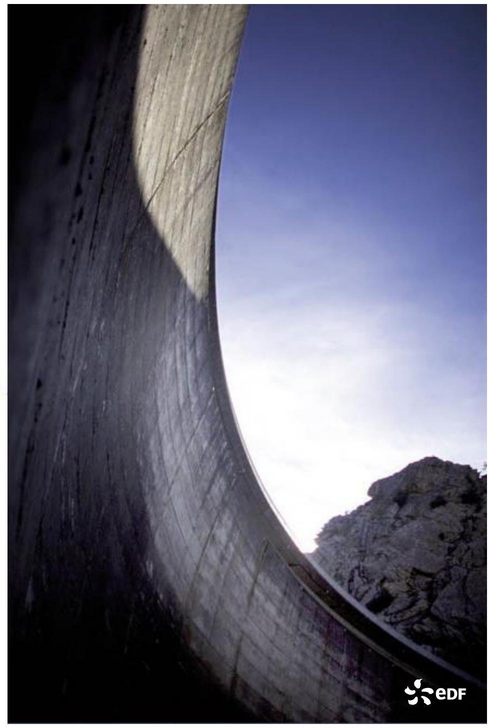
TANDEM Tsunami Summer School

Coastal impacts: Run up and inundations

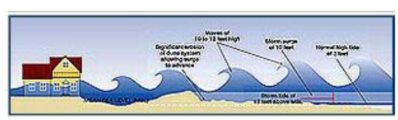
Riadh Ata, Ph.D. Eng.,
Expert researcher
LNHE: National Laboratory for Hydraulics & Environment – **EDF R&D - France**
LHSV: Saint-Venant Laboratory for Hydraulics - France

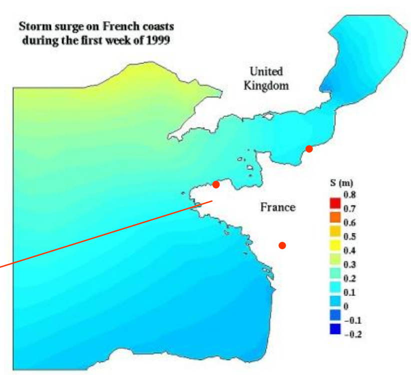


Tsunami Hazard for NPP

Protection of coastal NPP

- After Fukushima 2011
- Different aspects of risk
- Design of protection features (dyke, spare generators, …)



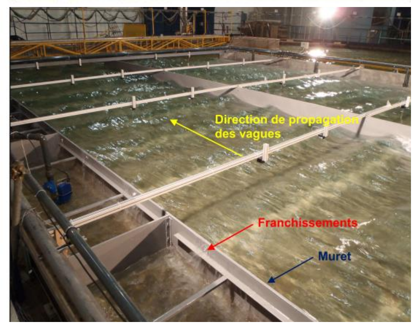


Tsunami Hazard for NPP

How to design ?

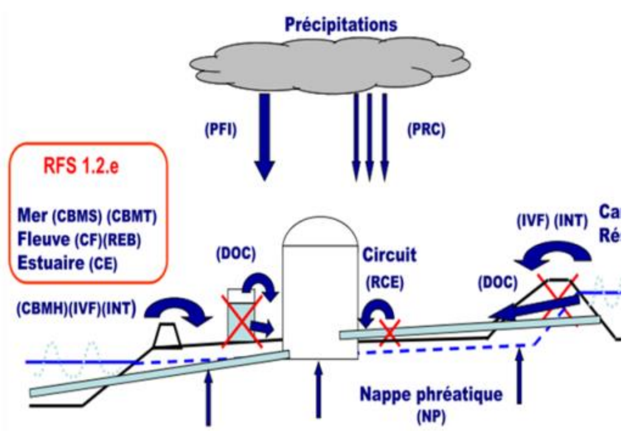
Experimental reduced models

- Mainly for complex features unfeasable (unreliable) numerical simulations
- $$$
- Technical & resources limitations



Hazard conjunction

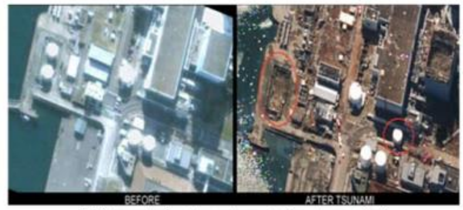
- High tide coefficients
- storm surge
- Heavy rains
- Underwater contribution
- Dyke failure (breaching)
- …



Hazard conjunction

- Objectives: avoid this

Bâche d'effluents déformée près de la SdP tr 5



Bâches de fuel lourd arrachées devant tr 1

Moteurs SdP tranche 4

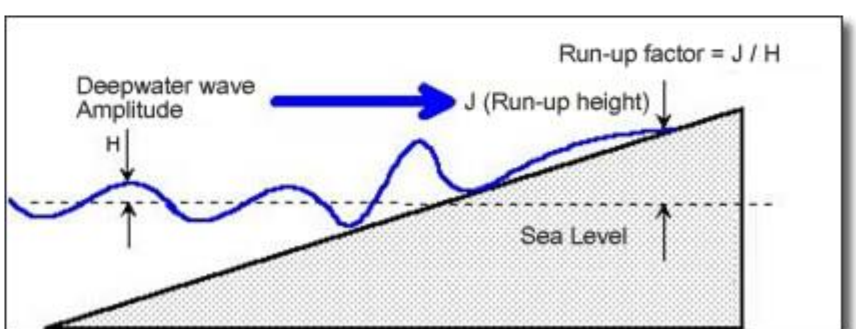
Source : TEPCO

Tableaux électriques SdM tr 1 – boue au sol

Run up

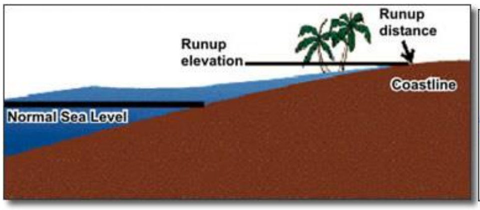
"When the tsunami's wave peak reaches the shore, the resulting temporary rise in sea level is termed run up. Run up is measured in metres above a reference sea level"

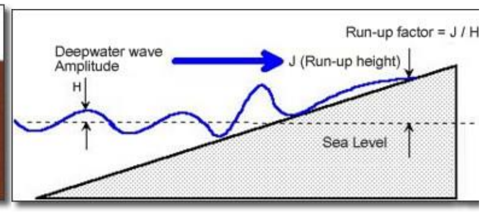
Western Coastal & Marine Geology.



http://www.sms-tsunami-warning.com

Run up





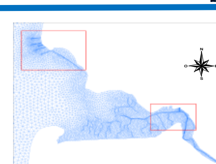
Some definitions

- **Tsunami Amplitude :** maximum height of the wave above the sea level in deep water
- **Run-up height :** tsunami vertical height above sea level at its furthest point inland
- **Run-uo factor :** run-up height divided by tsunami amplitude
- **Run-up distance :** maximum distance between shoreline and the furthest point inland reached by the wave

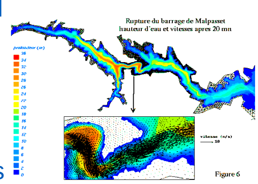
http://www.sms-tsunami-warning.com

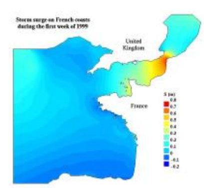
The Telemac-Mascaret system

Main characteristics



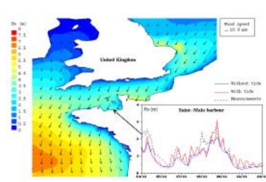
- Developed since 1987 at EDF R&D / LNHE
- World distributed (first commercial with 200 licences, now freeware and open source)
- FORTRAN 90/95, Perl, Python, MPI
- Based on unstructured grids
- Documentation and validation



