Coastal impact of a tsunami
Review of numerical models

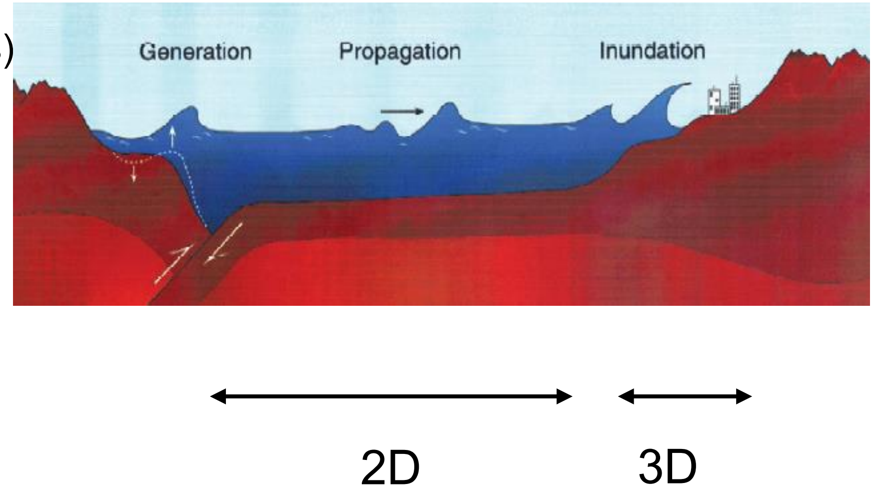
Richard Marcer

Content

- **Physics to simulate**
- **Different approaches of modelling**
  - **2D depth average**
  - **Full 3D Navier-Stokes**
- **3D model**
  - **Key point : free surface simulation**
  - **Loads on structures**
- **Synthesis on the validity domain of the different approaches**

Coastal impact of a tsunami

- **Complex physics**
  - ⇒ **From 2D large scale (including source) to 3D local scale problem**
  - **Shoaling, refraction, up to breaking**
  - **Breaking**
    - Two-phase flow with interface
    - Entrapped air pockets
    - Emulsion (mixing of water and bubbles)
    - Turbulence
  - **Runup, Flooding**
    - Friction on bottom, roughness
  - **Fluid / structure interactions**
    - Hydrodynamic loads on structures
    - Possible collapse of the structures
    - Debris moving in the flow



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2D depth average models

- **Saint-Venant (Non linear shallow water)**

$$\frac{\partial \xi}{\partial t} + \nabla.\left((\xi + h)\bar{u}\right) = 0$$
$$\frac{\partial \bar{u}}{\partial t} + \bar{u}.\nabla\bar{u} + g\nabla\xi = 0$$
$$P = \rho g(\xi - z)$$

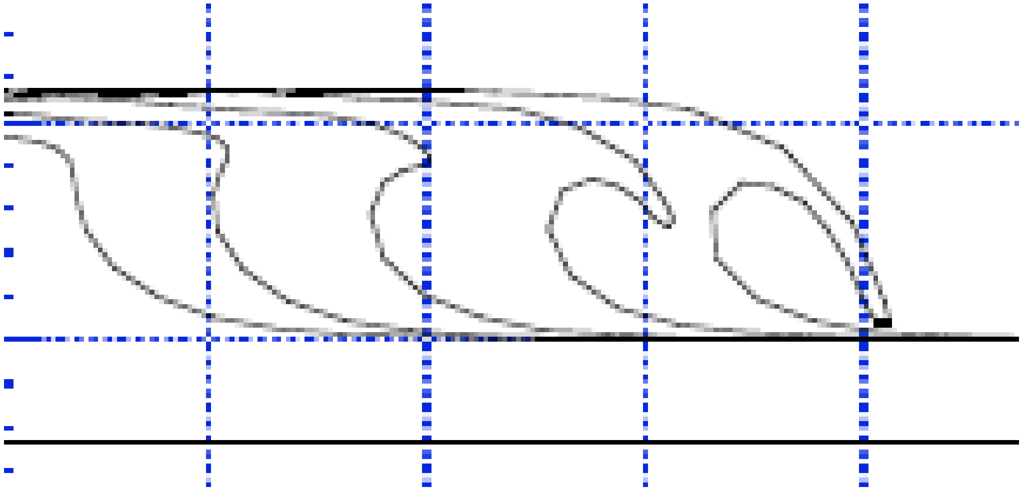
$\bar{u}$: mean velocity
ξ: wave elevation

