Click to view movie (frontal splays—pulse – continuous flow).

Turbulent Process Modeling of the Dynamic Flow-Bottom Interaction*

Paulo L.B. Paraizo[1], Marco A.S. Moraes[1], Renato N. Elias[2], and Alvaro L.G.A. Coutinho[3]

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[3]COPPE/Federal University of Rio de Janeiro, Brazil.

Abstract

The application of mathematical modeling in sedimentological studies is still in its infancy for practical purposes due to several reasons: complexity of the problems, lack of theoretical models, simplicity and drawbacks of mathematical models, and suspicion by the geological community. Despite that, the growing evidence of these studies as a complementary approach is being demonstrated by the increasing number of papers dealing with the subject in the last years.

The mechanism of turbulent flows transporting and depositing a huge amount of sand is a good example of a relevant problem being investigated by numerical models. Historically, Depth-Averaged models have been extensively used to represent the Navier-Stokes equation that governs fluid flows. The Depth-Average models are a simplified version in the sense that they do not take into account the vertical variability of flow properties. More recently, Direct Numerical Simulations (DNS) have been used, in which the full 3D Navier- Stokes is solved, allowing the vertical reproduction of the flow properties as well as the complete scale representation of the turbulence, because of the adoption of very refined grid. The main drawback of the DNS is the computational time, because the full 3D equation is solved for a grid built to represent every scale of the turbulence. This alternative reduces the ability to simulate geological situations, because of the time involved for reproducing each flow.

In this work we present a method to simulate a full 3D Navier - Stokes equation in unstructured grids, in which the turbulence is solved only for the larger scales, with a technique named Large Eddy Simulation (LES). This allows the reproduction in 3D of the flow properties, and it can be run in a significantly coarser grid than the DNS.

The sedimentation obtained in our model is quantitatively validated against the more precise DNS results. We implemented a dynamic interaction between the flow and the bottom that allows the flow to be influenced by the previous sedimentation, either in one or multiple flows, without the necessity of remeshing.

We validate the reproduction of the depositional elements (lobes and channel levee systems) against quantitative outcrop data, and we performed a preliminary comparative study of steady vs. unsteady flows. We also tested the flow over irregular surfaces, mimicking real cases, benefiting from the unstructured grid characteristics to deal with complex geometries.

Selected References

Fei, J., 1982, Explanation of the hydrogeologic map of storing surface water underground in the Huang-Huai-Hai Plain: Annual Report of the Institute of Hydrogeology and Engineering Geology, p. 23-26.

Necker, F., Hartel, C., Kleiser, L., and Meiburg, E., 2002, High-resolution simulations of particle-driven gravity currents: International Journal of Multiphase Flow, v. 28, p. 279-300

Straub, K. M., and D. Mohrig, 2008, Quantifying the morphology and growth of levees in aggrading submarine channels: Journal of Geophysical Research, v. 113, p. F03012, doi:10.1029/2007JF000896.

TURBULENT PROCESS MODELING OF THE DYNAMIC FLOW-BOTTOM INTERACTION

Paulo L. B. Paraizo[1], Marco A. S. Moraes[1], Renato N. Elias[2], Alvaro L.G. A. Coutinho[3]

[1]Petrobrás / Research Center
[2]Federal Rural University of Rio de Janeiro, Brazil
[3]COPPE/Federal University of Rio de Janeiro, Brazil

AAPG – 2010 – New Orleans

Objectives

of the Work:

- intend to apply a new way to solve a known problem

of the presentation:

- present the code
- show a quantitative validation
- show some qualitative results

OUTLINE:

1 – MOTIVATION

2 – DEFINING THE PROBLEM

3 – NUMERICAL MODEL

4 - SAND TRANSPORT AND DEPOSITION

5 – DEPOSITION

6 - FLOW- BOTTOM INTERACTION

7 - CASE STUDIES

8 - CONCLUSIONS

9 – NEXT STEPS

OUTLINE:

1 – MOTIVATION

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7 - CASE STUDIES

8 - CONCLUSIONS

9 – NEXT STEPS

1 – MOTIVATION

Based on inspection in the literature, we can arbitrarily classify the turbidite numerical models in two general trends:

a – LAYER – AVERAGED MODELS

- 2D models
- use vertically averaged velocity and concentration
- no explicit turbulence model
- easy to handle
- run very fast

b – 3D – DIRECT NUMERICAL SIMULATIONS

- 3D model
- 3D description of velocity and concentration profile
- turbulence solved in all scales
- difficult to handle (need parallel super-computers)
- run very slowly

1 – MOTIVATION

We developed a turbidite numerical model in which:

a – LAYER – AVERAGED MODELS

- 2D models
- use the vertical mean velocity and concentration
- simplified turbulent model
- easy to handle
- run very fast

b – 3D – DIRECT NUMERICAL SIMULATIONS

- 3D model
- 3D description of velocity and concentration profile
- all turbulent scales included
- difficult to handle (need paralel super-computers)
- run very slowly

1 – MOTIVATION

We developed a turbidite numerical model in which:

a – LAYER – AVERAGED MODELS

- 2D models
- use the vertical mean velocity and concentration
- simplified turbulent model
- easy to handle
- run very fast

b – 3D – DIRECT NUMERICAL SIMULATIONS

- 3D model
- 3D description of velocity and concentration profile
- all turbulent scales included
- difficult to handle (need paralel super-computers)
- run very slowly

C – 3D Large Eddy Simulation – FINITE ELEMENT METHOD

- **3D model**
- Solve large scale turbulence (model low scale)
- **Run much faster than DNS**
- Easily deals with complex topography

OUTLINE:

1 – MOTIVATION

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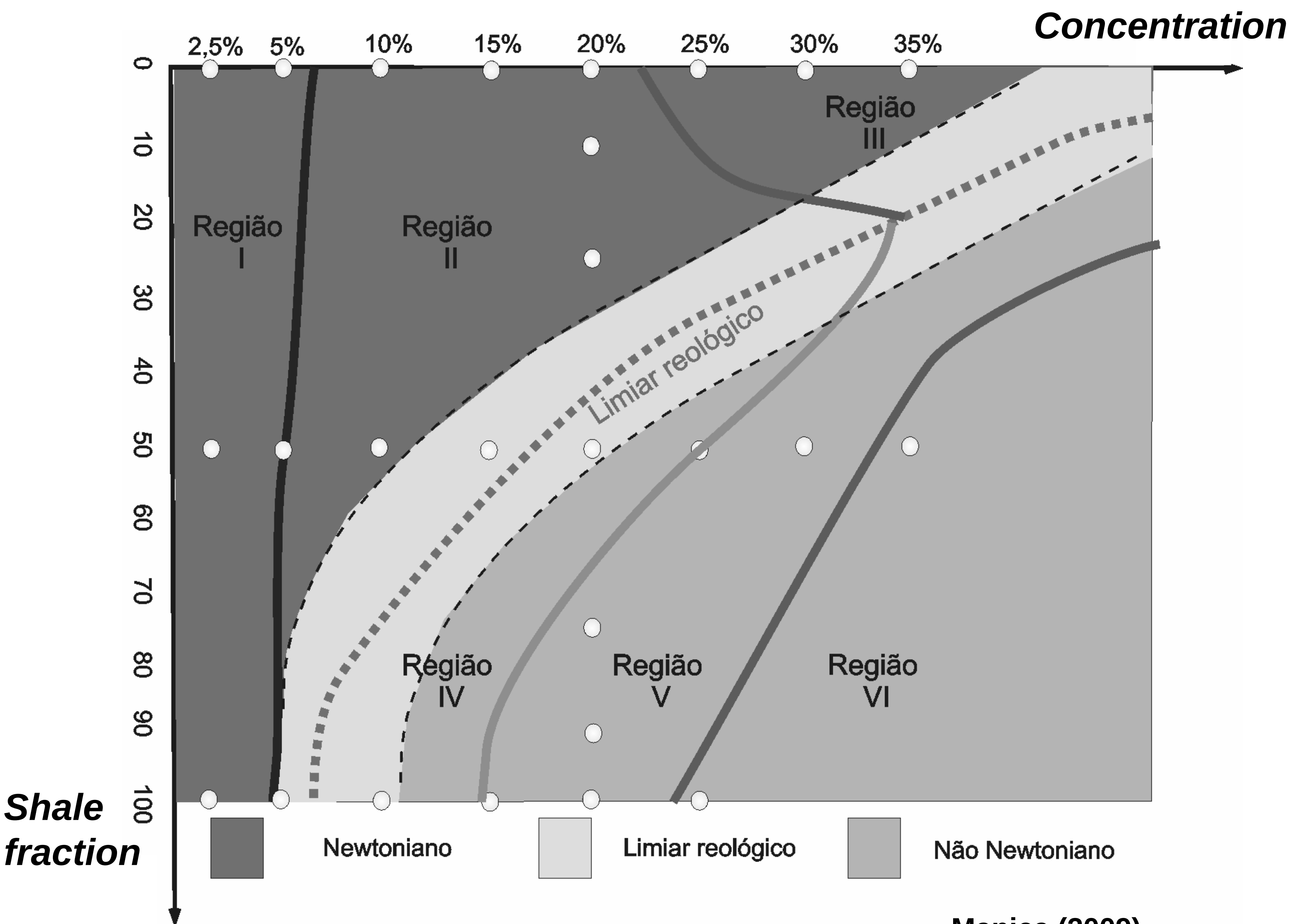
9 – NEXT STEPS

2 – DEFINING THE PROBLEM

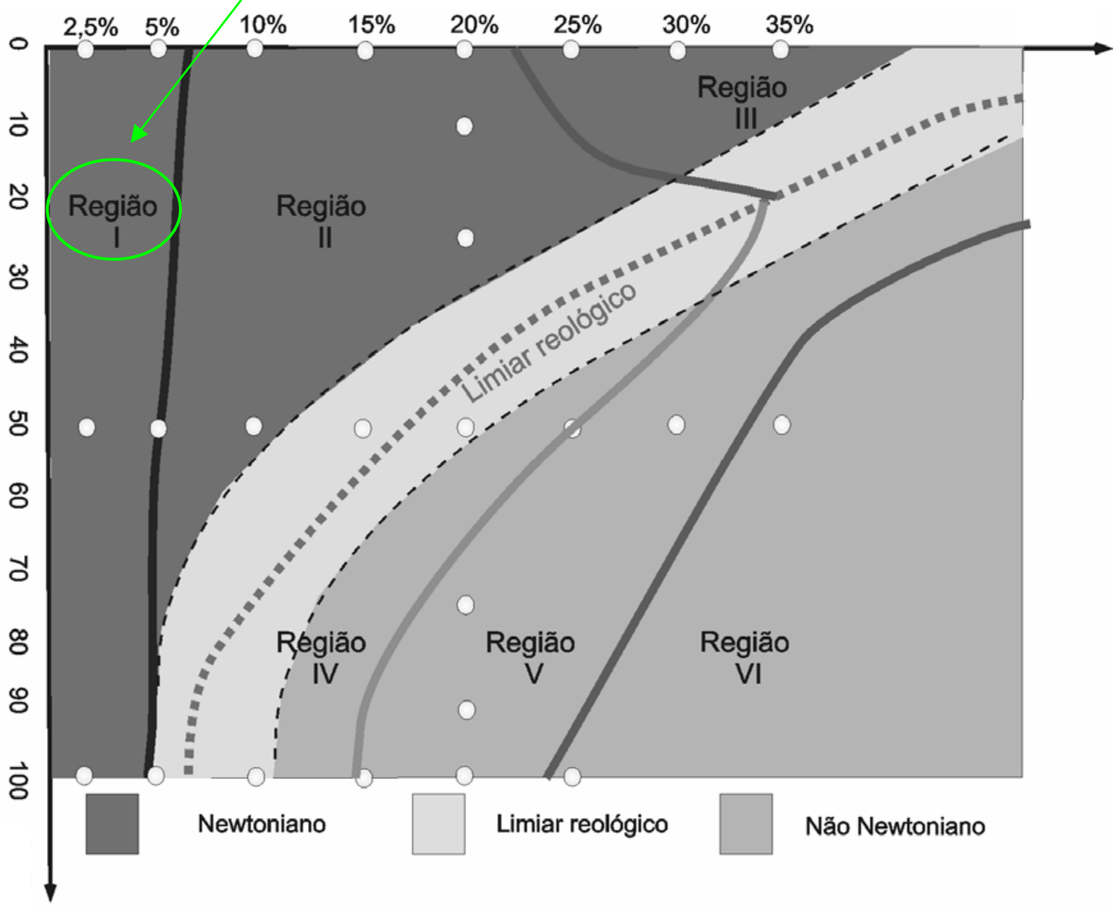


Manica (2009)