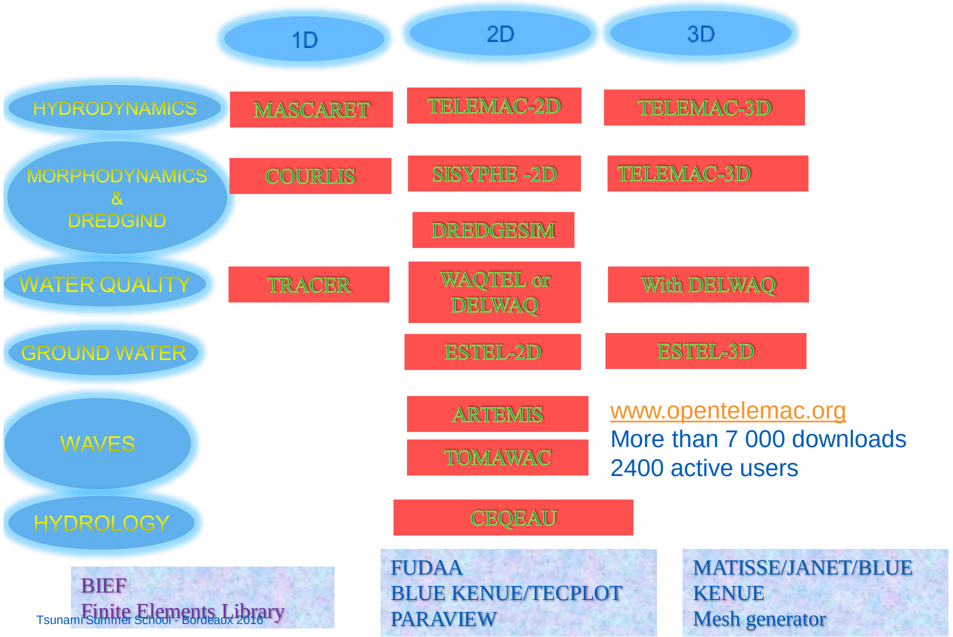


Key features

- FE & FV, Implicit & explicit schemes
- Parallelism with domain decomposition
- Dry zones
- Turbulence
- Free surface
- …



COMPLETE OPEN SOURCE HYDROINFORMATIC SYSTEM



What model shall we use?

	SWE	Boussinesq	NS	LagrangianNS
CPU	Yes	Yes (but)	Yes (but)	Yes (but but)
Propagation	Yes (but…)	Yes	Yes	Yes
Breaking	No	No	No	Yes
Inundation	Yes	Yes (but)	Yes (but)	yes

$$\frac{\partial U}{\partial x}+\frac{\partial V}{\partial y}+\frac{\partial W}{\partial z}=0$$

$$\frac{\partial U}{\partial t}+U\frac{\partial U}{\partial x}+V\frac{\partial U}{\partial y}+W\frac{\partial U}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial x}+\nu\Delta U+F_x$$

$$\frac{\partial V}{\partial t}+U\frac{\partial V}{\partial x}+V\frac{\partial V}{\partial y}+W\frac{\partial V}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial y}+\nu\Delta V+F_y$$

$$\frac{\partial W}{\partial t}+U\frac{\partial W}{\partial x}+V\frac{\partial W}{\partial y}+W\frac{\partial W}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial z}+g+\nu\Delta W+F_z$$

What model shall we use?

	Propagation	Runup & inundation	CPU
High order schemes	+	-	↗
Dispersion	+	- (?)	↗
Non newtonian	-	+(?)	↗
Refined mesh	-	+	↗

What model shall we use?

Extra term in the Saint-Venant momentum equation:

$$\frac{d\vec{u}}{dt} = \ldots - \frac{H_0^2}{6}\overrightarrow{grad}\left(div\left(\frac{\partial \vec{u}}{\partial t}\right)\right) + \frac{H_0}{2}\overrightarrow{grad}\left(div\left(H_0\frac{\partial \vec{u}}{\partial t}\right)\right)$$

Reference depth H_0: precludes high variations of depth

What is the cost for these extra-terms

- CPU time
- Numerical properties

What model shall we use?

Serre equations

$$W(z) = \frac{dZ_f}{dt} + \frac{(z - Z_f)}{h}\left(\frac{dh}{dt}\right)$$

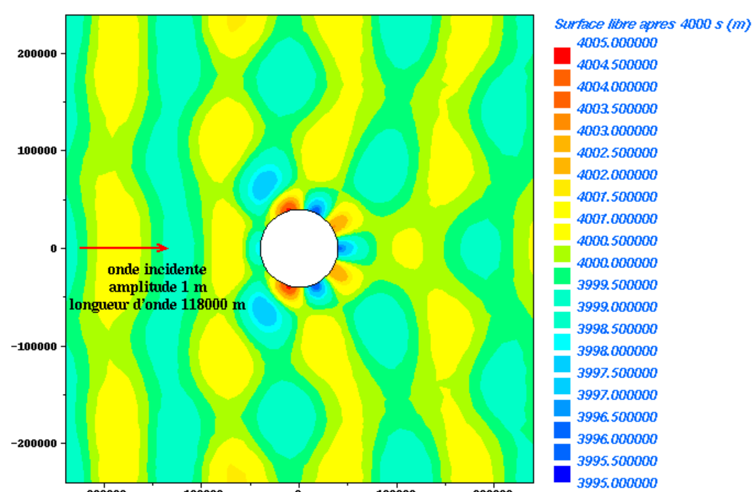
$$\frac{1}{\rho}\frac{\partial p}{\partial z} = -g - \frac{dW}{dt}$$

Extra terms in the Saint-Venant momentum equation

$$\frac{d\vec{u}}{dt} = ... - h\,\overrightarrow{grad}\left(\frac{\alpha}{3} + \frac{\beta}{2}\right) - \left(\frac{\alpha}{2} + \beta\right)\overrightarrow{grad}(Z_s) - \frac{\alpha}{6}\,\overrightarrow{grad}(h)$$

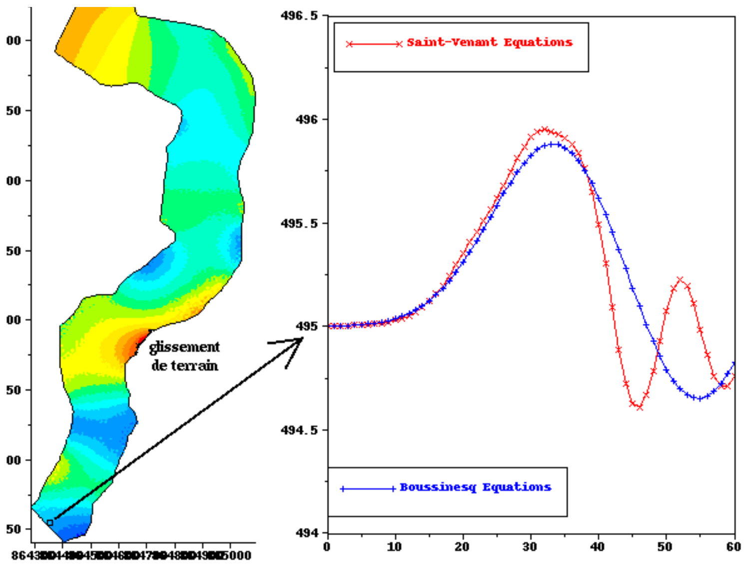
$$\alpha = \frac{d^2 h}{dt^2} \qquad \beta = \frac{d^2 Z_f}{dt^2}$$

