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Better understand the vulnerability of hydraulic structures

Julien CHAUCHAT

Chaire Oxalia/LEGI-ENSE3

August 28th 2024

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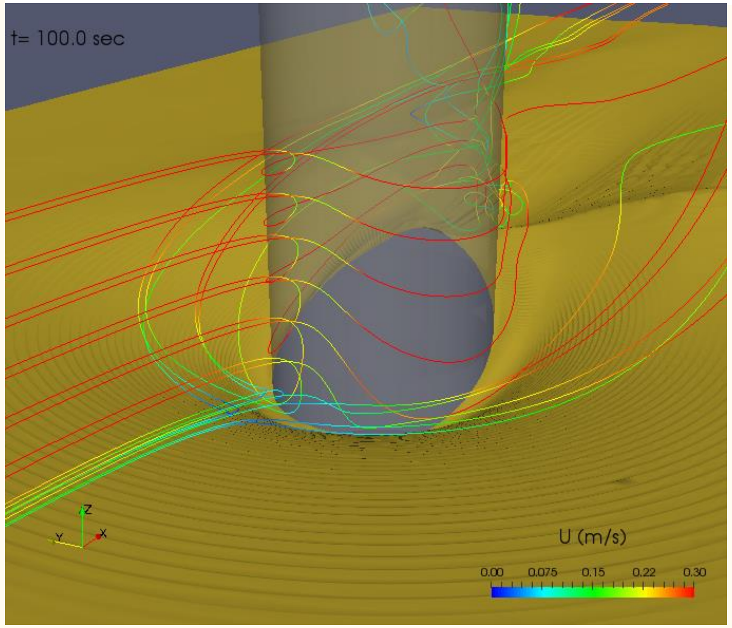
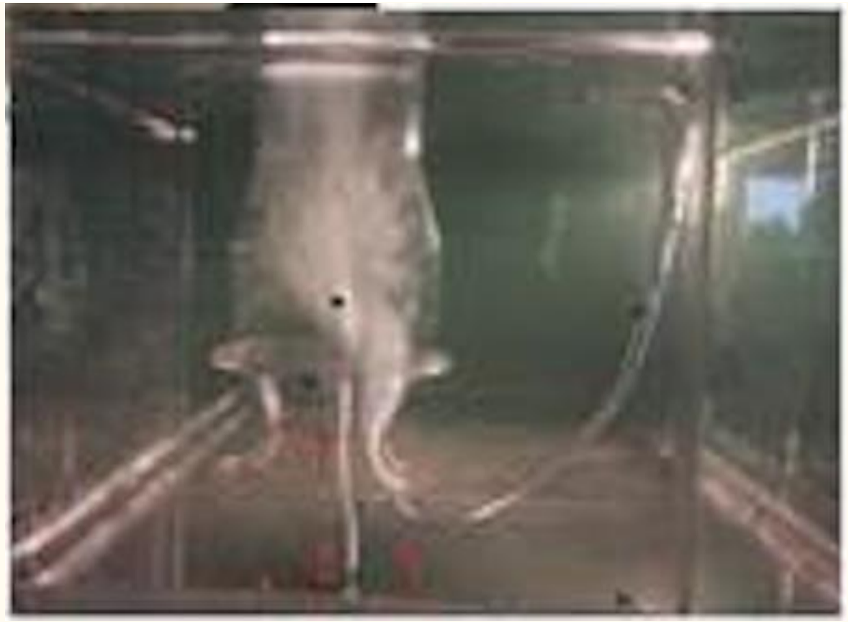
Chaire d'excellence industrielle sur les Ecoulements Hydrauliques Multiphasiques





Julien CHAUCHAT

LEGI / GINP-UGA / CNRS

30 juin 2022

Thématiques

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Ingénierie de l'environnement

- Affouillement
- Impact des dragages/envasement des retenues
- Génie urbain
- Recul du trait de côtes

Energie renouvelable

- Energie hydroélectrique
  - ✓ Hydraulique des barrages
  - ✓ Stations de pompage
- Implémentation Hydroliennes

3 thèmes prioritaires :

1. L'affouillement autour de structure / scour around hydraulic structures
2. L'évolution morphologique des zones côtières et des eaux intérieures
3. La modélisation des mélanges air-eau

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Scour around hydraulic structures: the main cause for bridge failures

Julien CHAUCHAT

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Outline

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- Motivations
- Analysis of recent bridge failure in the USA
- Flow and sediment transport processes
- Numerical modeling
- A case study: the bridge pile of the LGV Paris-Bordeaux
- Development of a new generation of numerical model for scour

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Motivations

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Collapse of one of the two RN1 bridges over the Saint-Etienne river during cyclone Gamède on Reunion Island, February 25, 2007.

Marine Renewable Energy

Arrival of the first four jackets for the future Saint Brieuc wind farm in the port of Brest

Analysis of recent bridge failure in the USA

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Table 4. Number of Principal Causes of Failure

Principal cause	Collapse	Distress
Design	2	1
Detailing	0	0
Construction	11	2
Maintenance	37	6
Material	4	2
External	415	5
Others (NA)	17	1
Total	486	17

Analysis of Recent Bridge Failures in the United States

Kumalasari Wardhana[1] and Fabian C. Hadipriono, P.E., F.ASCE[2]

Journal of Hydraulic Engineering 2003

Analysis of recent bridge failure in the USA

- 700,000 bridges in the United States (2002)

  ~ 500 failures between 1989 and 2000

- Age of collapsed bridges: 1 year - 157 years

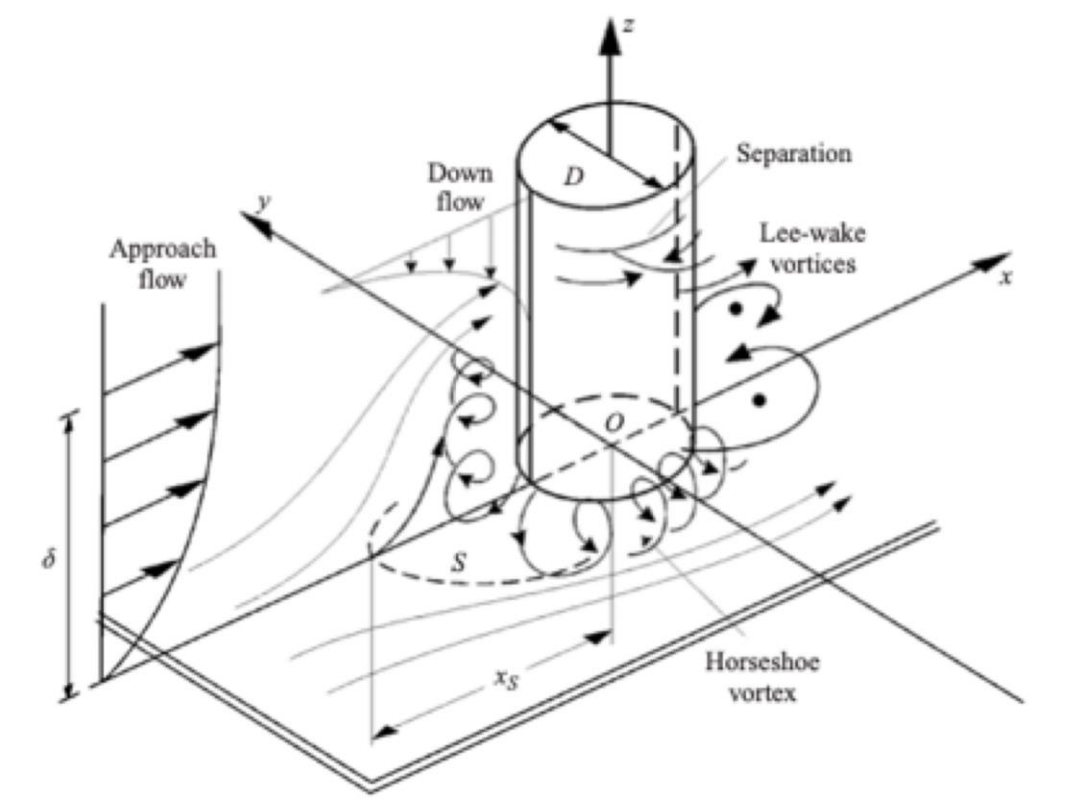
  Average lifetime = 52 years

- 2,500 new bridges / year (FHWA, USA, 2000)

Table 5. Type and Number of Failure Causes

Failure causes and events	Number of occurrences	Percentage of total
Hydraulic	266	52.88
Flood	165	32.80
Scour	78	15.51
Debris	16	3.18
Drift	2	0.40
Others	5	0.99
Collision	59	11.73
Auto/truck	14	2.78
Barge/ship/tanker	10	1.99
Train	3	0.60
Other	32	6.36
Overload	44	8.75
Deterioration	43	8.55
General	22	4.37
Steel deterioration	14	2.78
Steel-corrosion	6	1.19
Concrete-corrosion	1	0.20
Fire	16	3.18
Construction	13	2.58
Ice	10	1.99
Earthquake	17	3.38
Fatigue-steel	5	0.99
Design	3	0.60
Soil	3	0.60
Storm/hurricane/tsunami	2	0.40
Miscellaneous/other	22	4.37
Total	503	100.00

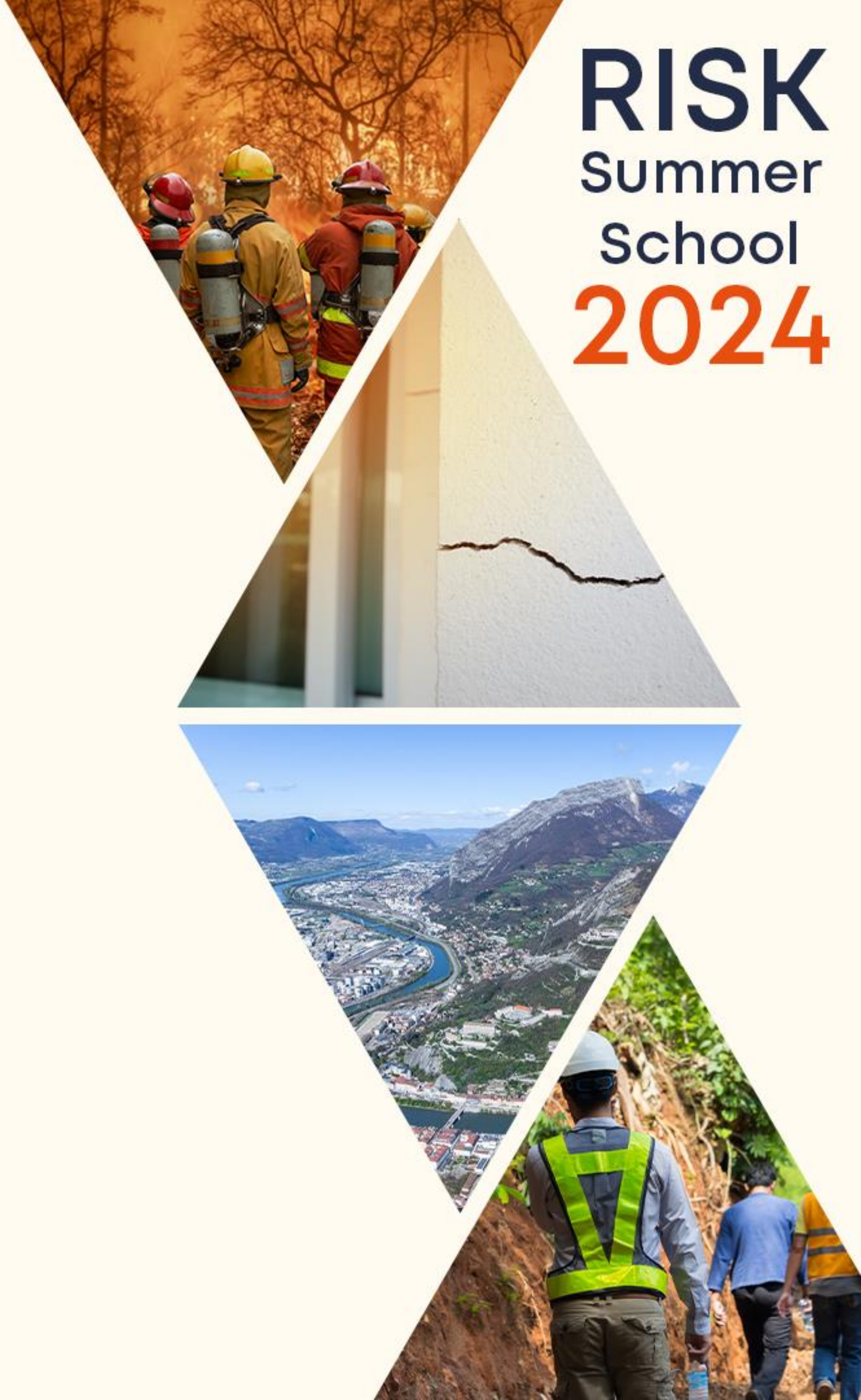
Flow and sediment transport processes



Roulund et al. (2005)

Flow around cylinders

National Committee for Fluid Mechanics Films (NCFMF) : https://web.mit.edu/hml/ncfmf.html
Flow Instabilities, E. L. Mollo-Christensen (MIT)



