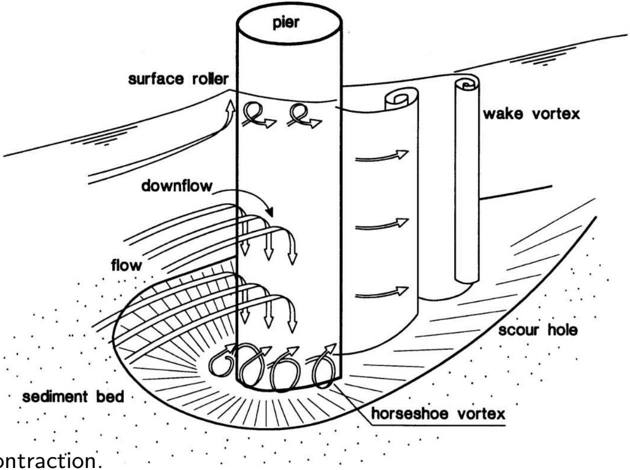
Two-Phase Flow Simulations Of Scour Around Vertical And Horizontal Cylinders

Tim NAGEL , Julien CHAUCHAT, Cyrille BONAMY, Antoine MATHIEU, Xiaofeng LIU, Zhen CHENG & Tian-Jian HSU

Vertical circular pile exposed to a steady current

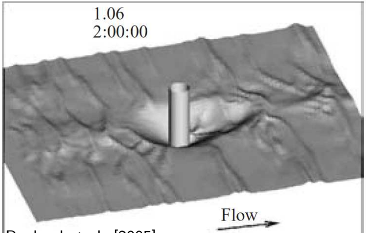
Melville [1988]



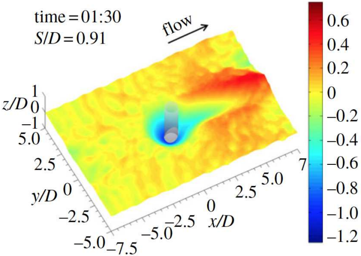
- Streamlines contraction.
- Lee-wake vortices (Vortex shedding).
- Downflow in front of the pile / Horseshoe vortex.
- Increase of the sediment transport ⇒ Scour (O. Link) ⇒ Potential structure failure.

3D Numerical modeling of scour

"Classical" approach



Roulund et al. [2005]



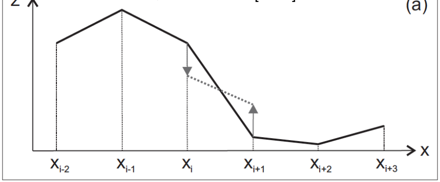
Baykal et al. [2015]

- Critical Shields parameter modification:

$$\theta_{cS} = \theta_c \left(\cos\beta \sqrt{1 - \frac{\sin^2\alpha \, \tan^2\beta}{\mu_s^2}} - \frac{\cos\alpha \, \sin\beta}{\mu_s} \right)$$

- Avalanching model (slope correction above $\beta = 32°$).

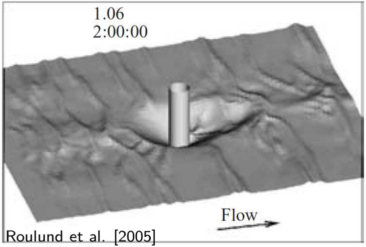
Marieu, PhD Thesis [2009]



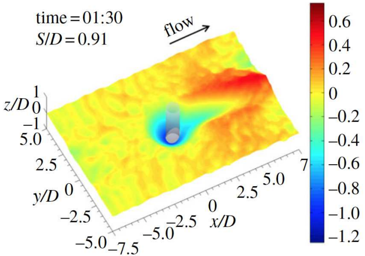
- **sediment transport rate ⇒ bed shear stress**

3D Numerical modeling of scour

"Classical" approach



Roulund et al. [2005]

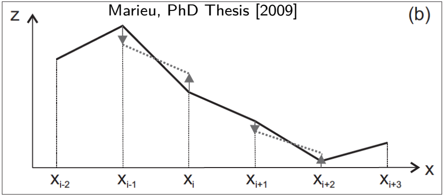


Baykal et al. [2015]

- Critical Shields parameter modification:

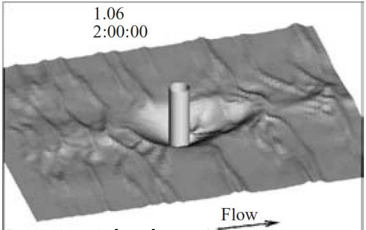
$$\theta_{cS} = \theta_c \left(\cos\beta \sqrt{1 - \frac{\sin^2\alpha \, \tan^2\beta}{\mu_s^2}} - \frac{\cos\alpha \, \sin\beta}{\mu_s} \right)$$

- Avalanching model (slope correction above $\beta = 32°$).

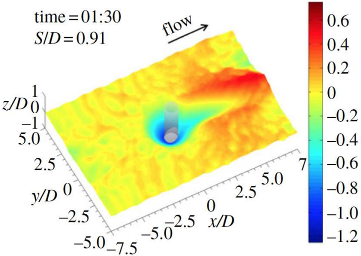


- **sediment transport rate ⇒ bed shear stress**

"Classical" approach



Roulund et al. [2005]

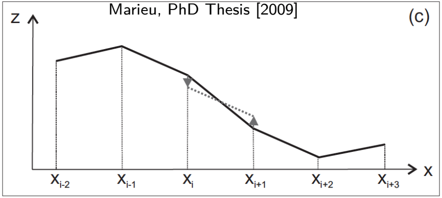


Baykal et al. [2015]

- Critical Shields parameter modification:

$$\theta_{cS} = \theta_c \left(\cos\beta \sqrt{1 - \frac{\sin^2\alpha \, \tan^2\beta}{\mu_s^2}} - \frac{\cos\alpha \, \sin\beta}{\mu_s} \right)$$

- Avalanching model (slope correction above $\beta = 32°$).



Marieu, PhD Thesis [2009]

- **sediment transport rate ⇒ bed shear stress**

3D Numerical modeling of scour

Eulerian-Eulerian two-phase flow

- **Does a Eulerian-Eulerian two-phase flow model reproduce the scour phenomenon?**
- **Can we get more insight into the fine scale sediment transport mechanisms involved in the scour process?**
- **Is it possible to parametrize them in "classical" morphodynamics models (upscaling)?**

3D Two-phase flow model equations

Fluid: $\frac{\partial(1-\phi)}{\partial t} + \vec{\nabla}.\left((1-\phi)\vec{u^f}\right) = 0$

$$\overbrace{\rho^f(1-\phi)\frac{D\vec{u^f}}{Dt}}^{\text{unsteady+inertia}} = \overbrace{-(1-\phi)\vec{\nabla}p}^{\text{fluid pressure}} + \overbrace{\vec{\nabla}.\overline{\overline{\tau^f}}}^{\text{Fluid st.}} + (1-\phi)\vec{f} + \rho^f(1-\phi)\vec{g} \overbrace{-M_D}^{\text{drag}}$$

Solid: $\frac{\partial\phi}{\partial t} + \vec{\nabla}.\left(\phi\vec{u^s}\right) = 0$

$$\rho^s\phi\frac{D\vec{u^s}}{Dt} = -\phi\vec{\nabla}p \underbrace{-\vec{\nabla}\tilde{p^s} + \vec{\nabla}.\overline{\overline{\tau^s}}}_{\text{granular st.}} + \phi\vec{f} + \rho^s\phi\vec{g} + M_D$$