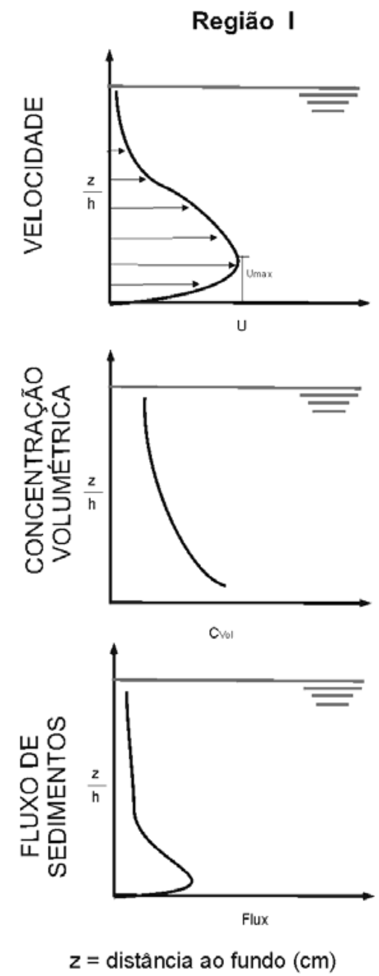
REGION I Characteristic:

Low concentration

Concentration

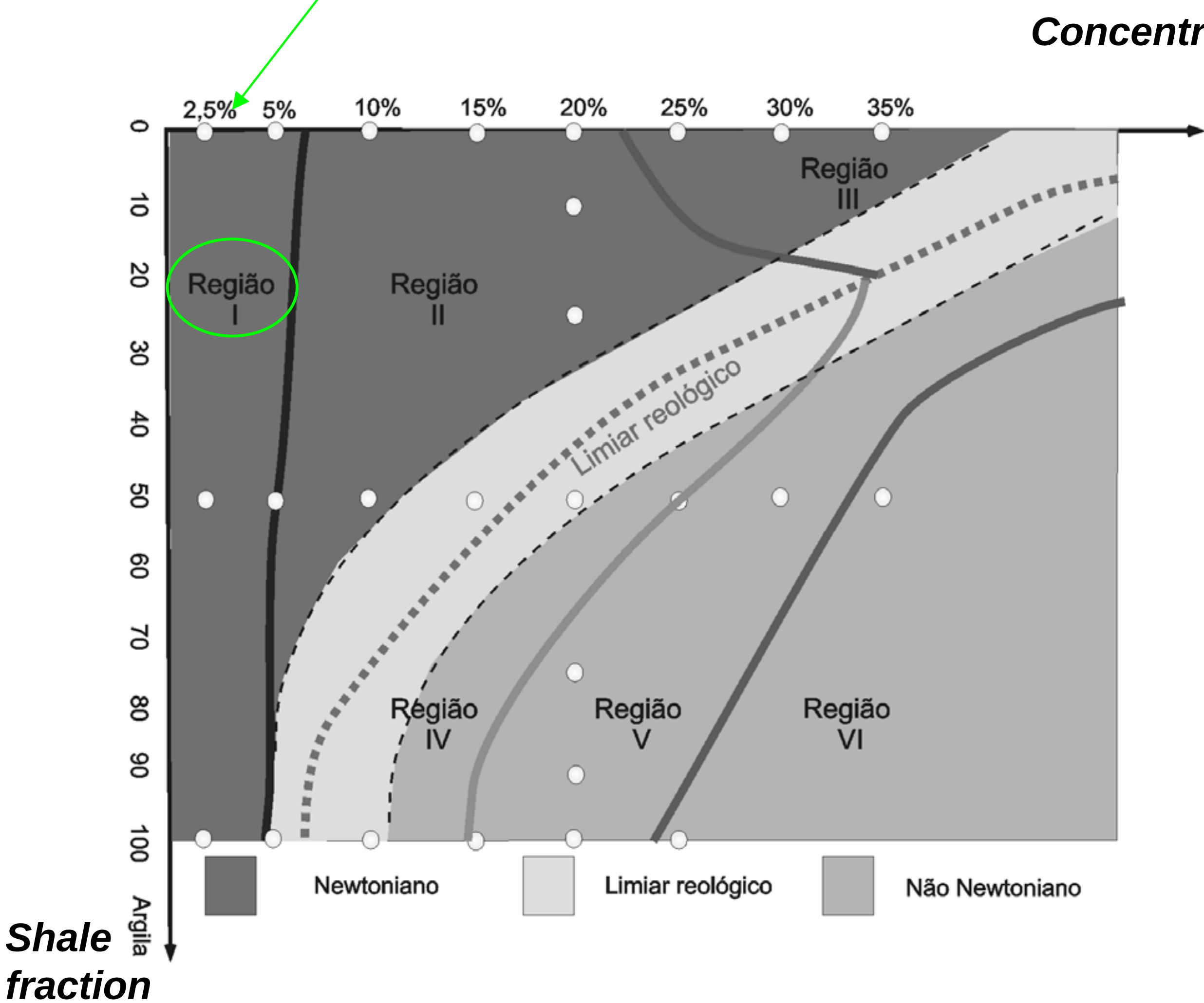


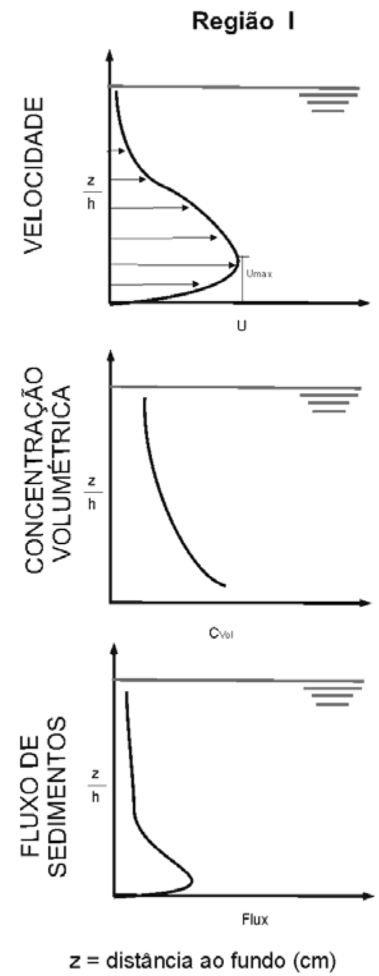
Shale fraction



THIS CODE Characteristic:

Low concentration
No shale

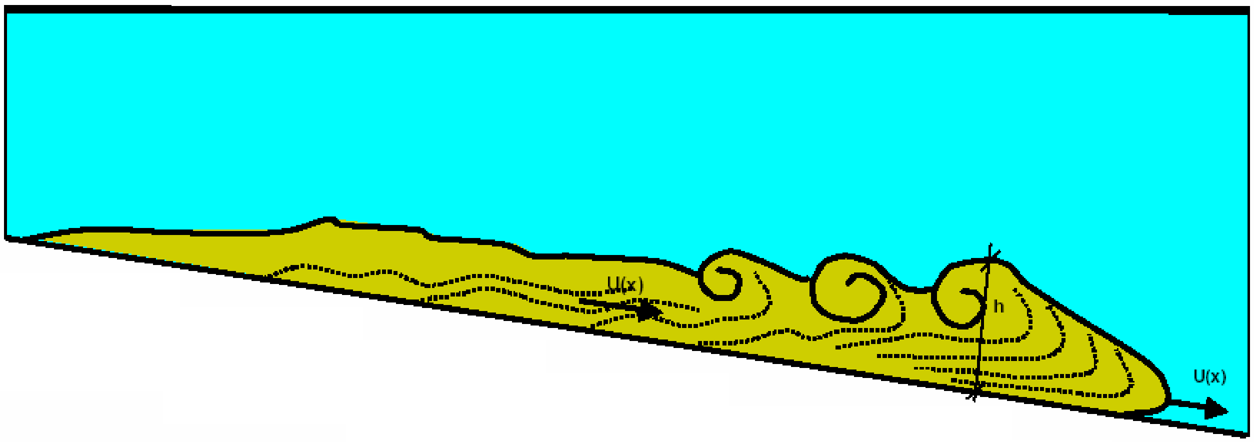




2 – DEFINING THE PROBLEM

Main Aspects of the Current

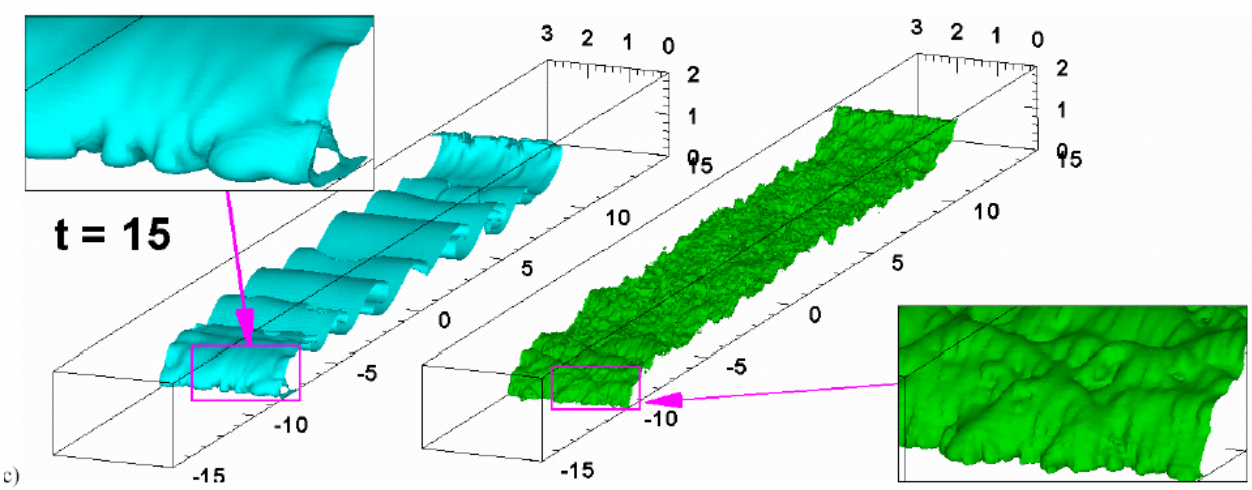
Geometry:



Del Rey (2006)

Instabilities:

-KH (*Kelvin - Helmholtz*)
-Lobes and clefts

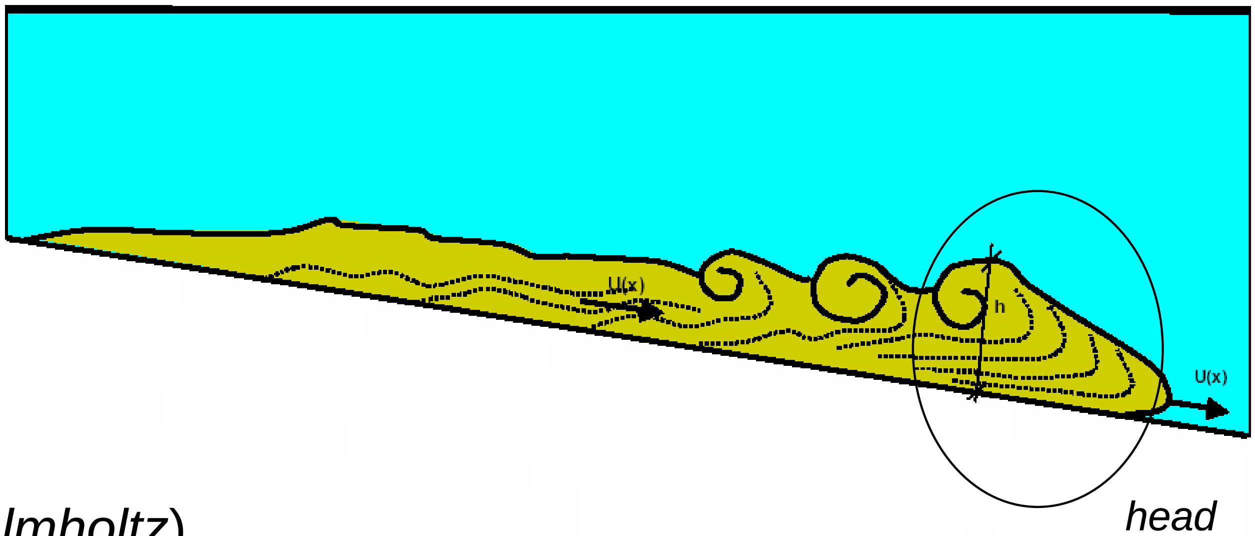


Ooi (2006)

2 – DEFINING THE PROBLEM

Main Aspects of the Current

Geometry:



Del Rey (2006)

