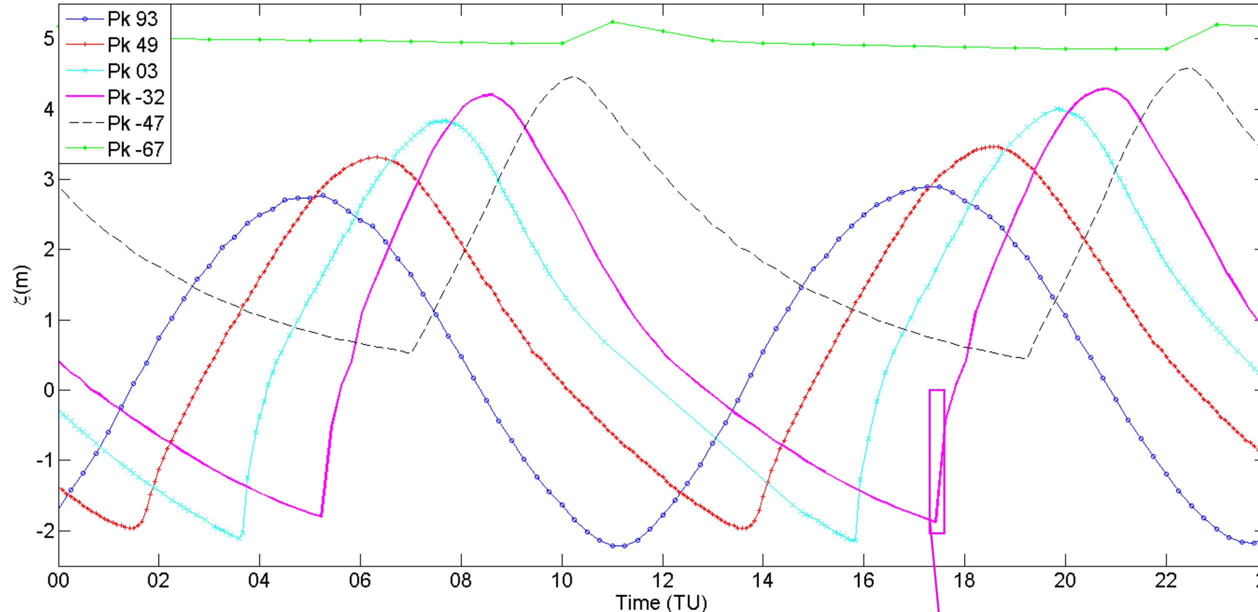
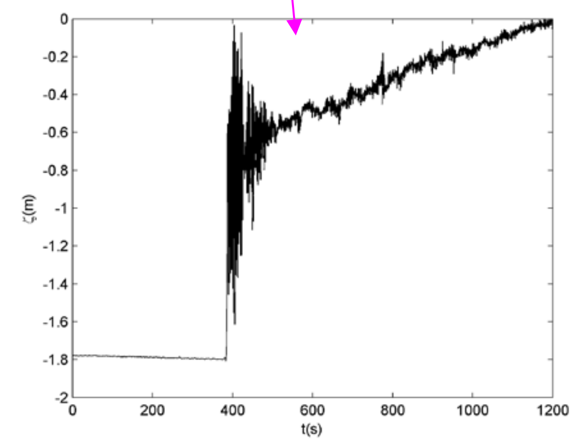
Observation of non-hydrostatic processes | Tidal waves



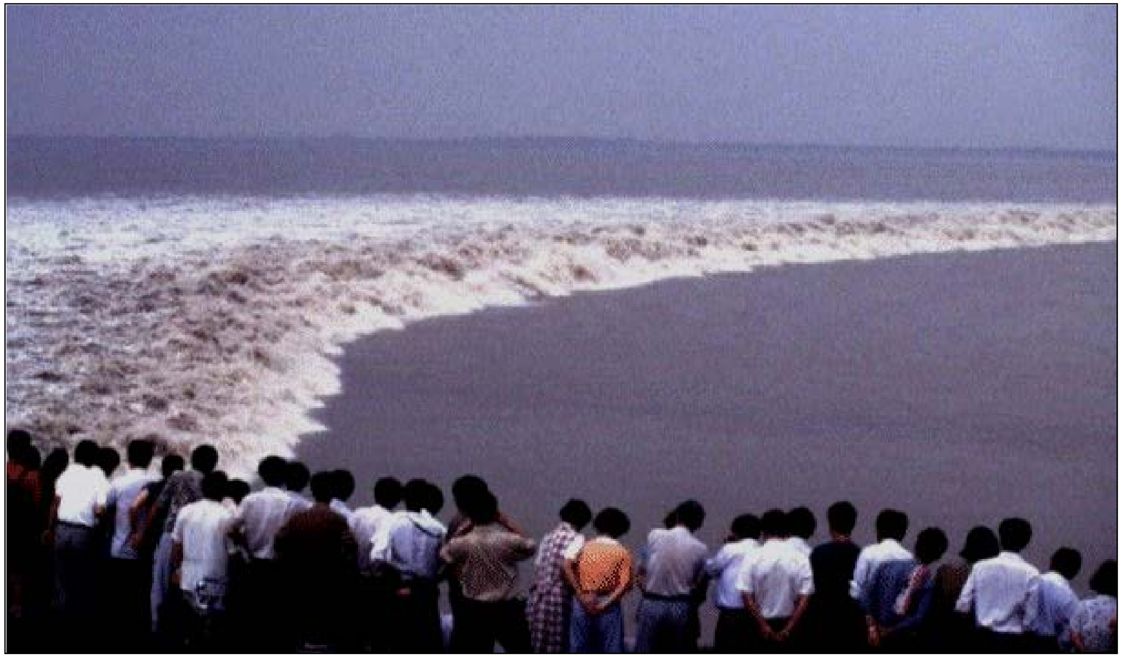


Large amplitude spring tide – 10th September 2010



Bonneton et al., 2011

Tidal bore: a fascinating hydrodynamic phenomenon observed worldwide



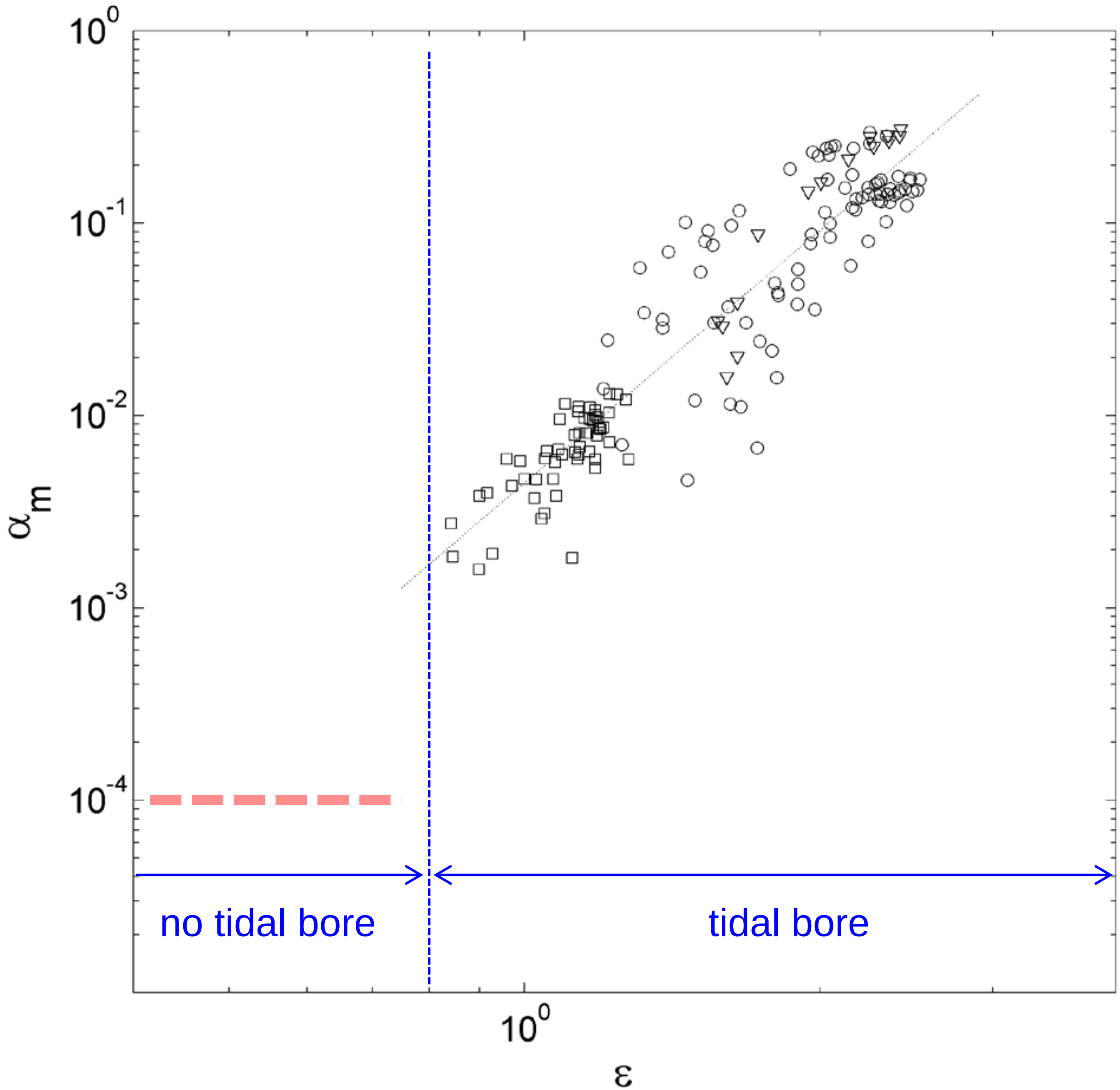
Qiantang River – China

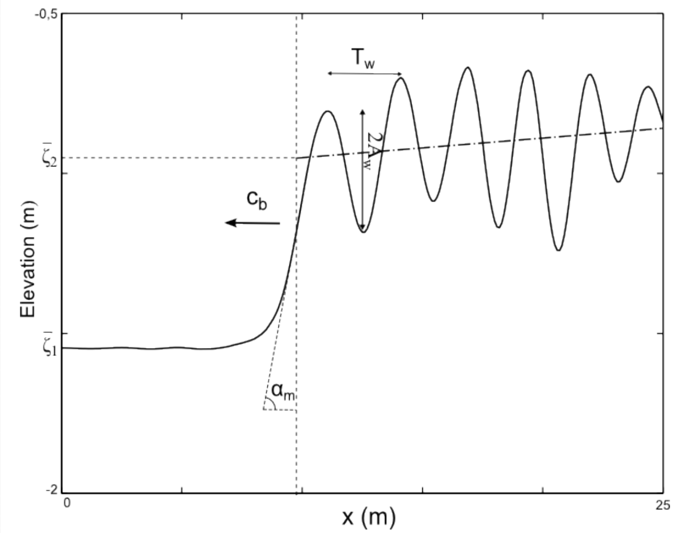
Kampar River – Sumatra (Bono)