Flow around cylinders

➢ Reynolds number: $Re_D = \dfrac{V\ D}{\nu}$

where V is the mean flow velocity, D is the cylinder diameter and ν is the fluid kinematic viscosity

➢ Typical values for bridges:

✓ D = 10 m

✓ V = 1 m/s

$$Re_D = 10^7$$

Sumer and Fredsoe (1997)

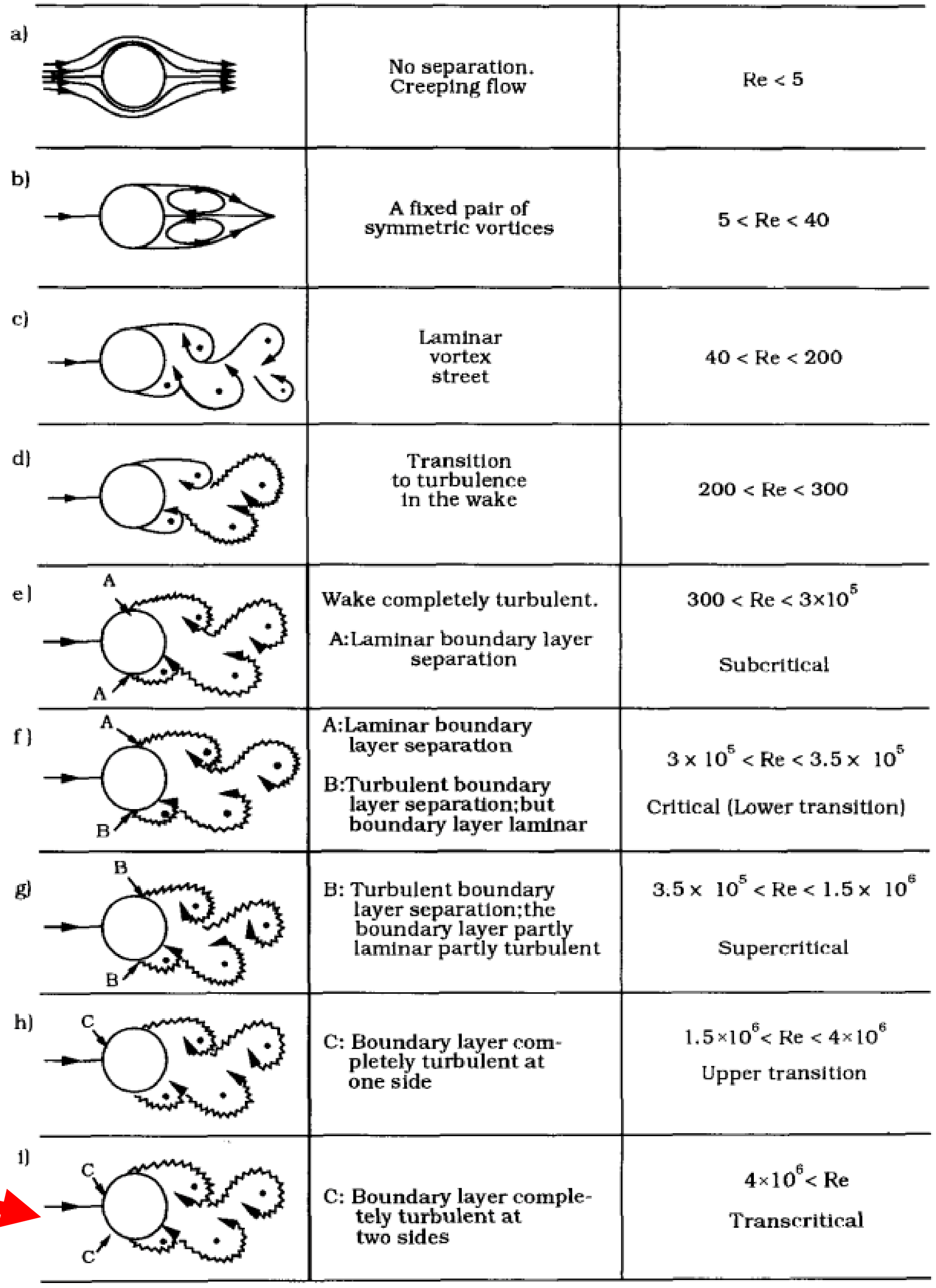


Figure 1.1 Regimes of flow around a smooth, circular cylinder in steady current.

Horseshoe vortex

- ➢ The cylinder imposes an arrest pressure to the upstream flow which generates a strong adverse pressure gradient
- ➢ The flow separates and a vortex system is generated:
  - ✓ The horseshoe vortex system

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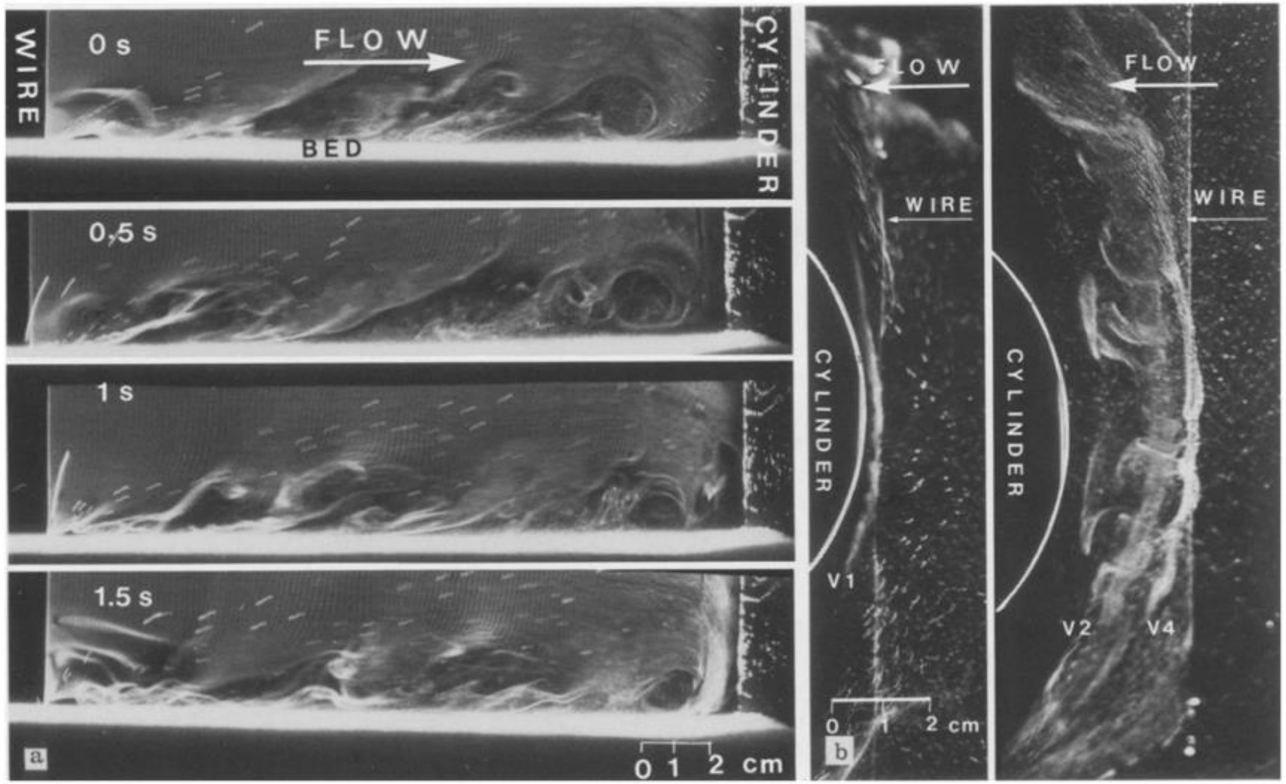
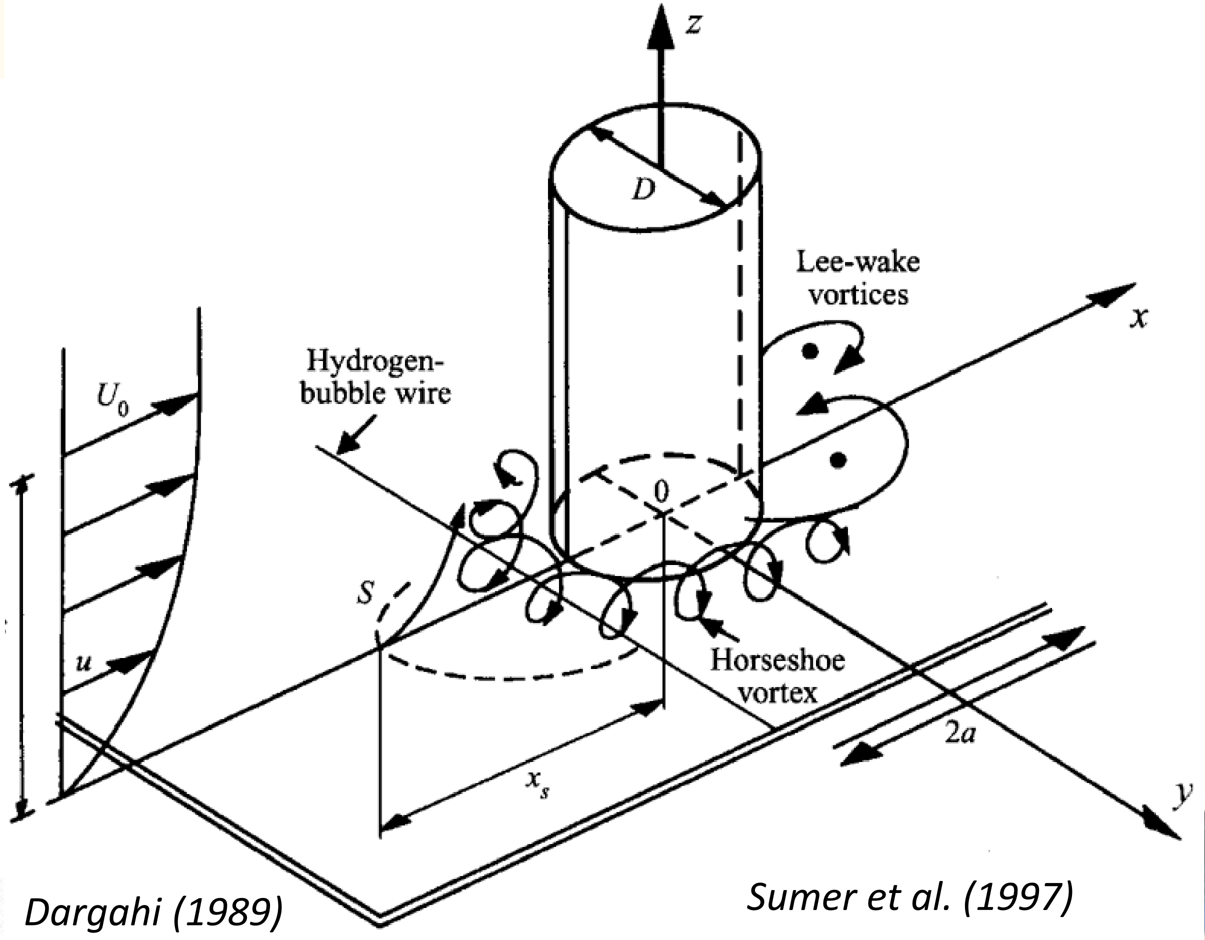


Fig. 1. **a** The horse-shoe vortex system in the plane of symmetry upstream of the cylinder at $Re(D) = 20{,}000$; wire position: $X/D = -1.83$ and $Z/D = 0$; **b** the horse-shoe vortex system in a horizontal plane close to the bed ($y/Ym = 0.005$), upstream of the cylinder at $Re(D) = 20{,}000$

Dargahi (1989)



Sumer et al. (1997)