  - **Shallow water (h<<λ) and non dispersive**
  - **Hydrostatic flow and constant horizontal velocity in water depth**
  - **Friction model at the sea bottom (Chezy, Manning coefficients)**
  - **Breaking**
    - Quite good for energy dissipation
    - But free surface not well represented
  - **Low CPU time consuming**

- **Boussinesq**
  - **Dispersive**
  - **Non hydrostatic**

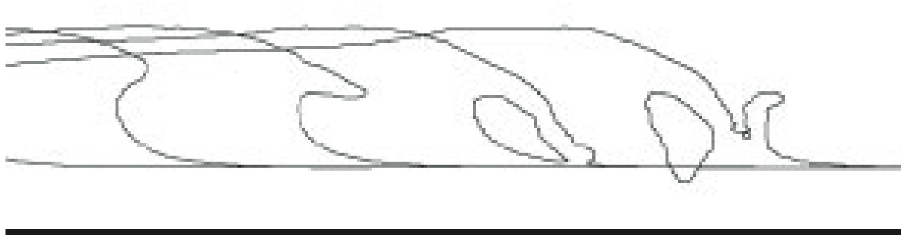
BIEM model

- **Boundary Integral Element Method (BIEM)**
  - **Perfect fluid**
  - **Irrotational**
  - **Very accurate for shoaling up to breaking**
  - **No valid after breaking (large deformation of FS, reconnection, vorticity)**



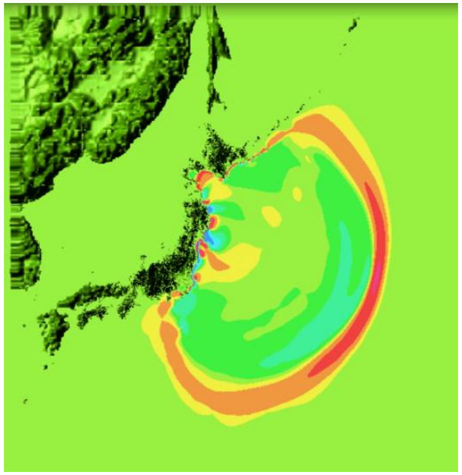
Navier-Stokes models

- **Navier-Stokes 3D**
  - **Highest validity domain**
  - **Viscous, rotational, turbulence**
  - **Able to simulate all the breaking process**
  - **Loads on structures**
  - **But large CPU time consuming**

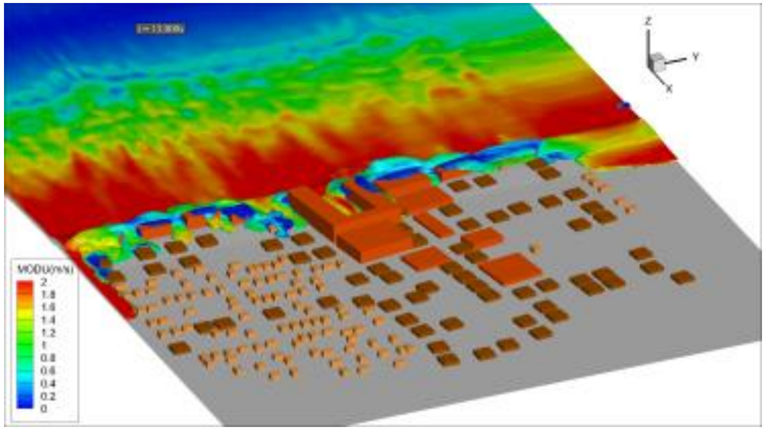


Examples of applications

- **2D depth average model of the Tohuku Tsunami in Japan (large scale)**



- **3D Navier-Stokes : tsunami impacting an urban area (local scale)**



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Focus on the Navier-Stokes model