Tidal bore occurrence is strongly underestimated

see Bonneton et al., 2012, 2014

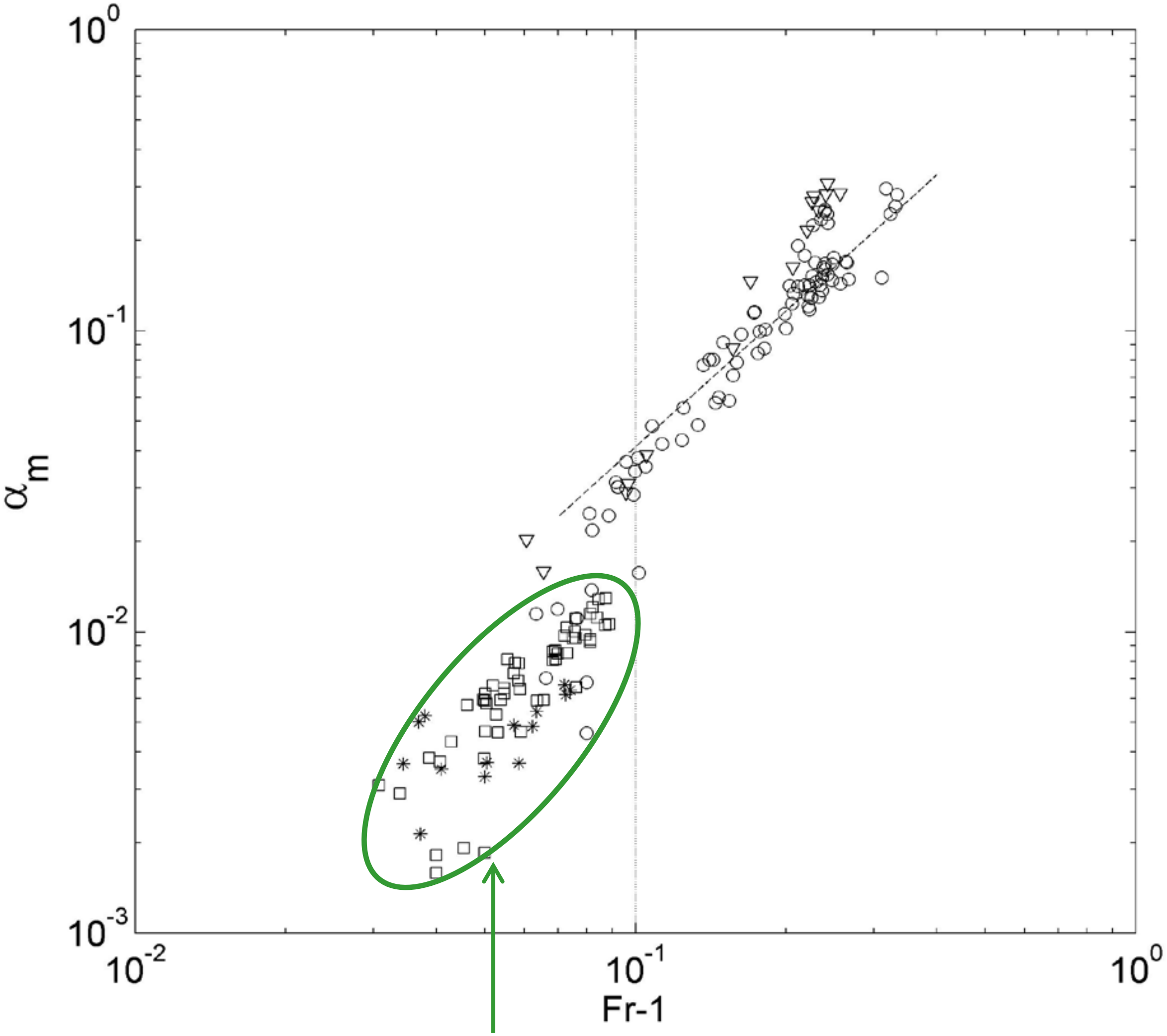
Observation of non-hydrostatic processes | Tidal waves