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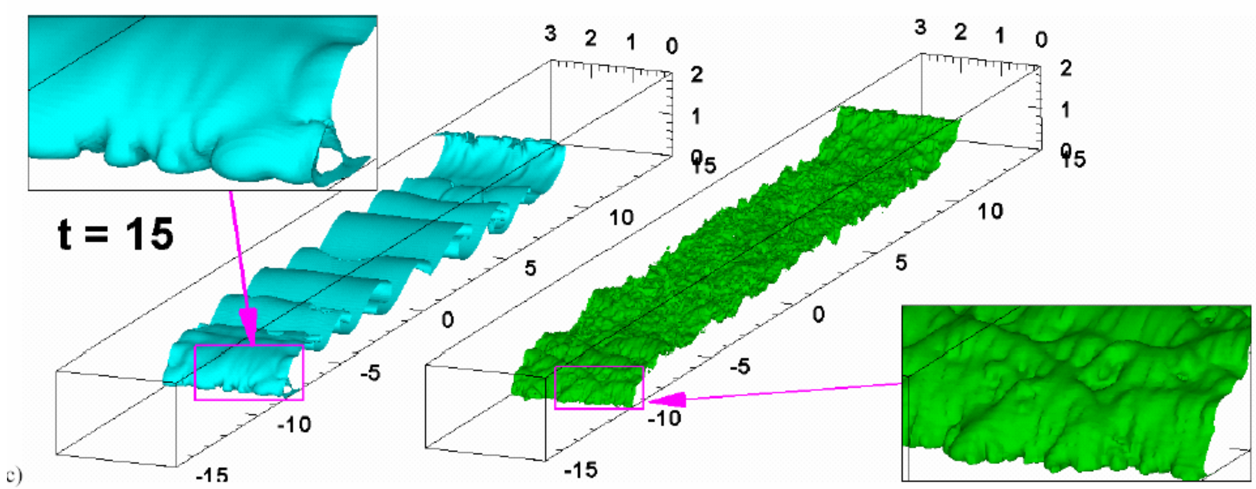
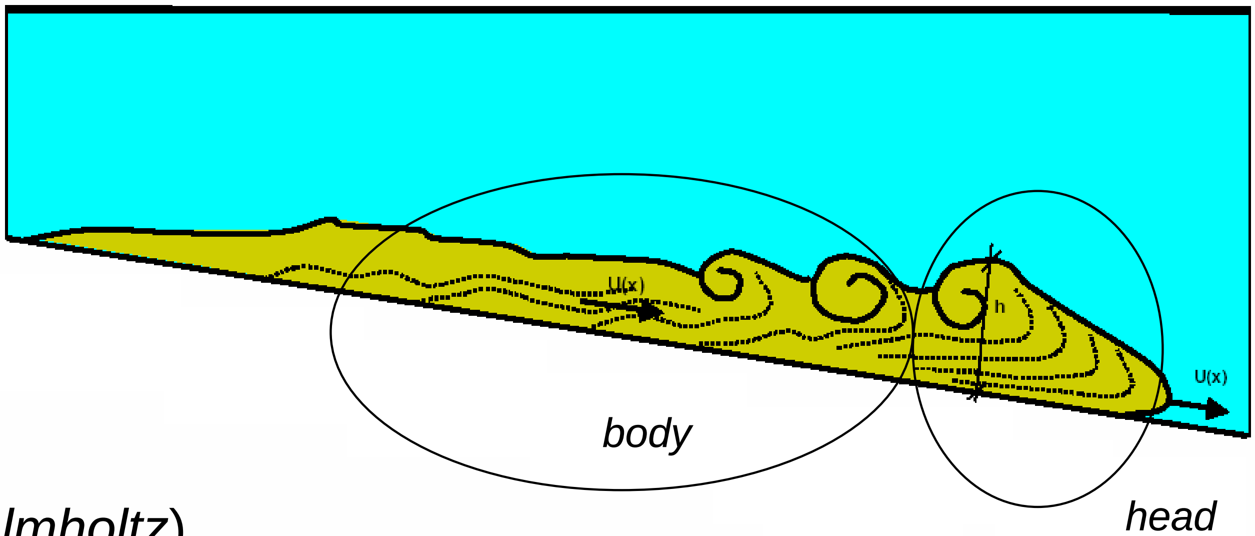


Ooi (2006)

2 – DEFINING THE PROBLEM

Main Aspects of the Current

Geometry:



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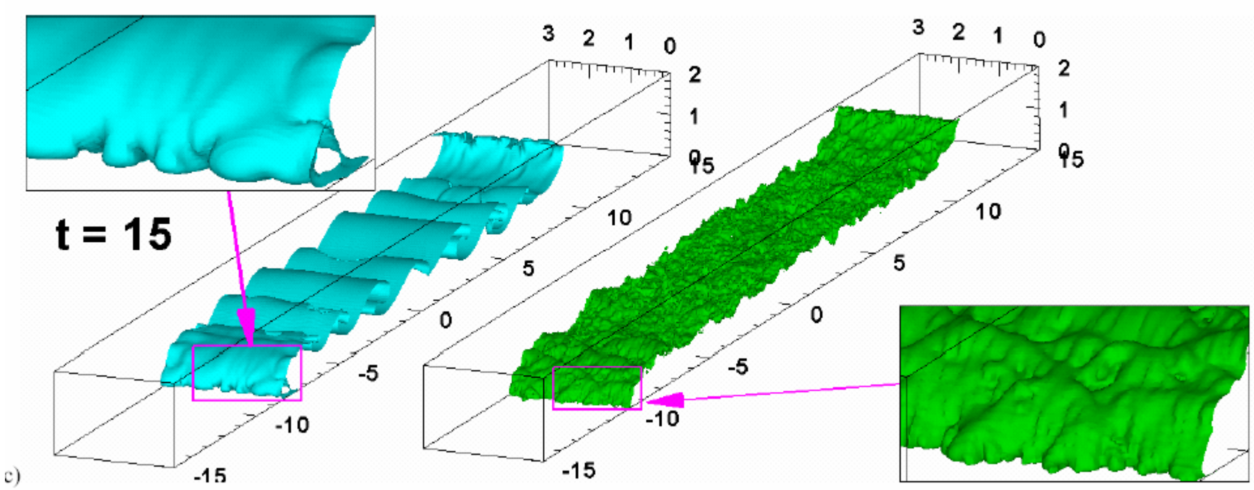
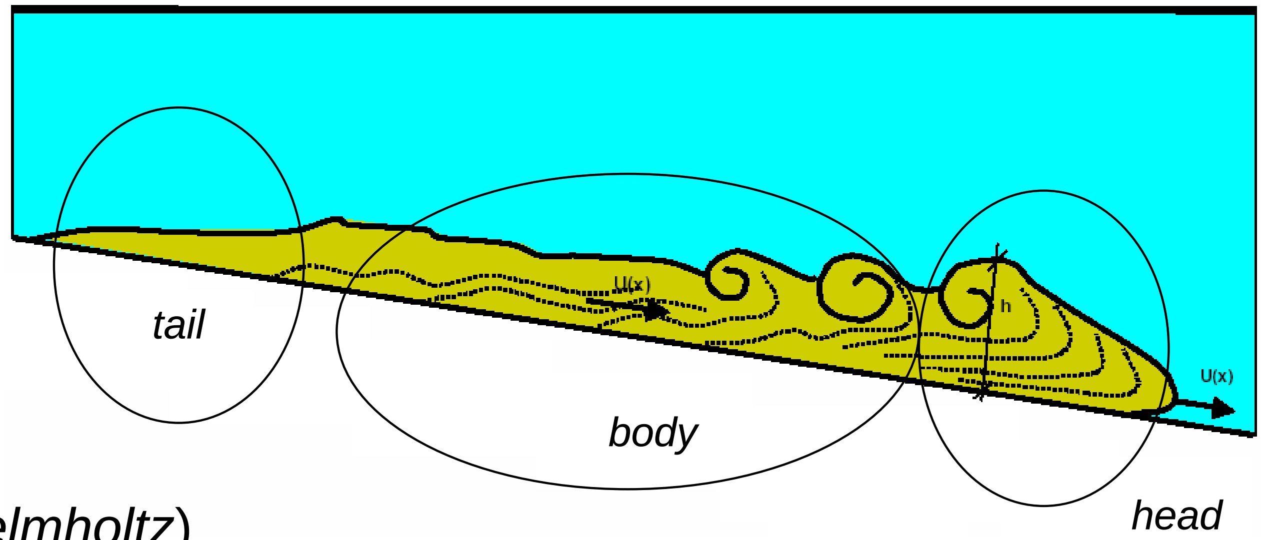


Ooi (2006)

2 – DEFINING THE PROBLEM

Main Aspects of the Current

Geometry:



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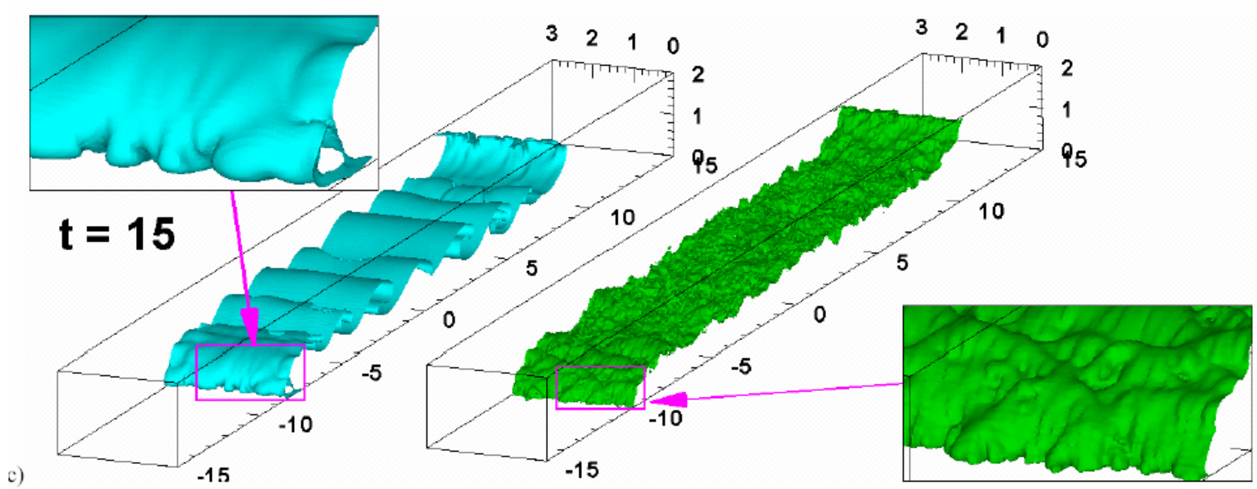
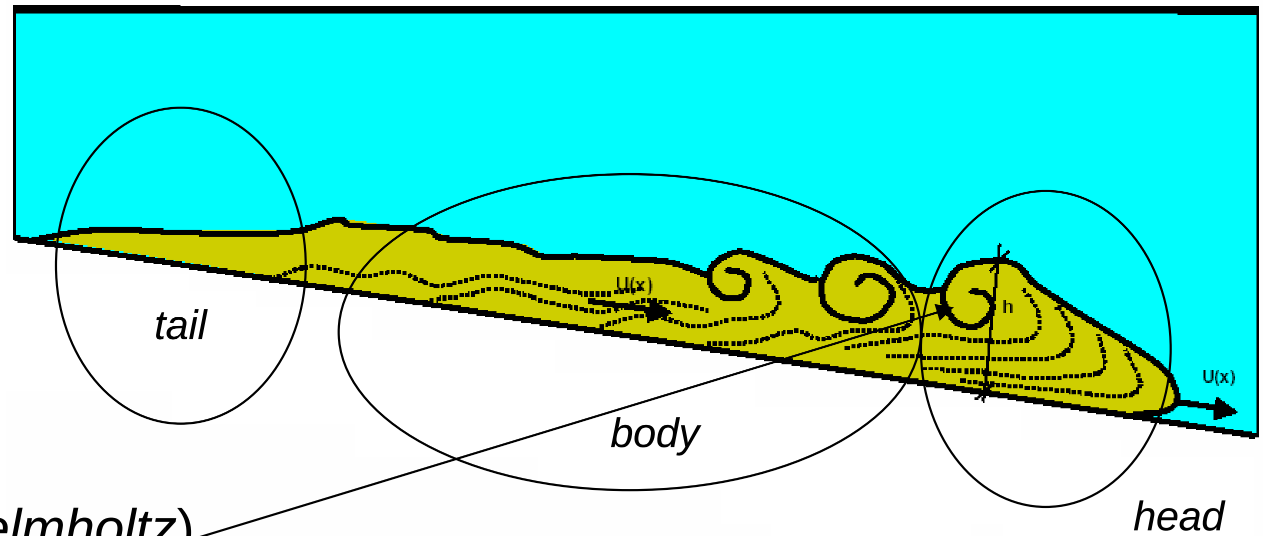


Ooi (2006)

2 – DEFINING THE PROBLEM

Main Aspects of the Current

Geometry:



Del Rey (2006)