- **System of equations (URANS)**

  - **Mass** $$\frac{\partial U_k}{\partial x_k} = 0$$

  - **Momentum (3)** $$\rho \frac{\partial U_i}{\partial t} + \rho U_j \frac{\partial U_i}{\partial x_j} = \rho g \delta_{i3} - \frac{\partial P}{\partial x_i} - \frac{\partial}{x_j}\left((\mu + \mu_t) \left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) \right)$$

+ free surface model

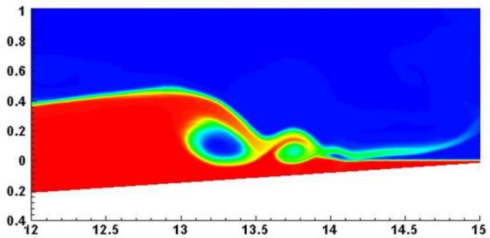
+ if necessary

- thermal / salinity equations

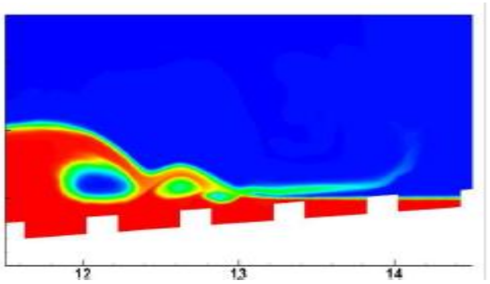
- state of the law : ρ=f(T,S)

Navier-Stokes model main characteristics /hypotheses

- **2-phase flow**
  - **Separated air/water phases (sharp interface)**
  - **But possible emulsion : bubbles and water mixture**
  - **Ideally including compressible air phase**



- **Free surface model : eulerian, lagrangian**
- **Turbulent**
  - **DNS / LES (much CPU consuming)**
  - **RANS (k-ε, k-ω,…): the most widely used**
    - Reynolds tensor $\rightarrow \mu_t$ turbulent coefficient diffusion
    - Boundary layer model
      - logarithm law of the wall (high Reynolds model)



- **Roughness**
  - **Macro: buildings, breakwaters,…**
  - **Micro:**
    - Bottom friction (roughness coefficient ks in boundary layer model)
    - Porosity of the media (pressure loss)

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Free surface models for Navier-Stokes

- **Interface tracking**
  - **Deforming mesh**

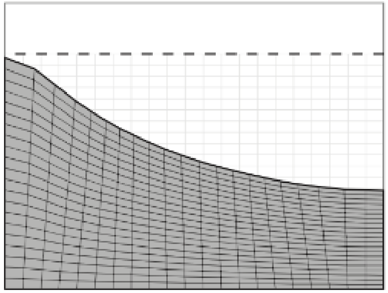


Figure 1. Interface tracking.

- **Interface capturing**
  - **Volume Of Fluid (VOF)**
  - **Level Set**
  - **Scalar color function**

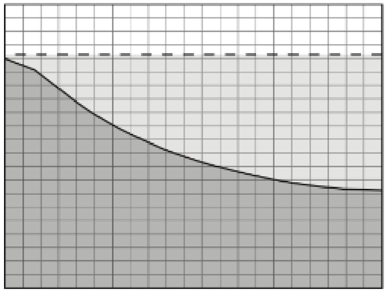
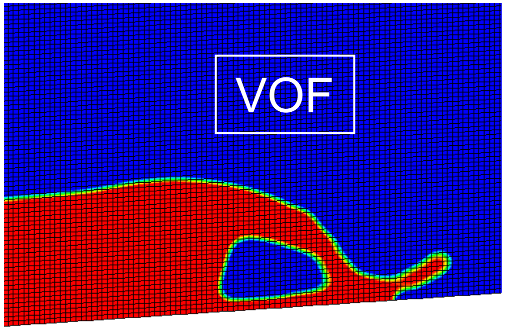
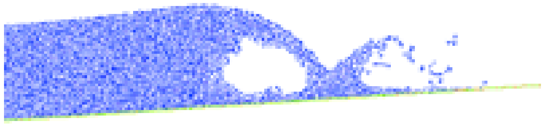


Figure 2. Interface capturing.