- $(1-\phi), \phi$: fluid and particles volume fractions
- u^f : Average fluid velocity
- u^s : Average particle velocity
- p : Fluid pressure
- $\tilde{p^s}$: Particulate pressure
- S_c : Schmidt Number

Drag law:

$$K = 0.75\frac{24}{Re_p}\left(1 + 0.15Re_p^{0.687}\right)\frac{\rho^f}{d}||\vec{u^f} - \vec{u^s}||\,(1-\phi)^{-2.65}$$

$Re_p = (1-\phi)||\vec{u^f} - \vec{u^s}||\,d/\nu^f$: particulate Reynolds number

Schiller & Naumann [1933] + Richardson & Zaki [1954]

3D Two-phase flow model equations

Fluid: $$\frac{\partial(1-\phi)}{\partial t} + \vec{\nabla}.\left((1-\phi)\vec{u^f}\right) = 0$$

$$\overbrace{\rho^f(1-\phi)\frac{D\vec{u^f}}{Dt}}^{\text{unsteady+inertia}} = \overbrace{-(1-\phi)\vec{\nabla}p}^{\text{fluid pressure}} + \overbrace{\vec{\nabla}.\overline{\overline{\tau^f}}}^{\text{Fluid st.}} + (1-\phi)\vec{f} + \rho^f(1-\phi)\vec{g} \overbrace{-M_D}^{\text{drag}}$$

Solid: $$\frac{\partial\phi}{\partial t} + \vec{\nabla}.\left(\phi\vec{u^s}\right) = 0$$

$$\rho^s\phi\frac{D\vec{u^s}}{Dt} = -\phi\vec{\nabla}p \underbrace{-\vec{\nabla}\tilde{p^s} + \vec{\nabla}.\overline{\overline{\tau^s}}}_{\text{granular st.}} + \phi\vec{f} + \rho^s\phi\vec{g} + M_D$$

Momentum coupling through drag force:

$$M_D = \phi(1-\phi)K(\vec{u^f} - \vec{u^s}) - \frac{1}{S_c}(1-\phi)K\nu_t^f\vec{\nabla}\phi$$

- $(1-\phi)$, ϕ : fluid and particles volume fractions
- u^f : Average fluid velocity
- u^s : Average particle velocity
- p : Fluid pressure
- $\tilde{p^s}$: Particulate pressure
- S_c : Schmidt Number

Drag law:

$$K = 0.75\frac{24}{Re_p}\left(1 + 0.15Re_p^{0.687}\right)\frac{\rho^f}{d}||\vec{u^f} - \vec{u^s}||(1-\phi)^{-2.65}$$

$Re_p = (1-\phi)||\vec{u^f} - \vec{u^s}||\, d/\nu^f$: particulate Reynolds number

Schiller & Naumann [1933] + Richardson & Zaki [1954]

3D Two-phase flow model equations

Fluid: $\frac{\partial(1-\phi)}{\partial t} + \overrightarrow{\nabla}.\left((1-\phi)\overrightarrow{u^f}\right) = 0$

$$\overbrace{\rho^f(1-\phi)\frac{D\overrightarrow{u^f}}{Dt}}^{\text{unsteady+inertia}} = \overbrace{-(1-\phi)\overrightarrow{\nabla}p}^{\text{fluid pressure}} + \overbrace{\overrightarrow{\nabla}.\overline{\overline{\tau^f}}}^{\text{Fluid st.}} + (1-\phi)\overrightarrow{f} + \rho^f(1-\phi)\overrightarrow{g} \overbrace{-M_D}^{\text{drag}}$$

Solid: $\frac{\partial\phi}{\partial t} + \overrightarrow{\nabla}.\left(\phi\overrightarrow{u^s}\right) = 0$

$$\rho^s\phi\frac{D\overrightarrow{u^s}}{Dt} = -\phi\overrightarrow{\nabla}p \underbrace{-\overrightarrow{\nabla}\tilde{p^s} + \overrightarrow{\nabla}.\overline{\overline{\tau^s}}}_{\text{granular st.}} + \phi\overrightarrow{f} + \rho^s\phi\overrightarrow{g} + M_D$$

Momentum coupling through drag force:

$$M_D = \phi(1-\phi)K(\overrightarrow{u^f} - \overrightarrow{u^s}) - \frac{1}{S_c}(1-\phi)K\nu_t^f\overrightarrow{\nabla}\phi$$

- $(1-\phi), \phi$: fluid and particles volume fractions
- u^f : Average fluid velocity
- u^s : Average particle velocity
- p : Fluid pressure
- $\tilde{p^s}$: Particulate pressure
- S_c : Schmidt Number

Drag law:

$$K = 0.75\frac{24}{Re_p}\left(1 + 0.15Re_p^{0.687}\right)\frac{\rho^f}{d}||\overrightarrow{u^f} - \overrightarrow{u^s}||\,(1-\phi)^{-2.65}$$

$Re_p = (1-\phi)||\overrightarrow{u^f} - \overrightarrow{u^s}||\, d/\nu^f$: particulate Reynolds number

Schiller & Naumann [1933] + Richardson & Zaki [1954]

Dense granular flow rheology: $\mu(I)$

Particulate pressure: $\tilde{p^s} = p^{ff} + p^s$

$\phi_{min}^{fric} = 0.57$; $\phi_{max} = 0.635$ (spheres).

Permanent Contact: $p^{ff} = Fr \dfrac{\left(\phi - \phi_{min}^{fric}\right)^{\eta}}{(\phi_{max} - \phi)^{p}}$

Johnson & Jackson [1987]

Shear induced: $p^s = \left(\dfrac{B_\phi \phi}{\phi_{max} - \phi}\right)^2 \rho^s d^2 ||\overline{\overline{S^s}}||^2$

$\overline{\overline{S^s}}$: solid phase velocity shear rate tensor

Dense granular flow rheology: $\mu(I)$

Particulate pressure: $\tilde{p}^s = p^{ff} + p^s$

$\phi_{min}^{fric} = 0.57$; $\phi_{max} = 0.635$ (spheres).

Permanent Contact: $p^{ff} = Fr \dfrac{\left(\phi - \phi_{min}^{fric}\right)^{\eta}}{(\phi_{max} - \phi)^{p}}$

Johnson & Jackson [1987]

Shear induced: $p^s = \left(\dfrac{B_\phi \phi}{\phi_{max} - \phi}\right)^2 \rho^s d^2 ||\overline{\overline{S^s}}||^2$

$\overline{\overline{S^s}}$: solid phase velocity shear rate tensor

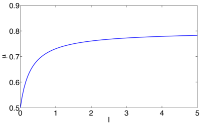
Particulate shear stress: $\overline{\overline{\tau^s}} = \nu_{Fr}^s \overline{\overline{S^s}}$

Frictional shear viscosity:

$$\nu_{Fr}^s = \min\left(\frac{\mu(I)\ \tilde{p}^s}{\rho^s \left(||\ \overline{\overline{S^s}}\ ||^2 + D_{small}^2\right)^{1/2}}, \nu_{max}\right)$$

Relates particle shear str. & total part. pressure

$\mu(I) = \mu_s + \dfrac{\mu_2 - \mu_s}{I_0/I + 1}$, I: Inertial number



GDR Midi [2004], Jop et al. [2006], Forterre & Pouliquen [2008]

Two phase k-ω 2006 fluid turbulence model

Turbulent eddy viscosity: $\nu_t^f = \dfrac{k}{max\left(\omega, \frac{7}{8}\sqrt{\frac{2S_{ij}^f S_{ij}^f}{C_\mu}}\right)}$, Wilcox [2006].