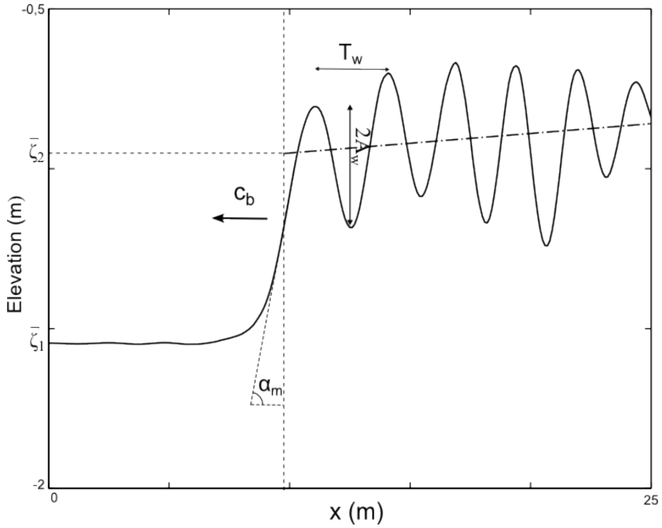


$$\varepsilon = \frac{T_R}{D_1}$$

Garonne River, *Bonneton et al., 2014*



Low intensity tidal bores



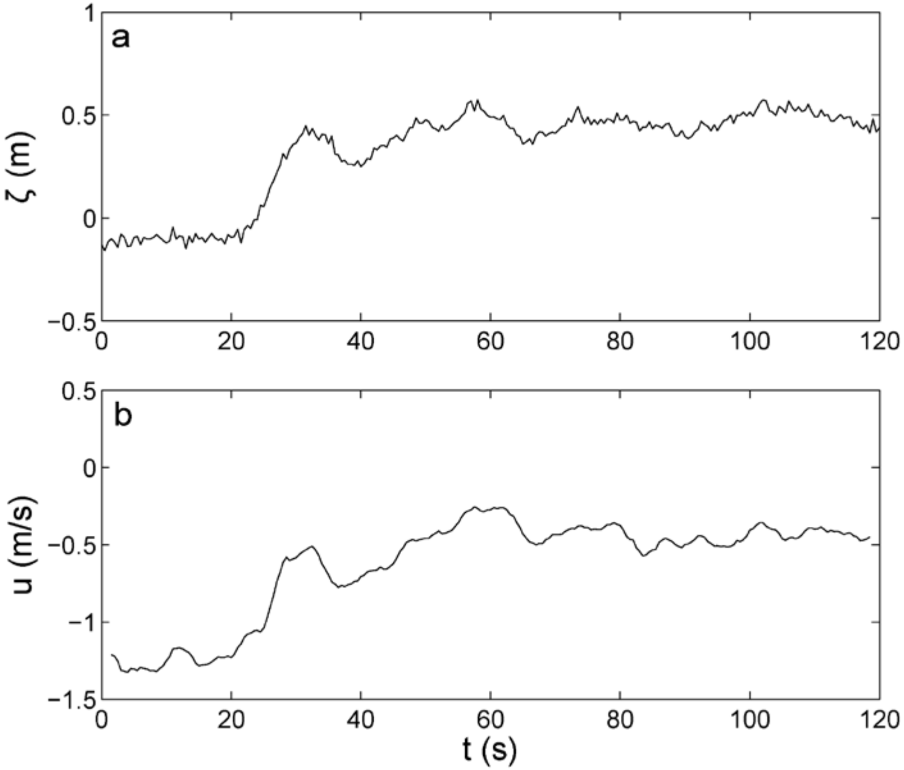
$$F_r = \frac{c - u_1}{\sqrt{g D_1}}$$

$$D_1 = \frac{\mathcal{A}_1}{\frac{\partial \mathcal{A}_1}{\partial h}}$$

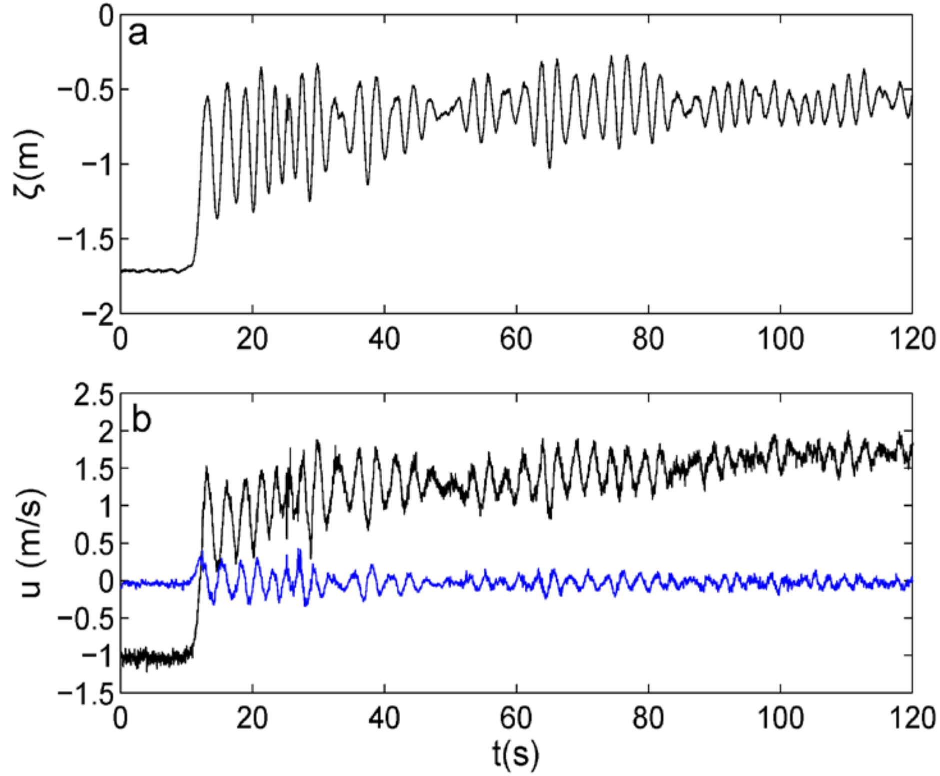
Garonne River, *Bonneton et al., 2014*

Observation of non-hydrostatic processes | Tidal waves

F=1.08



F=1.24



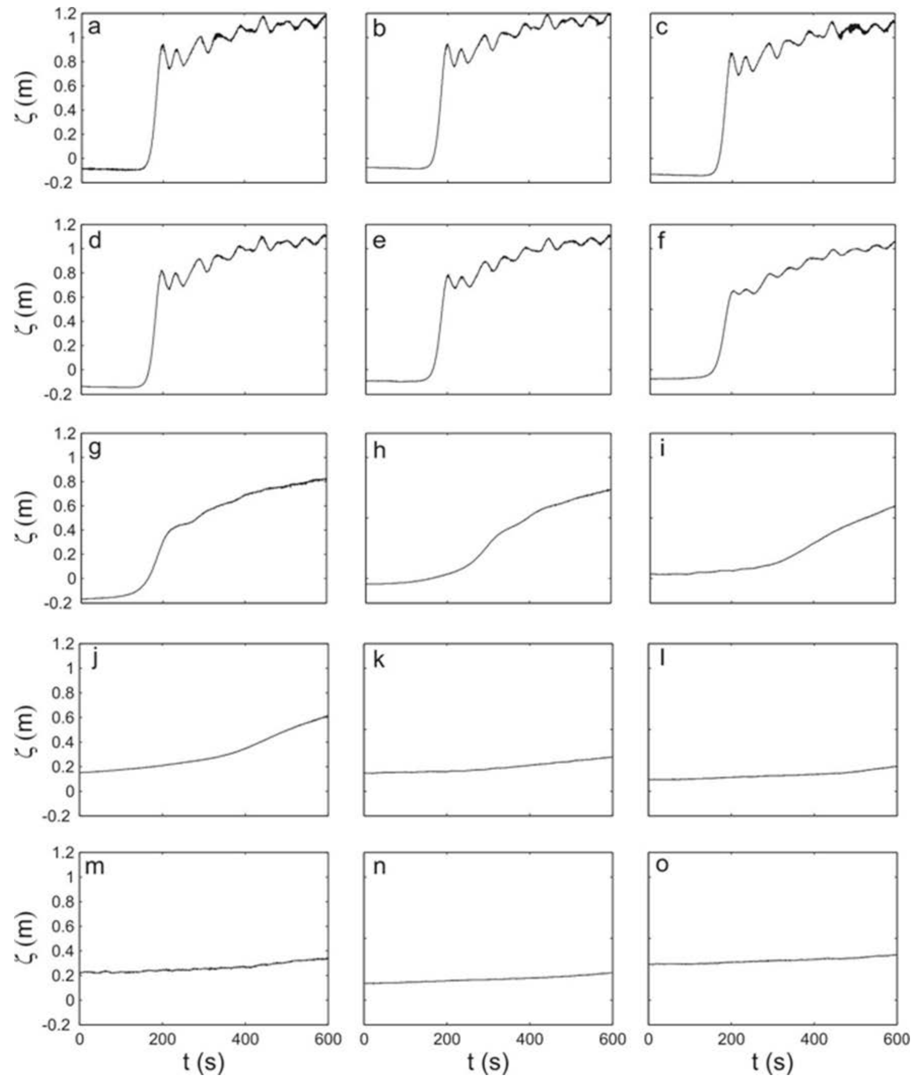
low intensity tidal bore

high intensity tidal bore

most of the time this phenomenon is ignored in estuaries

Seine estuary

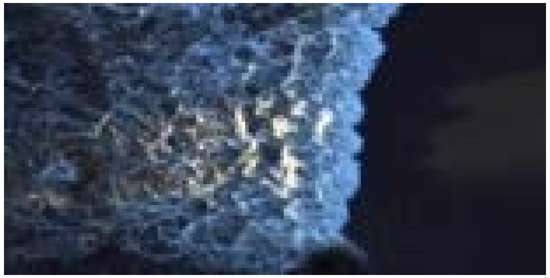
Field site
100 km from the estuary mouth



Bonneton et al., 2012

- need to reassess tidal bore occurrence in meso and macro-tidal estuaries worldwide (including Asian & Pacific estuaries)
  → high frequency measurements are required

- tidal bores play a significant role in estuarine ecosystems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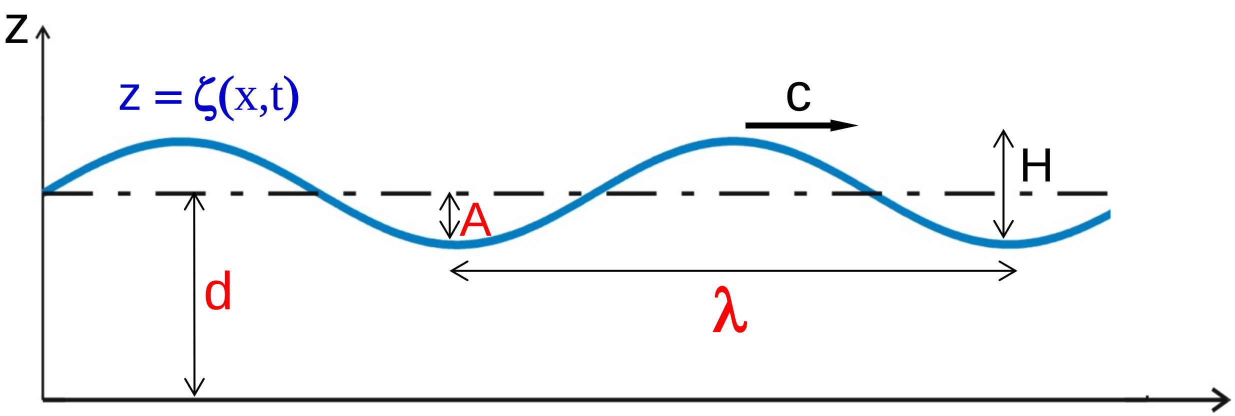


$$\varepsilon = \frac{A}{d}$$

$$\mu = \left(\frac{d}{\lambda}\right)^2$$

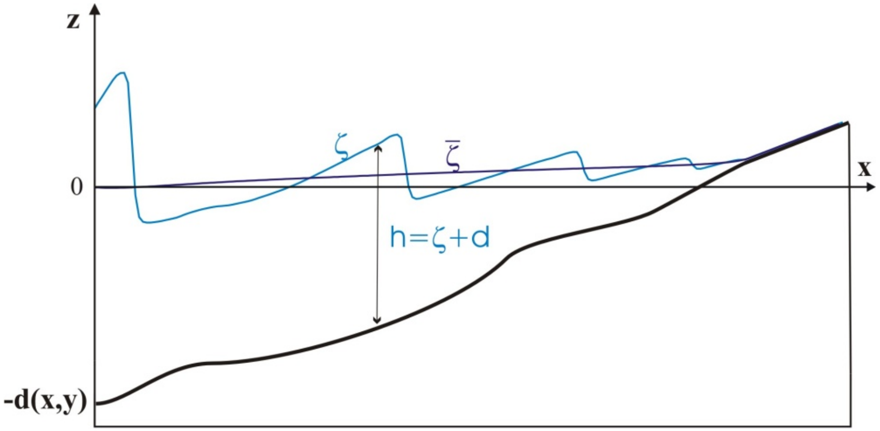
- $\mu \leq 0.01$
- $\varepsilon = O(1)$ → ~~$\varepsilon = O(\mu)$~~

$$\mu = \left(\frac{d_0}{\lambda_0}\right)^2 << 1 \qquad \varepsilon = \frac{A_0}{d_0} = O(1)$$

Inviscid 3D incompressible irrotational Euler equations

$\rightarrow$ asymptotic expansion with respect to μ

$$\begin{aligned} \partial_t \zeta + \nabla \cdot (h\mathbf{u}) &= 0 \\ \partial_t \mathbf{u} + \varepsilon(\mathbf{u}\cdot\nabla)\mathbf{u} + \nabla\zeta &= \mu\mathcal{D} + O(\mu^2) \end{aligned}$$

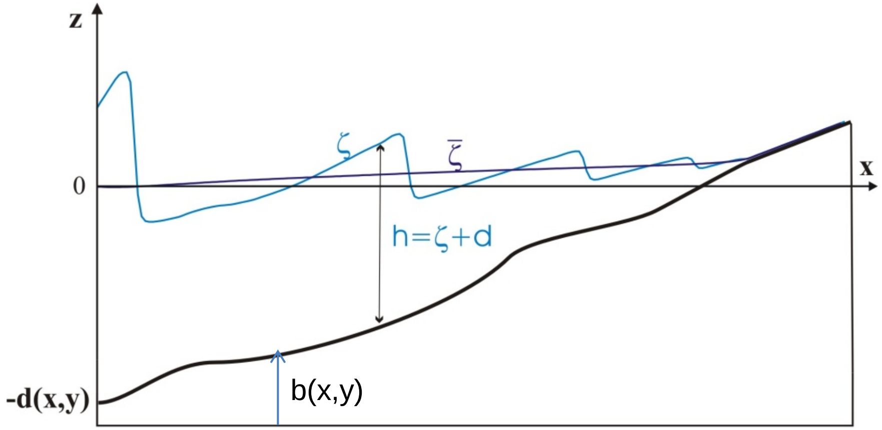


$\varepsilon = O(1)$

Serre or Green Naghdi equations

$$\begin{aligned}\partial_t \zeta + \nabla \cdot (h\mathbf{u}) &= 0 \\ \partial_t \mathbf{u} + \varepsilon(\mathbf{u}\cdot\nabla)\mathbf{u} + \nabla\zeta &= \mu\mathcal{D} + O(\mu^2)\end{aligned}$$