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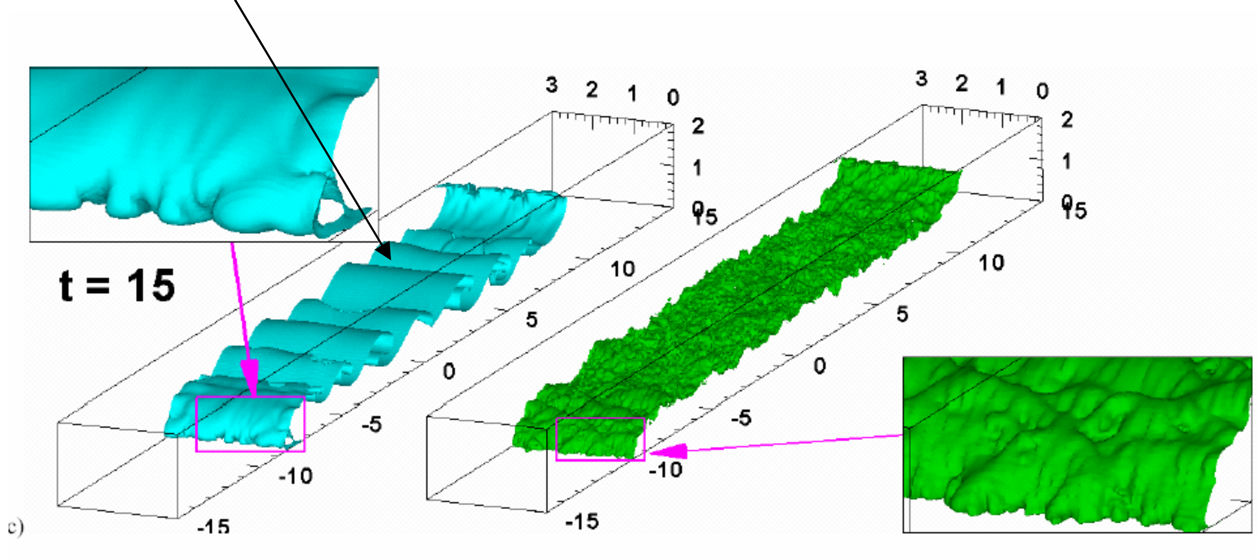
-Lobes and clefts



Ooi (2006)

OUTLINE:

1 – MOTIVATION

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3 – NUMERICAL MODEL – 2 sets of EQUATIONS

1 – INCOMPRESSIBLE NAVIER-STOKES EQUATION

A – momentum conservation

$$\frac{\partial u}{\partial t} + u.\nabla u = \rho g + \nabla.\sigma$$

B –mass conservation

$$\nabla.u = 0$$

3 – NUMERICAL MODEL

1 – INCOMPRESSIBLE NAVIER-STOKES EQUATION

A – momentum conservation

$$\frac{\partial u}{\partial t} + u.\nabla u = \rho g + \nabla.\sigma$$

density term based on density differences

$$\rho = \frac{\left(\bar{\rho}_1 - \bar{\rho}_2\right)}{\bar{\rho}_1}$$

B –mass conservation

$$\nabla.u = 0$$

2 - ADVECTION – DIFUSION EQUATION OF THE CONCENTRATION

$$\frac{\partial \phi}{\partial t} + u.\nabla \phi - \nabla.\left(\left(\frac{1}{Sc\sqrt{Gr}}\right)\nabla \phi\right) = 0$$

$$Sc = \frac{\bar{v}}{\bar{k}}$$

$$Gr = \left(\frac{\bar{u}_b \bar{l}}{\bar{v}}\right)^2$$

2 - ADVECCTION – DIFUSION EQUATION OF THE VARIABLE DENSITY

$$\frac{\partial \phi}{\partial t} + u.\nabla \phi - \nabla.\left(\left(\frac{1}{Sc\sqrt{Gr}}\right)\nabla \phi\right) = 0$$

concentration calculated from densities

$$\phi = \frac{(\bar{\rho} - \bar{\rho}_2)}{(\bar{\rho}_1 - \bar{\rho}_2)}$$

$$Sc = \frac{\bar{v}}{\bar{k}}$$

$$Gr = \left(\frac{\bar{u}_b \bar{l}}{\bar{v}}\right)^2$$

3 – NUMERICAL MODEL

TURBULENCE CONSIDERATION

1 – DNS (*Direct Numerical Simulation)*

- Extremely refined mesh. NSE solves turbulence explicitly in all scales

2 – LES (*Large Eddy Simulation)*

- Refined mesh. NSE solves turbulence in the mesh scale. Sub-mesh scale is modeled

Explicit LES – An adittional dissipation models the sub-mesh effects

Implicit LES – The numerical method dissipation models the sub-mesh effects

OUTLINE:

4 – SAND TRANSPORT AND DEPOSITION

$$\frac{\partial \phi}{\partial t} + u.\nabla \phi - \nabla.((\frac{1}{Sc\sqrt{Gr}})\nabla \phi) = 0$$

4 – SAND TRANSPORT AND DEPOSITION

- incorporation of *fall velocity (u_s)* on the transport equation

$$\frac{\partial \phi}{\partial t} + u.\nabla \phi - \nabla.((\frac{1}{Sc\sqrt{Gr}})\nabla \phi) = 0$$

$$\frac{\partial \phi}{\partial t} + (u + u_s).\nabla \phi - \nabla.((\frac{1}{Sc\sqrt{Gr}}\nabla \phi) = 0$$

4 – SAND TRANSPORT AND DEPOSITION

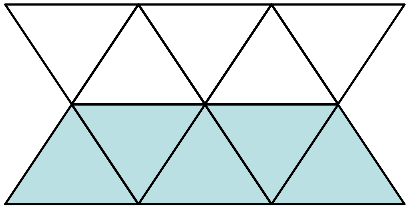
- incorporation of *fall velocity (u_s)* on the transport equation

$$\frac{\partial \phi}{\partial t} + u.\nabla \phi - \nabla.((\frac{1}{Sc\sqrt{Gr}})\nabla \phi) = 0$$

$$\frac{\partial \phi}{\partial t} + (u + u_s).\nabla \phi - \nabla.((\frac{1}{Sc\sqrt{Gr}}\nabla \phi) = 0$$

- calculation of the volume deposited for every time-step for each mesh element

$$D_t^h = \int_A u_s c^h \, dA$$



sediment flow at the very bottom

OUTLINE:

OUTLINE:

5 – DEPOSITION

VALIDATION

1 – DNS PLANAR CASE

NECKER, F., HARTEL, C., KLEISER, L., MEIBURG, E., 2002, “High-resolution simulations of particle-driven gravity currents”. ***International Journal of Multiphase Flow***, v. 28, pp. 279-300.

5 – DEPOSITION

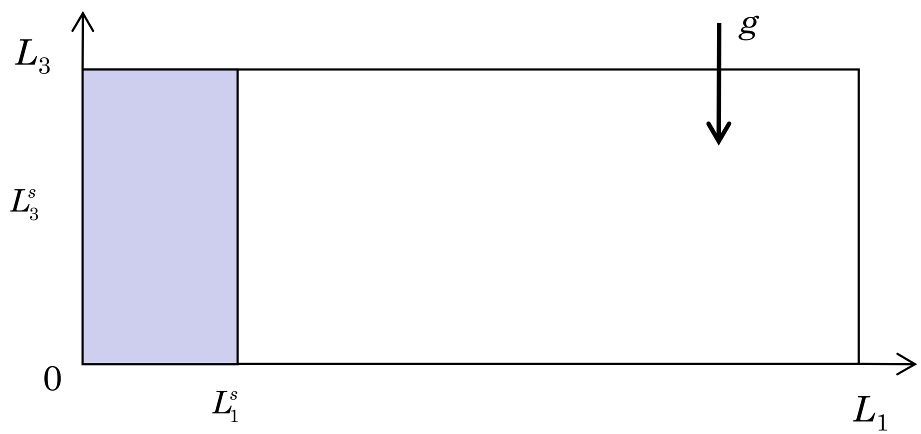
VALIDATION

1 – DNS PLANAR CASE

x = 19 units
y = 2 units
z = 2 units
Re = 10^3

REFERENCE MODEL (DNS): 63,648,000 POINTS (25x bigger)

THIS WORK: 2,530,090 POINTS



5 – DEPOSITION

VALIDATION

3 CRITERIA OF COMPARISON

A – Visual aspect of the current

B – Sedimentation rate

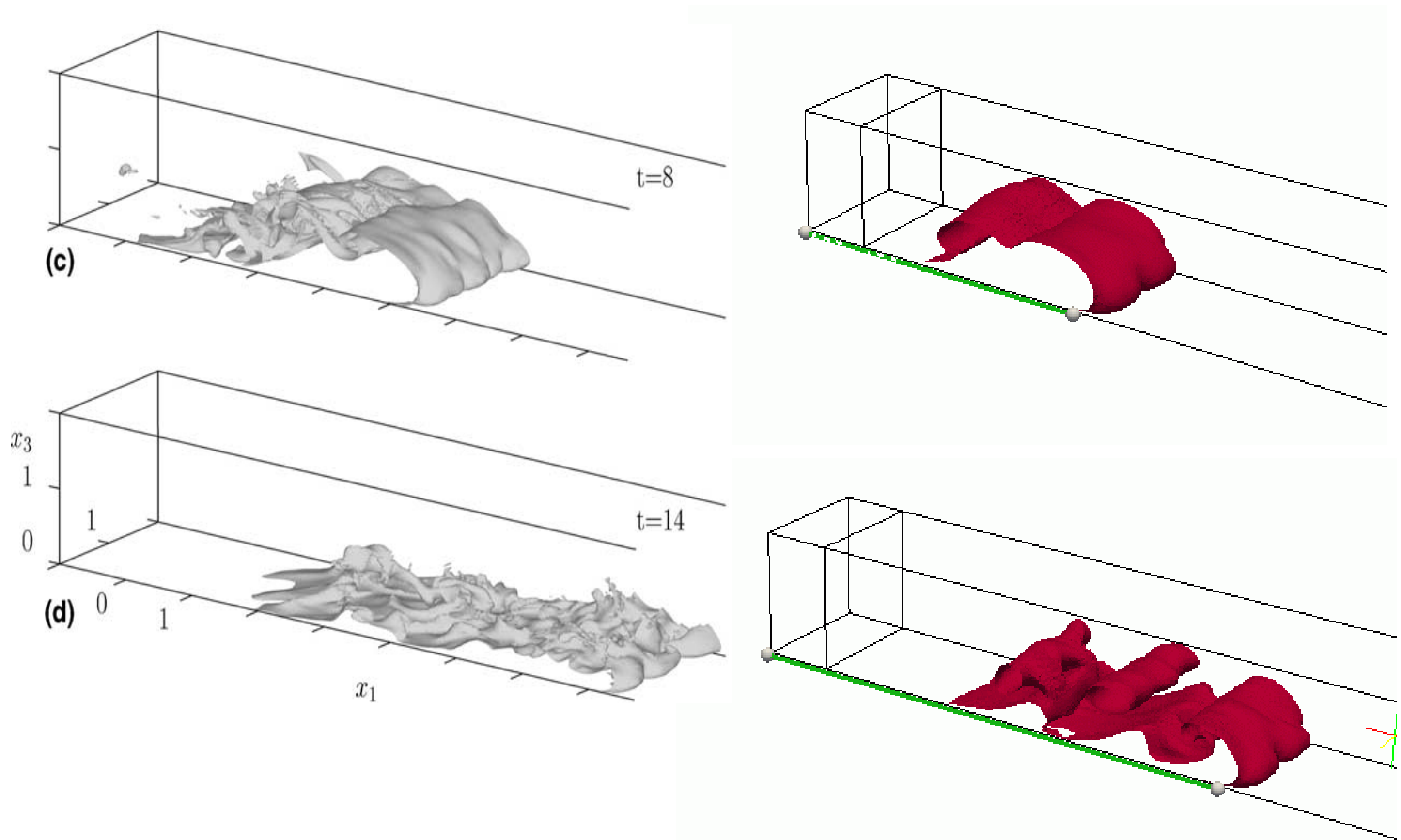
C – Sedimentation volume along x direction