$P = R_{ij}^f \dfrac{\partial {u^f}_i}{\partial x_j}, \; \nu_G = \nu^f + \sigma {\nu_t}^f$

Turbulent Kinetic Energy

$$\frac{Dk}{Dt} = P - C_\mu k\omega + \frac{\partial}{\partial x_j}\left[\nu_G \frac{\partial k}{\partial x_j}\right] \underbrace{- \frac{2K\phi(1-e^{-BS_t})k}{\rho^f\ (1-\phi)}}_{\text{Turbulent drag modulation}} \underbrace{- \frac{{\nu_t}^f(s-1)}{S_c(1-\phi)} \frac{\partial \phi}{\partial x_j} g_j}_{\text{turb. suspension}}$$

Specific Dissipation Rate

$$\frac{D\omega}{Dt} = A_1 \frac{\omega}{k} P - B_1 \omega^2 + \frac{\partial}{\partial x_j}\left[\nu_G \frac{\partial \omega}{\partial x_j}\right] + C_{k\omega} - C_{3_\omega} \frac{2K\phi(1-e^{-BS_t})\omega}{\rho^f\ (1-\phi)} - C_{4_\omega} \frac{\omega(s-1){\nu_t}^f}{S_c(1-\phi)k} \frac{\partial \phi}{\partial x_j} g_j$$

$C_{k\omega}$: Cross-diffusion term (Wilcox [2006]).

With S_t the Stokes Number: $S_t = \frac{t_p}{t_l} = \frac{\rho^a/K}{k/6\varepsilon} = \frac{\text{particle response time}}{\text{time scale of en. eddies}}$

Adapted from two-phase flow $k-\varepsilon$ model (Hsu et al. [2004]).

sedFoam: 3D two-phase num model for sediment transport

- New sedFoam version (openFOAM 5.0 and v1806): https://github.com/SedFoam/sedfoam/releases/tag/3.0.
- Turbulence-averaged Eulerian two- phase model for sediment transport based on openFOAM (Cheng et al. [2017], Chauchat et al. [2017])
- *fluidfoam* a python package to perform plots with OpenFoam data (http://bitbucket.org/fluiddyn/fluidfoam/).
- Latest release improvements:
  - reduced pressure algorithm + stability improvement
  - **two phase k-ω 2006 turbulence model(sedFoamv3.1)**
  - **two phase k-ω/ε turbulence model(sedFoamv3.1)**


Geoscientific Model Development
An interactive open-access journal of the European Geosciences Union

| EGU.eu | EGU Journals | EGU Highlight Articles | Contact | Imprint | Data protection |

Geosci. Model Dev., 10, 4367-4392, 2017
https://doi.org/10.5194/gmd-10-4367-2017
© Author(s) 2017. This work is distributed under the Creative Commons Attribution 3.0 License.

Volume 10, issue 12

Article | Assets | Peer review | Metrics | Related articles

Model description paper — 30 Nov 2017

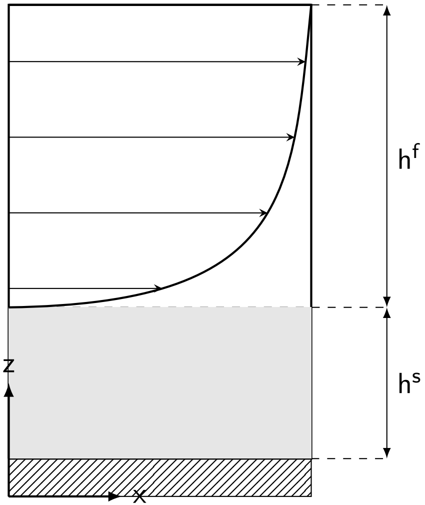
SedFoam-2.0: a 3-D two-phase flow numerical model for sediment transport

Julien Chauchat[1], Zhen Cheng[2,a], Tim Nagel[1], Cyrille Bonamy[1], and Tian-Jian Hsu[2]
[1]University of Grenoble Alpes, LEGI, G-INP, CNRS, 38000 Grenoble, France
[2]Civil and Environmental Engineering, Center for Applied Coastal Research, University of Delaware, Newark, DE 19711, USA
[a]now at: Applied Ocean Physics & Engineering, Woods Hole Oceanographic Institution, Woods Hole, MA 02543, USA

Received: 22 Apr 2017 – Discussion started: 07 Jun 2017
Revised: 04 Oct 2017 – Accepted: 20 Oct 2017 – Published: 30 Nov 2017

Abstract. In this paper, a three-dimensional two-phase flow solver, SedFoam-2.0, is presented for sediment transport applications. The solver is extended from twoPhaseEulerFoam available in the 2.1.0 release of the open-source CFD (computational fluid dynamics) toolbox OpenFOAM. In this approach the sediment phase is modeled as a continuum, and constitutive laws have to be prescribed for the sediment stresses. In the proposed solver, two different intergranular stress models are implemented: the kinetic theory of granular flows and the dense granular flow rheology $\mu(I)$. For the fluid stress, laminar or turbulent flow regimes can be simulated and three different turbulence models are available for sediment transport: a simple mixing length model (one-dimensional configuration only), a $k-\varepsilon$, and a $k-\omega$ model. The numerical implementation is demonstrated on four test cases: sedimentation of suspended particles, laminar bed load, sheet flow, and scour at an apron. These test cases illustrate the capabilities of SedFoam-2.0 to deal with complex turbulent sediment transport problems with different combinations of intergranular stress and turbulence models.

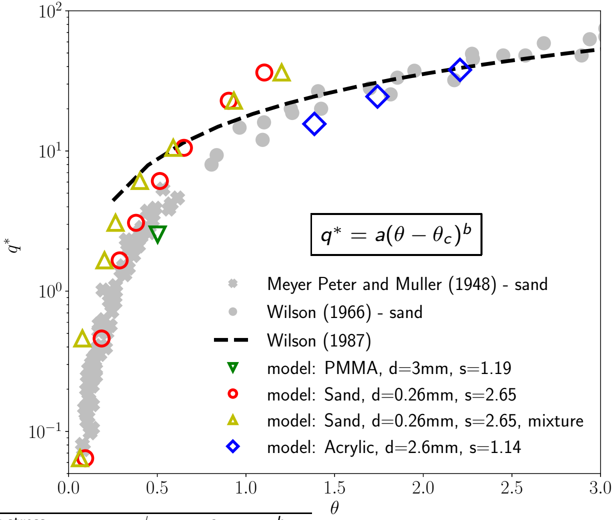
Unidirectional flows (1D2C Computations)



3 experimental reference cases:

- Roulund et al. [2005]: **BedLoad**; d=0.26 mm ; Sand; $\rho^s = 2650$ kg/m^3.
- Revil-Baudard et al. [2015]: **Sheet-Flow**; d=3 mm ; PMMA; $\rho^s = 1190$ kg/m^3.
- Sumer et al. [1996]: **Sheet-Flow**; d=2.6 mm ; Acrylic; $\rho^s = 1140$ kg/m^3.