Lannes and Bonneton (2009)



$$\mathcal{D} = -\mathcal{T}[h,b]\mathbf{u}_t - \varepsilon\mathcal{Q}[h,b](\mathbf{u})$$

where the linear operator $\mathcal{T}[h,b]$ is defined as

$$\mathcal{T}[h,b]W = -\frac{1}{3h}\nabla(h^3\nabla\cdot W) + \frac{1}{2h}[\nabla(h^2\nabla b\cdot W) - h^2\nabla b\nabla\cdot W] + \nabla b\nabla b\cdot W$$

and the quadratic term $\mathcal{Q}[h,b](\mathbf{u})$ is given by

$$\begin{aligned}\mathcal{Q}[h,b](\mathbf{u}) = & -\frac{1}{3h}\nabla\left(h^3((\mathbf{u}\cdot\nabla)(\nabla\cdot\mathbf{u}) - (\nabla\cdot\mathbf{u})^2)\right) \\ & +\frac{1}{2h}[\nabla(h^2(\mathbf{u}\cdot\nabla)^2 b) - h^2((\mathbf{u}\cdot\nabla)(\nabla\cdot\mathbf{u}) - (\nabla\cdot\mathbf{u})^2)\nabla b] + ((\mathbf{u}\cdot\nabla)^2 b)\nabla b\end{aligned}$$

Reformulation of SGN equations

$$\partial_t h + \nabla \cdot (h\mathbf{u}) = 0$$

$$\partial_t (h\mathbf{u}) + \nabla \cdot (h\mathbf{u} \otimes \mathbf{u}) + \nabla(\frac{1}{2} g h^2) = -gh\nabla b + \frac{1}{\alpha} gh\nabla\zeta - (I + \alpha h \mathcal{T} \frac{1}{h})^{-1} [\frac{1}{\alpha} gh\nabla\zeta + h\mathcal{Q}_1(\mathbf{u})]$$

$\mathcal{Q}_1(\mathbf{u}) = \mathcal{Q}(\mathbf{u}) - \mathcal{T}((\mathbf{u} \cdot \nabla)\mathbf{u})$ only involves second order derivatives of $\mathbf{u}$

α −− > improved dispersive properties (Madsen et al., 1991)

$kd_0 \leq 3$

*Bonneton, Chazel, **Lannes**, Marche and Tissier (2011)*

$$\partial_t h + \nabla \cdot (h\mathbf{u}) = 0$$

$$\partial_t (h\mathbf{u}) + \nabla \cdot (h\mathbf{u} \otimes \mathbf{u}) + \nabla(\frac{1}{2}gh^2) = -gh\nabla b + \frac{1}{\alpha}gh\nabla\zeta - (I + \alpha h\mathcal{T}\frac{1}{h})^{-1}[\frac{1}{\alpha}gh\nabla\zeta + h\mathcal{Q}_1(\mathbf{u})]$$

Lannes and Marche (2014) have proposed a new formulation where

the **operator to invert** is **time independent**

$\rightarrow$ **a considerable decrease of the computational time!**

Hybrid method

$$
\begin{aligned}
\partial_t \zeta + \nabla \cdot (h\mathbf{u}) &= 0 \\
\partial_t \mathbf{u} + \varepsilon(\mathbf{u}\cdot\nabla)\mathbf{u} + \nabla\zeta &= \mu\mathcal{D}
\end{aligned}
$$

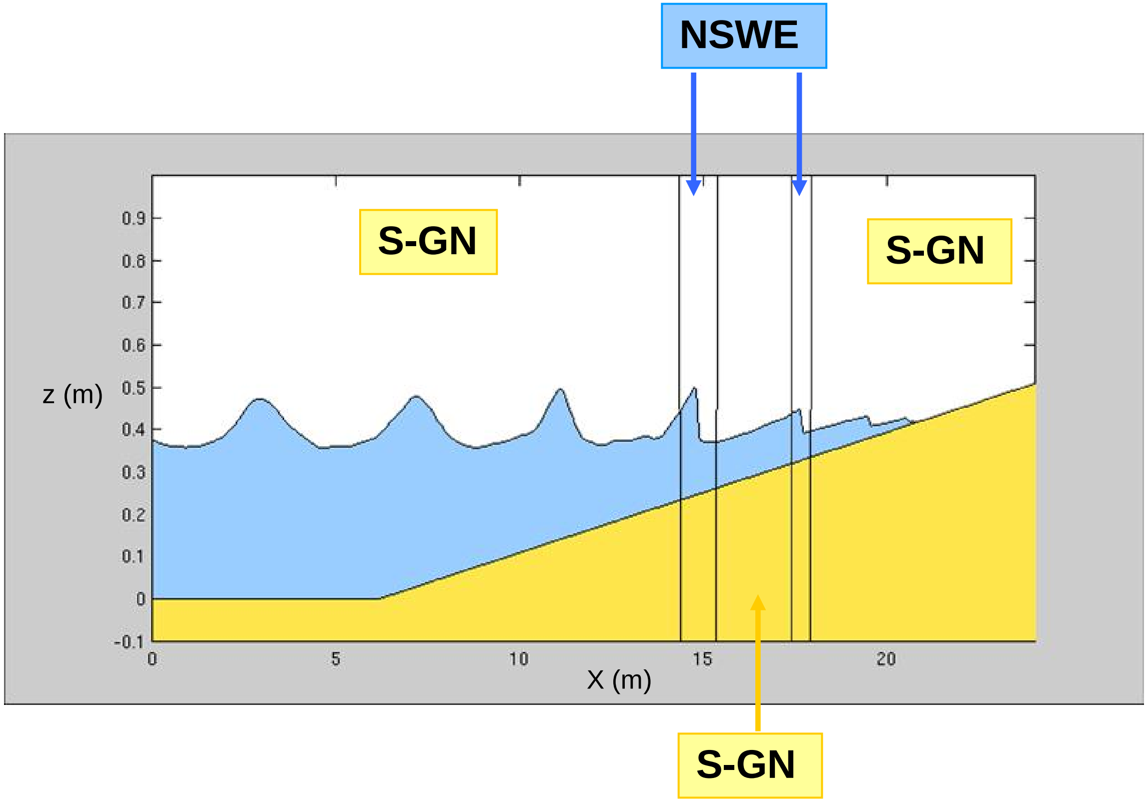
non-breaking waves:

SGN

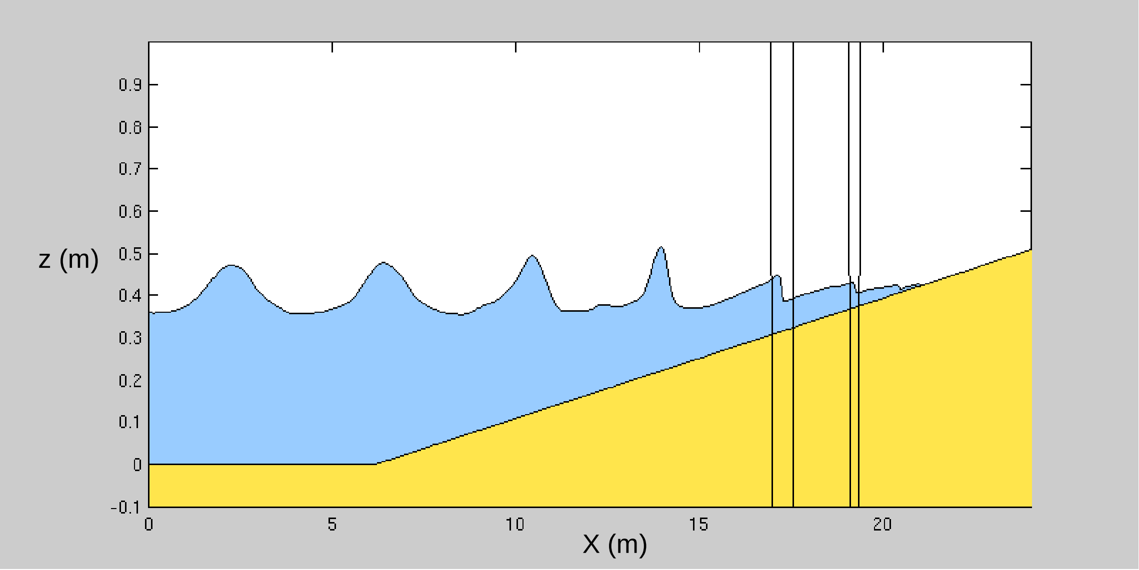
broken wave fronts and swash motions:

NSWE

Shoaling and breaking of regular waves over a sloping beach

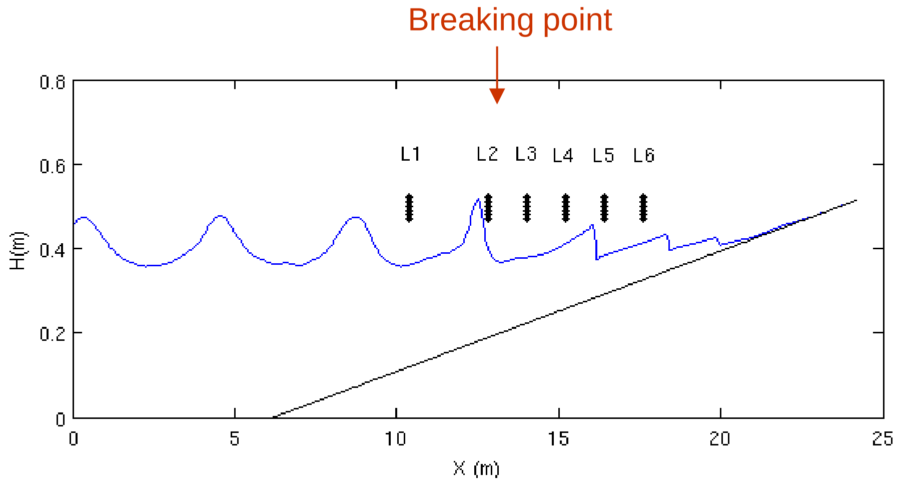


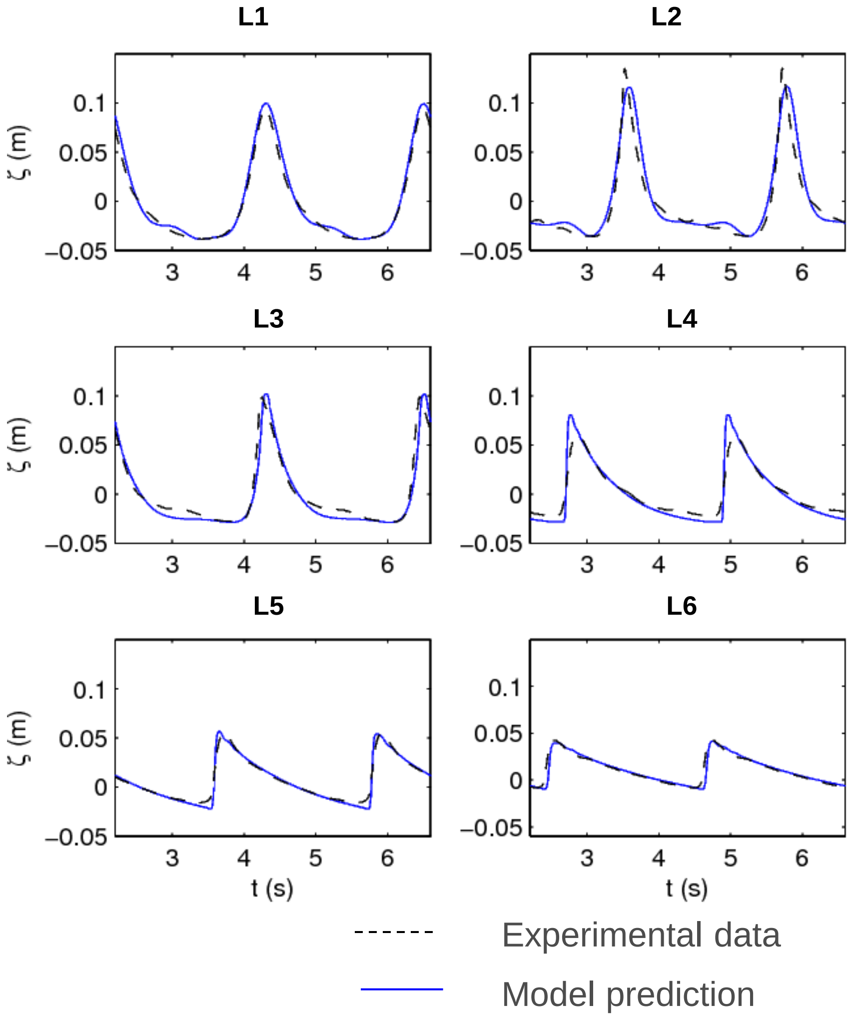
Shoaling and breaking of regular waves over a sloping beach