- **SPH**
  - **Lagrangian**

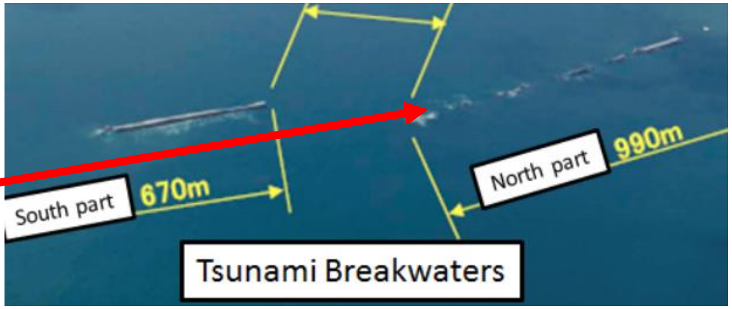


Free surface models – most commonly used

Model	Strenght	Weakness / difficulty
BIEM	Low numerical dissipation Accuracy	Not valid for breaking (when reconnection)
Front tracking	Interface directly followed Accuracy for quite small deformation	For large deformation of the interface
Level set	Easy interface reconstruction	Mass conservation Necessity to frequently reset level set function
VOF	Intrinsic mass conservation Well adapted for large deformation, break-up, reconnection	Possible loss of mass
SPH	Meshless Well adapted for large deformation Break-up, reconnection	Free surface conditions, viscosity / turbulence CPU and memory cost to reach a good accuracy

Wave impact on structures

- **Fixed structures (ex: breakwaters)**
  - Influence on the flow (reflection, diffraction, overtopping)
  - Possible collapse
  - Flowing debris

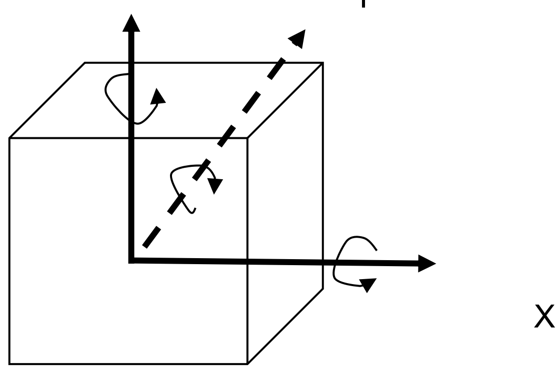


Kamaishi Bay (Japan)

- **Structures laid on the sea bed**
  - Possible motion
    - Sliding (balance frictional force / weight)
    - Capsizing

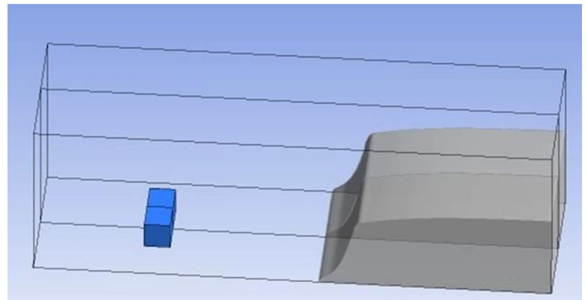
Loads on structures

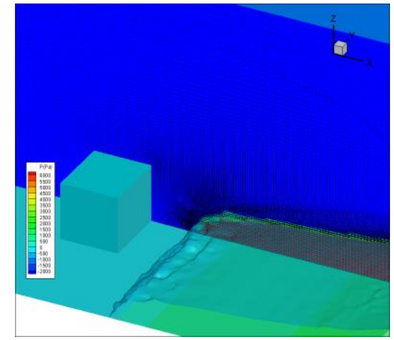
- **Loads**
  - 3D hydrodynamic loads (Navier-Stokes) applied on structure
  - Components of the total load
    - Translation (3)
    - Rotation (3)