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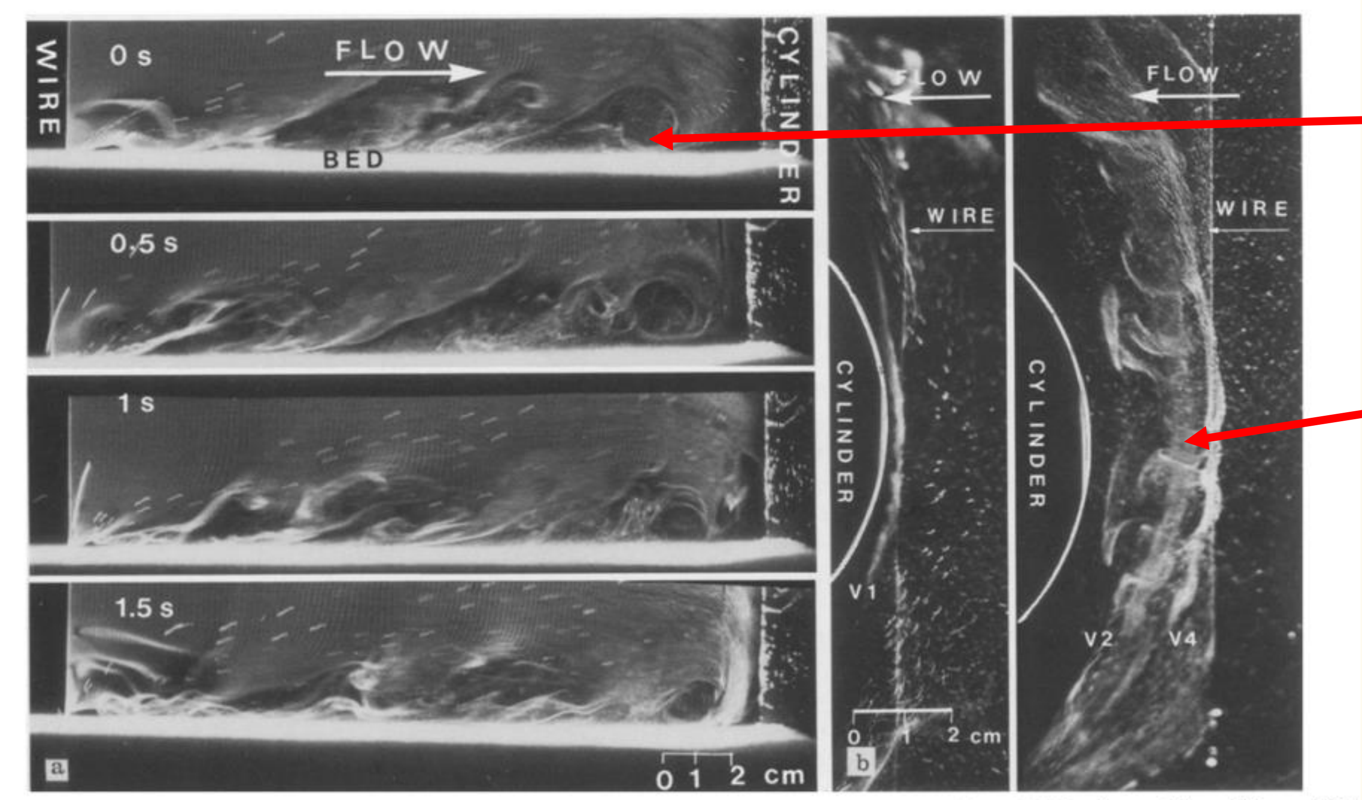

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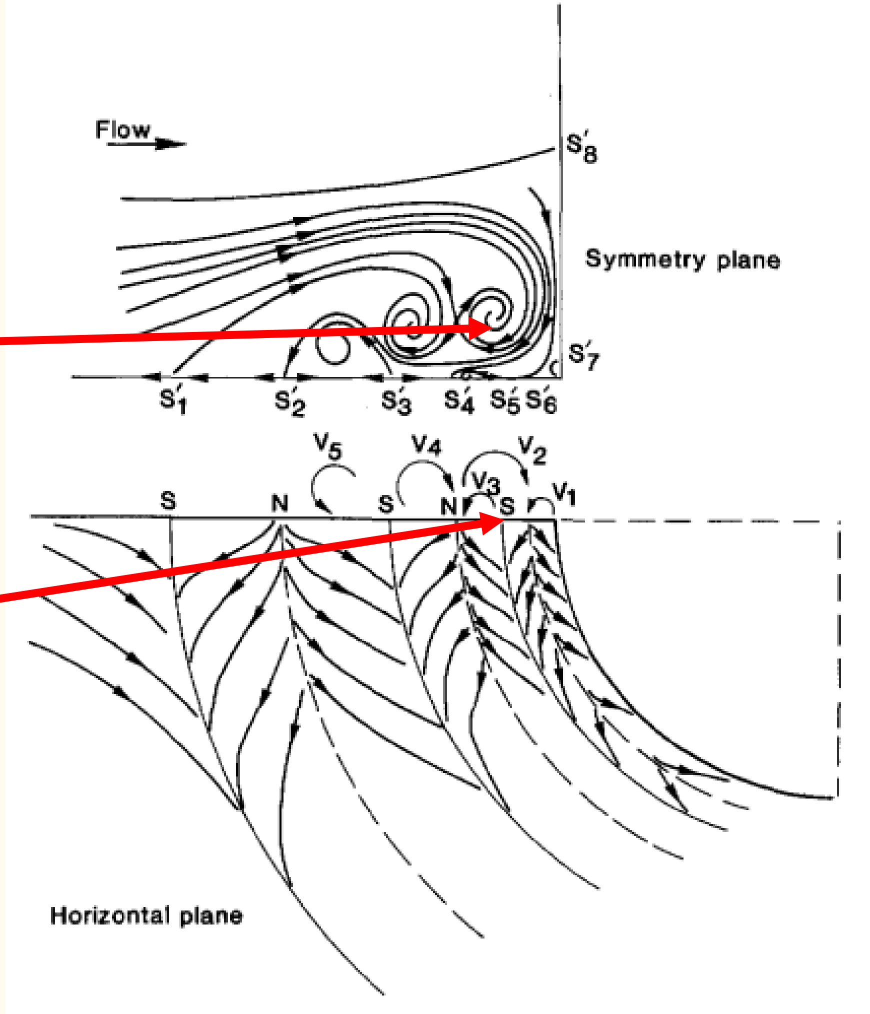
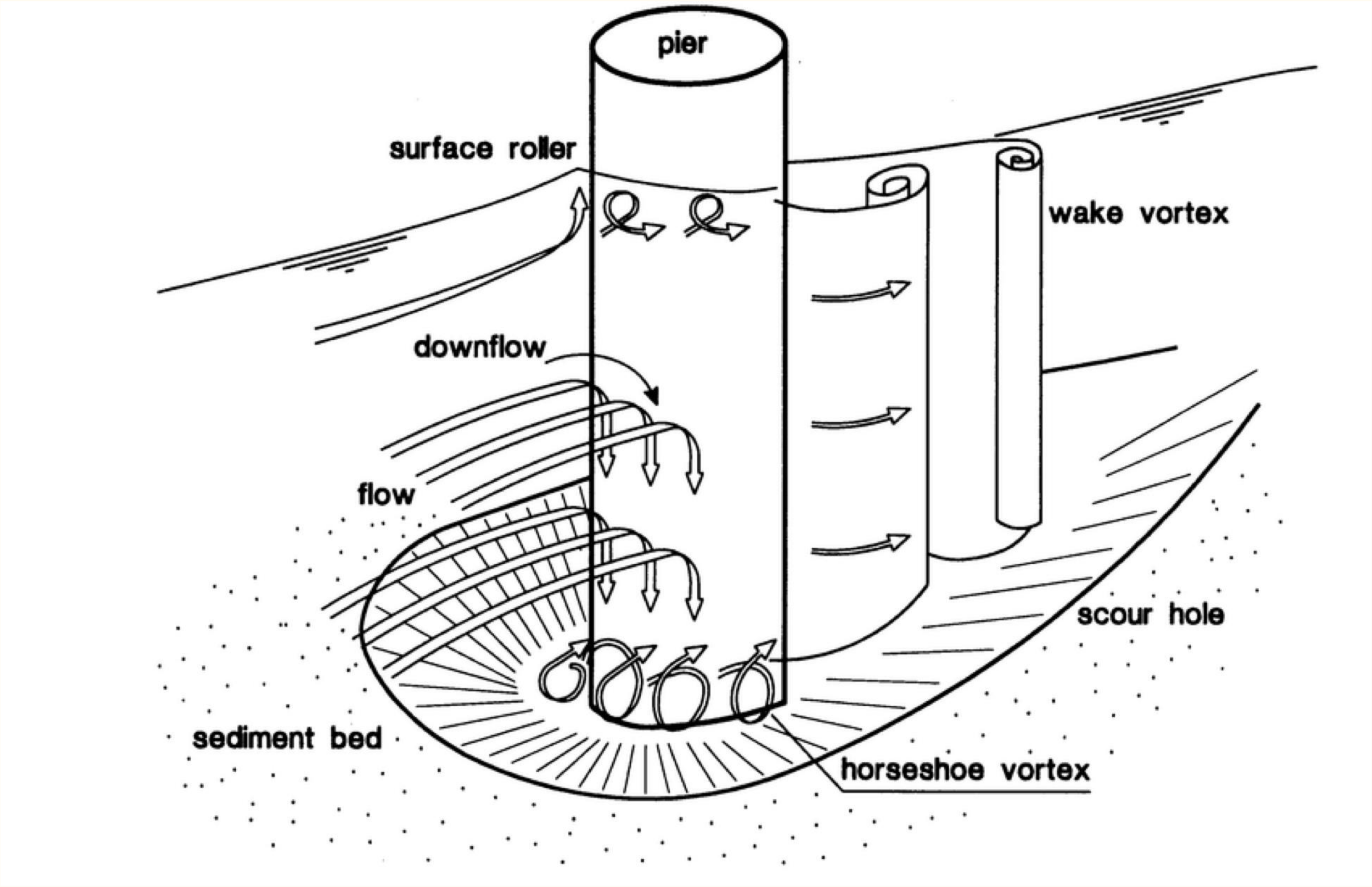


Fig. 3. The topological structure of the flow upstream of the cylinder at $Re(D) = 20{,}000$

Flow and sediment transport processes



Melville and Sutherland (2009)

Flow and sediment transport processes

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Numerical modeling

- Reynolds-Averaged Navier-Stokes equations

$$\frac{\partial \langle u_i \rangle}{\partial x_i} = 0$$

$$\frac{\partial \langle u_i \rangle}{\partial t} + \frac{\partial \langle u_i \rangle \langle u_j \rangle}{\partial x_j} = -\frac{\partial \langle p^* \rangle}{\partial x_i} + \frac{\partial}{\partial x_j}\left(2(\nu + \nu_T)\langle S_{ij} \rangle\right)$$

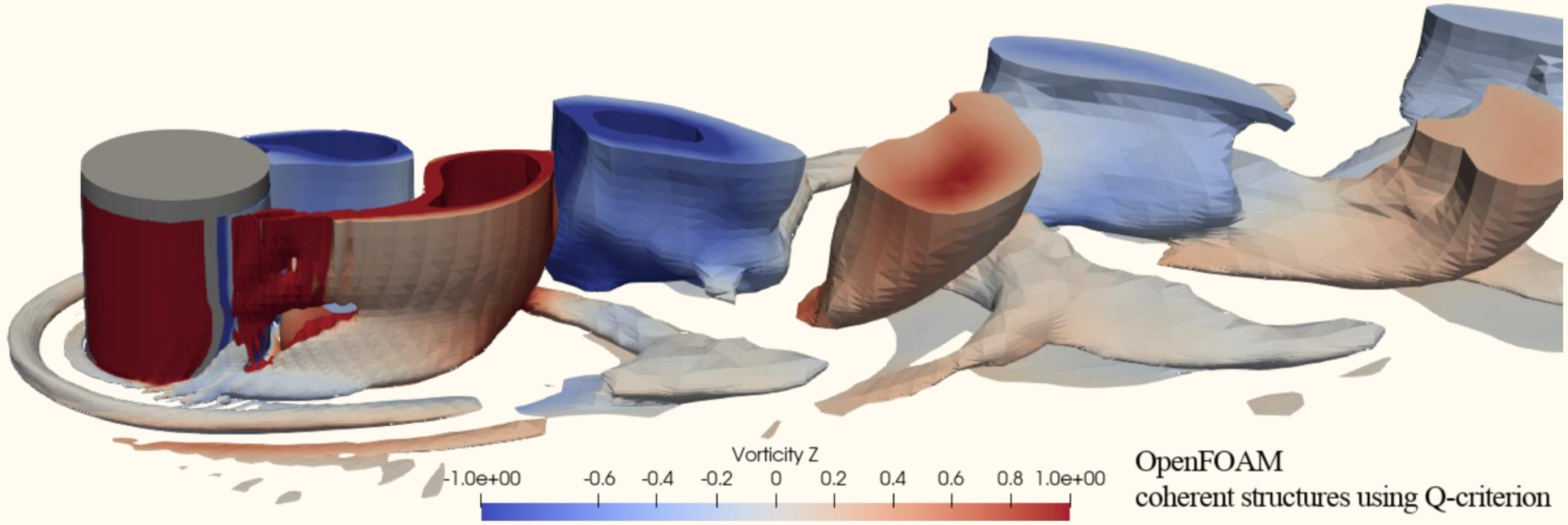
- Turbulence models
  - ✓ K-Epsilon or K-Omega SST, e.g. $\nu_T = C_\mu \frac{k^2}{\epsilon}$

M2 Matthias Renaud
Funded by OXALIA
Superviors: C. Bonamy (LEGI), T. Oudart (ARTELIA),O. Bertrand (ARTELIA), M. De Linares (ARTELIA)

- OpenFOAM versus TELEMAC3D
  - ✓ Different numerical methods : Finite Volume Method vs Finite Element Method
  - ✓ Different meshing strategies : Fixed unstructured grid vs Sigma coordinate (terrain following + free surface)
  - ✓ TELEMAC3D has been developed for large-scale problems while OpenFOAM is well-suited for small-scale