5 – DEPOSITION

VALIDATION

COMPARISON CRITERIA

A – Visual aspect of the current



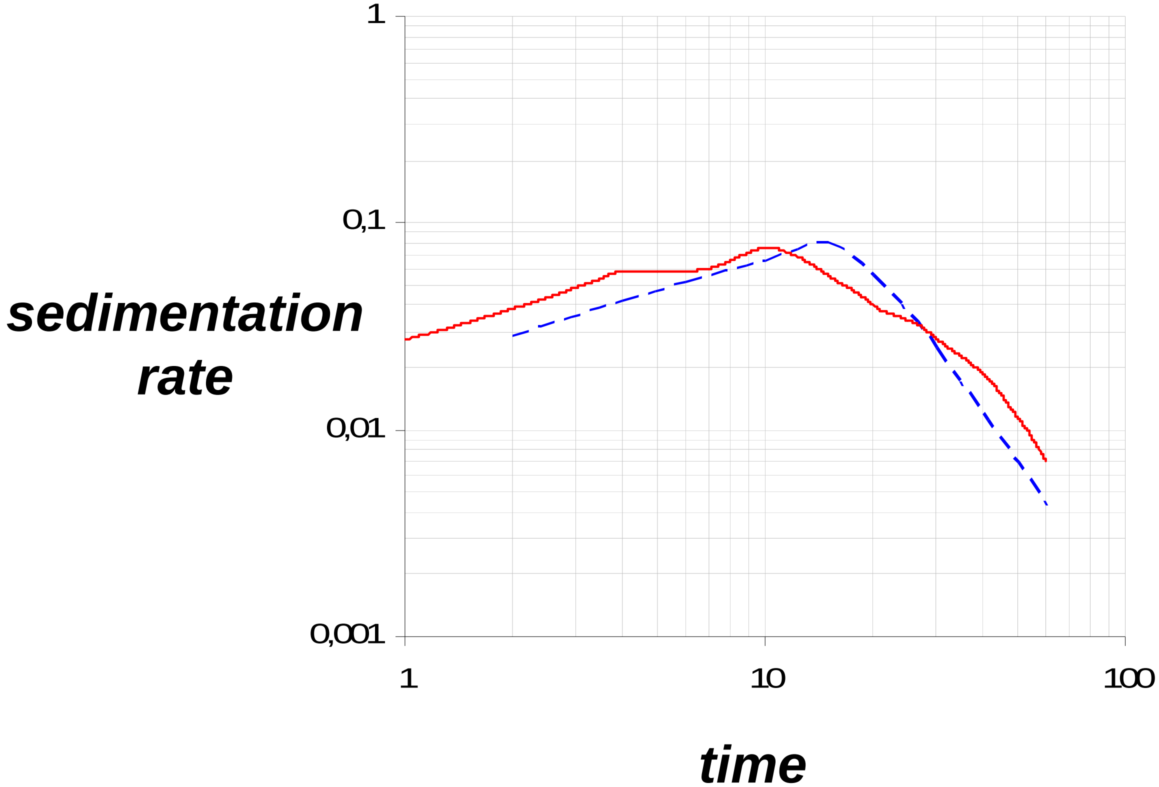
DNS reference *This work*

5 – DEPOSITION

VALIDATION

COMPARISON CRITERIA

B – Sedimentation rate



Blue – DNS reference
Red – This Work

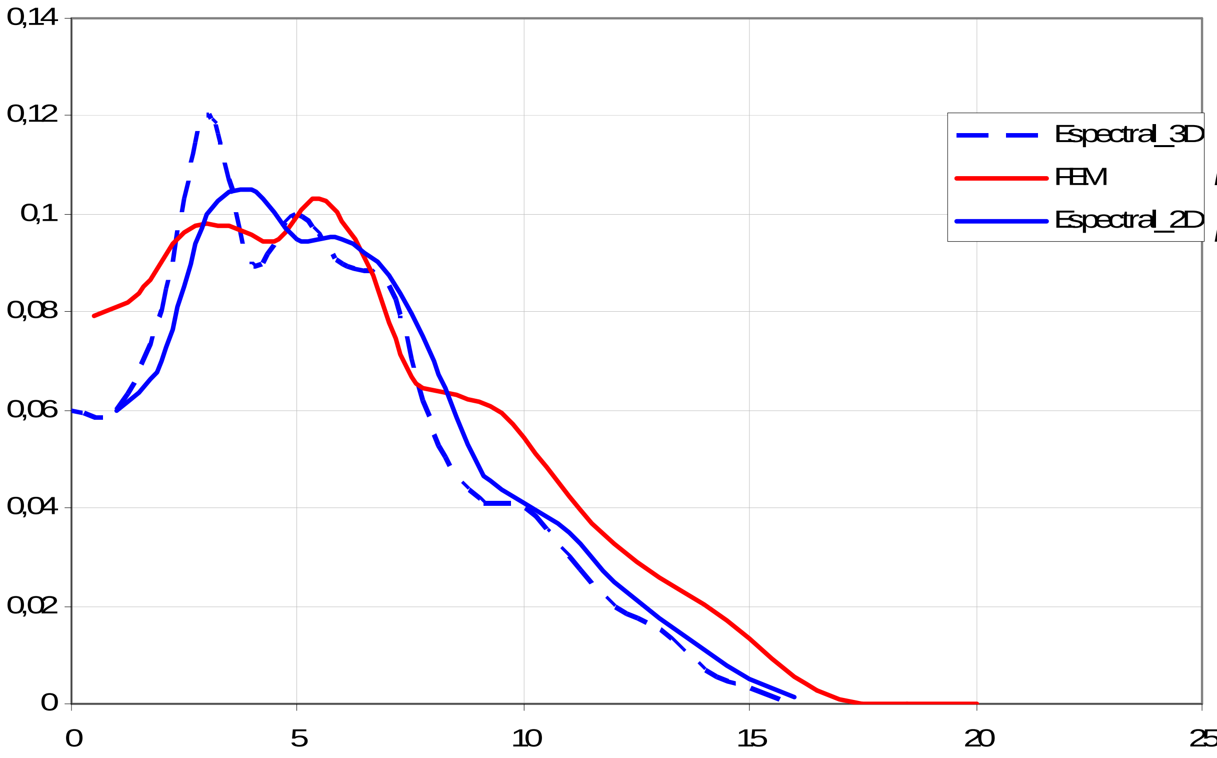
5 – DEPOSITION

VALIDATION

COMPARISON CRITERIA

C – Sedimentation volume along x direction

volume deposited



Blue – DNS reference
Red – This Work

x

5 – DEPOSITION

VALIDATION

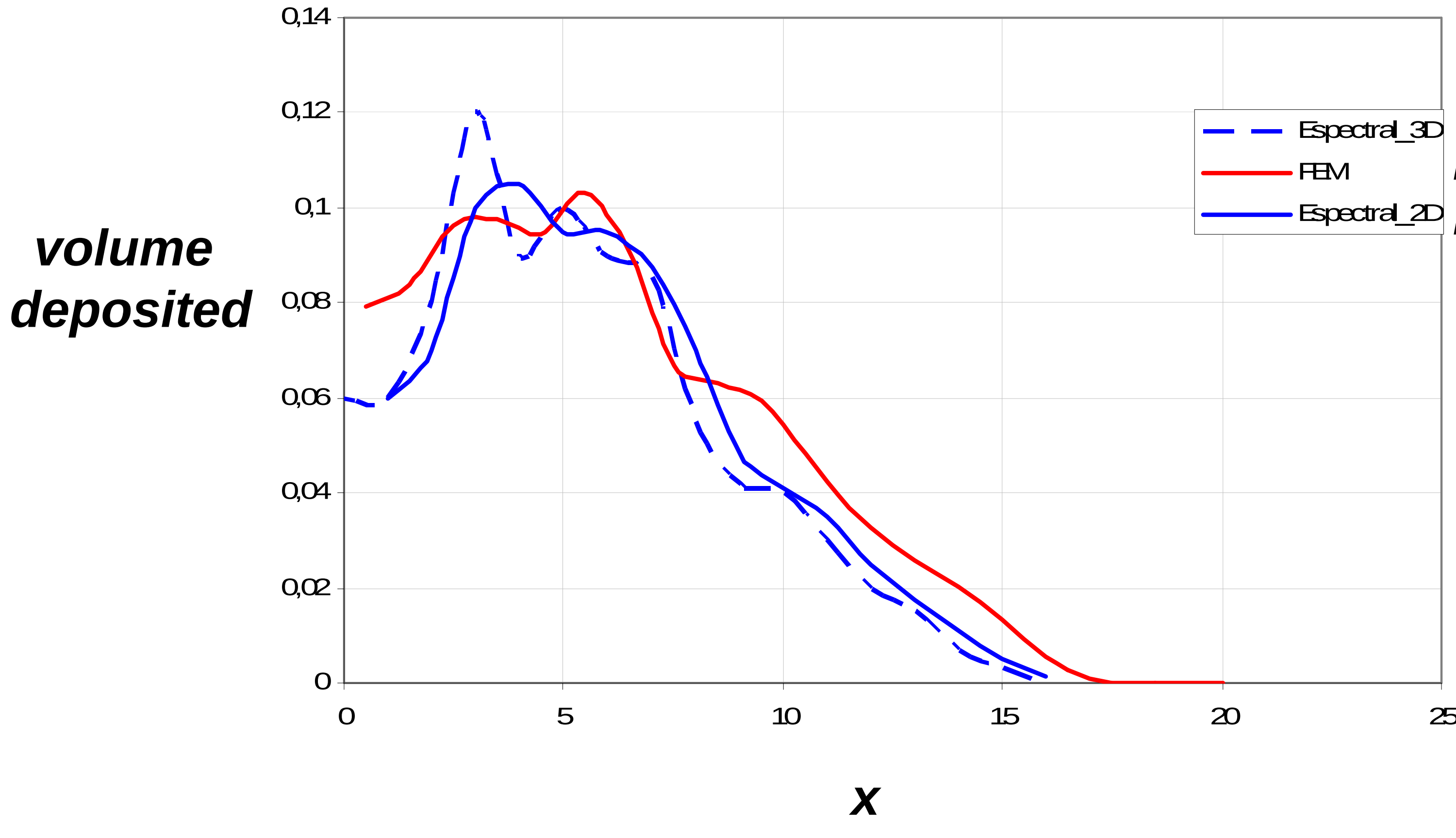
COMPARISON CRITERIA

C – Sedimentation volume along x direction

General Comparison:

- *good reproduction of the shape of the curves;*

- *bad reproduction of details (smooth effect caused by differences in the mesh refinement)*



Blue – DNS reference
Red – This Work

OUTLINE:

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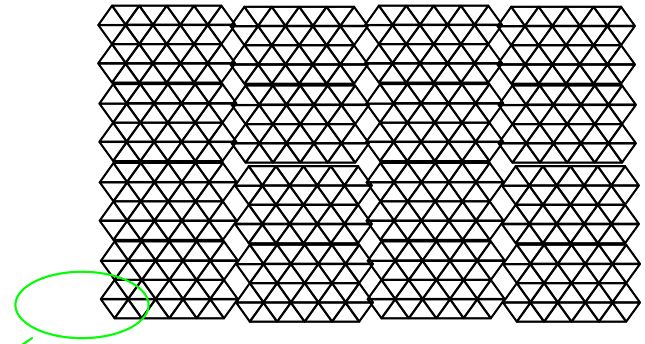
6 – FLOW - BOTTOM INTERACTION

WHAT IS IT ?? Create an interaction of the current and the bottom during the flow

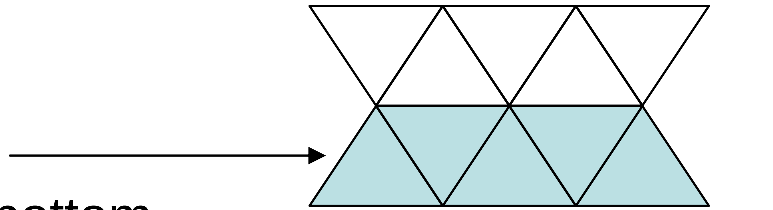
Geometrical aspect
Physical aspect

6 – FLOW - BOTTOM INTERACTION

WHAT IS IT ??



Initial position of the mesh

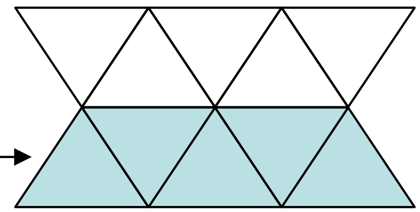


elements at the bottom

6 – FLOW - BOTTOM INTERACTION

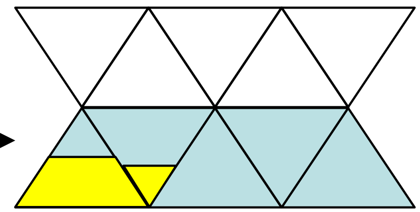
WHAT IS IT ??

Initial position of the mesh



elements of the bottom

General situation during simulation

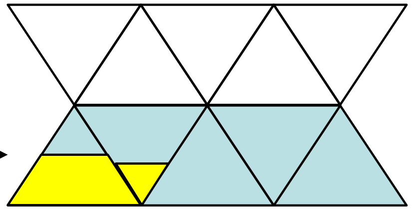


elements at the bottom
with sediments

6 – FLOW - BOTTOM INTERACTION

HOW TO CONSIDER ??

<u>Geometrical Aspect</u>

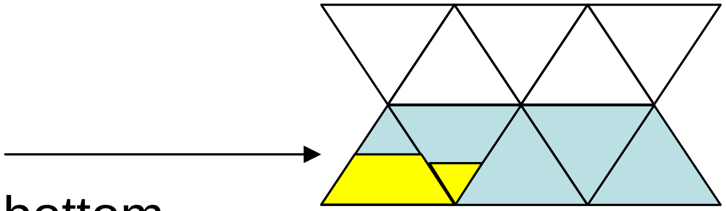


elements at the bottom
with sediments

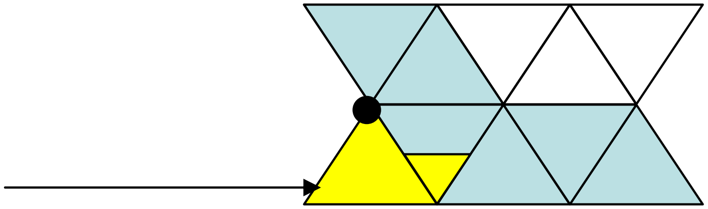
6 – FLOW - BOTTOM INTERACTION

HOW TO CONSIDER ??