Unidirectional flows validation



$$q_n^* = \frac{\int || \vec{u^s} . \vec{t} || \phi dz}{\sqrt{(s-1)gd^3}}$$

$$\theta = \frac{max(R^f_{xz})}{(\rho^s - \rho^f)gd}$$

$$\theta = \frac{\tau^f_{xz}(\phi) + \tau^s_{xz}(\phi)}{(\rho^s - \rho^f)gd}$$

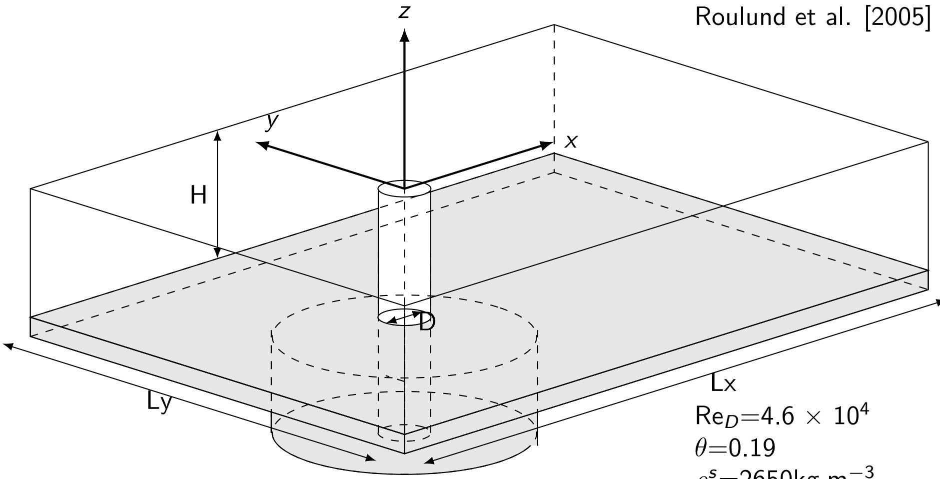
Bed shear stress	ϕ	a	b
Meyer-Peter and Muller [1948]	-	8	1.50
fluid	-	32.13	2.18
mixture	0.45	31.06	1.57
mixture	**0.08**	**26.14**	**2.09**

$q^* = f(\theta)$ recovered for a large range of θ

Live-Bed case: geometry

5 308 368 cells (Resolution: 1.2 10^{-3}m around cyl perimeter)

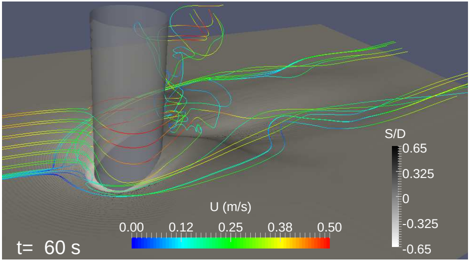
D=0.1m
H=2D
Lx=13D, Ly=8D
Roulund et al. [2005]

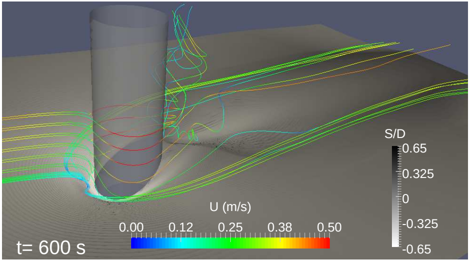


Re_D=4.6 × 10^4
θ=0.19
ρ^s=2650kg.m^{-3}
d=0.26mm

Live-Bed case: 3D Scour

Simulation run up to 600s ⇒ 60% of the scour equilibrium

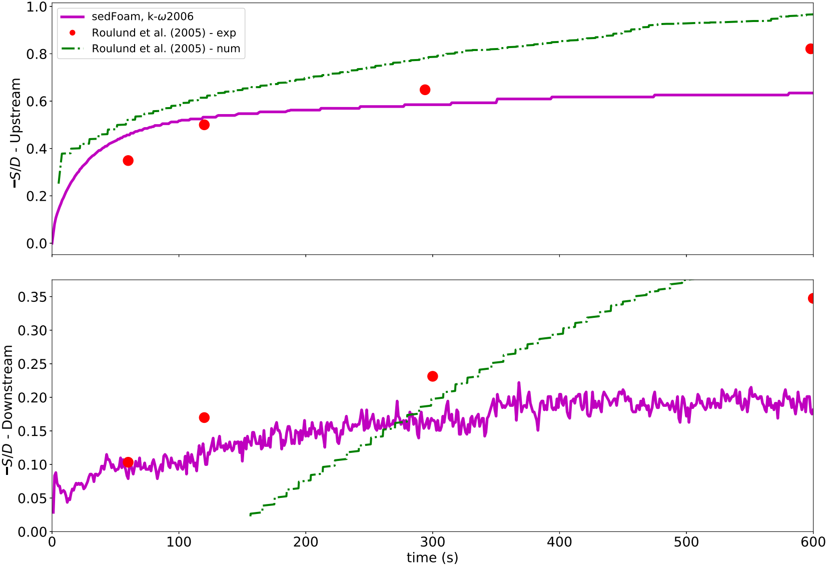




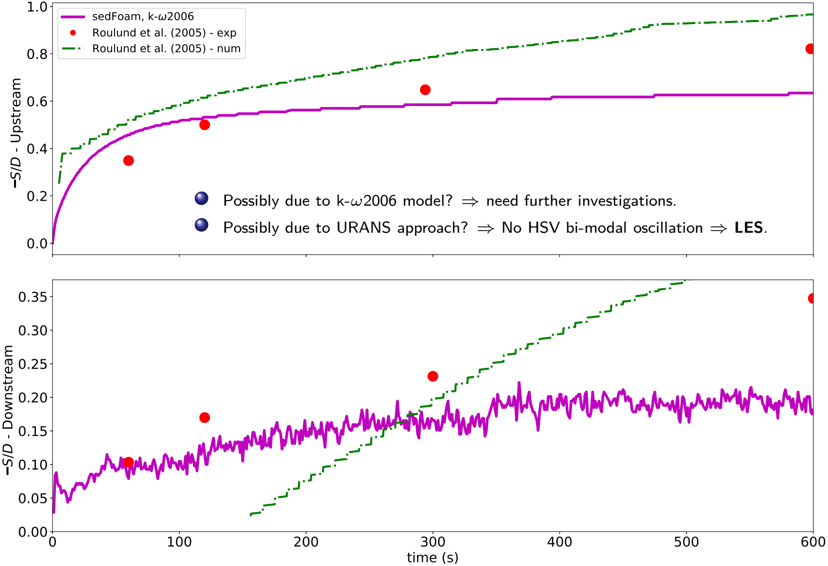
S=Scour depth

- Computational challenge.
- High computational cost ⇒ equivalent to 12 years on a single processor.

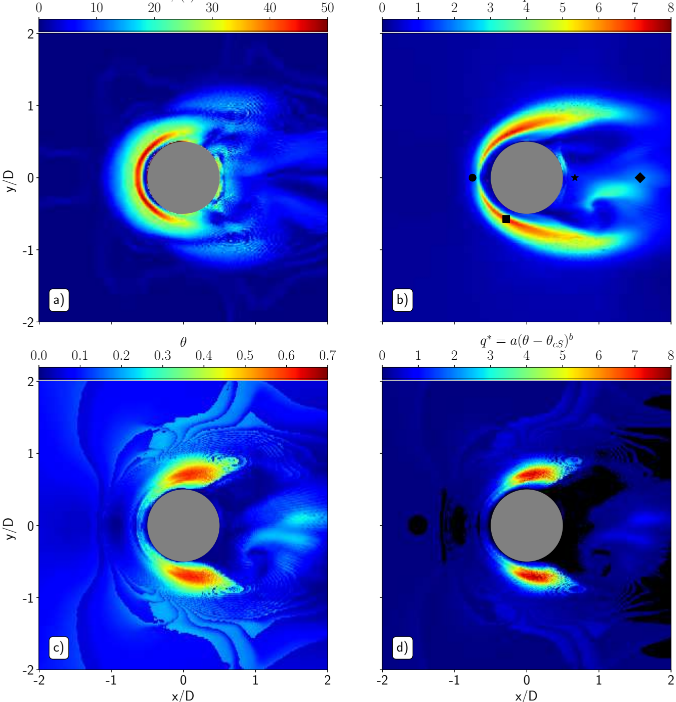
Live-Bed case: Erosion depth evolution in time



Live-Bed case: Erosion depth evolution in time



t=10s



The **sediment flux** in **b)** is computed using the local sediment velocity and concentration.