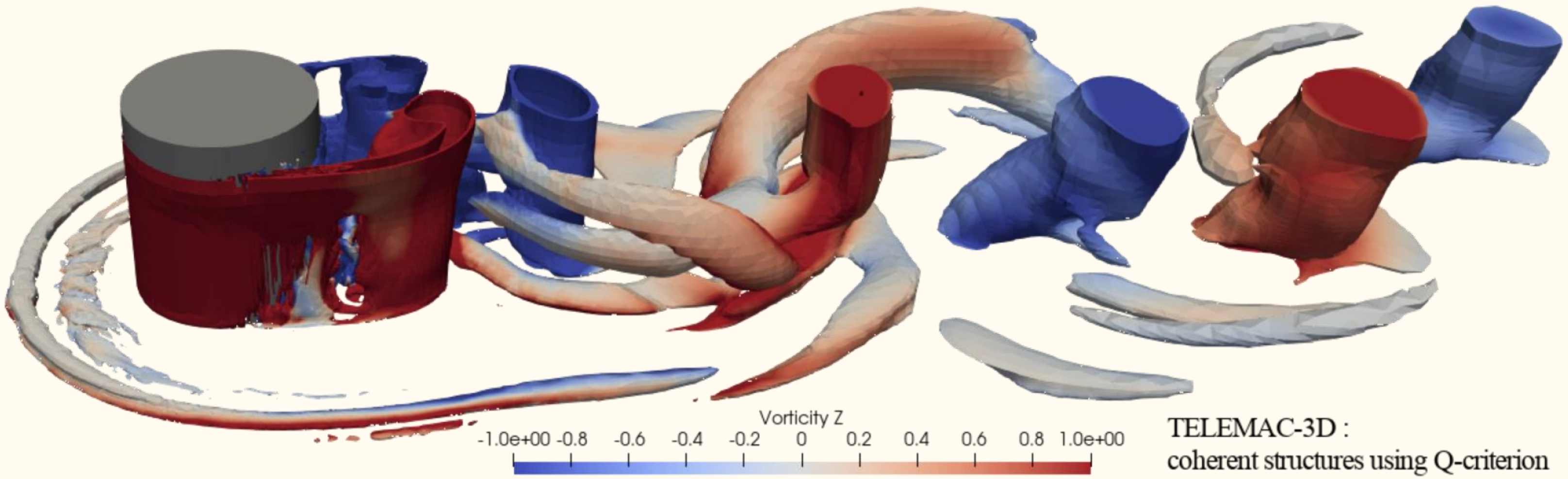
Numerical modeling

- Coherent structures around the cylinder (HSV and VS)



OpenFOAM
coherent structures using Q-criterion

openFOAM
K-omega SST



TELEMAC-3D :
coherent structures using Q-criterion

Telemac3D
K-epsilon

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D=0.54m
$Re_D = 1.7\ 10^5$

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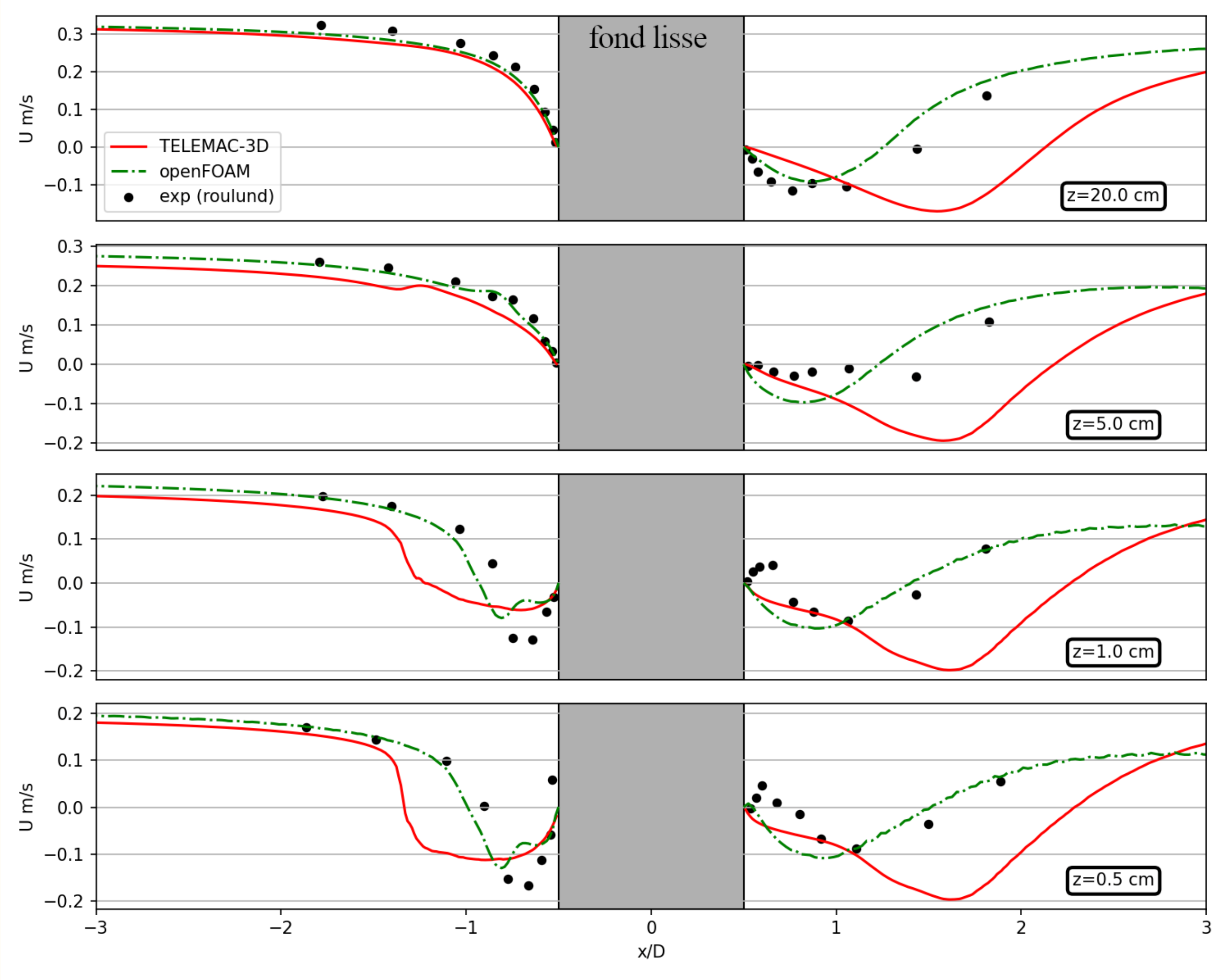
Numerical modeling

- Validation on streamwise velocity profiles



✓ OpenFOAM > TELEMAC3D for near field

D=0.54m
Re_D = 1.7 10^5

openFOAM : K-omega SST

Telemac3D : K-epsilon

Exp : Roulund et al. JFM (2005)

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Sediment transport modeling

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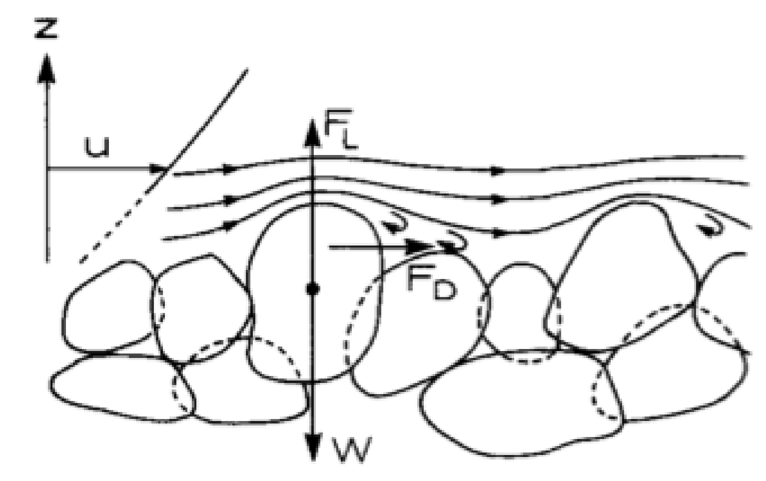
- Sediment particles at the bed will start to move as soon as the fluid velocity exceeds a given critical velocity for which the driving force exceeds the stabilizing one.



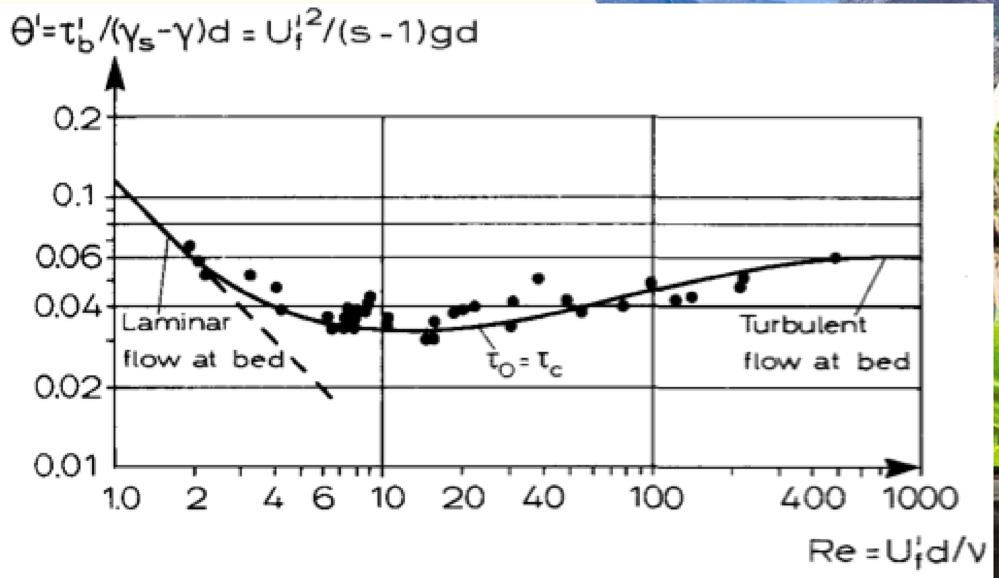
Driving force : $F_D = \frac{1}{2}\rho_f \; \frac{\pi}{4}d^2 \; C_D \; U_f^2$

Stabilizing force : $F_S = \mu_s \; W = \mu_s \; (\rho_p - \rho_f) \; g \; \frac{\pi}{6}d^3$

$\Longrightarrow \mu_s$ Friction coef. $=$ tan(angle of repose)

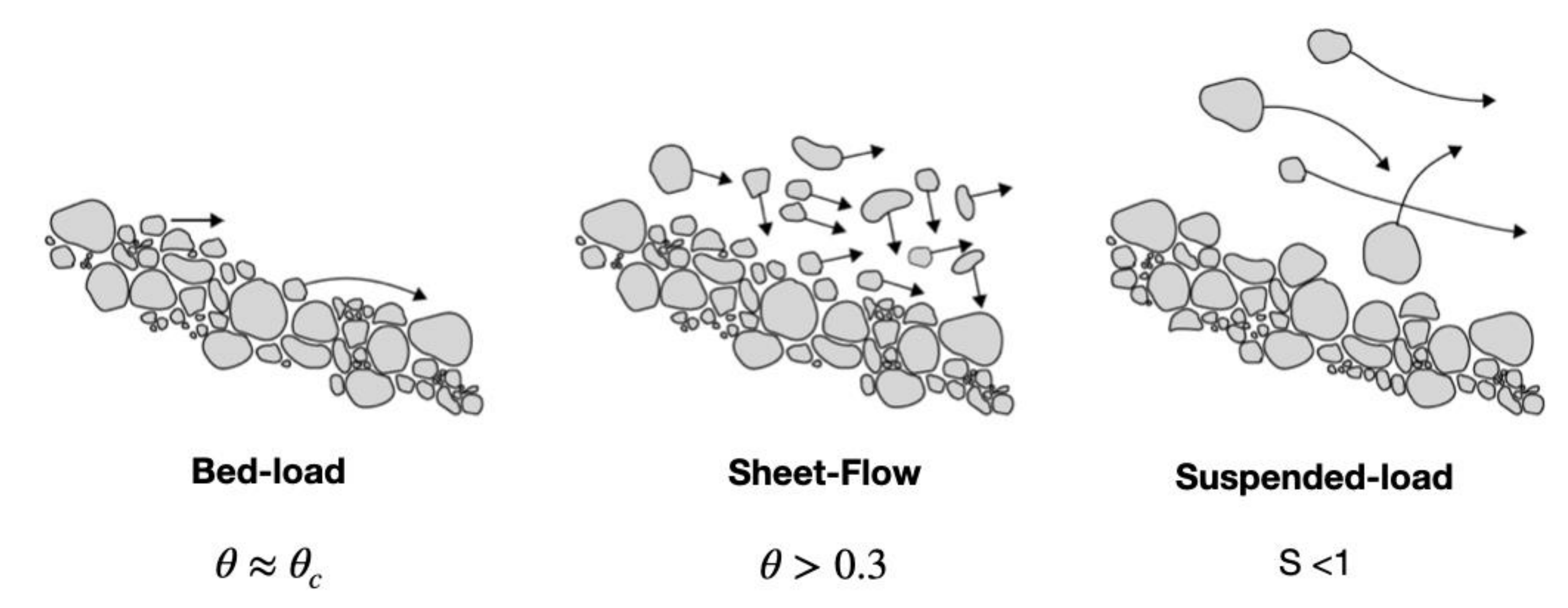
The sediment starts to move when $F_D = F_S \Longrightarrow \frac{1}{2}\rho_f \; \frac{\pi}{4}d^2 \; C_D \; U_{fc}^2 = \mu_s \; (\rho_p - \rho_f) \; g \; \frac{\pi}{6}d^3$