Shoaling and breaking of regular waves over a sloping beach

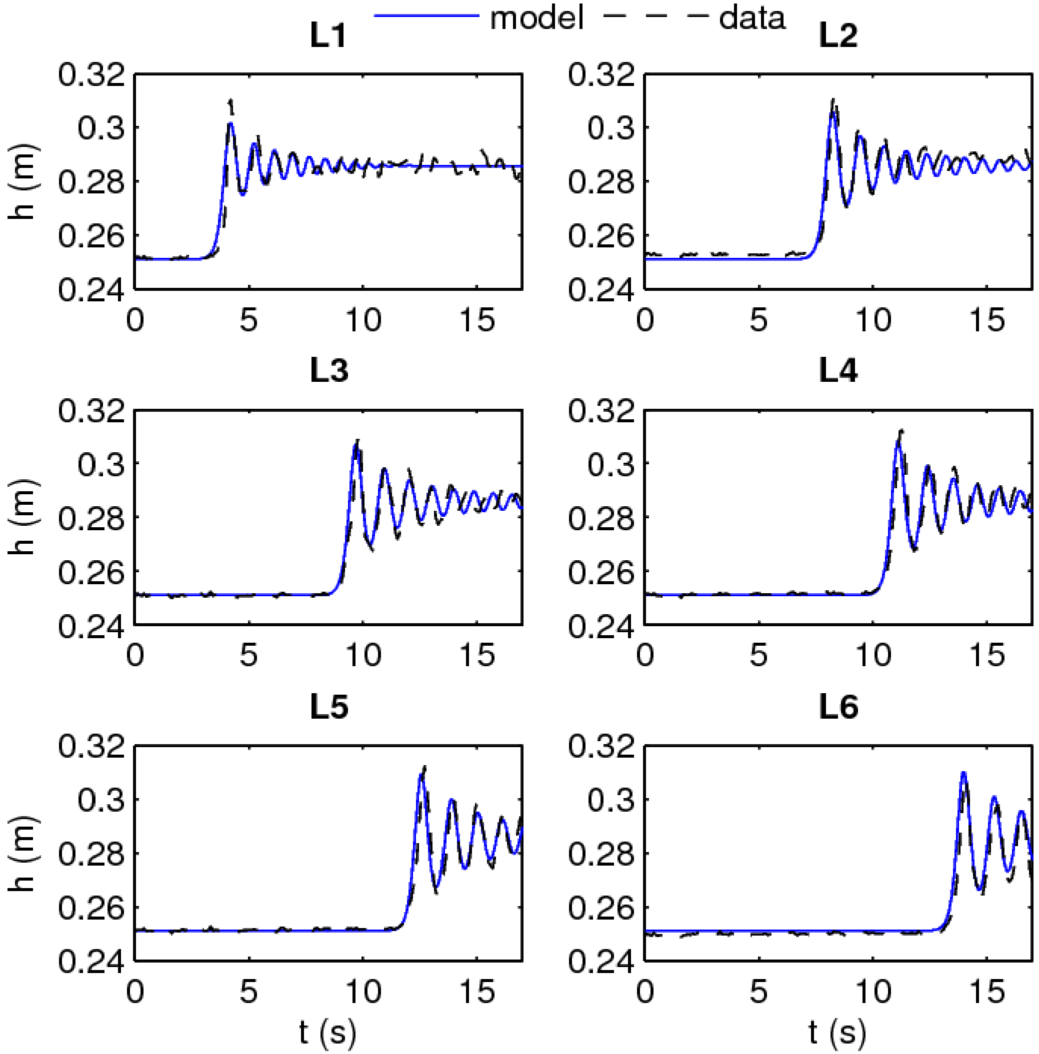
Validation with Cox (1995) experiments





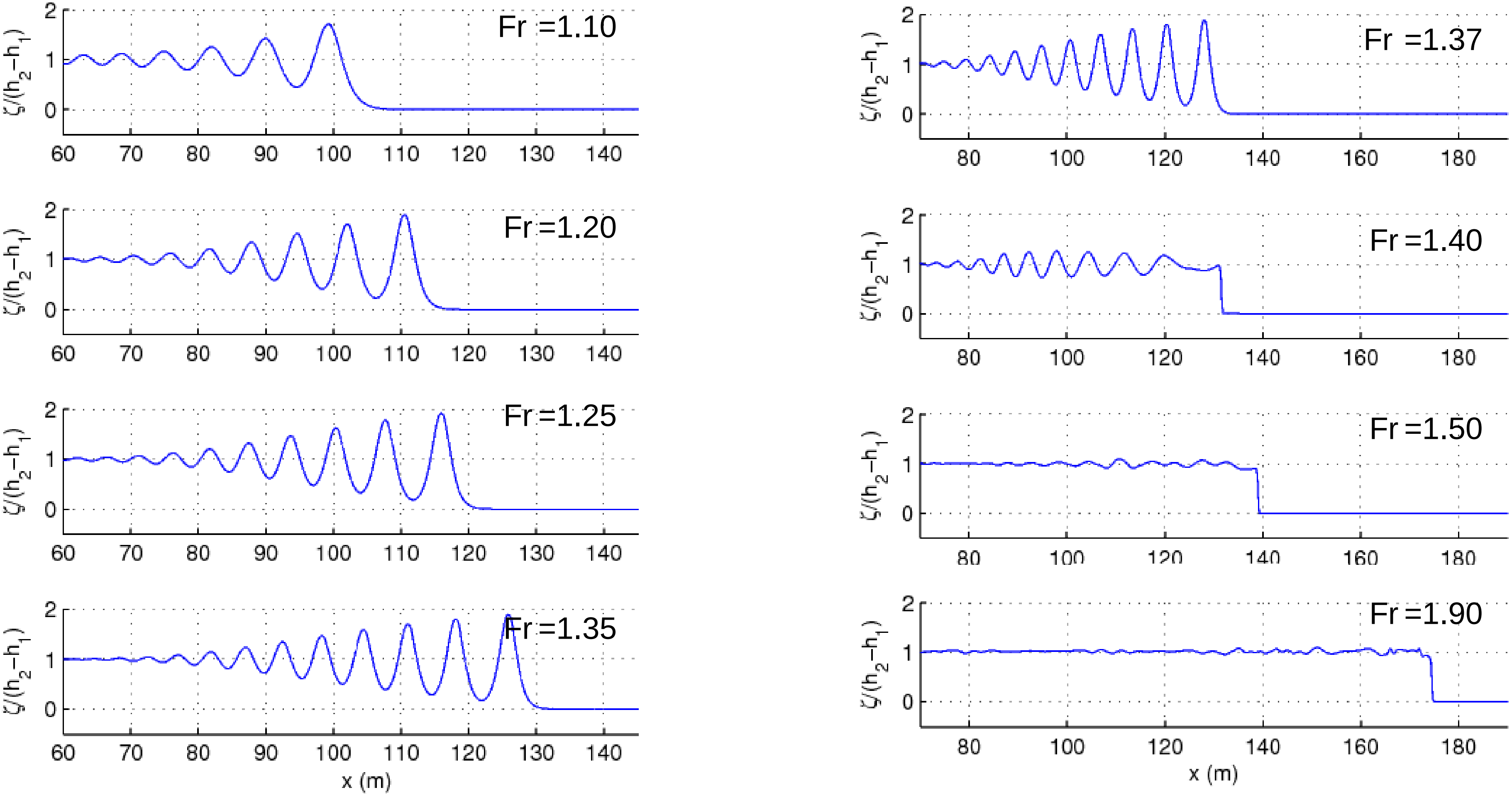
Tissier et al., 2012

Undular bore propagation



Laboratory experiments by Soares-Frazao et Zech (2002), Fr = 1.104

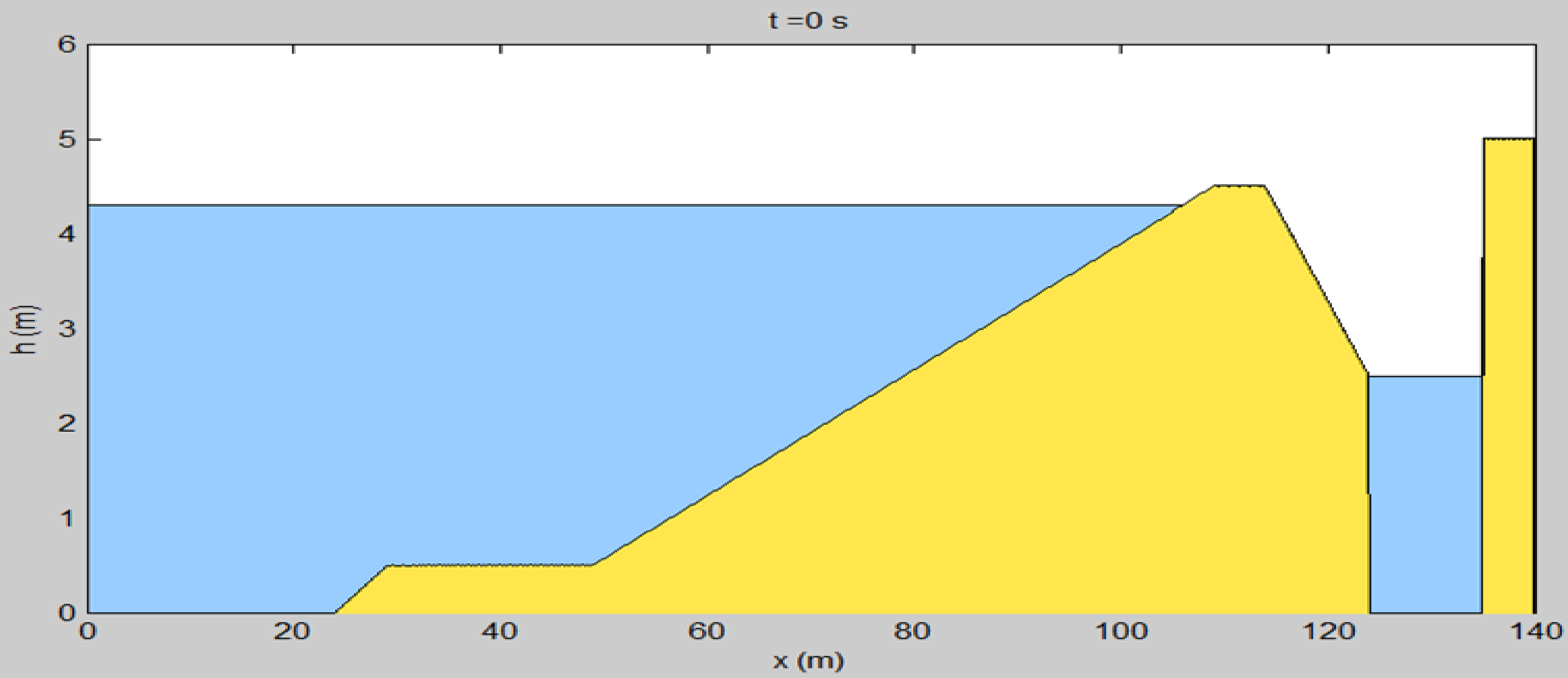
Undular bore propagation



t=24s

Wave overtopping and multiple shorelines

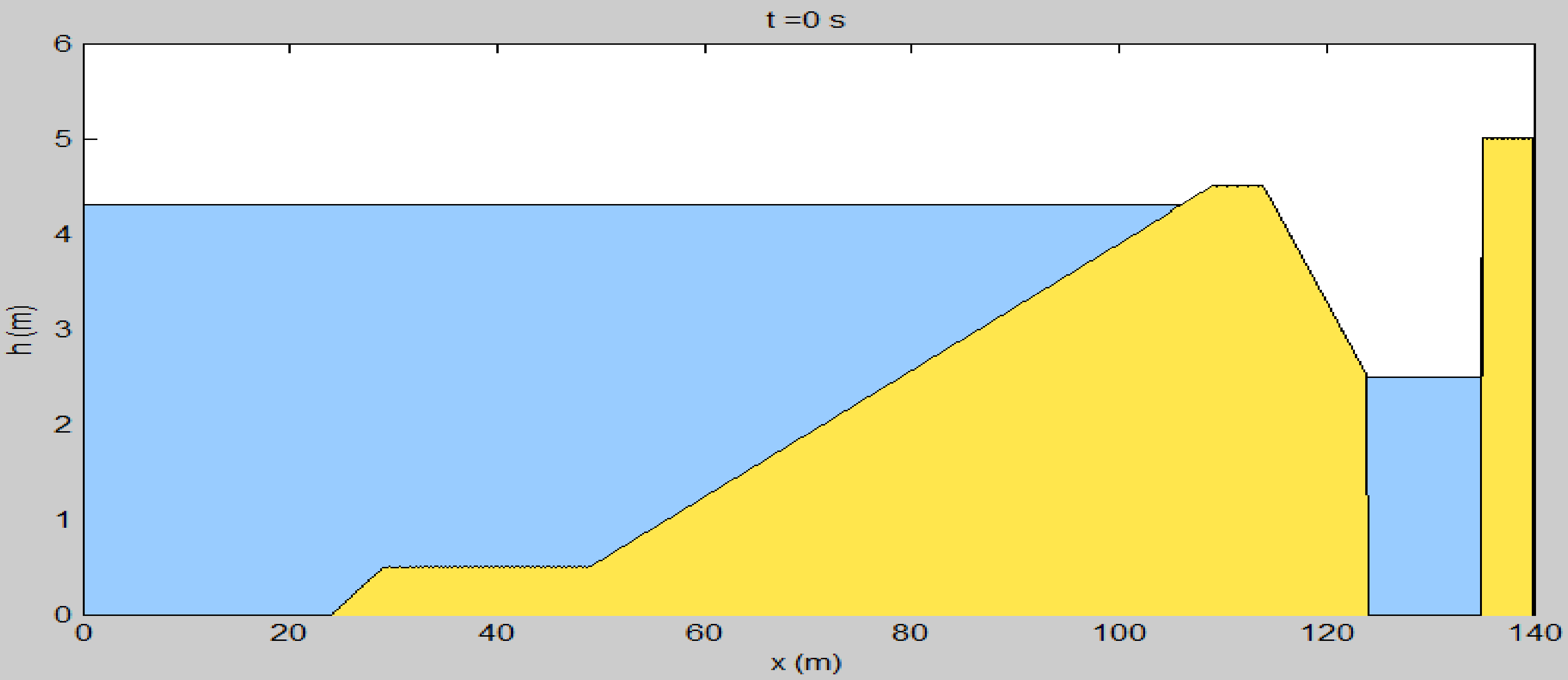
BARDEX II - HYDRALAB project



Bonneton et al., 2013

Wave overtopping and multiple shorelines

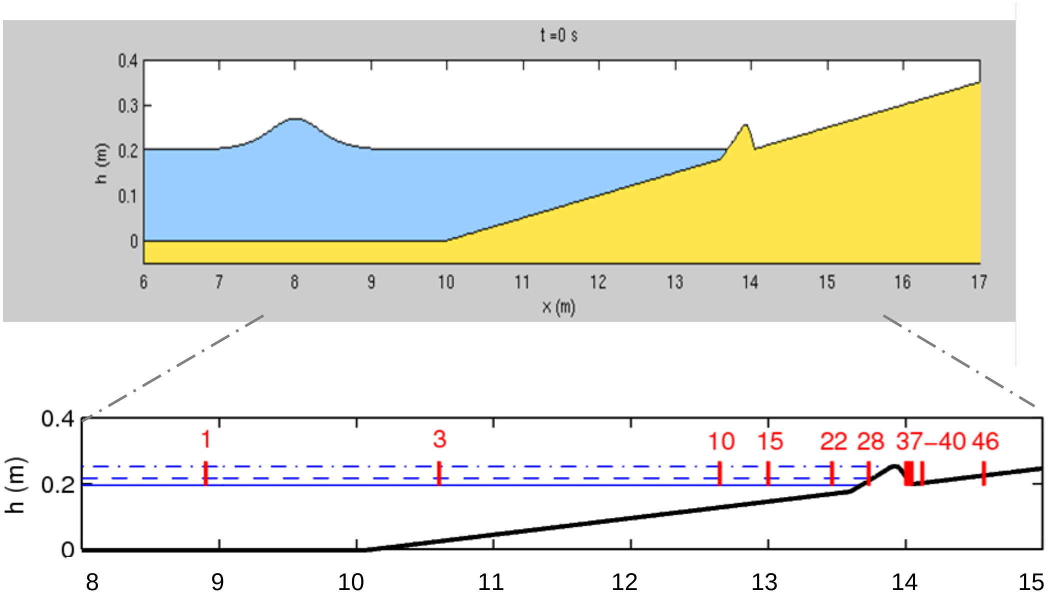
BARDEX II - HYDRALAB project



Bonneton et al., 2013

Wave overtopping and multiple shorelines

Solitary waves overtopping a seawall (Hsiao and Lin, 2010)