Island with a parabolic bottom, Boussinesq equations

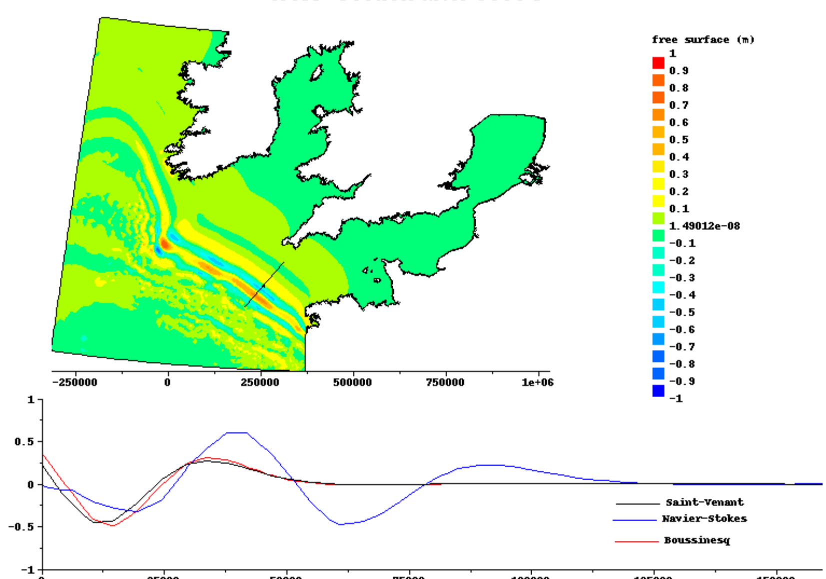


CHANGER L'ÉNERGIE ENSEMBLE

Waves due to a landslide. Comparing Boussinesq and Saint-Venant equations

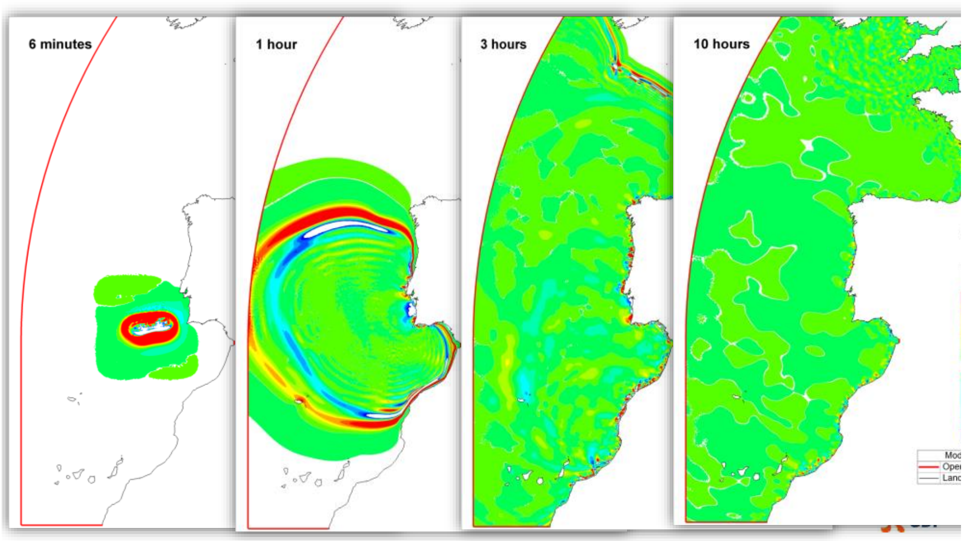


Lisbon tsunami in 1755
Comparison of Navier–Stokes, Boussinesq and Saint–Venant equations
cross–section after 8000 s



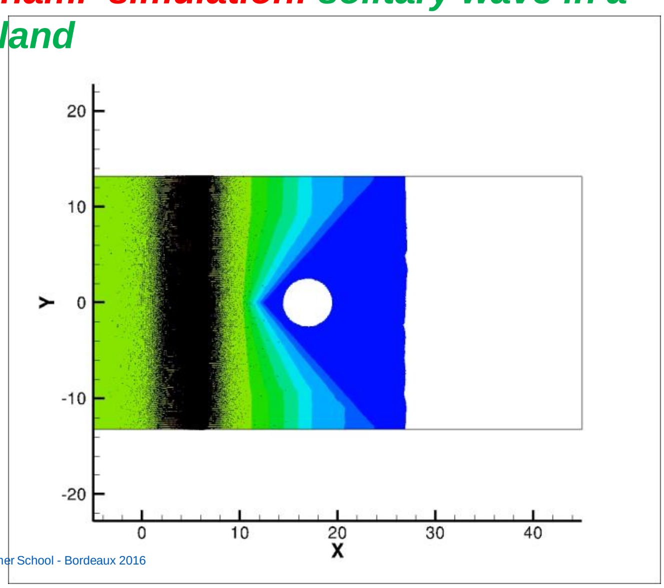
Some examples

Tsunami simulation: Lisbon Tsunami



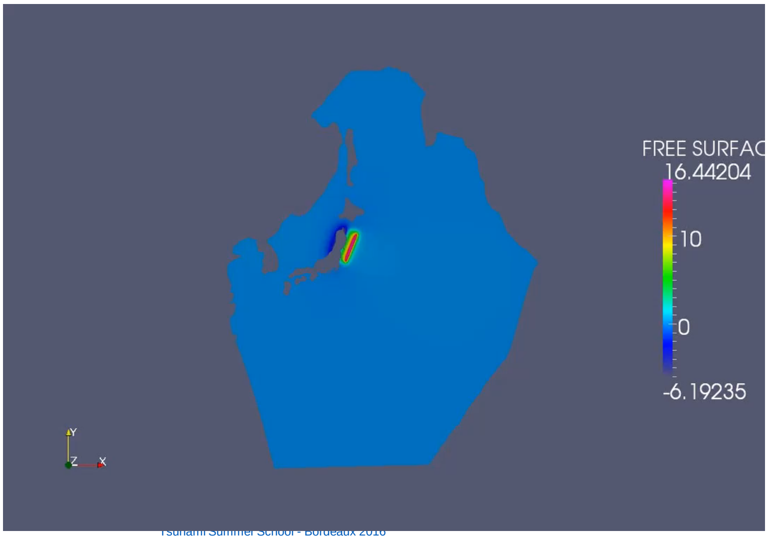
Tandem Benchmarks

Laboratory Tsunami simulation: solitary wave in a shelf with an island



Tandem Benchmarks

Tohoku Tsunami (M. Le Gal PhD)



NUMERICAL ISSUES FOR PRACTICAL STUDIES

Numerical issues

- **Assumptions validity**
- **Dispersive effects (for propagation),**
- **Computational cost**
- **Breaking or not (physical /numerical)**
- **Calibration issues**
- **What to include in the model ?**

Numerical issues: assumptions validity

- Continuum (breaking, sloshing, gas-liquid mixture,…)

Numerical issues: assumptions validity

- continuum
- Shallow water assumptions (for deep regions)

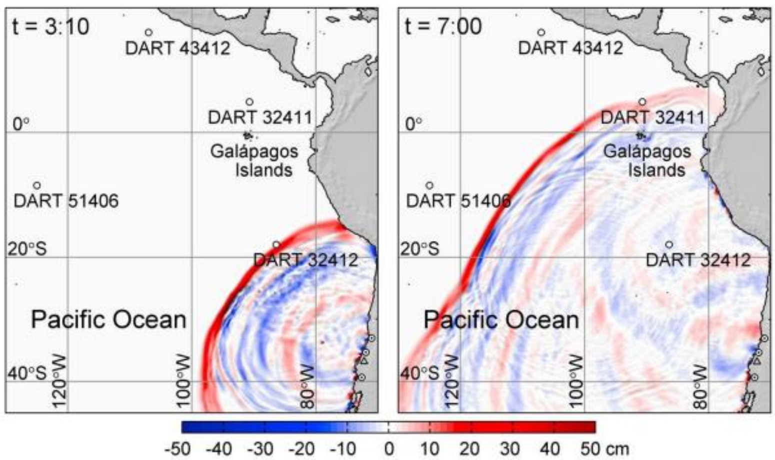


Figure 1.2: Snapshots of modelled surface elevation. Triangle indicates Talcahuano and circle-dots indicate Valparaiso, Constitución, and Tolten from north to south (Yamazaki & Cheung, 2011).