- Critical Shields number: $\theta_{cr} = \frac{U_f^2}{\left(\rho_p/\rho_f - 1\right)gd}$



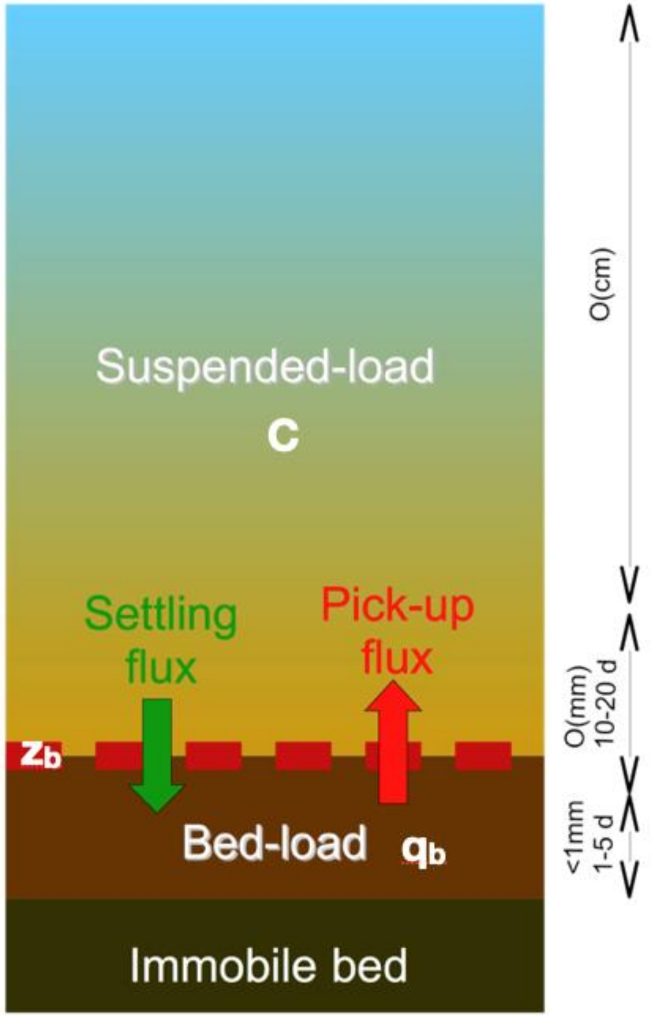
Fredsoe and Deigaard (1992)

Sediment transport modeling

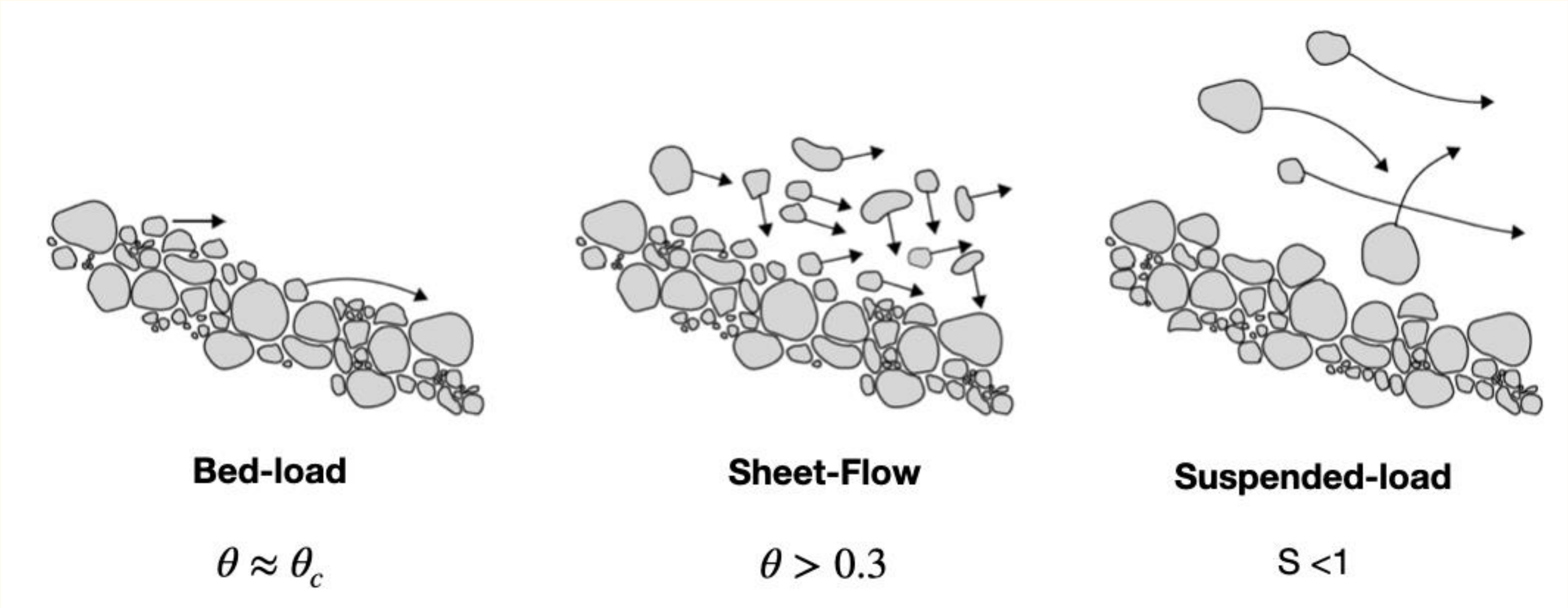


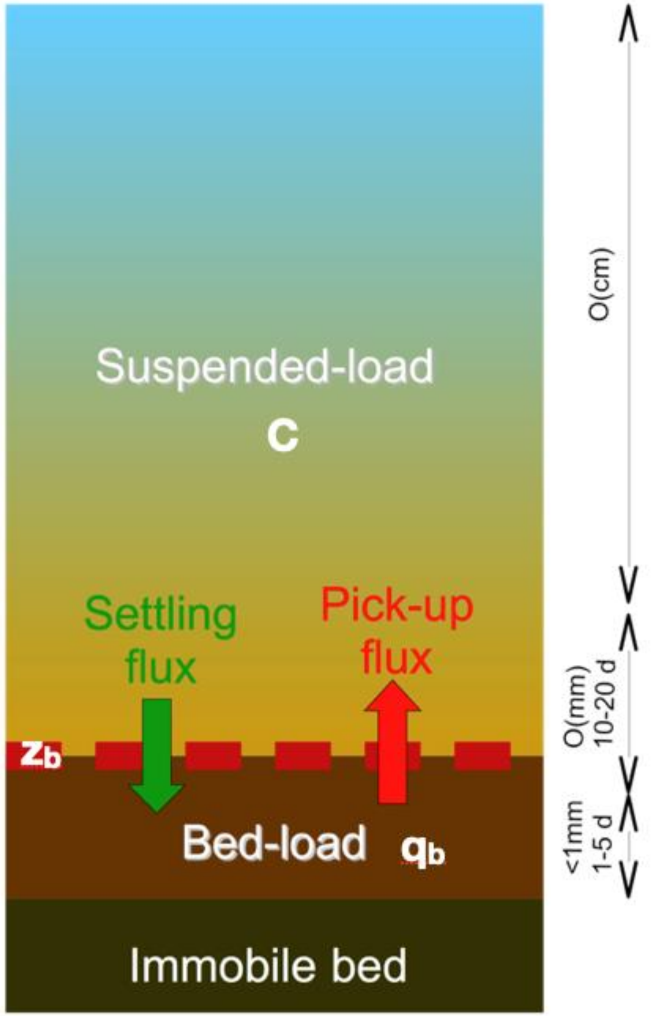
- Shields number: $\theta = \frac{\tau_b}{(\rho_s - \rho_f)gd}$ or $\frac{u_*^2}{\left({\rho_s}/{\rho_f} - 1\right)gd}$

- Suspension number: $S = \frac{u_*}{w_s}$ where w_s is the settling velocity



Sediment transport modeling





- Bed-load flux: $$\frac{q_b}{\sqrt{\left(\rho_s/\rho_f - 1\right) g d^3}} = 8\left(\theta - \theta_c\right)^{3/2}$$ *Meyer-Peter & Muller (1948)*

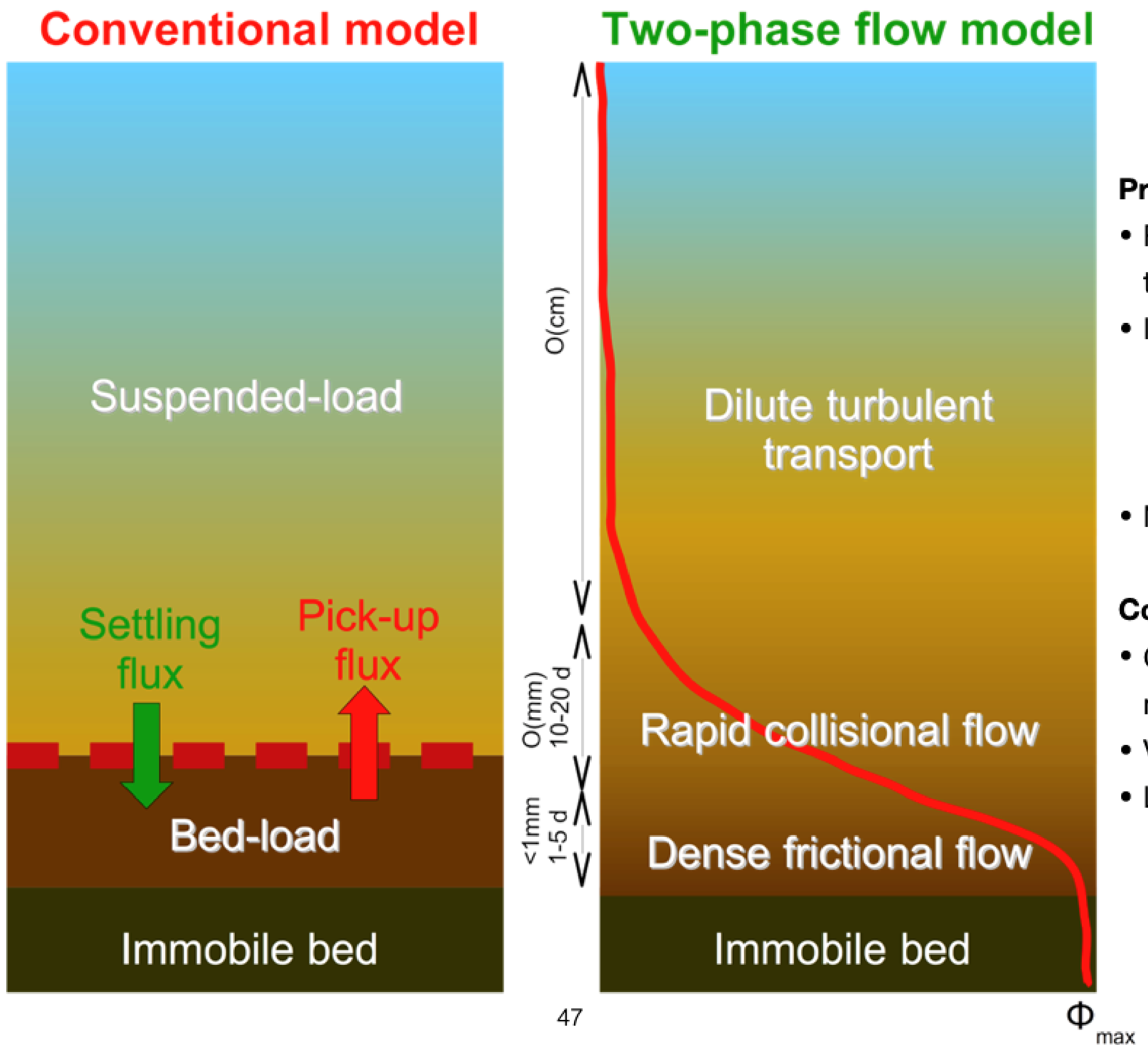
- Pick-up flux: $$\frac{E}{\sqrt{\left(\rho_s/\rho_f - 1\right) g d}} = 3.3e^{-4} D_*^{0.3} \left(\frac{u_*^2 - u_{*,cr}^2}{u_{*,cr}^2}\right)^{3/2}$$ *van Rijn (1984)*

Numerical modeling

- Alternative approach: two-phase flow simulations

Pros
- Simple
- Applicable at large-scale

Cons
- Empirical formulas
  - Especially bed-load
  - Large scatter (~100%)
  - Missing physics
- Arbitrary separation between bed-load and suspended-load