<u>Geometrical Aspect</u>



elements of the bottom
with sediments

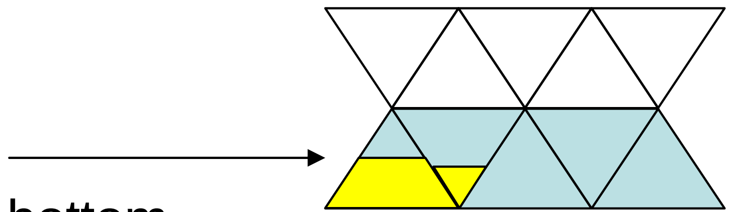


elements at the bottom
FILLED with sediments

6 – FLOW - BOTTOM INTERACTION

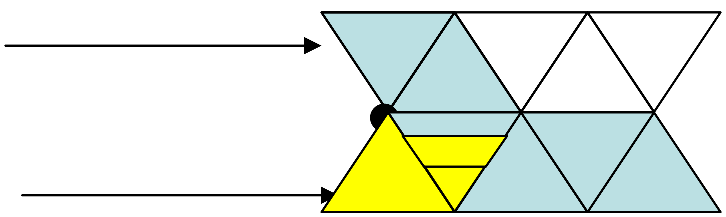
HOW TO CONSIDER ??

<u>Geometrical Aspect</u>



elements of the bottom
with sediments

NEW elements
at the bottom

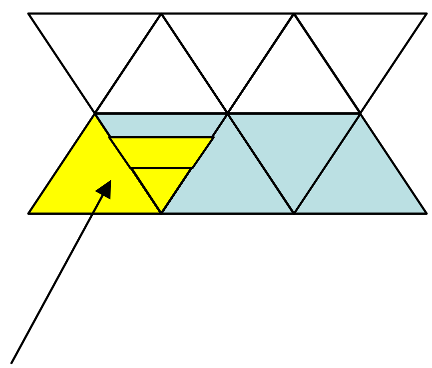


elements of the bottom
FILLED with sediments

6 – FLOW - BOTTOM INTERACTION

HOW TO CONSIDER ??

Physical Aspect: Rheology of mixtures (water & sediments).



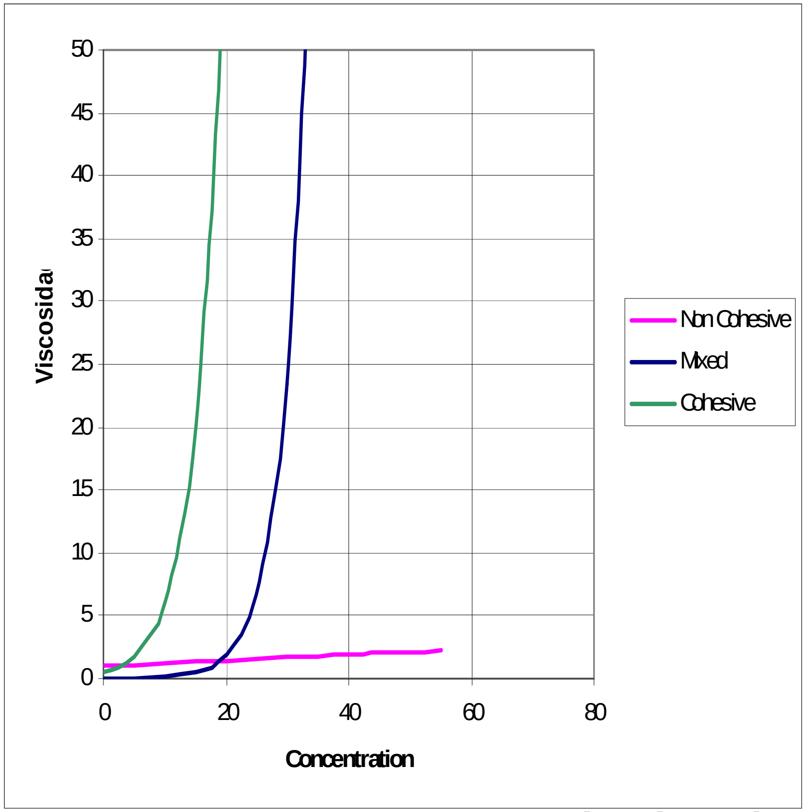
Changes in viscosity of the elements

6 – FLOW - BOTTOM INTERACTION

HOW TO CONSIDER ??

Physical Aspect: Rheology of mixtures (water & sand particles).

$$\eta_r = (1 + 2.5c)$$



Manica (2009)

equations adjusted from lab data

6 – FLOW - BOTTOM INTERACTION

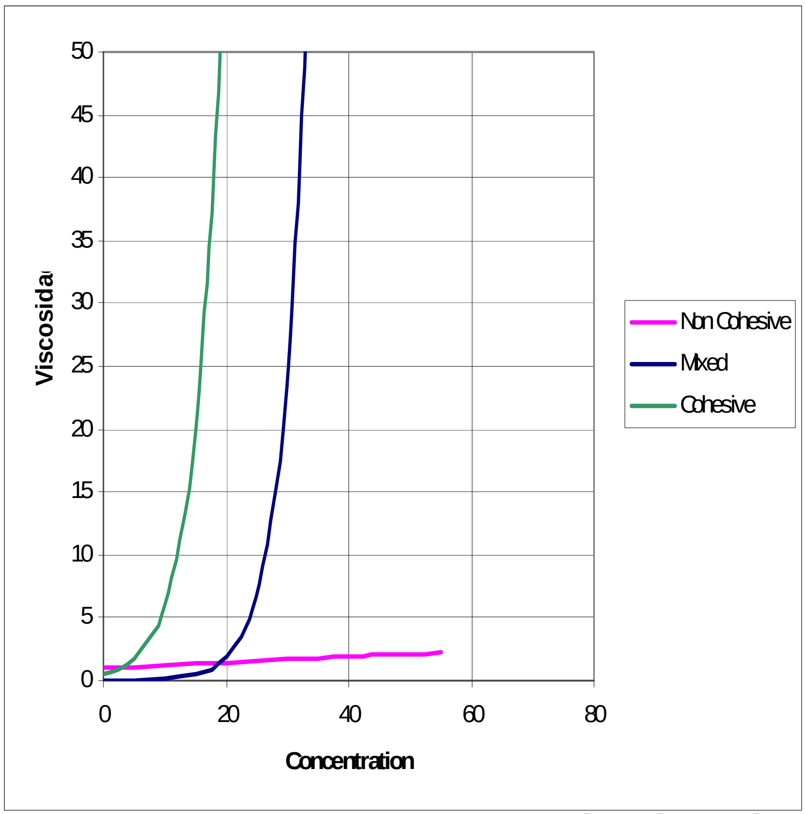
HOW TO CONSIDER ??

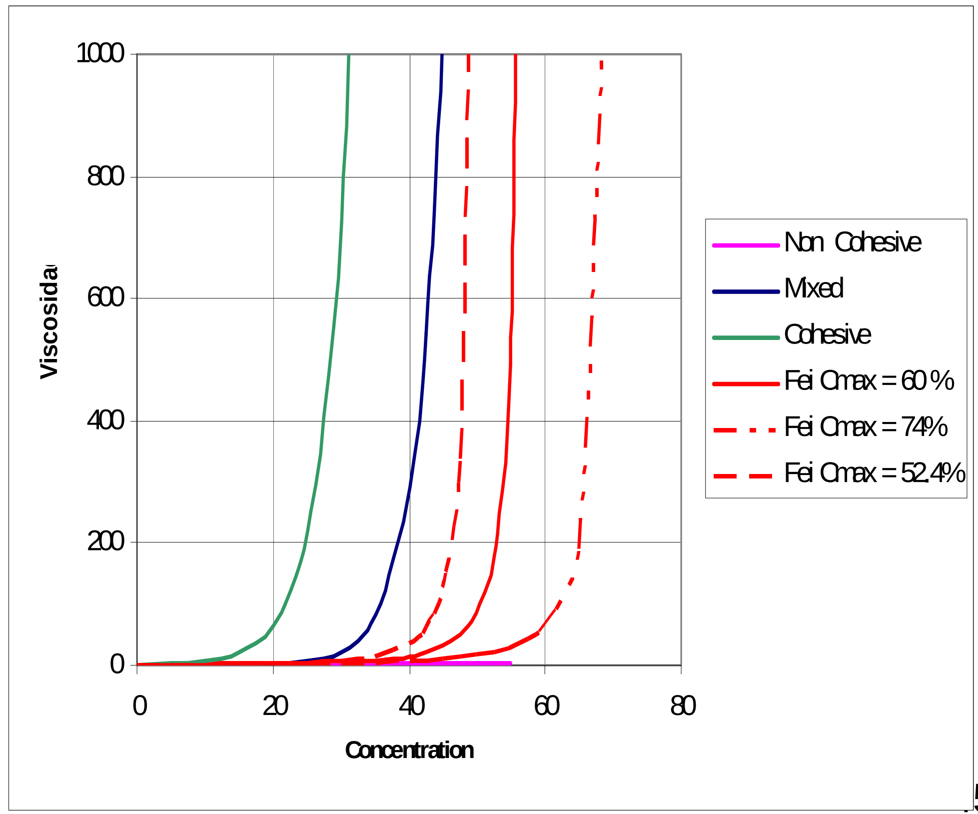
<u>Physical Aspect:</u> Rheology of mixtures (water & sand particles).

Fei (1982)

$$\eta_r = (1 - k'c)^{-2.5} \qquad k' = \frac{1}{1-\phi}$$

empirical relationship





Manica (2009)

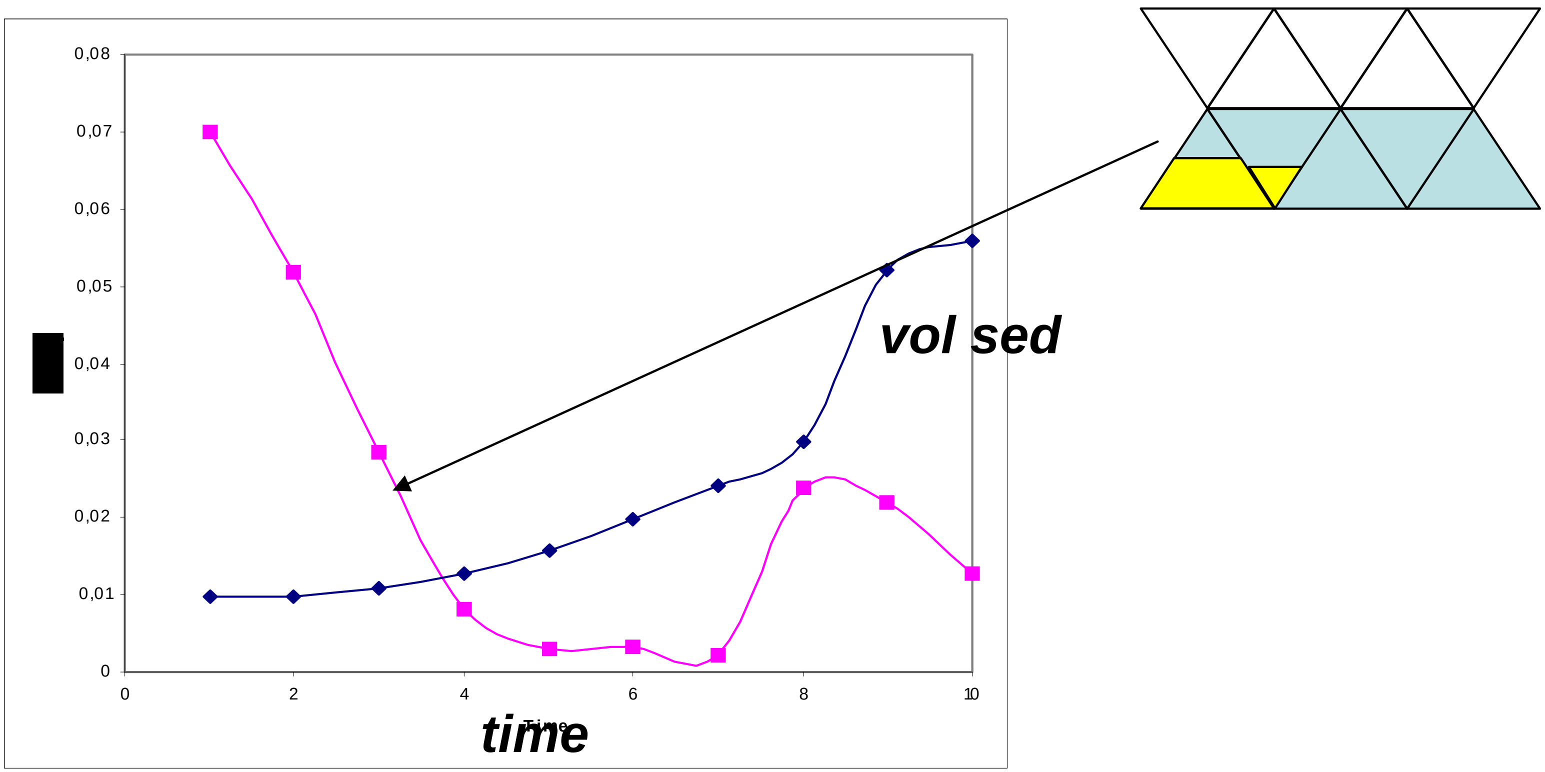
6 – FLOW - BOTTOM INTERACTION

HOW TO CONSIDER ??