Numerical issues: assumptions validity

- Shallow water assumptions (for deep regions)
- Dispersive 2DH models: Representative reference H_0 water depth and wavelegth λ

$$\bar{u}_t + \eta_x + \alpha \bar{u}\bar{u}_x - \epsilon[\frac{h}{2}(h\bar{u})_{xxt} - \frac{h^2}{6}\bar{u}_{xxt}] + O(\epsilon^2, \alpha\epsilon) = 0$$

$$\eta_t + (h\bar{u})_x + \alpha(\eta\bar{u})_x = 0$$

  - Not trivial for shallow areas
  - Not trivial for highly varying bathymetry

Numerical issues: assumptions validity

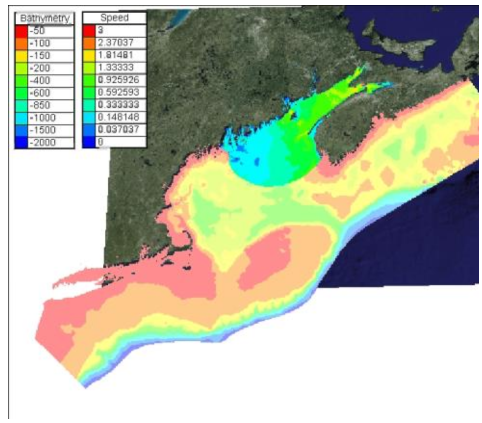
- Shallow water assumptions (for deep regions)
- Dispersive models: Representative reference H_0 water depth and wavelegth λ
- Potential models:
  - Inviscid fluid ➔less valid near the shore
  - Irrotational flow (curl(u)=0) ➔ restrictive hypothesis
  - Linear theory ➔ limited to small steepness, small relative depths
  - Nonlinear theory: ongoing improvements (talks of D. Lannes and M. Benoît)
  - Elliptic behaving ➔ issues with BC

Numerical issues: assumptions validity

- Shallow water assumptions (for deep regions)
- Continuum (breaking, sloshing, gas-liquid mexture,…)
- Potential theory
- Newtonian fluid

Numerical issues: assumptions validity

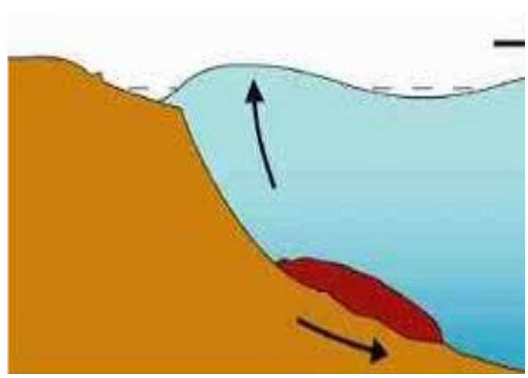
- Shallow water assumptions (for deep regions)
- Continuum (breaking, sloshing, gas-liquid mexture,…)
- Potential theory
- Newtonian fluid,
- Multiphysics aspects (tide, atmospheric pressure, wind, vegetation, debris,…)



Courtesy of the CHC

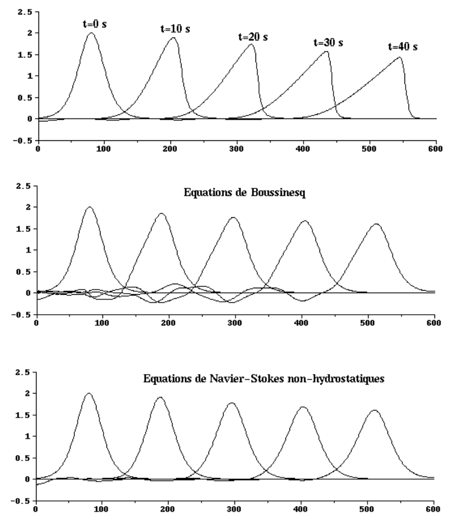
Numerical issues: assumptions validity

- Continuum (breaking, sloshing, gas-liquid mexture,…)
- Potential theory
- Newtonian fluid,
- Multiphysics aspects (tide, atmospheric pressure, wind, vegetation, debris,…)
- **Rigid (undeformable) bed**
    - Unphysical coupling
    - DT << eps
    - Sub-iterations $$$
    - Implicitness ?



Numerical issues : dispersion

- **Dispersive effects (for propagation),**
- **Numerical dispersion: is it physical ?)**
  - Wave arrival time
  - Wave arrival height
- **Breaking or not (physical /numerical)**



Hervouet (2007)

Numerical issues : what schemes

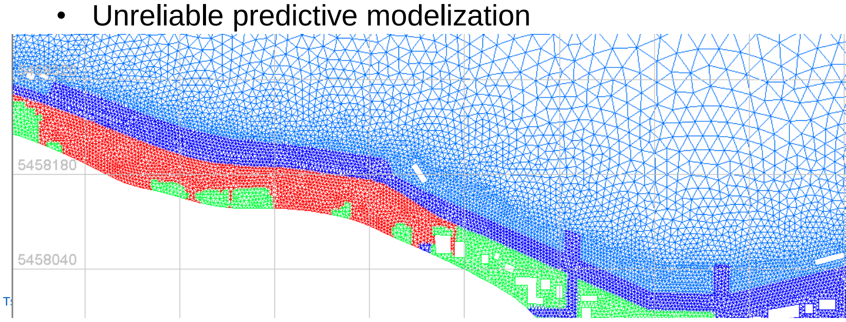
- **Good numerical properties are necessary for the flooding event simulations (talk of A. Durand):**
  - **No need for high order**
  - **Well-balaceness**
  - **Stability - positivity of water depth**
  - **Wet/dry – dry/wet transitions**
  - **Steep bathymetry gradient**
  - **Good implementation of the bed friction effects**

Numerical issues : what schemes

- **Good numerical properties are necesary for the propagation:**
  - **absolute need for high order**
  - **At least accurate and with low diffusion**
  - **Implicit time discretization**
  - **Stability - positivity of water depth**
  - **Dispersion**

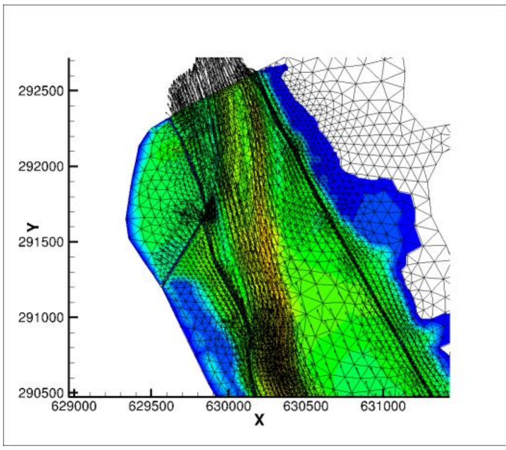
Numerical issues: calibration

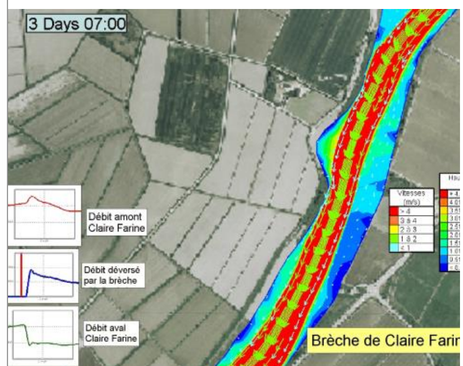
- **Calibration issues**
  - Especially for urbain flows (storm surge, non extendable for tsunami)
  - Lack of data for calibration
  - Evolution of urbain areas ➔ calibration stands for short period of time
  - Unreliable predictive modelization