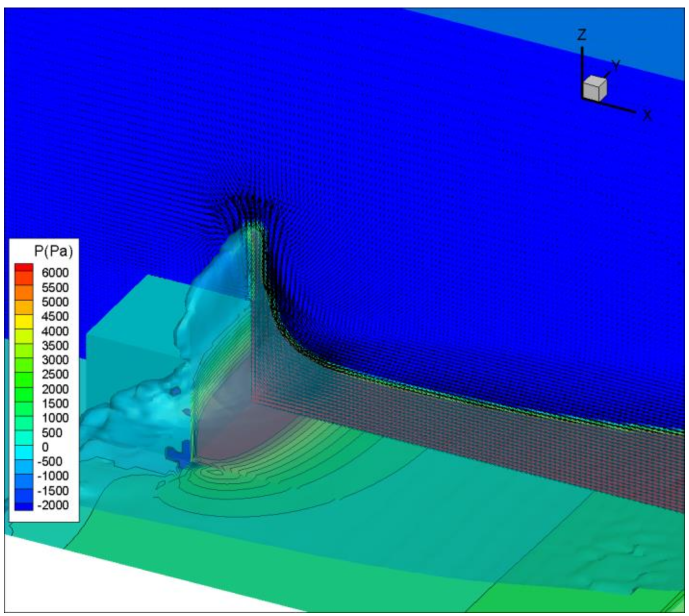


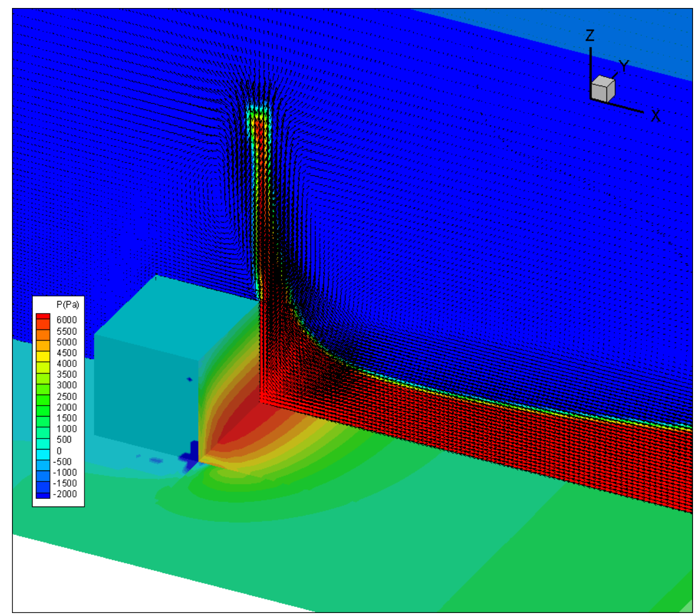
Loads on structures

- **3D hydrodynamic loads to compute**
  - **Dynamic pressure**
  - **Viscous**
  - **Hydrostatic**
  - **Buoyancy**



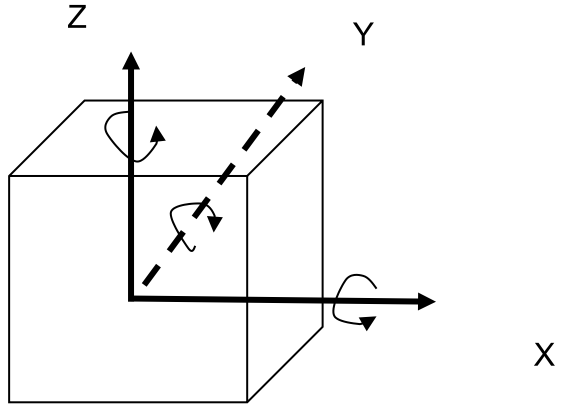






Wave impact on structures

- **Fluid / structure modelling**
  - Coupling Navier-Stokes / mechanical if structure in movement (ex. debris)
    - Acceleration / velocity / position of the structure issued from integration of the mechanic laws with hydrodynamic loads as forcing
    - 6 DOF (Degrees Of Freedom) motions