Pros
- Resolve continuously sediment transport profile
- Incorporate fine-scale processes:
  - Turbulence
  - Turbulence-particle interactions
  - Particle-particle interactions
- No arbitrary separation

Cons
- Complexity of the processes to be modeled
- Very expensive
- Limited to 'small scale' applications

Jenkins and Hanes JFM (1998)

Numerical modeling

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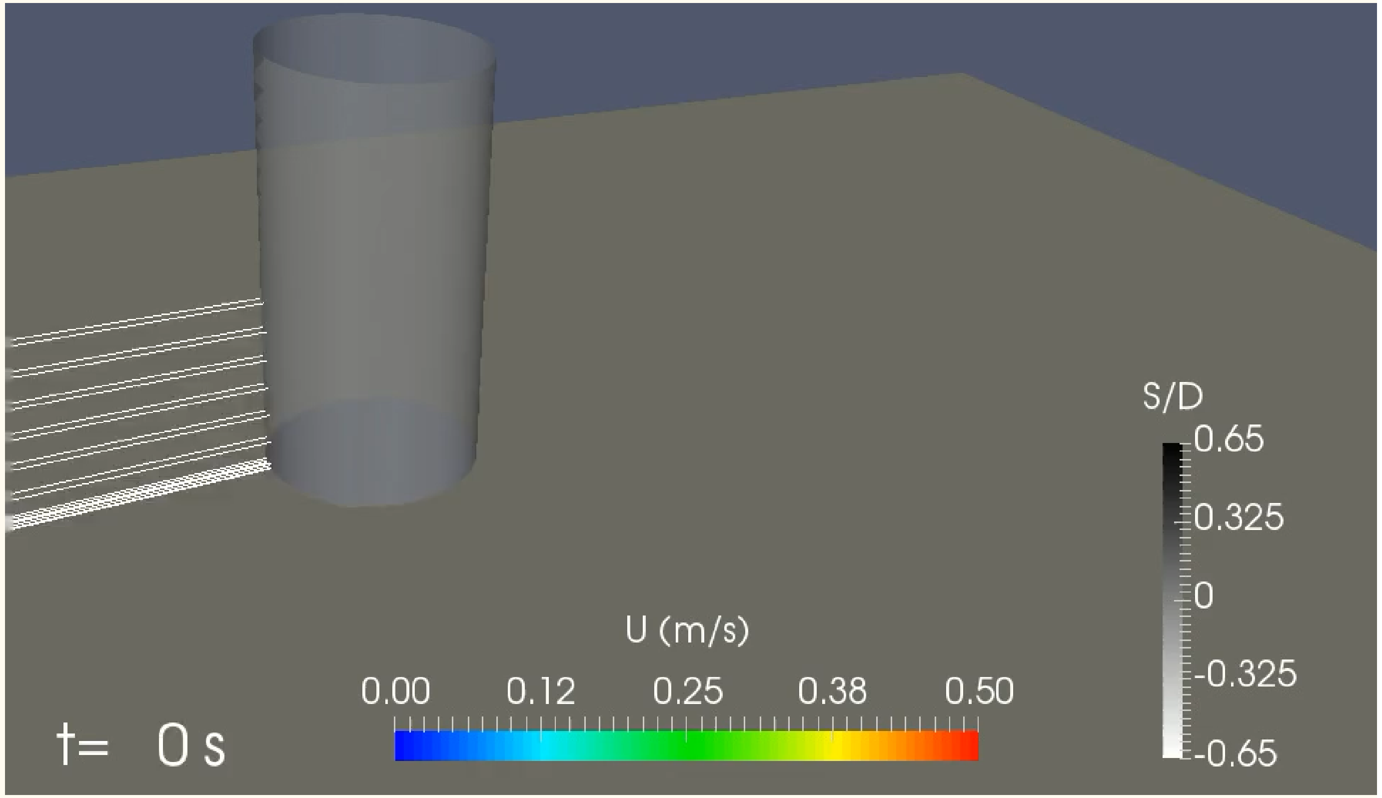
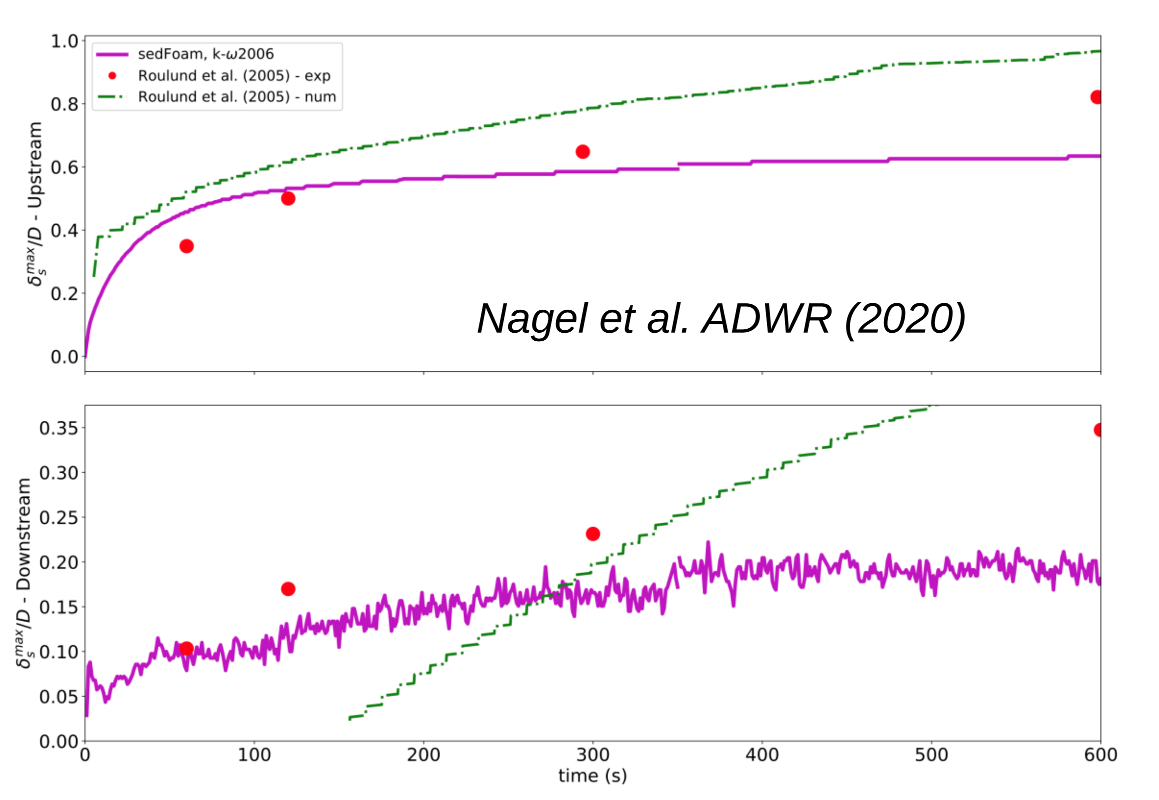
- ➢ First two-phase flow simulation pf the scour process





- ➢ Reasonable agreement with experimental data from Roulund et al. JFM (2005)
- ➢ Proof of concept that two-phase flow models can reproduce scour processes
- ➢ CPU cost is huge (2 months on 128 cores for 600s): not reasonable for Engineering applications

State-of-the-art in engineering

- 0D modeling: Riprap size design
  - ✓ $d_{50} \propto h \left(\frac{V}{\sqrt{(s-1)h}} \right)^{2.5}$ *(HEC-23)*

- Physical modeling
  - ✓ Scale issue
  - ✓ High cost

- Numerical modeling (mostly hydrodynamic simulations)
  - ✓ 2D
  - ✓ 3D

A case study by ARTELIA:
the LGV Sud Europe Atlantique (SEA)

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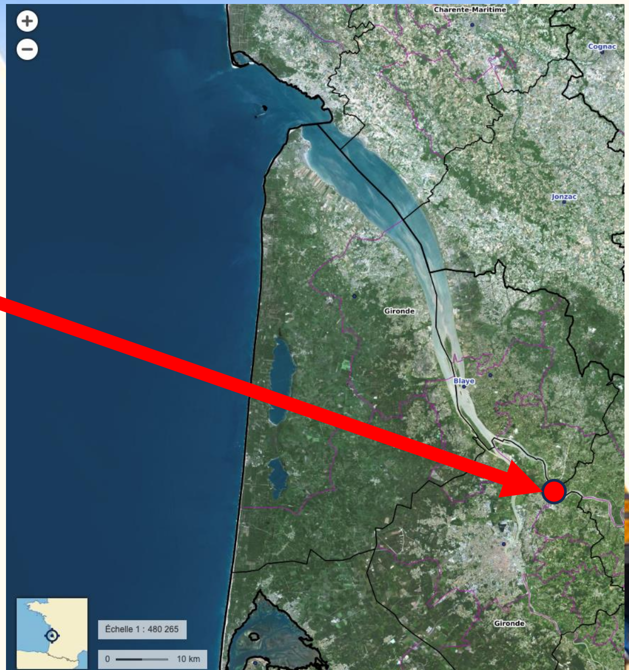
- Initial design of the Dordogne viaduct (2012)
  - ✓ Physical model of pile P11/P12 using movable bed to quantify scouring and determine a protection solution (2012) => Monitoring and filling

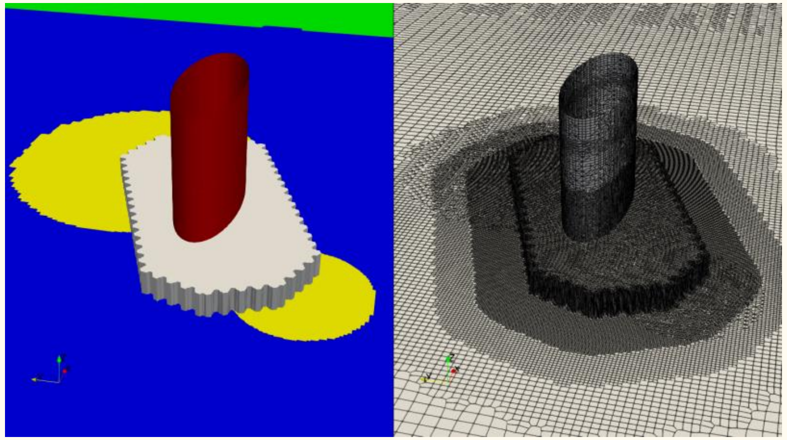
  - ✓ Viaduct built and LGV line in service since July 2, 2017



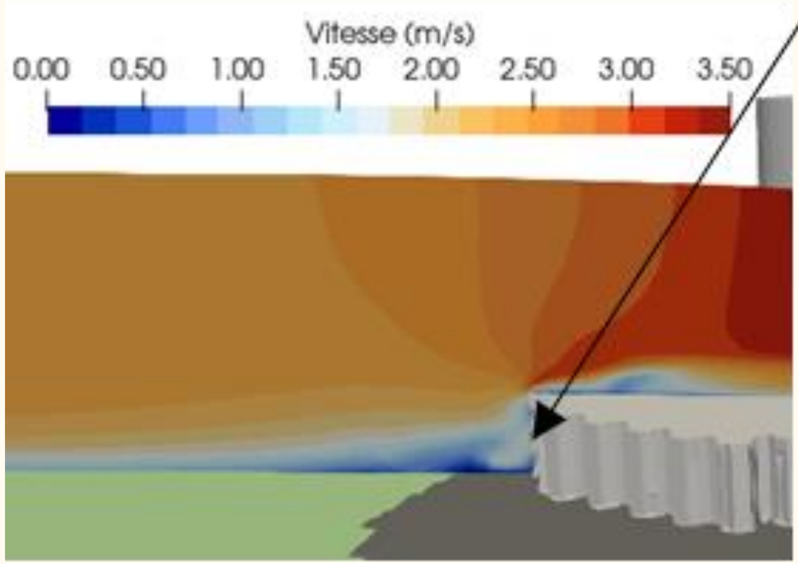
  - ✓ Bathymetric monitoring => depths reaching levels qualified as “vigilance »

A case study by ARTELIA:
the LGV Sud Europe Atlantique (SEA)

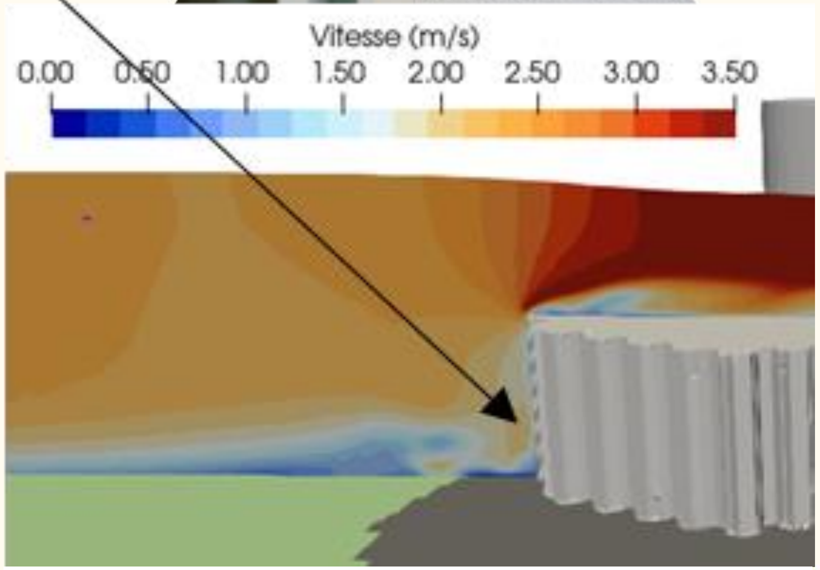
- Scour analysis (2021)
  - ✓ Expert analysis : greater-than-expected emergence of the footing above the bed
  - ✓ Implementation of a local 3D model (using OpenFOAM) of the pile simulated in the physical model