In the **upstream vicinity of the cylinder** the **sediment flux** is more **correlated with the high bed-slope** (0-45°)

Strong **correlation** between the maximum **bed shear stress** and the maximum **flux (45-120°)**

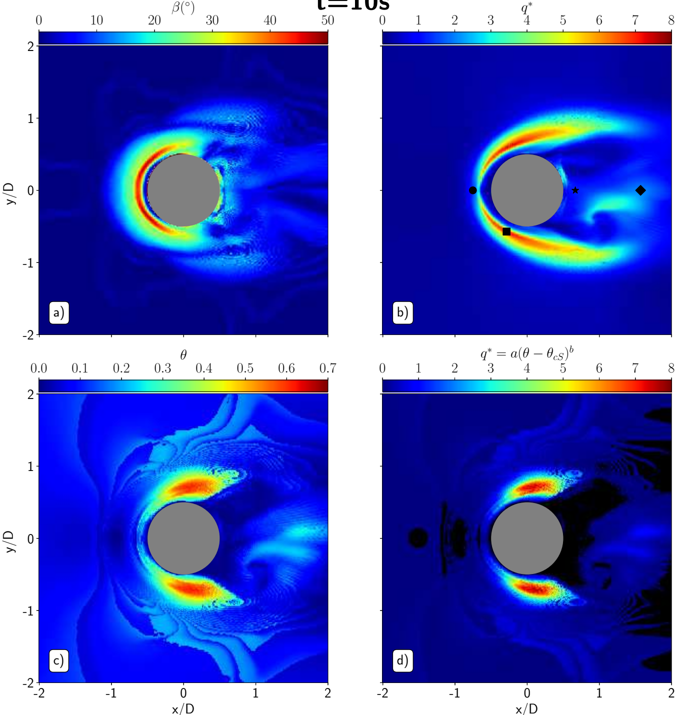
The **two legs of flux downstream** are correlated with the **HSV legs** (see Link et al. [2012]).

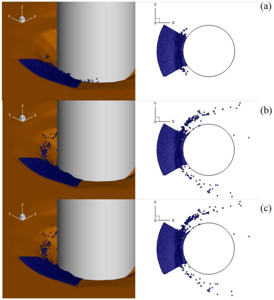
Sediment flux "classical" formula (d):

$$q^* = a(\theta - \theta_c(\beta))^b,$$

where a= 26.14 and b=2.09, from 1D simulations.

t=10s





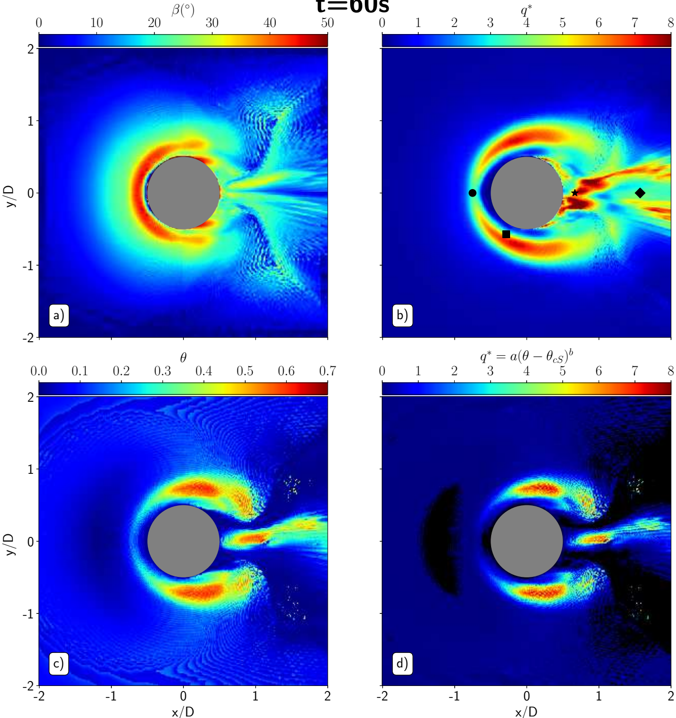
Link et al. [2012]

Sediment flux "classical" formula (d):

$$q^* = a(\theta - \theta_c(\beta))^b,$$

where a= 26.14 and b=2.09, from 1D simulations.

t=60s



The **sediment flux** in **b)** is computed using the local sediment velocity and concentration.

In the **upstream vicinity of the cylinder** the **sediment flux** is more **correlated with the high bed-slope** (0-45°)

Strong **correlation** between the maximum **bed shear stress** and the maximum **flux (45-120°)**

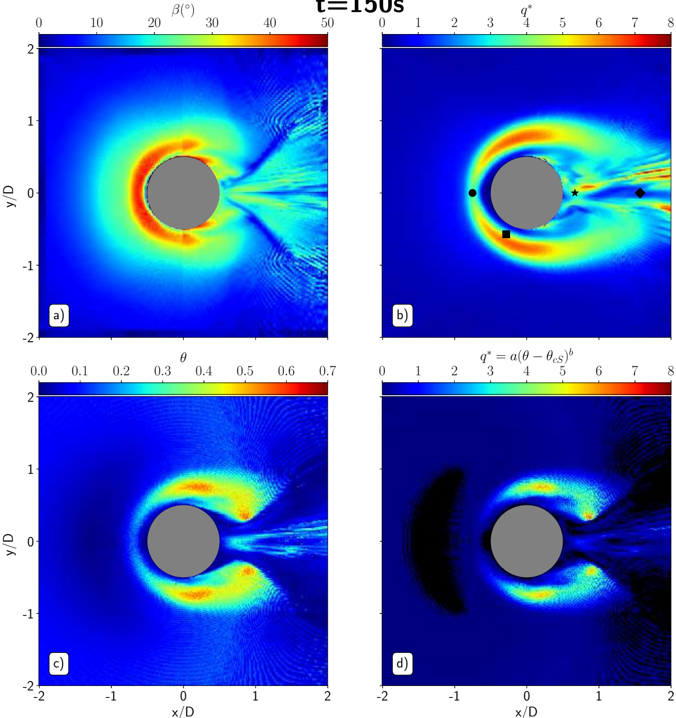
The **two legs of flux downstream** are correlated with the **HSV legs** (see Link et al. [2012]).

Sediment flux "classical" formula (d):

$$q^* = a(\theta - \theta_c(\beta))^b,$$

where a= 26.14 and b=2.09, from 1D simulations.

t=150s



The **sediment flux** in **b)** is computed using the local sediment velocity and concentration.