Tissier et al., 2012

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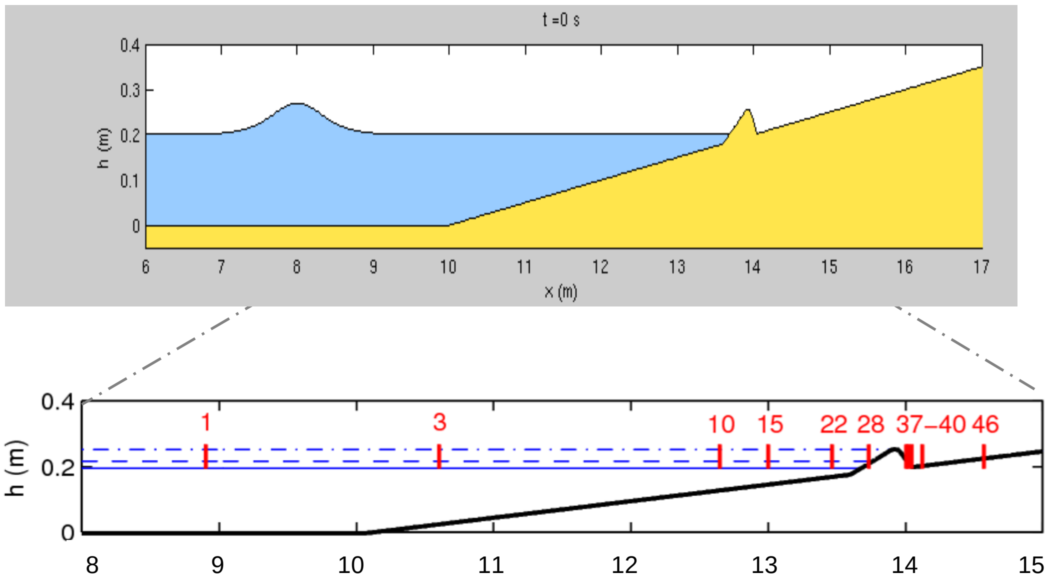

Tissier et al., 2012

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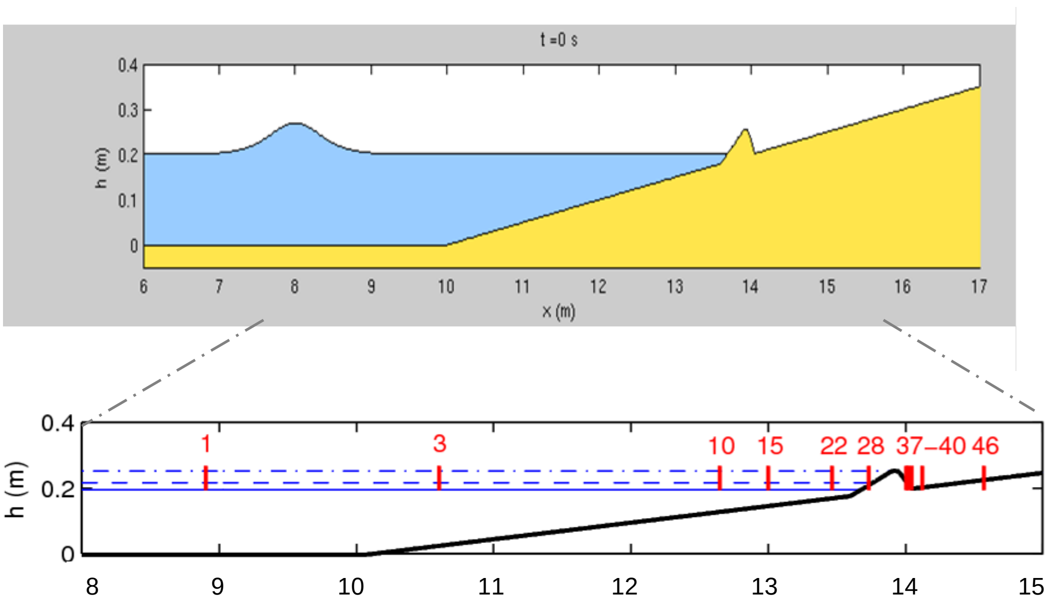
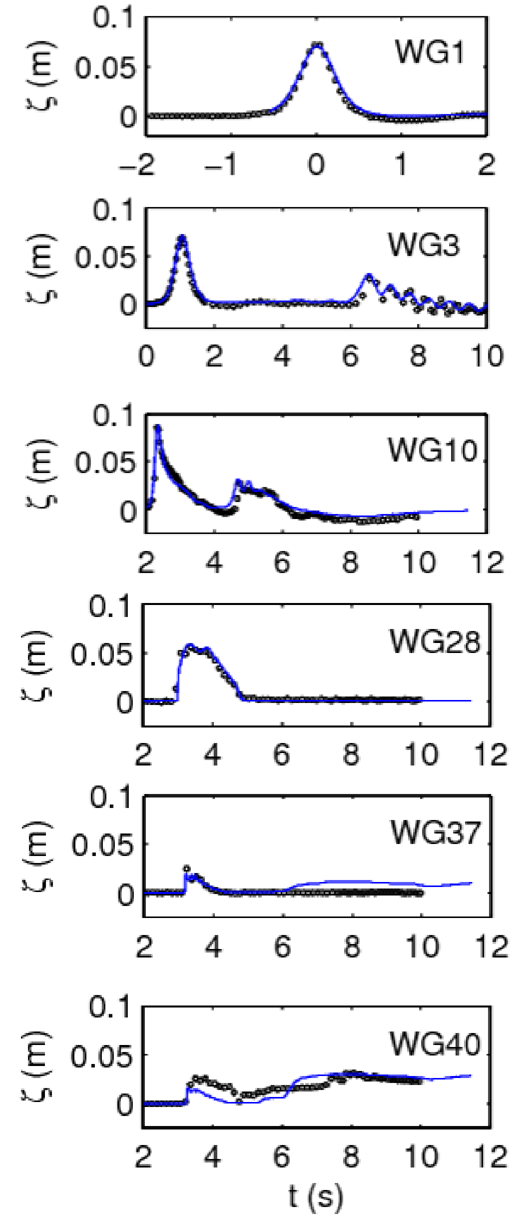