Jet plongeant



Physical model configuration



Raised footing configuration

Bed shear stress increased from 150 N/m^2 to 180 N/m^2 (extrapolated at field scale)

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A case study by ARTELIA:
the LGV Sud Europe Atlantique (SEA)

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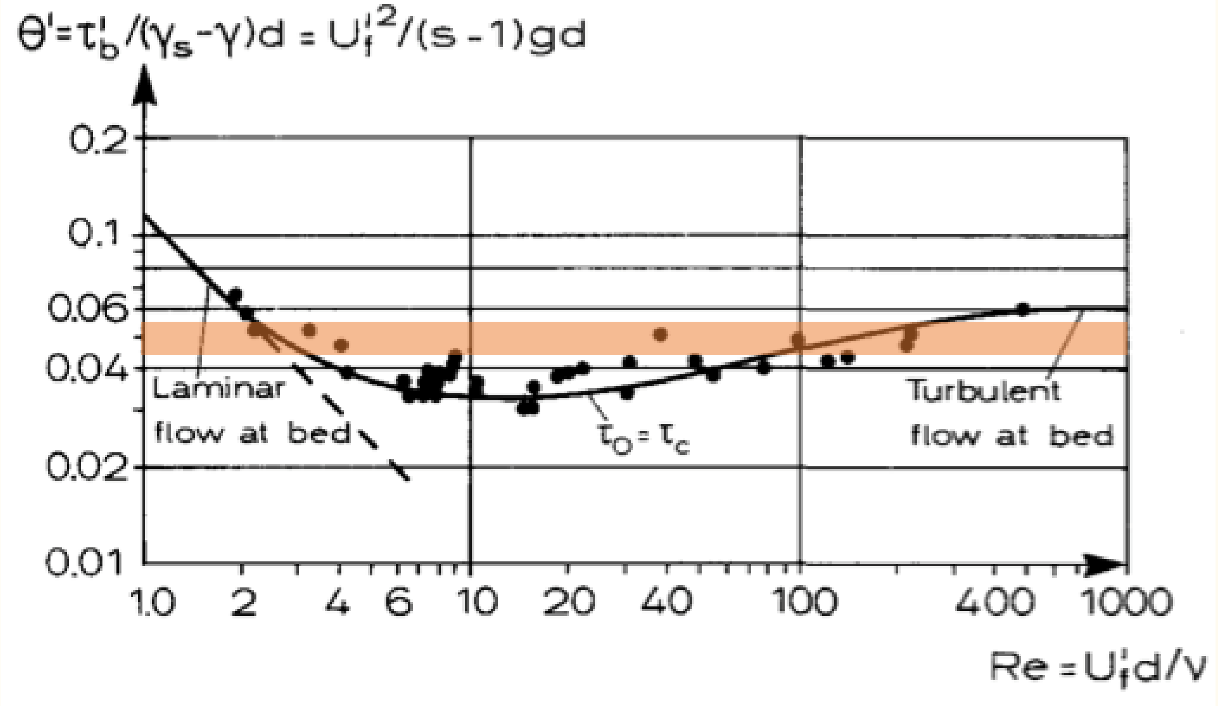
- ➢ Scour analysis (2021)
  - ✓ Bed shear stress increased from 150 N/m^2 to 180 N/m^2
  - ✓ Stability criteria : $\theta = \frac{\tau_b}{(\rho_s - \rho_f)gd} > \theta_c$

    $\Rightarrow$ For a given value of bed shear stress we deduce the largest particle size that can be transported
  - ✓ The riprap used for scour protection is d_{50}=0.2 m

    $\Rightarrow$ For τ_b = 150 N/m^2 θ= 0.046

    $\Rightarrow$ For τ_b = 180 N/m^2 θ= 0.055



In both scenario the stability is uncertain (θ close to θ_c)

These simulations suggest that the expert hypothesis is correct: the increase in footing height generate larger scour

A case study by ARTELIA:
the LGV Sud Europe Atlantique (SEA)

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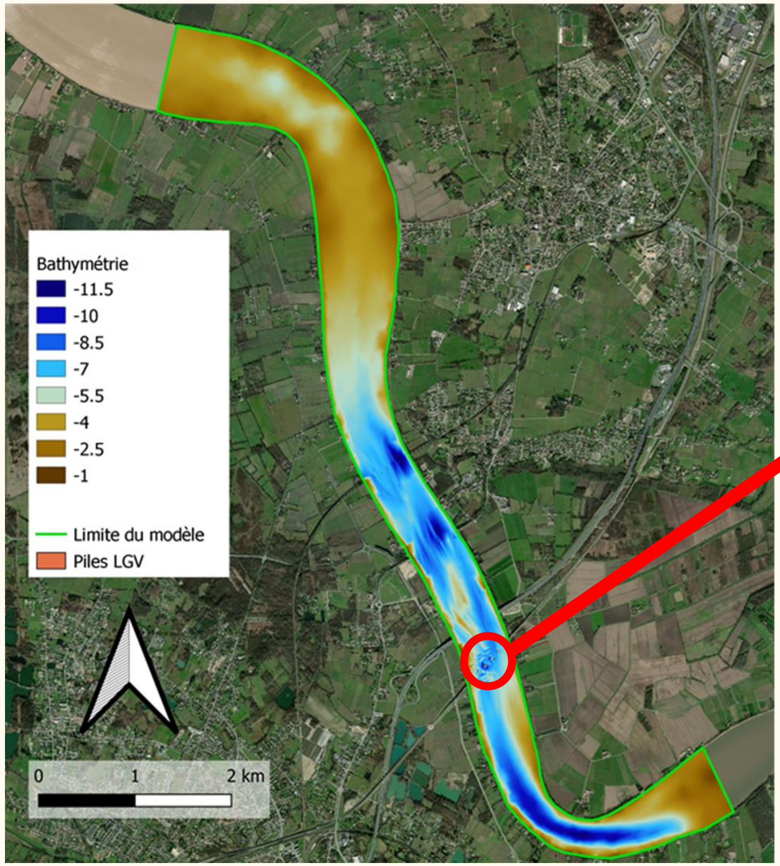
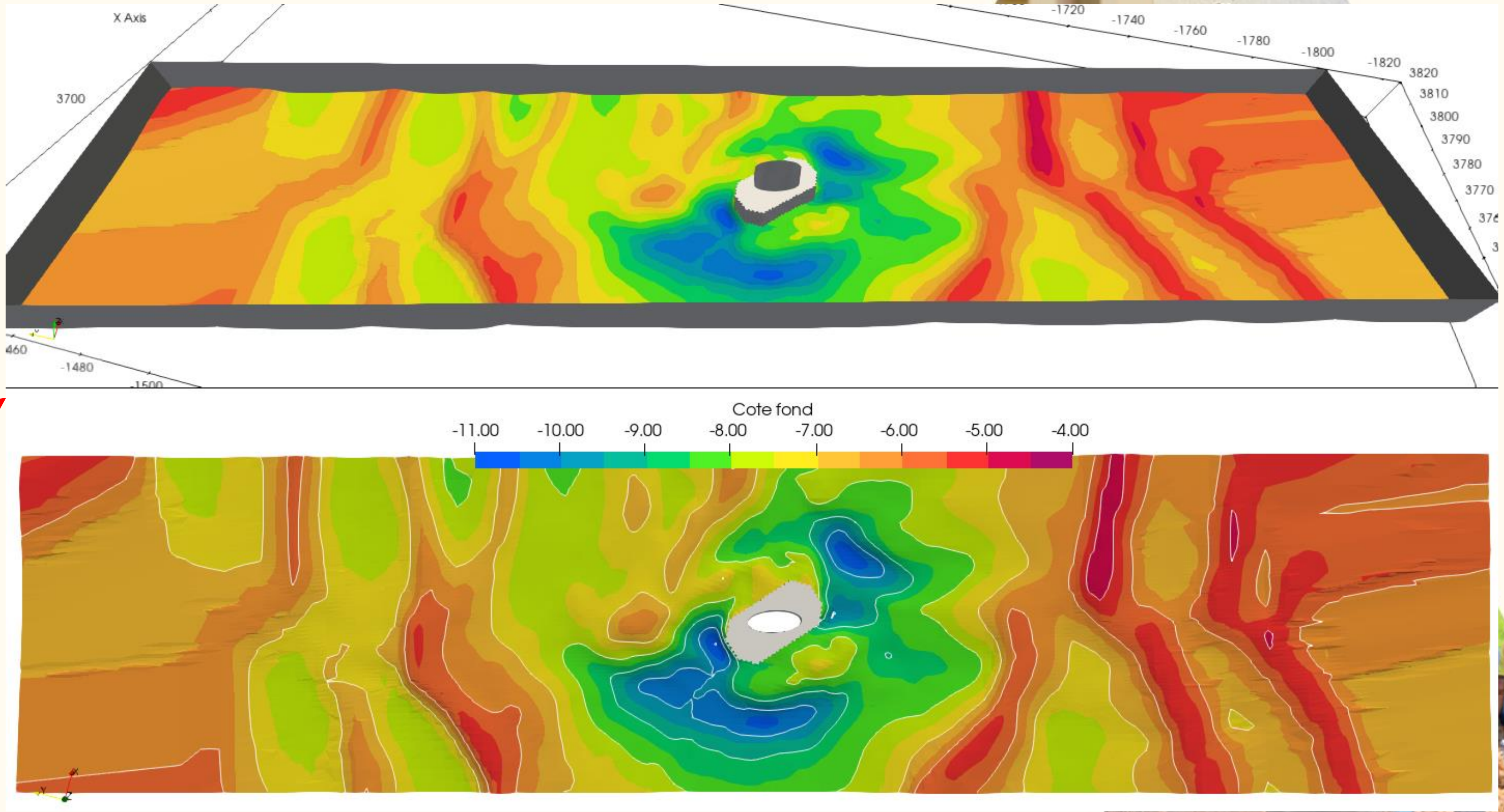
- Scour analysis (2021)
    - ✓ Coupling of a 3D model of the Dordogne section (using TELEMAC 3D) with a local OpenFOAM model representative of pile P12





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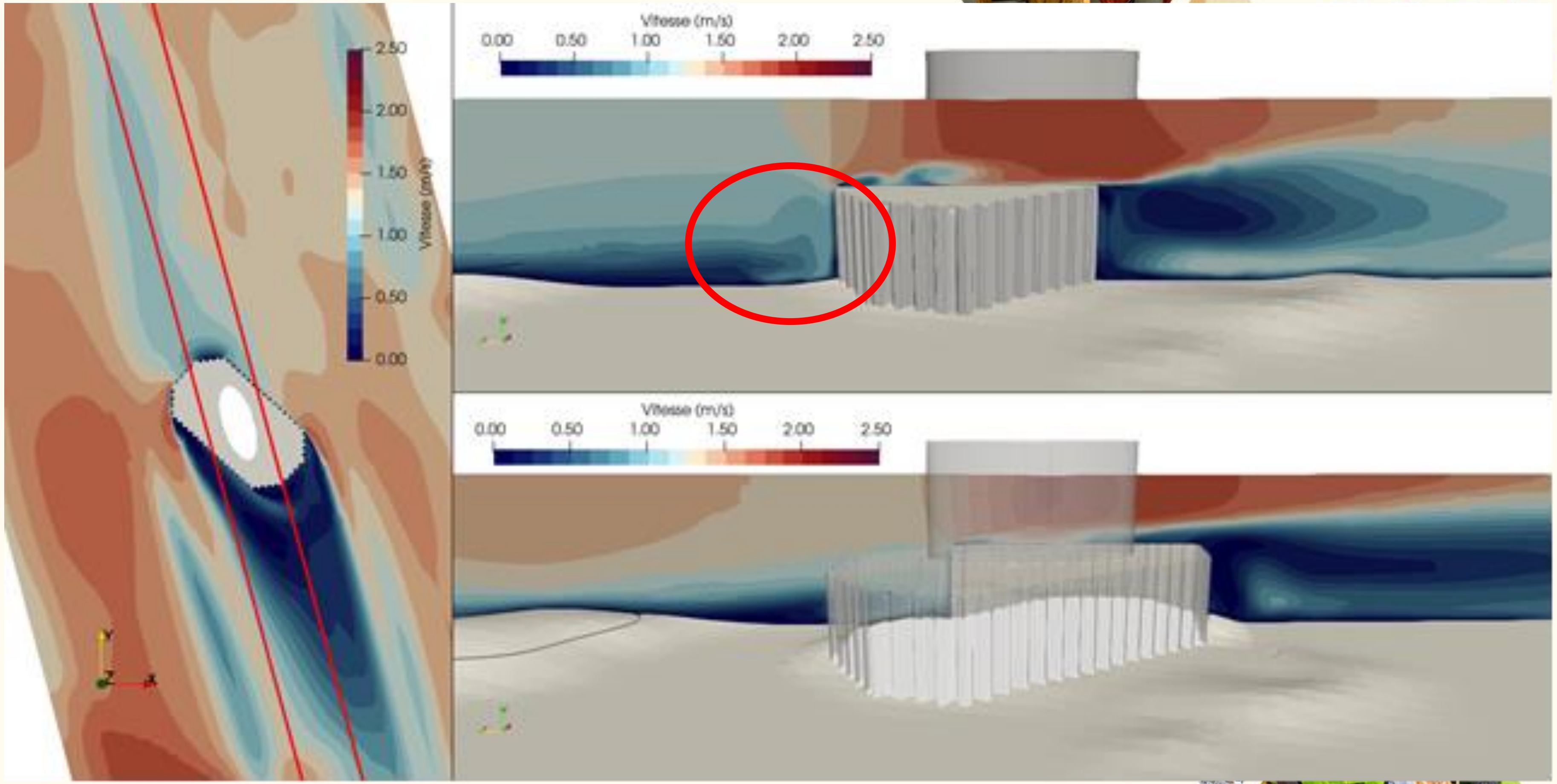
➢ Scour analysis (2021)