In the **upstream vicinity of the cylinder** the **sediment flux** is more **correlated with the high bed-slope** (0-45°)

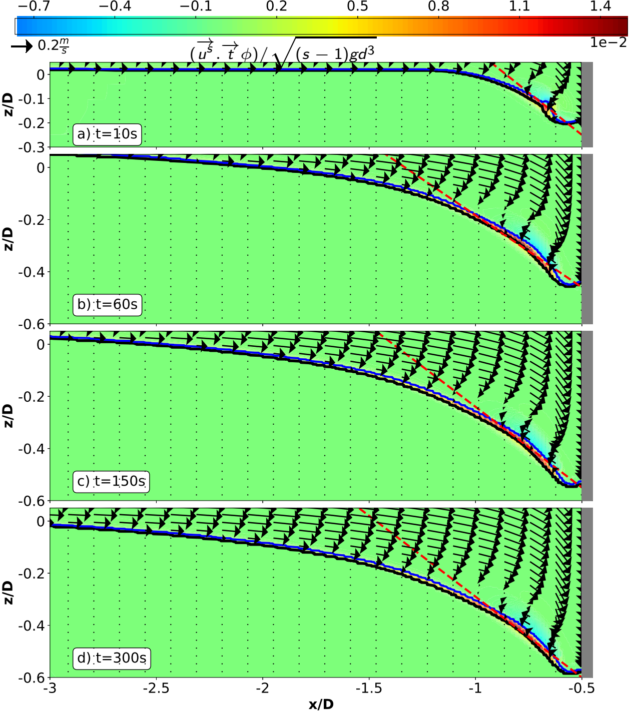
Strong **correlation** between the maximum **bed shear stress** and the maximum **flux (45-120°)**

The **two legs of flux downstream** are correlated with the **HSV legs** (see Link et al. [2012]).

Sediment flux "classical" formula (d):

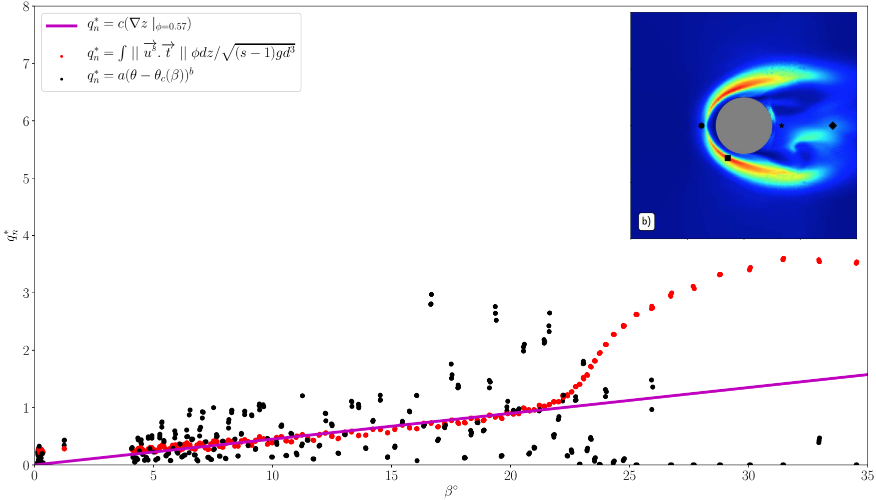
$$q^* = a(\theta - \theta_c(\beta))^b,$$

where a= 26.14 and b=2.09, from 1D simulations.



- Horseshoe vortex position seems stable.
- **A competition between the local bed shear stress (due to fluid flow over the sediments bed) and the gravity is taking place in the scour hole.**
- Bed shear stress is counter acting the gravity in the HSV.
- Avalanche downstream $X/D \approx -0.75$.
- **Importance of avalanches** in the scour process: video courtesy of O. Link, University of Conception, Chile.

Inspired from large scale morphodynamics models (Dubardier et al. [2017])



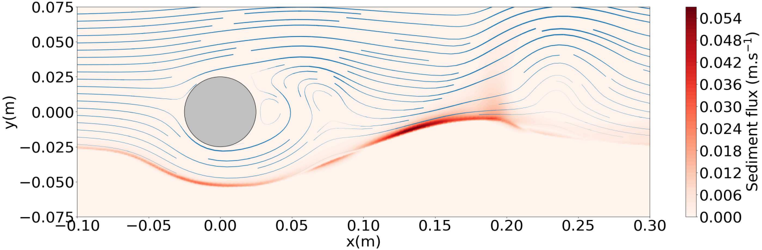
Conclusion

- **Proof of concept given:** Eulerian-Eulerian two-phase flow approach is able to simulate 3D scour process (**Pioneering work**).
- $\mu(I)$ rheology is **appropriate**. More work needs to be done on the turbulence models.
- Sediment transport around hydraulic structures **does not depend on the local bed shear stress only**.
- **Gravity is dominant** for sediment transport in the scour mark (**Avalanching**).
- **Parametrization** of the gravity contribution ($\approx$large scale beaches models) $\Rightarrow$ Ongoing work.

Perspectives

Two-phase flow simulation of scour:

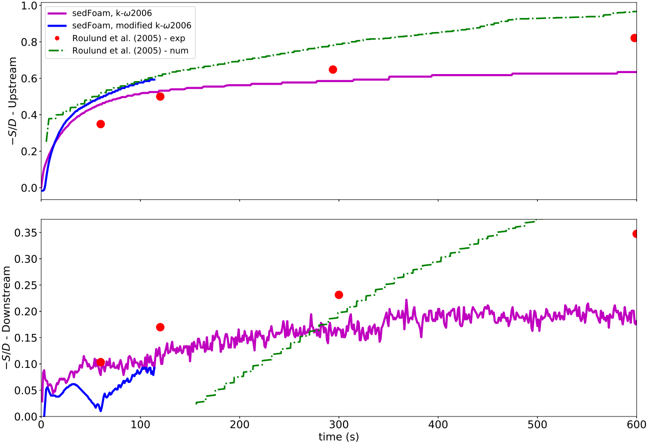
- Study two-dimensional configuration of scour under a pipeline - tunneling and lee-wake erosion stages.
- Simplified configuration for turbulence model improvement ⇒ modified k-ω 2006.



Mathieu, Chauchat, Bonamy & Nagel [In prep. for Adv. Water Ressources]

Perspectives

- Use the **modified k-ω2006** from Mathieu et al. [In prep.] to improve the long term agreement with Roulund et al. [2005] exp. results.



- Perform **LES two-phase flow simulations** of the 3D scour around the pile.

- Improve the proposed sediment transport parametrization ($\beta > 25°$...).

Modified k-ω2006 turbulence model

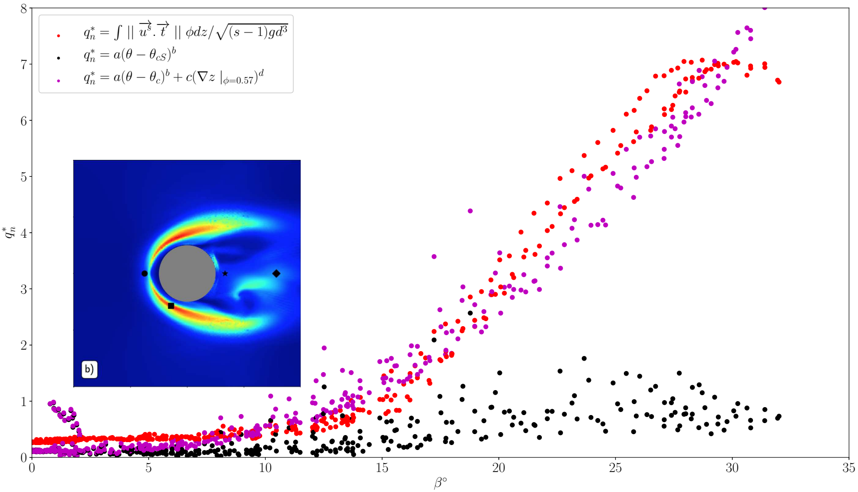
Turbulent eddy viscosity: $\nu_t^f = \dfrac{k}{max\left(\omega, C_{lim}\frac{||S^f||}{C_\mu}\mathcal{H}(\phi_{cut} - \phi)\right)}$, Mathieu et al [In prep].