Numerical issues: sediment management

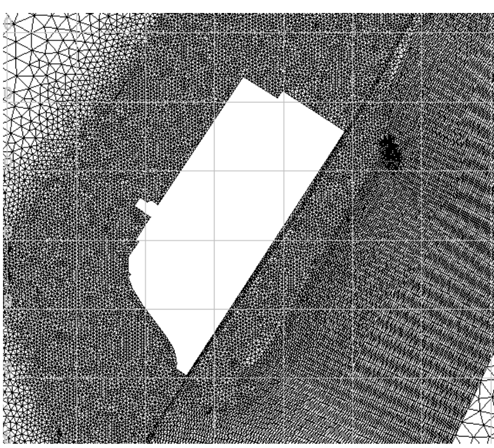
Dyke Breaching –sediment managing

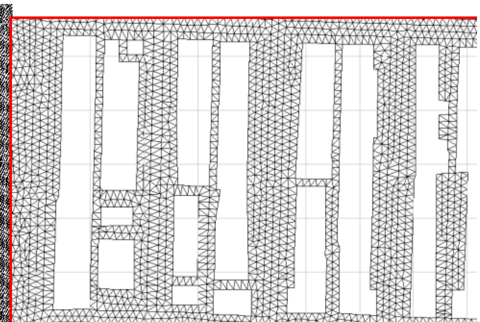




Numerical issues: model characteristics

- **What to include in the mesh : everything ?**





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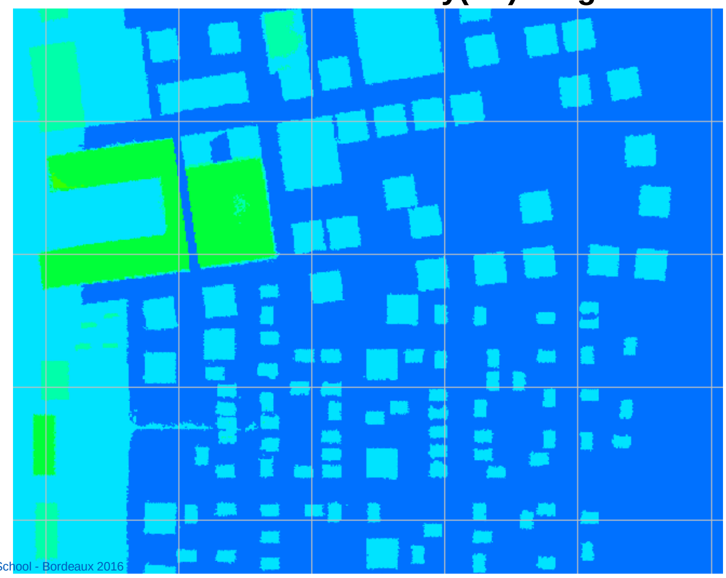
Numerical issues: model characteristics

- What to include in the model: every(no)thing ?



Numerical issues: model characteristics

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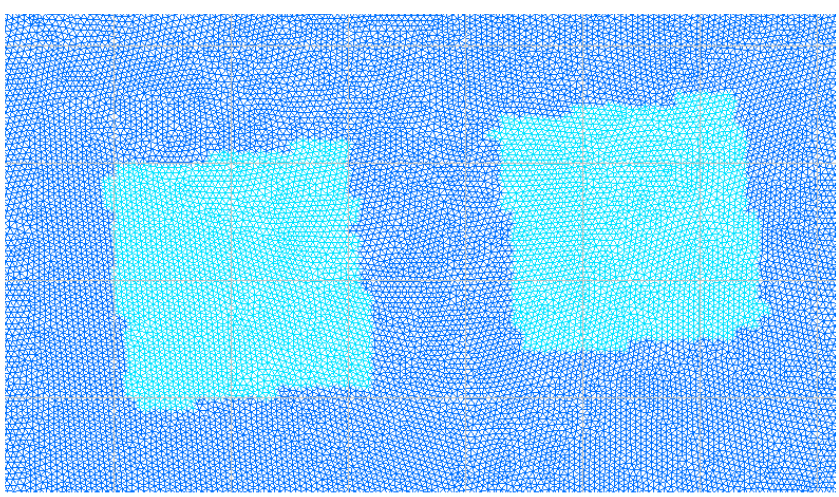
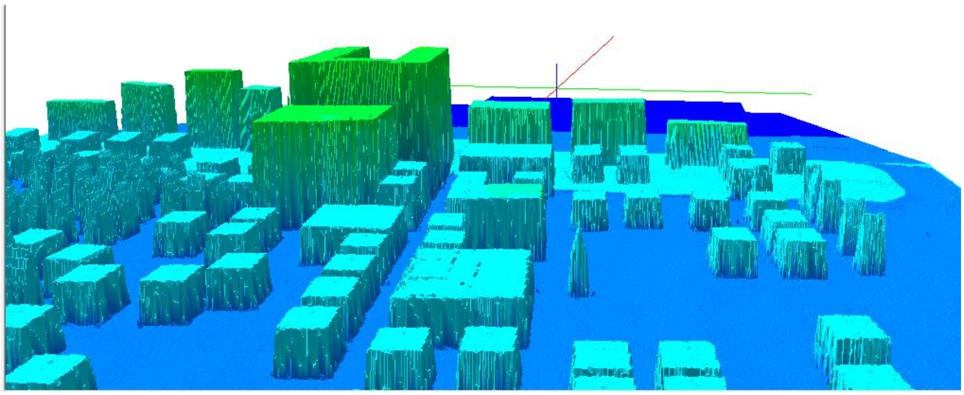


cf. Rodrigo talk

Numerical issues: model characteristics

- **interpolation issues: vertical walls, dykes, breakwater,…**



Numerical issues: model characteristics

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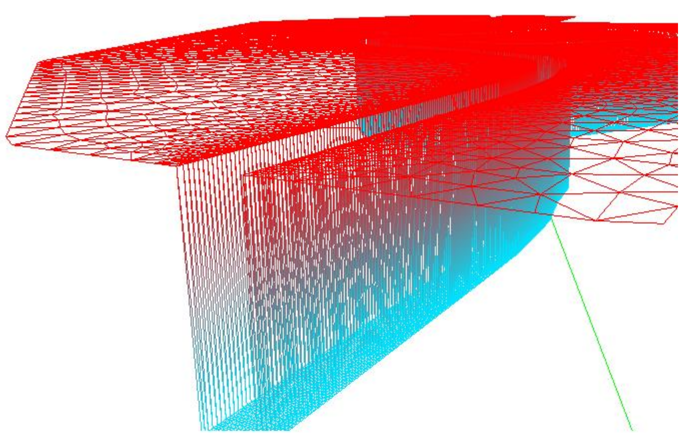
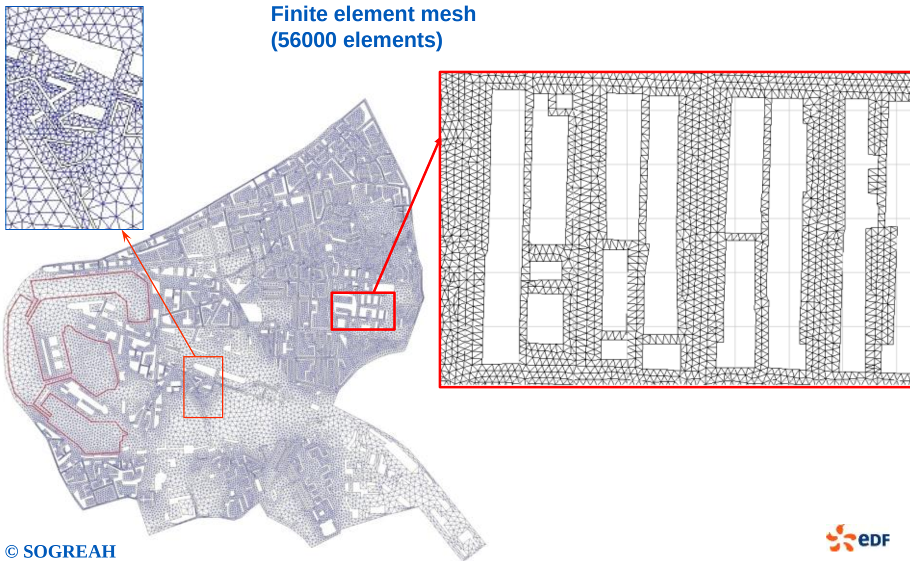


Numerical issues: model characteristics

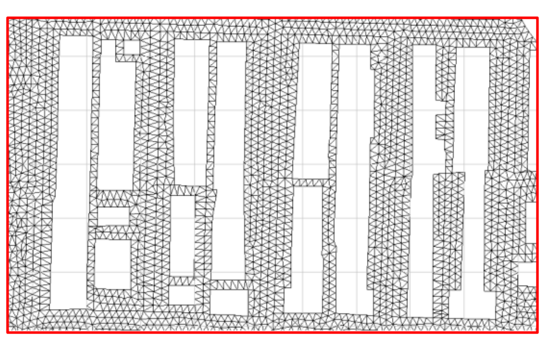
- **Refine urbain area (avoid over-constrained elements)**



Numerical issues: model characteristics

Refine the mesh – include everything

- **60% of Engineer time is for preprocessing**
- **Up to 80% for urbain models**



Numerical issues: model characteristics

How to avoid these awful tasks:

Porosity: Taking into account the volume of small obstacles that cannot be represented in a mesh

$$\frac{\partial(\theta h)}{\partial t} + div(\theta h\vec{u}) = 0$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -g\frac{\partial Z_s}{\partial x} + F_x + \frac{1}{h\theta}div(h\theta\nu_e\, grad(u))$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -g\frac{\partial Z_s}{\partial y} + F_y + \frac{1}{h\theta}div(h\theta\nu_e\, grad(v))$$