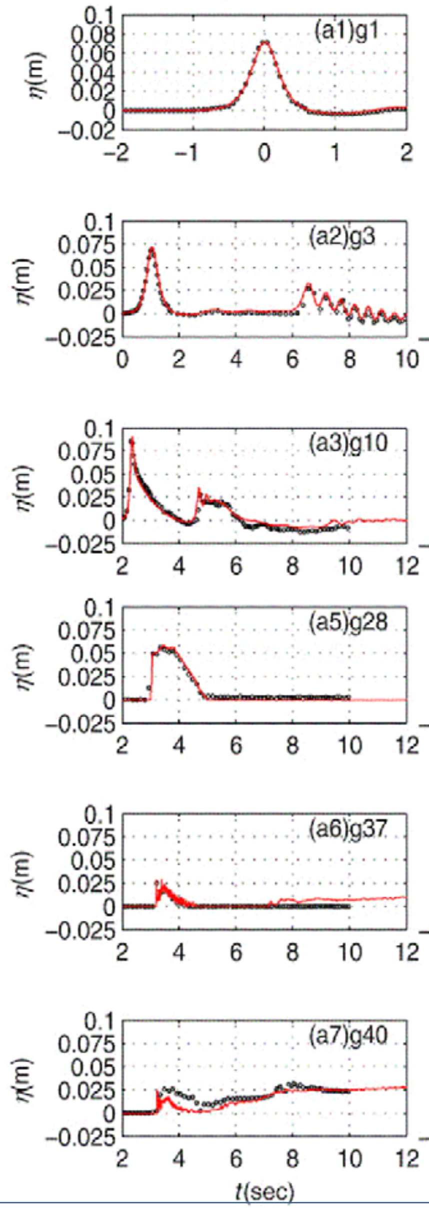
Tissier et al., 2012

Wave overtopping and multiple shorelines

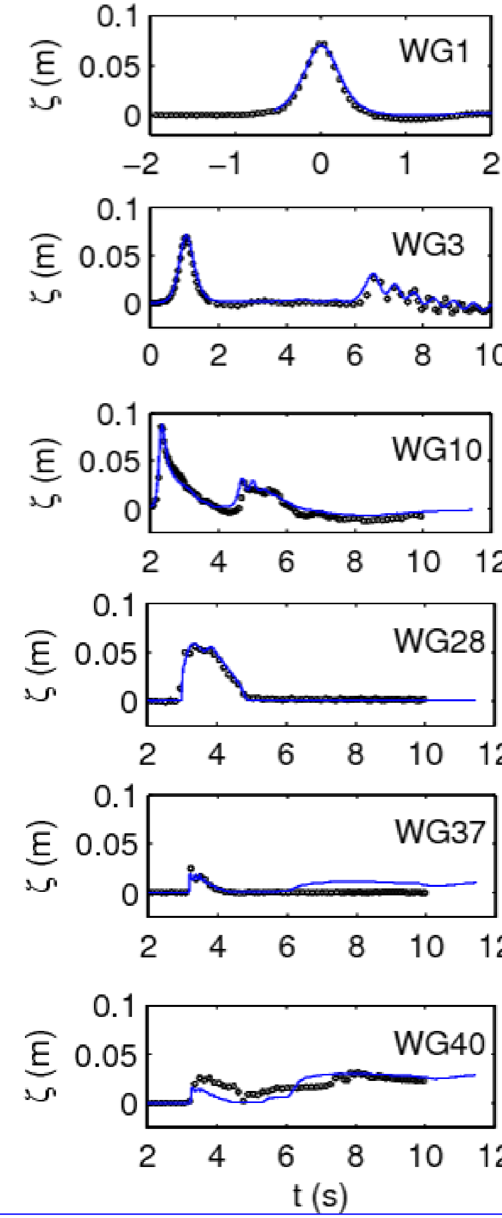
Hsiao et Lin (2010)
COBRAS model

2D VOF model

RANS equations K-ε



SURF-GN



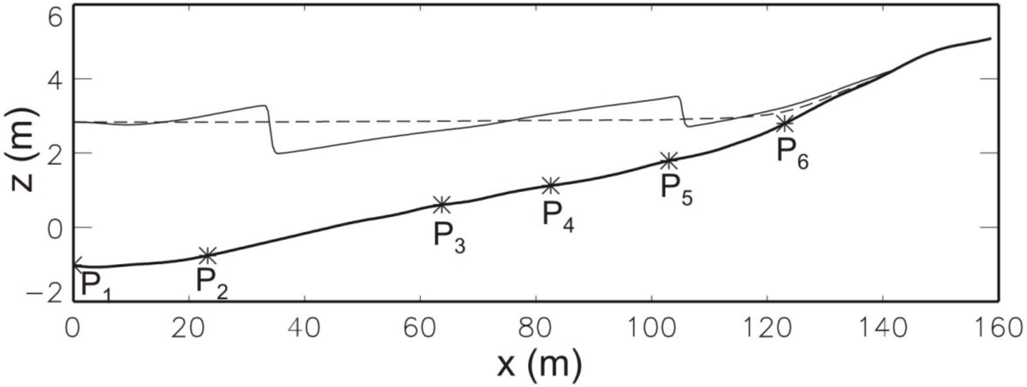
Non-hydrostatic modelling

Validations

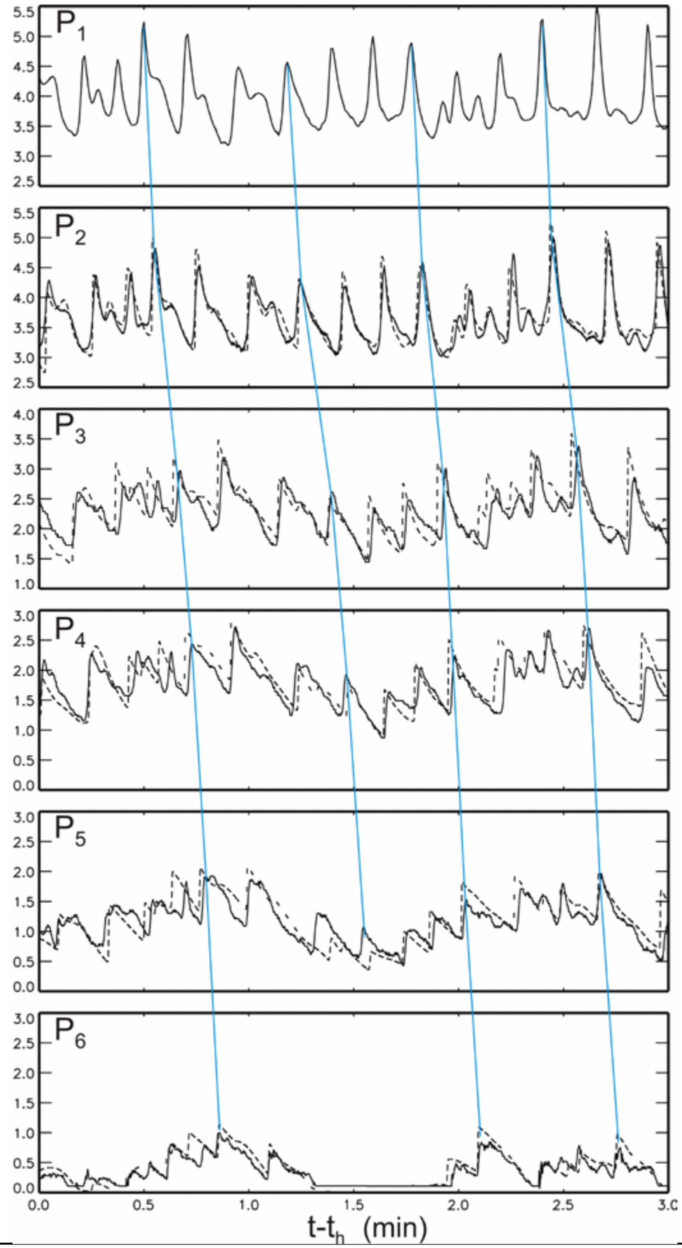
Long wave propagation in the swash zone

Truc Vert Beach 2001

- Offshore wave conditions: $\theta \approx 0°$, Hs=3 m, Ts=12 s
- Maximum surf zone width: 500 m

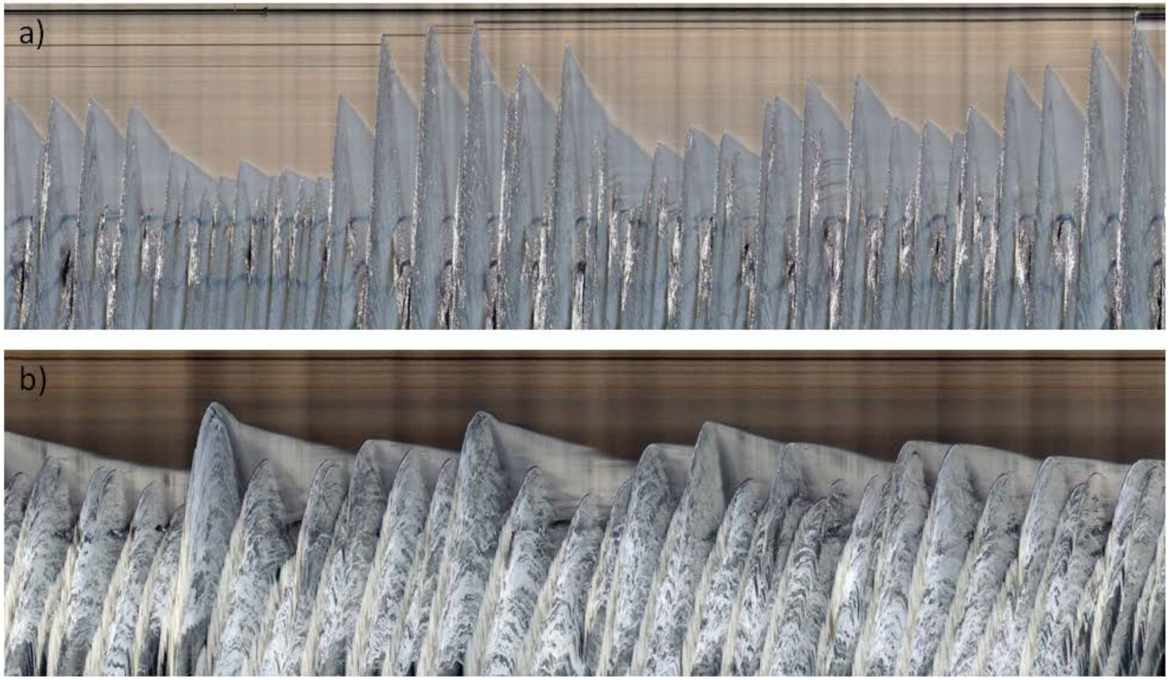


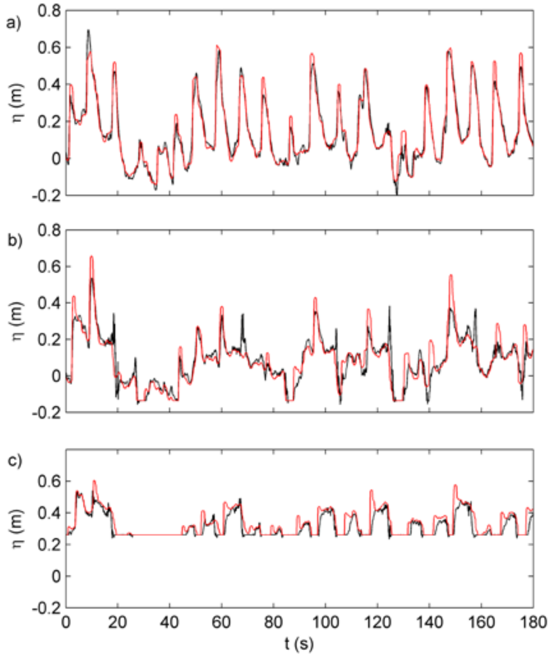
Bottom topography and pressure sensor locations



Long wave propagation in the swash zone

Nha Trang project (Vietnam/France): high frequency and high resolution swash database





⟶ *see Almar et al. (IAHR-APD 2014)*

Conclusion and perspectives

- ❑ non-hydrostatic and dispersive effects play a significant role in long wave dynamics in coastal and estuarine environments


Sumatra tsunami 2004


Tidal bore Garonne 2010

- ❑ need to reassess tidal bore occurrence in meso and macro-tidal estuaries worldwide (including Asian & Pacific estuaries)

  → impact on estuarine ecosystems

Conclusion and perspectives

- A new approach for long wave modelling

$$
\begin{aligned}
\partial_t h + \nabla \cdot (h\mathbf{u}) &= 0 \\
\partial_t (h\mathbf{u}) + \nabla \cdot (h\mathbf{u} \otimes \mathbf{u}) + \nabla(\frac{1}{2}gh^2) &= -gh\nabla b \\
&+ \frac{1}{\alpha}gh\nabla\zeta - (I + \alpha h\mathcal{T}\frac{1}{h})^{-1}[\frac{1}{\alpha}gh\nabla\zeta + h\mathcal{Q}_1(\mathbf{u})]
\end{aligned}
$$

  - new mathematical formulation

    $\rightarrow$ easy to implement in existing NSWE models

  - hybrid approach SGN/NSWE

    $\rightarrow$ wave transformation and wave breaking

- Development of Finite Element methods on unstructured grid

  Mario Ricchiuto (INRIA, Bordeaux)

Thank you for your attention