Heavyside function $\Rightarrow$ suppress stress limiting term where $\phi > \phi_{cut}$

Coefficiented differently:

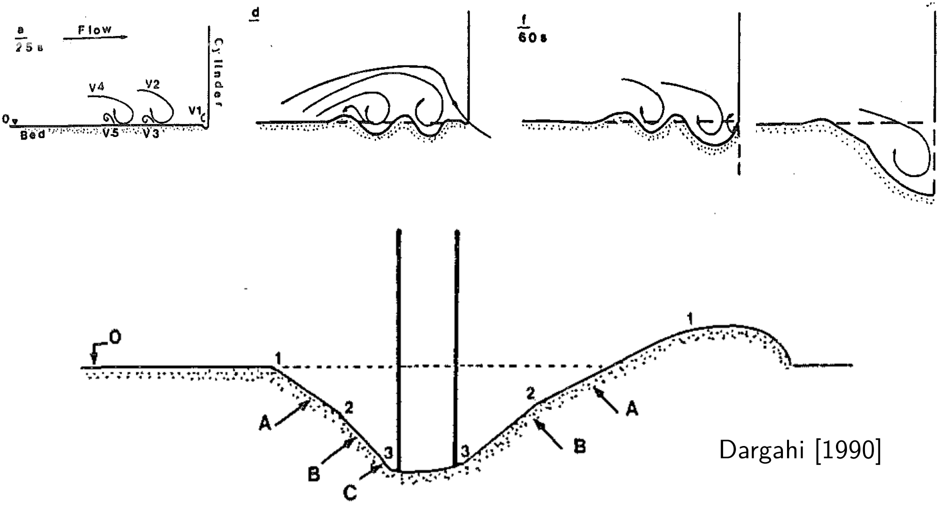
- $\phi > \phi_{cut}$ (dense sediment concentration regions) $\Rightarrow$ k-ε behavior
- $\phi < \phi_{cut}$ (dilute sediment concentration regions) $\Rightarrow$ k-ω2006 behavior

Sediment transport rate parametrization



Scour around a cylindrical pile

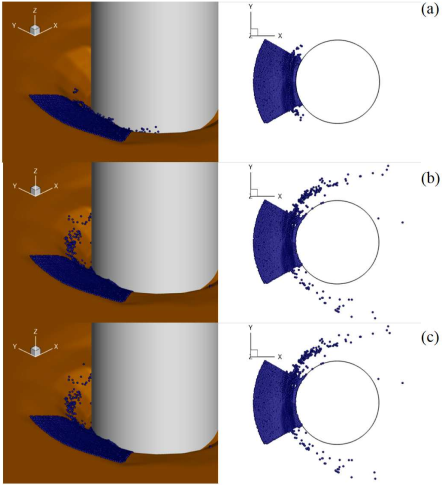
The Scour Hole formation



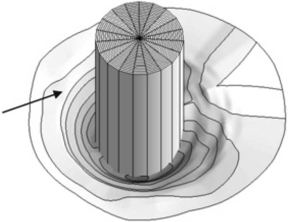
Dargahi [1990]

Scour around a cylindrical pile

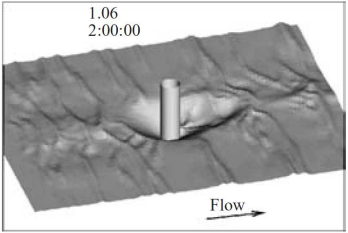
Sediment erosion and equilibrium



Link et al. [2012]

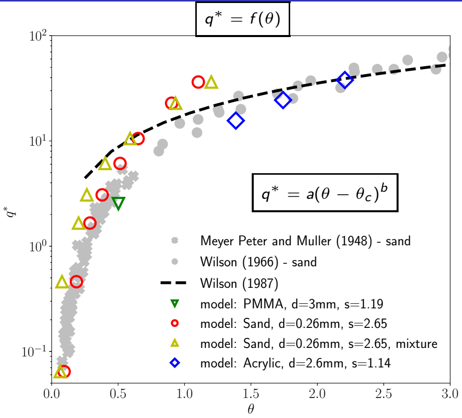


Link et al. [2012]. Clear water Regime.



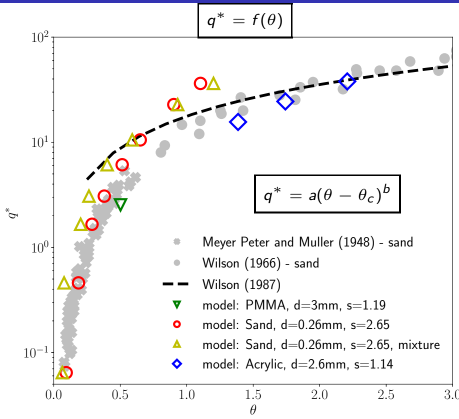
Roulund et al. [2005]. Live-Bed Regime.

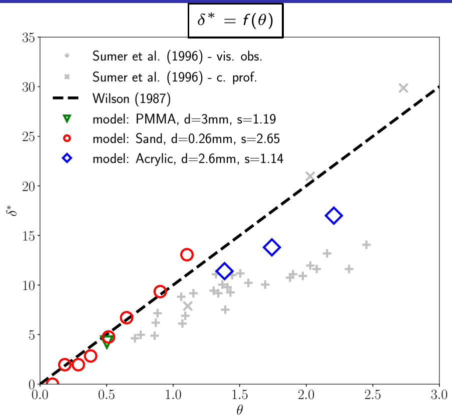
Unidirectional flows



Bed shear stress	ϕ	a	b
Meyer-Peter and Muller [1948]	-	8	1.50
Wong and Parker [2006]	-	3.97	1.50
fluid	-	32.13	2.18
mixture	0.45	31.06	1.57
mixture	0.3	28.56	1.59
mixture	**0.08**	**26.14**	**2.09**