Numerical issues: model characteristics

How to avoid these awful tasks:

Drag force: Taking into account the drag effect of small obstacles that cannot be represented in a mesh

$$\vec{F} = -\frac{n}{A}\frac{D}{2}C_D\left\|\vec{U}\right\|\vec{U}$$

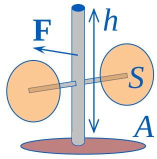
For n obstacles of diameter D spread on a area A

With a drag coefficient C_D

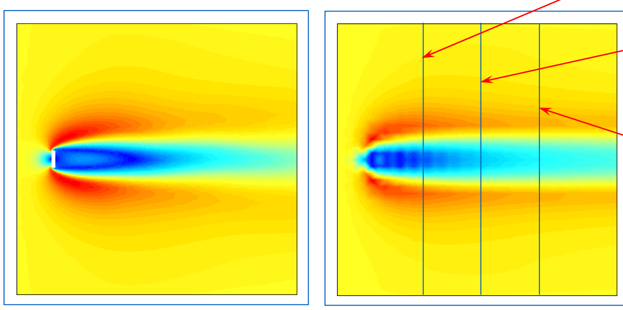
Numerical issues: model characteristics

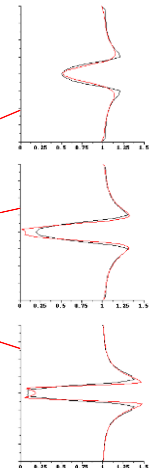
Taking into account drag forces (cf. Talk of BRGM)

Sink term for submerged structures (e.g. turbines) :

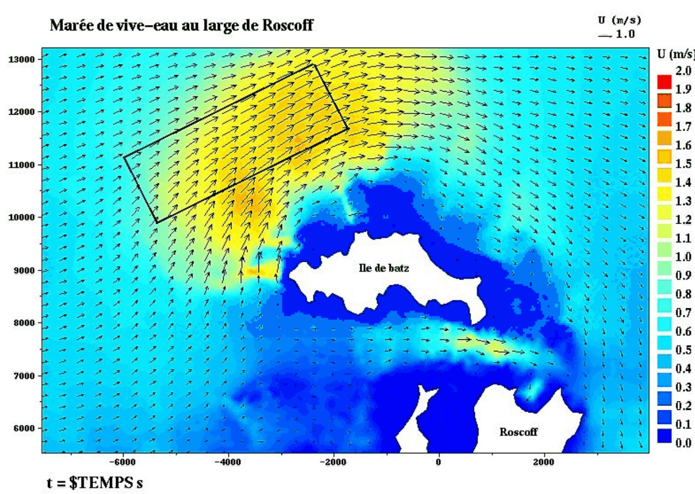


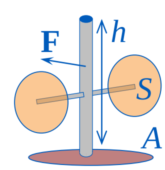
$$\mathbf{F}_{Stuctures} = -\frac{\tau}{\rho h} = -\frac{S}{2hA} C_D |\mathbf{U}|\mathbf{U}$$





Modelling marine current turbines





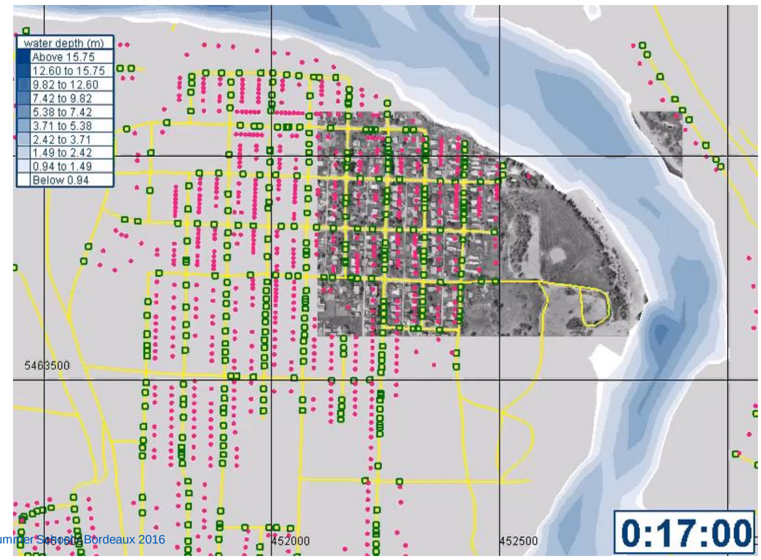
Sink term for submerged structures (e.g. turbines) :

$$\mathbf{F}_{Stuctures} = -\frac{\tau}{\rho h} = -\frac{S}{2hA} C_D |\mathbf{U}|\mathbf{U}$$

R. ATA - Kyoto university - November 2015

Numerical issues

- **What to include in the model ?**



NUMERICAL ISSUES: FOCUS ON TIDAL FLATS

Tidal flats for FV

Hydrostatic reconstruction: Audusse et al. (2004) Noelle et al. (2016)

- Well-balaceness:
- Positivity ensuring
- wetting/drying transition

Drawbacks: not accurate for some extreme cases

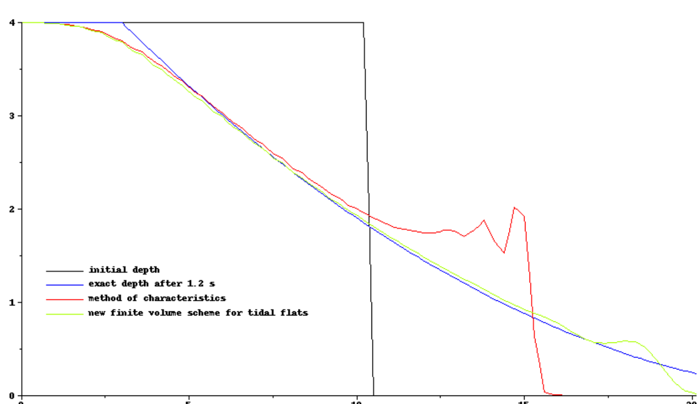
See talk of A. Durand

Tidal flats for FE

Problem 1:
propagation on dry zone (wetting)

Comparing advection solvers on the 1D dam break test case

advection of velocities: method of characteristics versus new finite volumes scheme for tidal flats



Tidal flats for FE

Problem 2: receding waters

Saint-Venant

Hydrostatic Navier-Stokes

Non-hydrostatic Navier-Stokes

Water at rest all equations

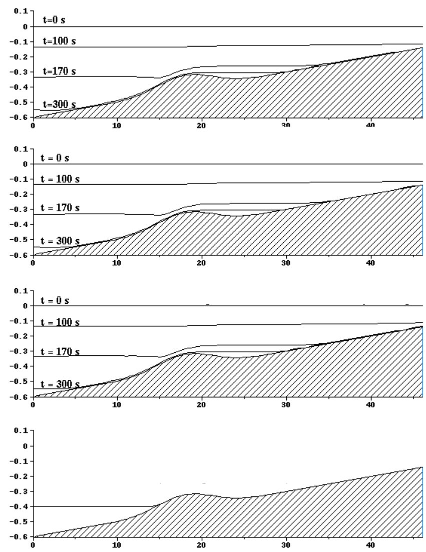
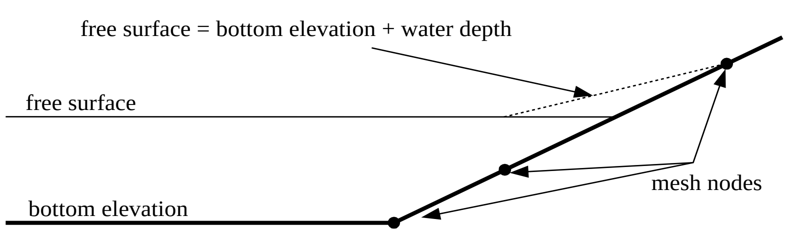


Figure 12

Tidal flats for FE

Problem 3: A lake at rest



Linear interpolation of free surface leads to spurious movements in the lake

➔ Standard discretisation fails

Tidal flats for FE

Problem 4: negative depths in numerical solutions

Continuity equation: $$\frac{\partial h}{\partial t} + div(h\vec{u}) = 0$$

In finite elements: $\frac{\partial h}{\partial t}$ becomes $M\frac{h^{n+1} - h^{n}}{\Delta t}$