✓ Formation of a strong horseshoe vortex upstream the footing is responsible for the intense scour

A case study by ARTELIA:
the LGV Sud Europe Atlantique (SEA)

- Scour analysis (2021)
  - ✓ Solution:
    - riprap refilling with larger particles to increase the intrinsic stability
    - d_{50}=0.4 m => θ= 0.023 $< \theta_c$

- Conclusion & perspectives
  - ✓ This study illustrates how 3D numerical simulations may be used to analyze scour and propose remediation solutions
  - ✓ Main limitation: no sediment transport or morphodynamic evolution in simulations
    - Developing such a model is one of the goal of the OXALIA chair

A new generation of numerical model

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- **Thèse M. Renaud (2022-2025)**
  - ✓ Development of an open-source operational morphodynamic model
  - ✓ Scouring: preventing the risk of hydraulic structure failure

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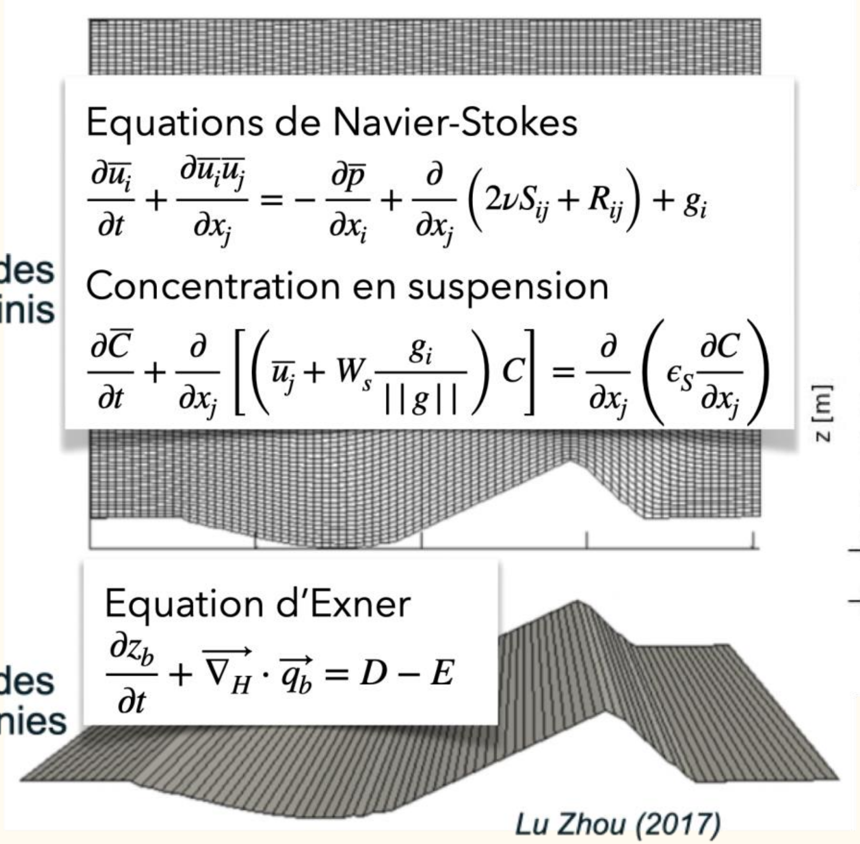
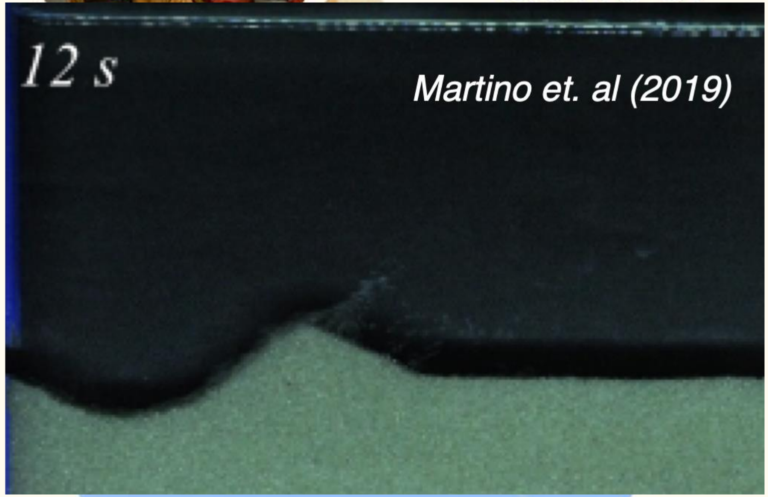
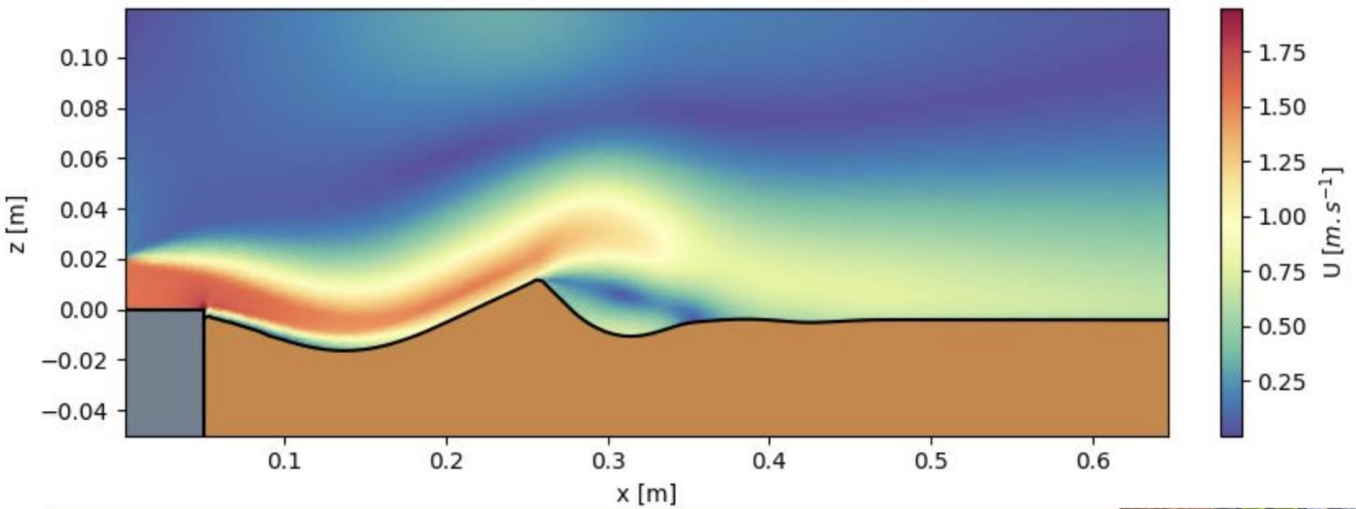
méthode des volumes finis

méthode des surfaces finies



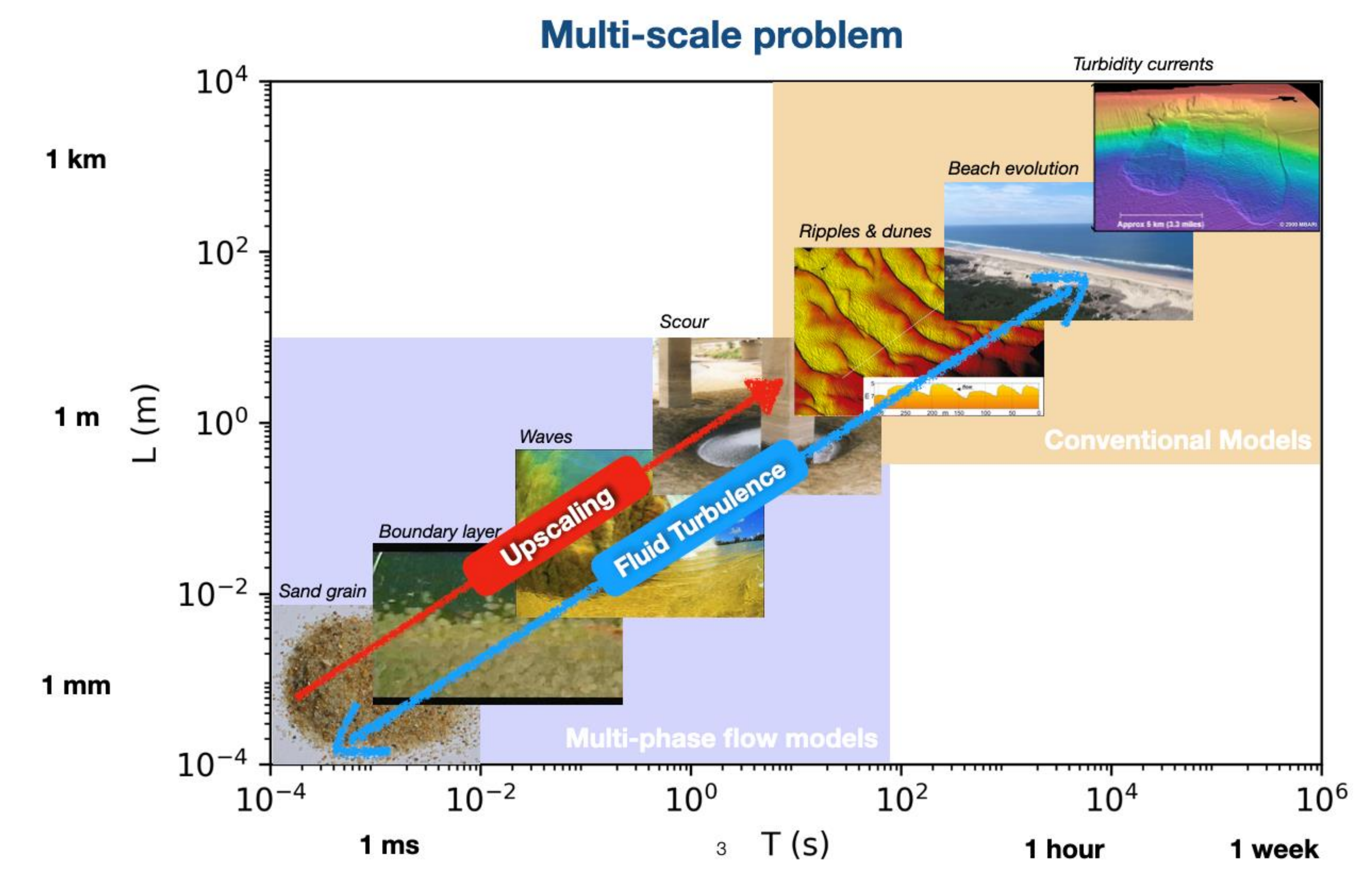




Conclusion & perspectives

- ➢ Scour is one of the main risk for hydraulic structures collapse
    - ✓ ~ 50% for bridge piers in the USA
- ➢ Coherent structures/vortices responsible for the digging of the river bed
- ➢ Scour protection such as riprap are estimated using empirical formulas
- ➢ Hydrodynamic parameters are obtained from physical or numerical models
- ➢ Goal of OXALIA chair: develop a new generation of model capable of simulating the flow and the bed evolution around hydraulic structures for practical applications

Upscaling



Multi-scale problem
Turbidity currents
Beach evolution
Ripples & dunes
Scour
Waves
Boundary layer
Sand grain
Upscaling
Fluid Turbulence
Conventional Models
Multi-phase flow models
1 km
1 m
1 mm
L (m)
10^4
10^2
10^0
10^{-2}
10^{-4}
10^{-4}
10^{-2}
10^0
10^2
10^4
10^6
T (s)
1 ms
1 hour
1 week

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Logos / Éléments graphiques individuels

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RISK Thematic program