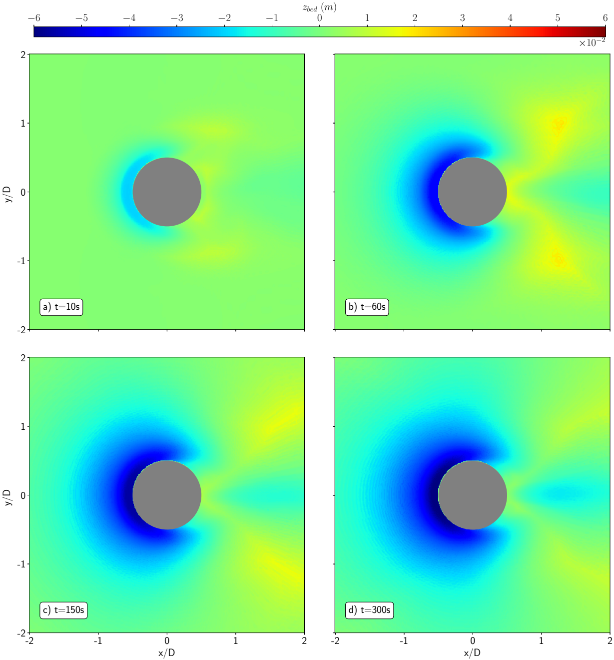
Unidirectional flows





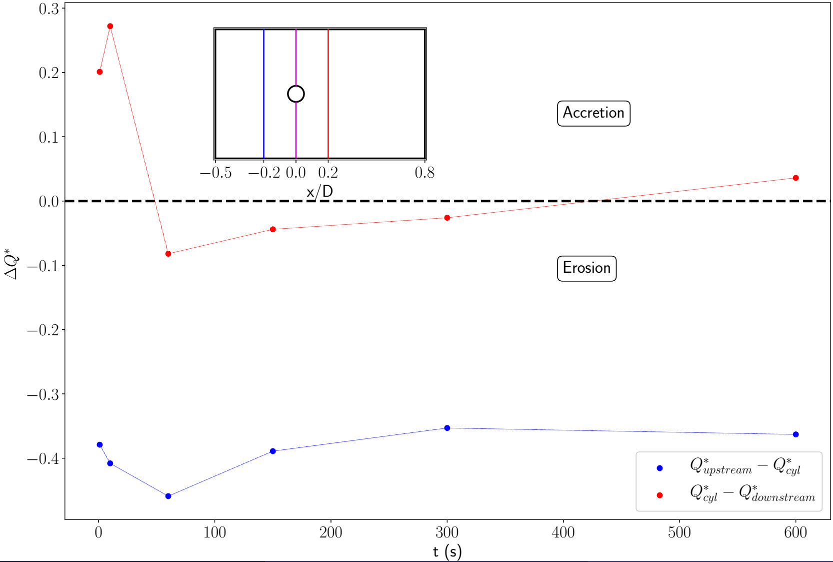
Bed shear stress	ϕ	a	b
Meyer-Peter and Muller [1948]	-	8	1.50
Wong and Parker [2006]	-	3.97	1.50
fluid	-	32.13	2.18
mixture	0.45	31.06	1.57
mixture	0.3	28.56	1.59
mixture	**0.08**	**26.14**	**2.09**

$$\underbrace{\delta^* = \frac{z(\phi|_{0.08}) - z(\phi|_{0.57})}{d}}_{\text{Dimensionless bedload transport layer}}$$



z_{bed} (m)
−6 −5 −4 −3 −2 −1 0 1 2 3 4 5 6
$\times10^{-2}$
a) t=10s
b) t=60s
c) t=150s
d) t=300s
y/D
x/D

Live-Bed case: Erosion depth evolution in time

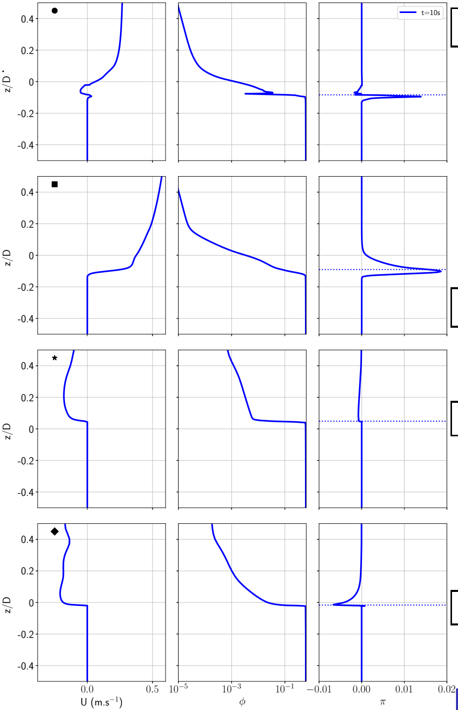


- Strong bedload sediments flux oriented toward the pile.
- Suspended load going upslope.

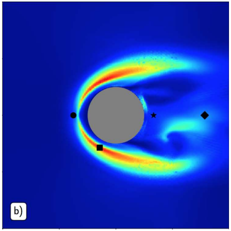
- Bedload (majority) and suspended load.
- Downstream sediments transport.

- Recirculation area.
- Upstream suspended load.

- Suspended load mostly.
- Upstream (10s),



0.25D upstream



HSV Legs

0.2D downstream

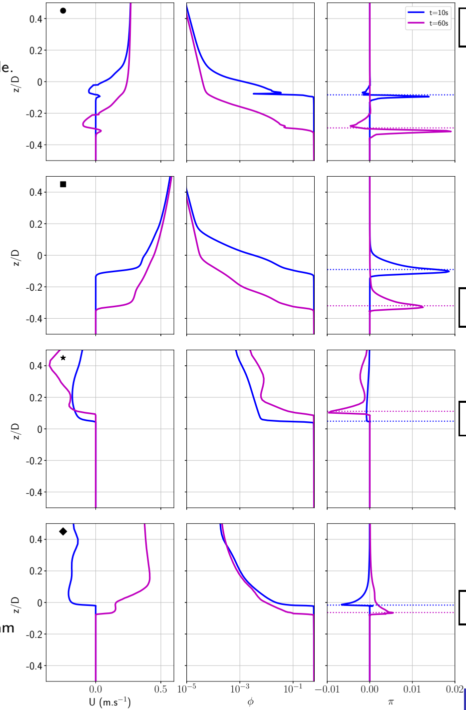
1.7D downstream

- Strong bedload sediments flux oriented toward the pile.
- Suspended load going upslope.

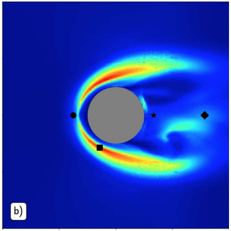
- Bedload (majority) and suspended load.
- Downstream sediments transport.

- Recirculation area.
- Upstream suspended load.

- Suspended load mostly.
- Upstream (10s), downstream (60s and 150s).



0.25D upstream

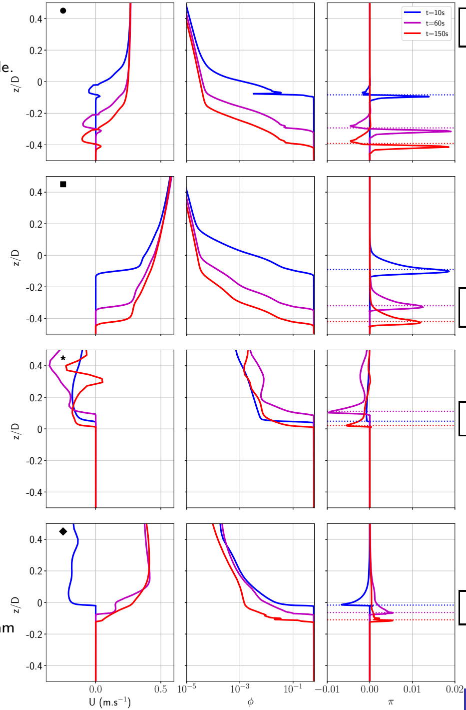


HSV Legs

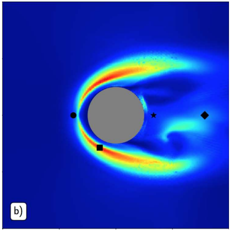
0.2D downstream

1.7D downstream

- Strong bedload sediments flux oriented toward the pile.
- Suspended load going upslope.



0.25D upstream



- Bedload (majority) and suspended load.
- Downstream sediments transport.

HSV Legs

- Recirculation area.
- Upstream suspended load.

0.2D downstream

- Suspended load mostly.
- Upstream (10s), downstream (60s and 150s).

1.7D downstream