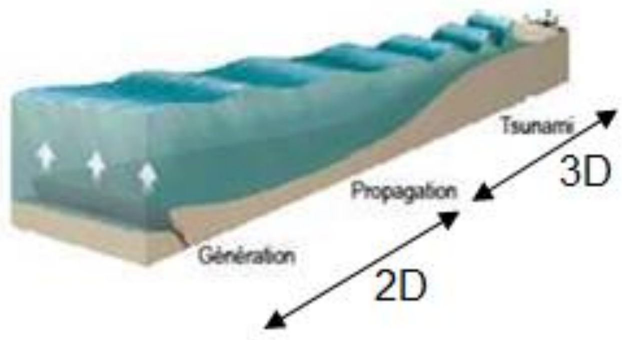


Synthesis - validity domain of the different models

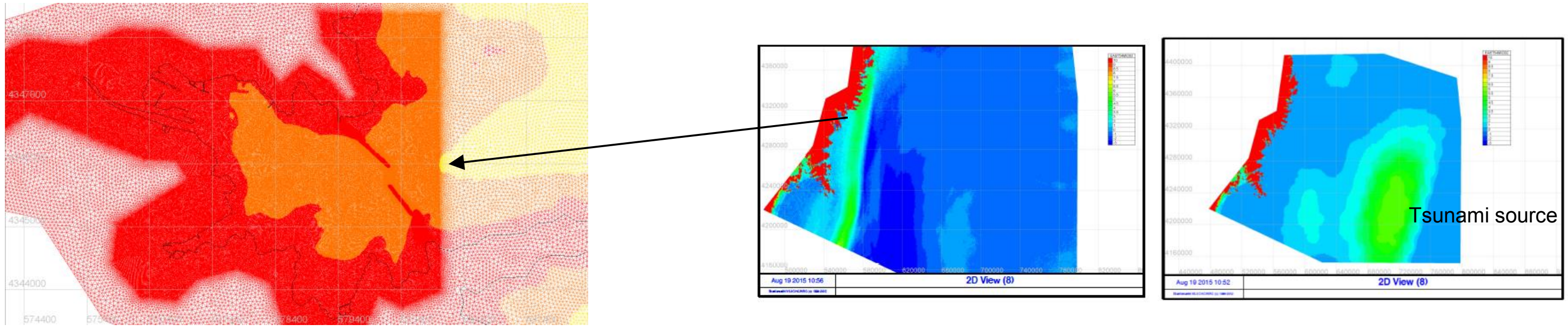
	Tsunami physics to model				
	Propagation	Breaking		Run-up / flooding	Loads on structures
Saint–Venant	possible	not relevant		possible	not relevant: Preliminary approximation
Boussinesq	appropriate	not relevant		possible	not relevant: Preliminary approximation
BIEM	appropriate	Before: appropriate	After: inappropriate	inappropriate	inappropriate
Navier-Stokes	not relevant	appropriate		appropriate	appropriate
Coupling 2D/3D	2D (or BEM): appropriate	3D: appropriate		3D: appropriate	3D: appropriate

dark green	appropriate
light green	possible
orange	not relevant
red	inappropriate

Going further with a 2D / 3D coupling



- **Direct calculation of the tsunami from generation up to coastal impact**
  - 2D propagation at large scale with depth average model
  - 3D impact at local scale with Navier-Stokes and using 2D model inputs (wave elevation and velocity)



3D local scale model of the Kamaishi Bay

2D large scale model of the Tohuku Tsunami

- **Remerciements**
  - **Kevin Pons (doctorant à Principia)**

Merci pour votre attention !