In finite volumes: $\frac{\partial h}{\partial t}$ becomes $S_i\frac{h_i^{n+1} - h_i^{n}}{\Delta t}$

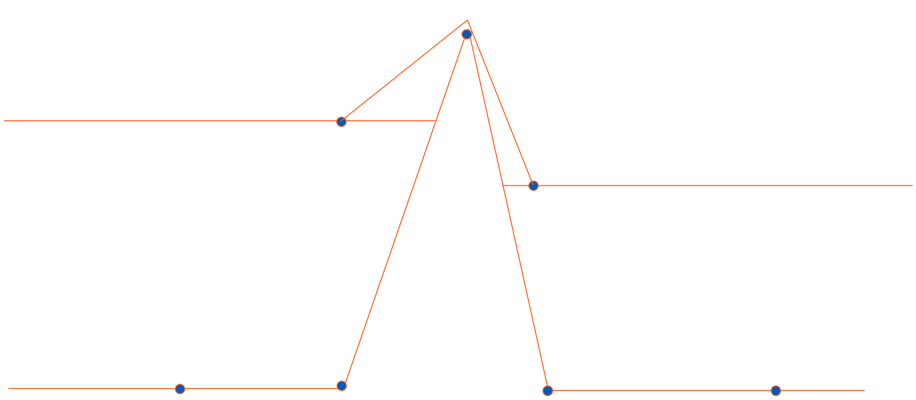
But: $div(h\vec{u})$ treated as: $div(h^n\left[\theta\vec{u}^{n+1} + (1-\theta)\vec{u}^{n}\right])$

$$\int_\Omega \Psi div(h^n\vec{u})d\Omega = \int_\Gamma h^n\vec{u}.\vec{n}\,d\Gamma - \int_\Omega h^n\vec{u}.\overrightarrow{grad}(\Psi)d\Omega$$

Boundary flux — Internal flux

Tidal flats for FE

Problem 5: Numerical pump for loosely refined dykes

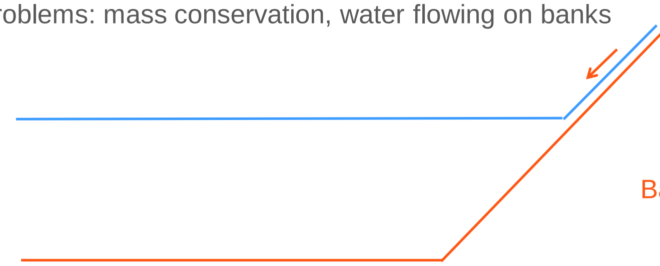


Tidal flats for FE

Available solutions:

Solution 1: Clipping+use of minimum depth

If h < hmin then h=hmin
Problems: mass conservation, water flowing on banks



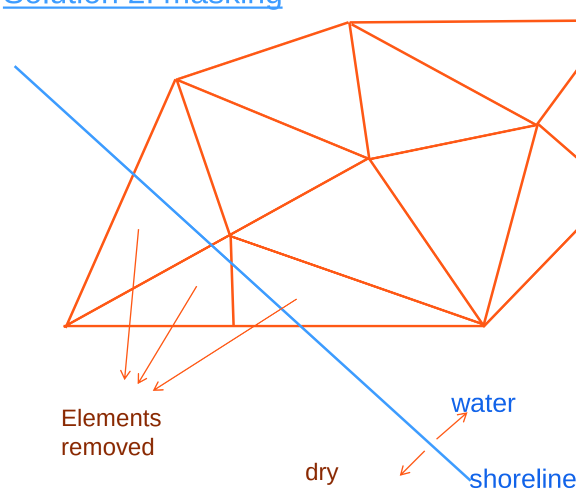
Bad Solution !

Keywords: H CLIPPING, MINIMUM DEPTH

Tidal flats for FE

Available solutions:

Solution 2: masking



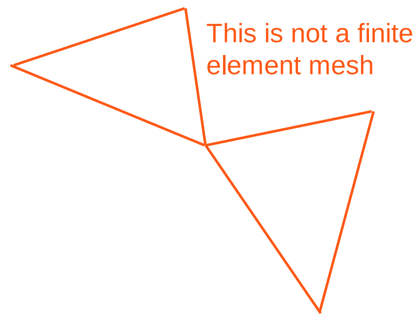
But how to find the shoreline, with hmin ???

not too good !!

Tidal flats for FE

Solution 2: masking (Cont'd)

1) Criterion for removing an element (hmin ??)
2) Criterion for putting back an element (celerity of flood waves)
3) Topology of finite element meshes
4) Book-keeping of water and tracers remaining in removed elements

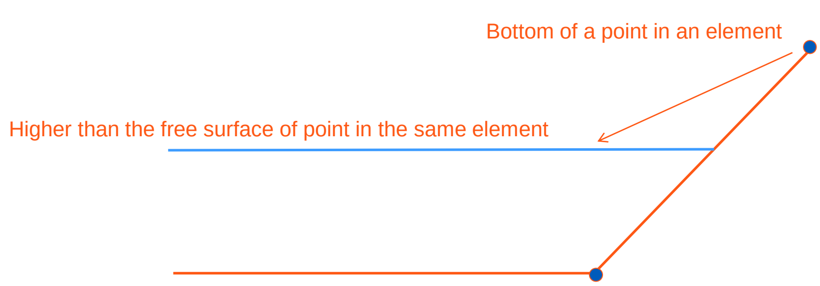


Can be envisaged for steady state flows or slowly varying free surfaces (OPTION FOR THE TREATMENT OF TIDAL FLATS: 2)

Tidal flats for FE

Solution 3: Free surface gradient correction

Main problem of dry zones: their wrong free surface gradient

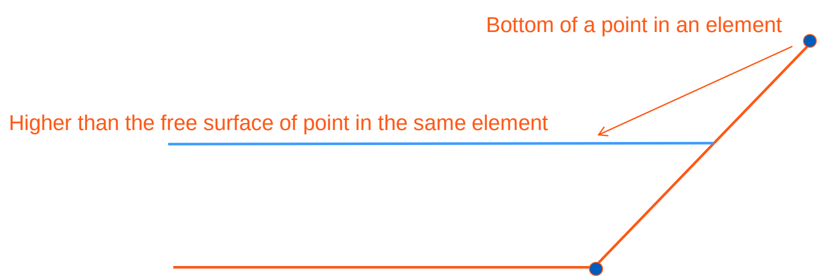


Step 1: identifying elements with tidal flats problems
Those where a bottom is higher than a free surface

Tidal flats for FE

Solution 3: Free surface gradient correction

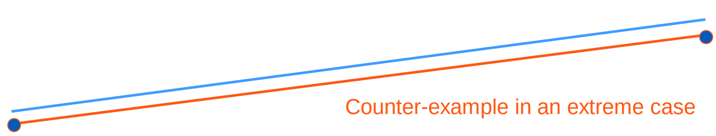
Main problem of dry zones: their wrong free surface gradient



Tidal flats for FE

Solution 3: Free surface gradient correction

Main problem of dry zones: their wrong free surface gradient

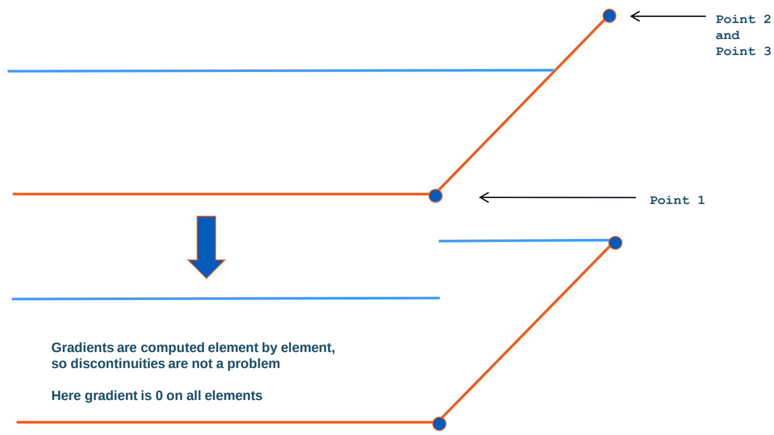


Tidal flats for FE

Solution 3: Free surface gradient correction

free surface gradient are piece-wise constant on elements

Idea: correcting free surface on every element, it becomes piece-wise linear:



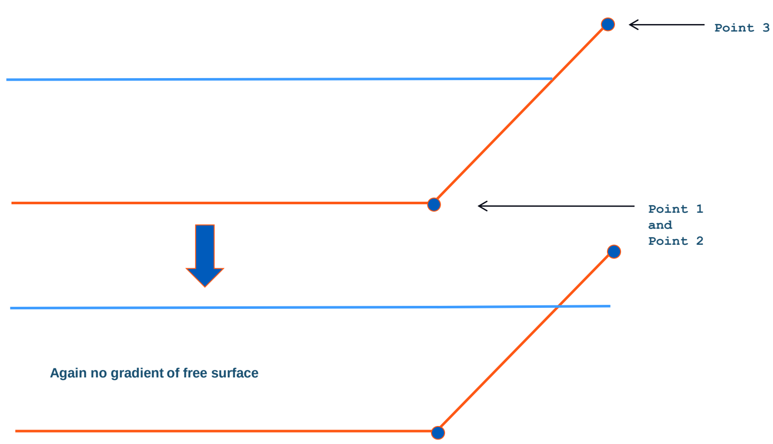
Step 2: correct free surface gradient : case where 2 points are dry

Tidal flats for FE

Solution 3: Free surface gradient correction

free surface gradient are piece-wise constant on elements

Idea: correcting free surface on every element, it becomes piece-wise linear:



Step 2: correct free surface gradient : case where 1 node is dry

Dealing with negative depths

Negative depths are not a problem for mass conservation (as soon as continuity is solved) and can be kept in a computation, but they must remain small.
They don't if not treated specifically.

In all cases, the continuity equation must be corrected:

$$\frac{\partial h}{\partial t} + div(\max(h,0)\vec{u}) = 0$$

Specific treatment: two options

TREATMENT OF NEGATIVE DEPTHS: 2

Continuity equation is solved by a specific edge-based algorithm that keeps depths positive (this is another lecture in itself)

TREATMENT OF NEGATIVE DEPTHS: 1

Negative depths are smoothed

Friction in Saint-Venant

Bottom stress in Navier-Stokes equations: $\frac{1}{\rho}\underline{\tau}_f.\vec{n}_f$

Stress computed with horizontal velocity: $\tau_f = -\frac{1}{2}\rho C_f \|\vec{u}\|^2$

Chézy law (for non conservative form)

$$\vec{F} = -\frac{1}{\cos(\alpha)}\frac{g}{hC^2}\sqrt{u^2+v^2}\vec{u} \qquad C = \sqrt{\frac{2g}{C_f}}$$

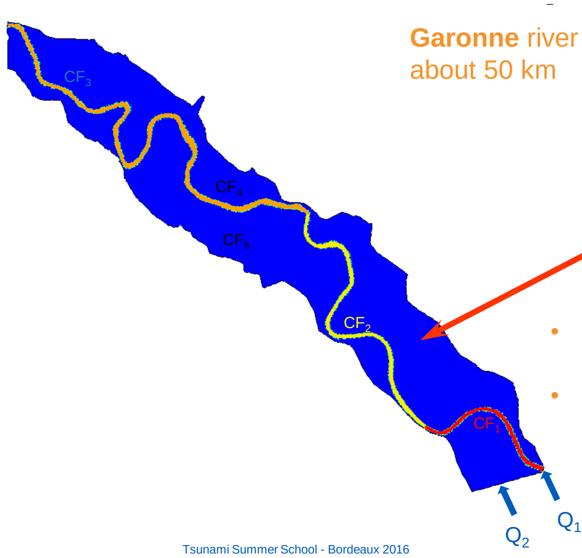
Strickler law (for non conservative form)

$$\vec{F} = -\frac{1}{\cos(\alpha)}\frac{g}{h^{4/3}K^2}\sqrt{u^2+v^2}\vec{u} \qquad C = KR_h^{1/6}$$

Cos(α) : cosinus of slope

And … What Else ?

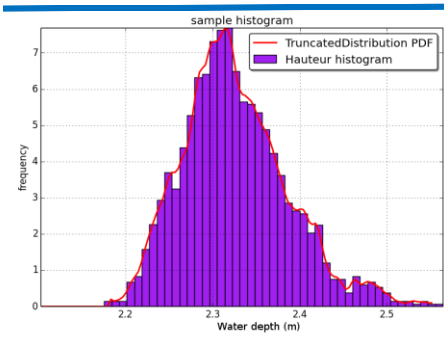
Uncertainty Quantification



Garonne river
about 50 km

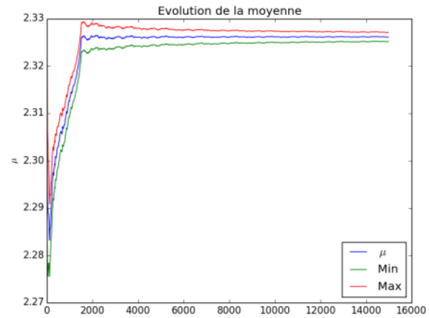
- **15000 serial runs 24h CPU**
- **Mesh with 54 000 nodes**

Uncertainty Quantification

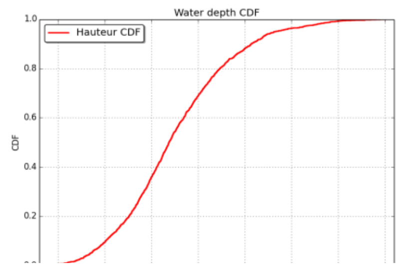


Empirical PDF abtained with
15000 runs

x



Convergence and 5% confidence of
estimated mean



Empirical CDF obtained wit
15000 runs

Codes coupling

Multiphysics coupling

- waves-hydrodynamics (internal)
- Sediment –hydrodynamics (internal)
- Water Quality – hydrodynamics (internal)
- groundwater flows – hydrodynamics (internal – ongoing)
- wave – sediment - hydrodynamics (internal – ongoing)
- hydrology – hydrodynamics – sediment (ongoing)
- hydrology – hydrodynamics – WAQ (ongoing)

Multi-dimensions coupling

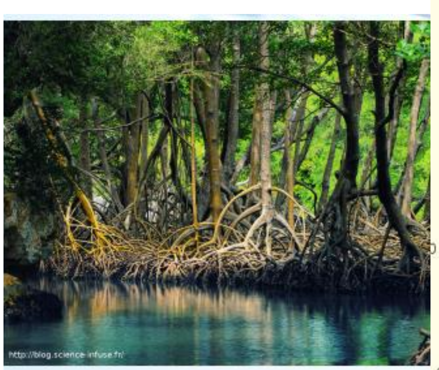
- Through SALOME and PALM coupling platforms
- 1D-2D longitudinal
- 1D-2D transversal
- 2D-3D SWE-NS
- 0D-1D hydrology-hydraulics

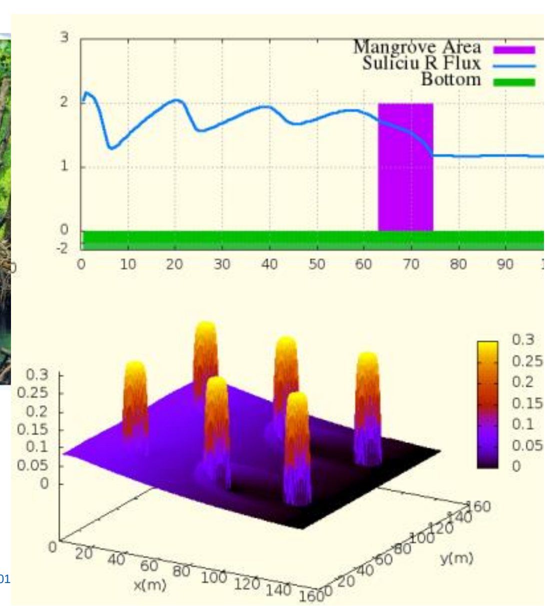
But the question is …

Are we safe?

Of course YES !

With mangrove we can be safer





Koh et al. (2009); Gunawan et al. (2014)

Thank you for your time