Physical Aspect: Rheology of mixtures.

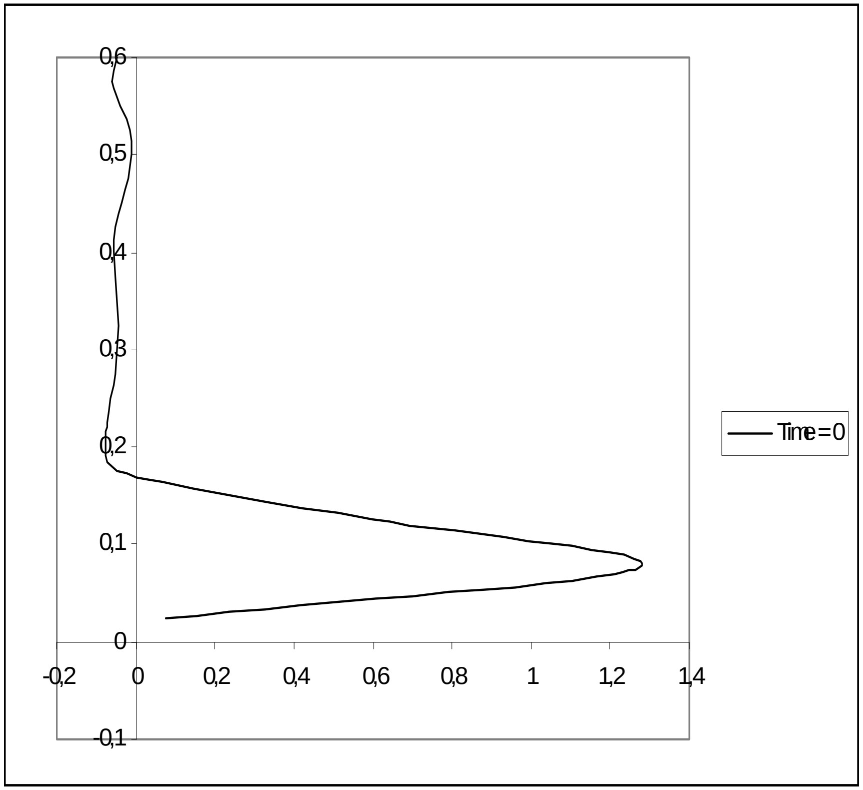
$$\mu_{el} = \frac{V_{sed}}{V_{el}} * \mu_{sed} + \frac{(V_{el} - V_{sed})}{V_{el}} \mu_f$$

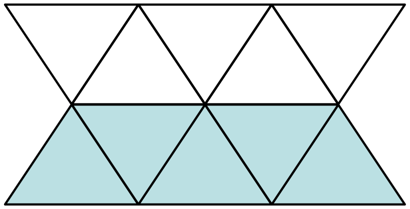
velocity in the yellow element



6 – FLOW - BOTTOM INTERACTION

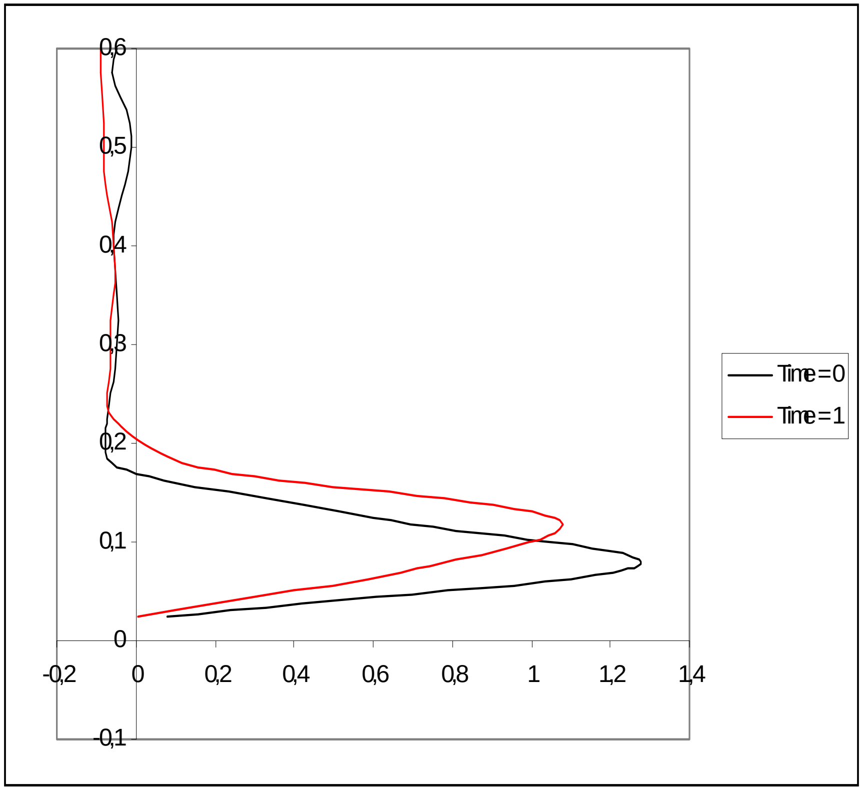
Hydrodynamic effect

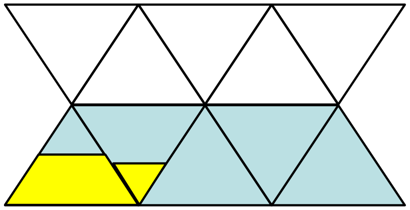




6 – FLOW - BOTTOM INTERACTION

<u>Hydrodynamic effect</u>

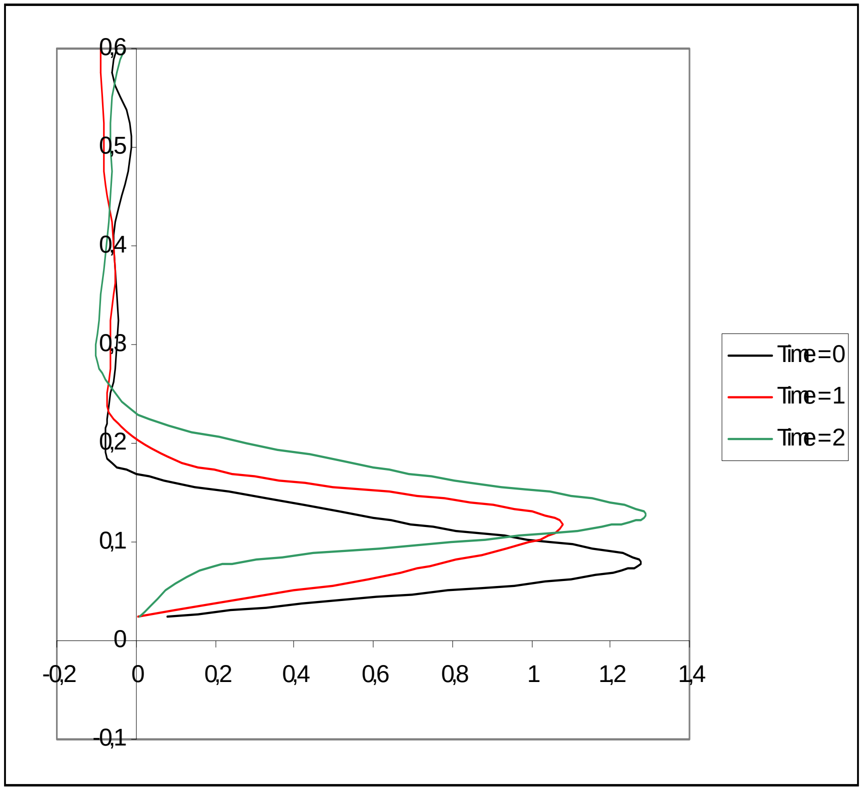


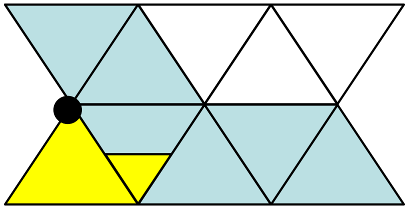


shift upward

6 – FLOW - BOTTOM INTERACTION

Hydrodynamic effect





shift upward

OUTLINE:

1 – MOTIVATION

2 – DEFINING THE PROBLEM

3 – NUMERICAL MODEL

4 - SAND TRANSPORT AND DEPOSITION

5 – DEPOSITION

6 - FLOW - BOTTOM INTERACTION

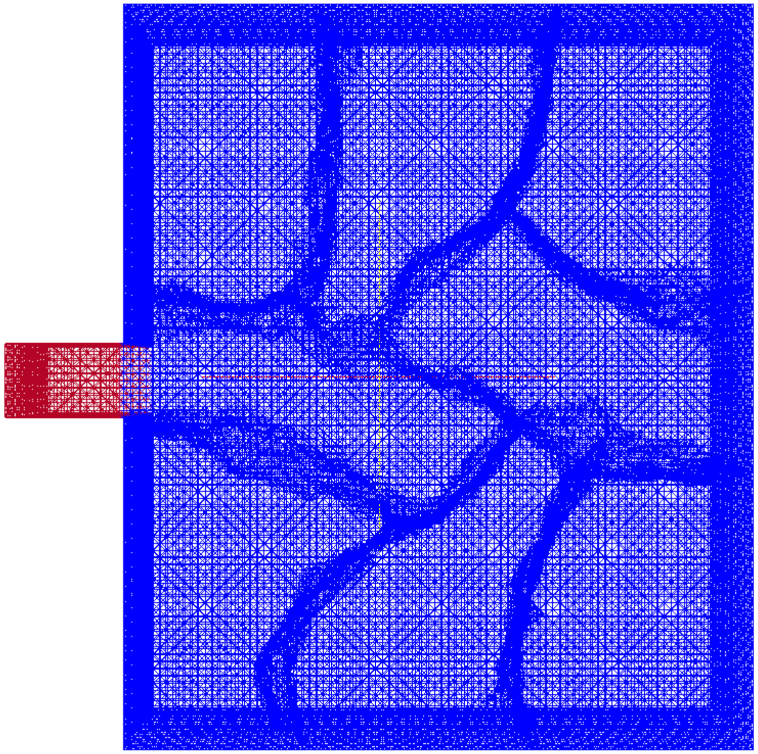
7 - CASE STUDIES

8 - CONCLUSIONS

9 – NEXT STEPS

7 – CASE STUDIES

FRONTAL SPLAYS



Elements: 1,121,125
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Lx = 4
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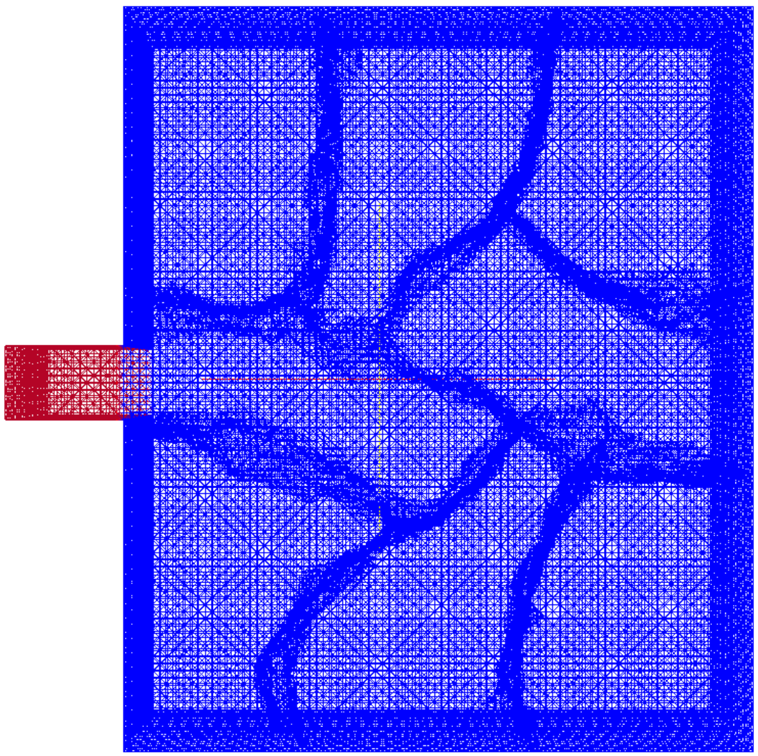
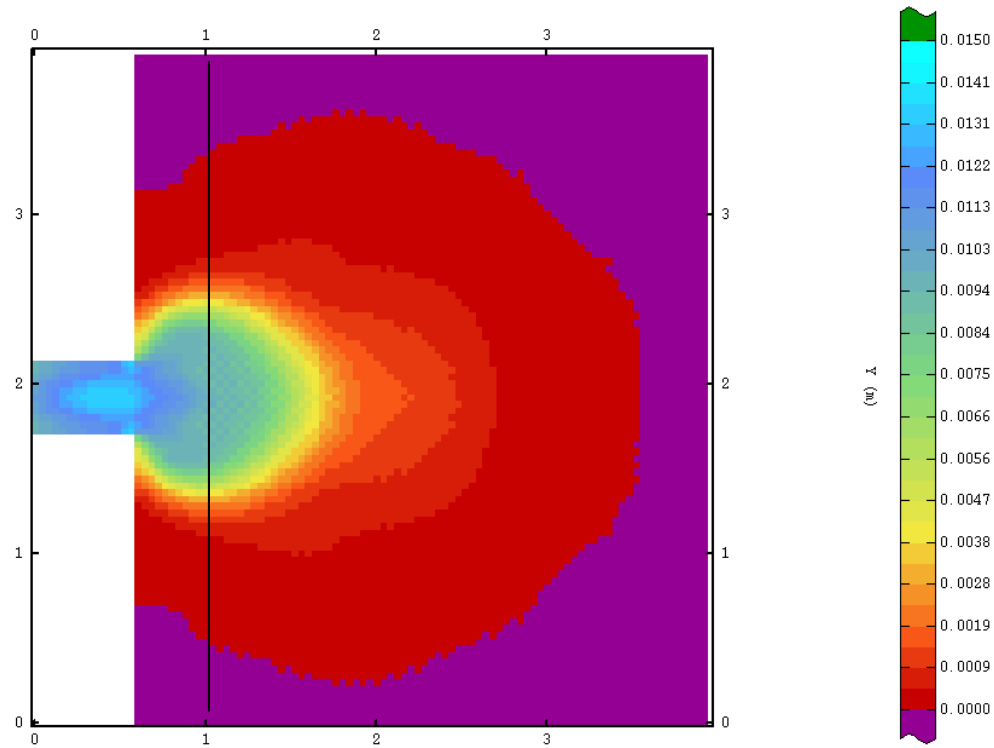
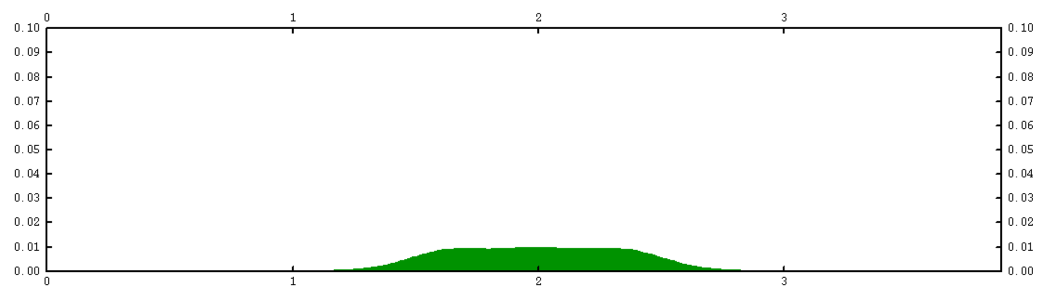
7 – CASE STUDIES

FRONTAL SPLAYS







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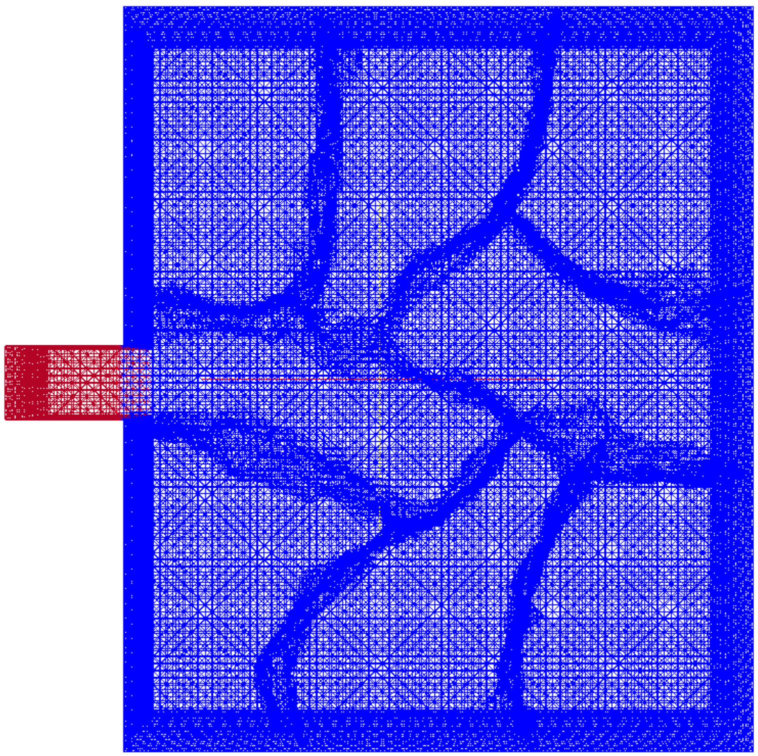
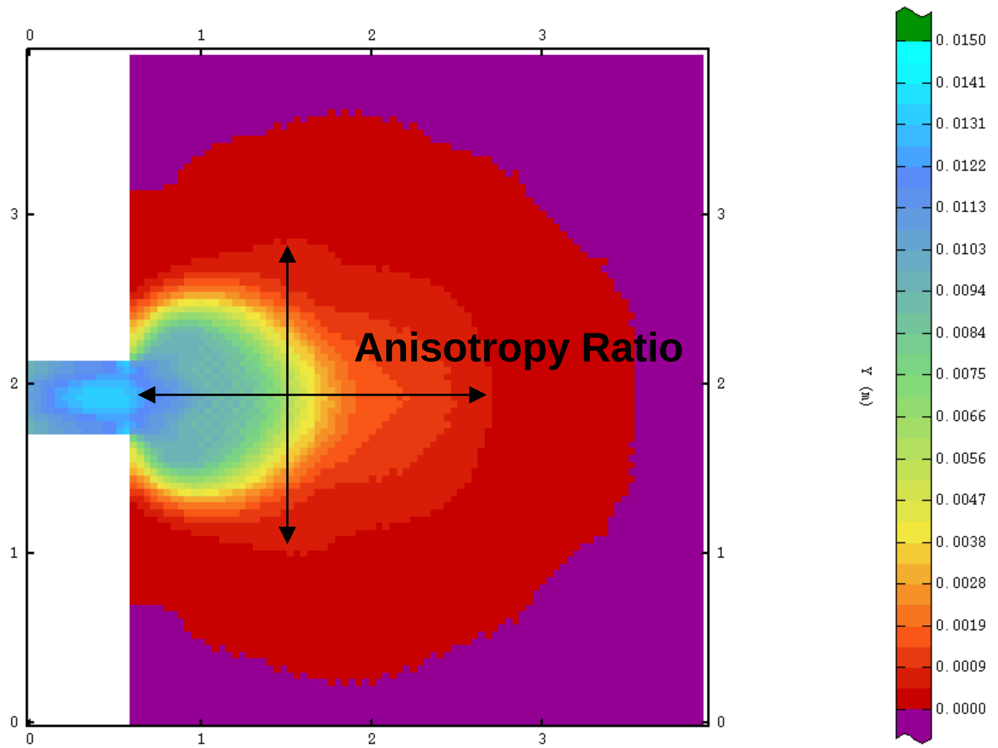
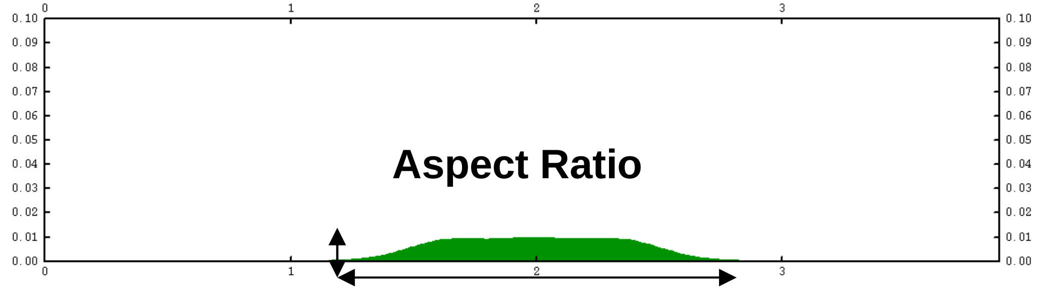




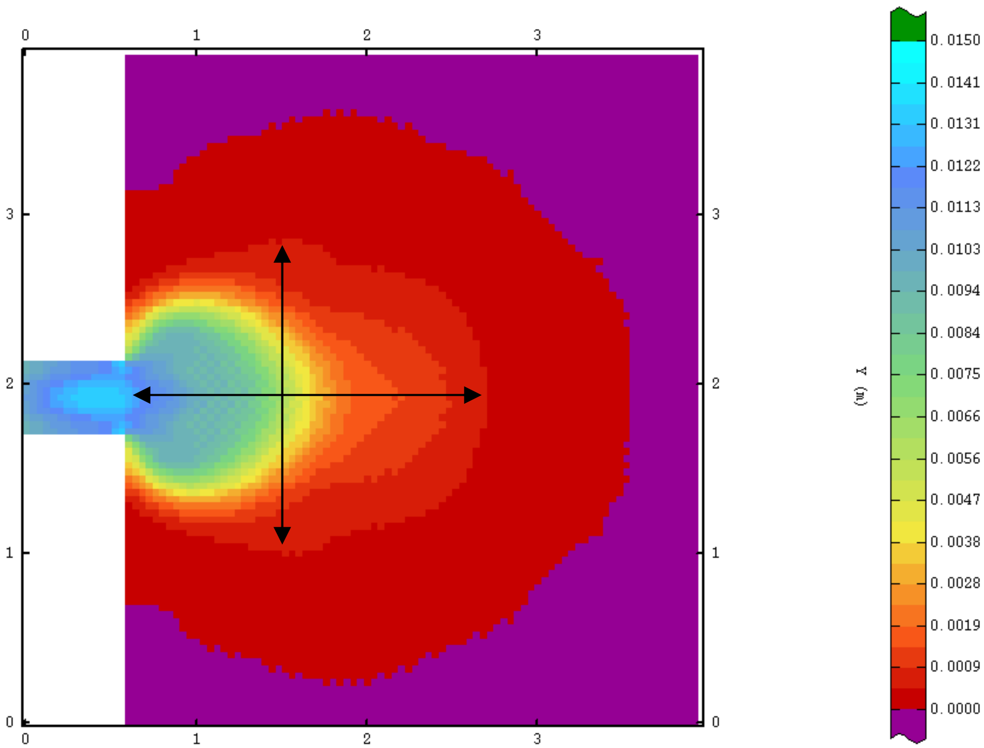


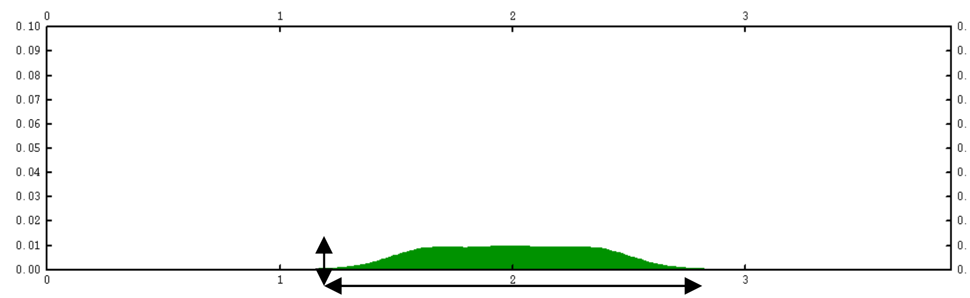
Anisotropy Ratio = Length / Width

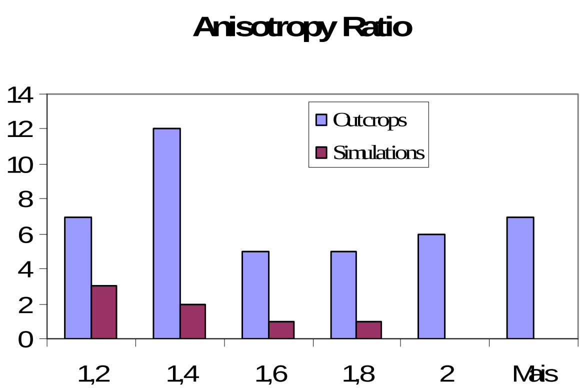
Aspect Ratio = Width / Thickness

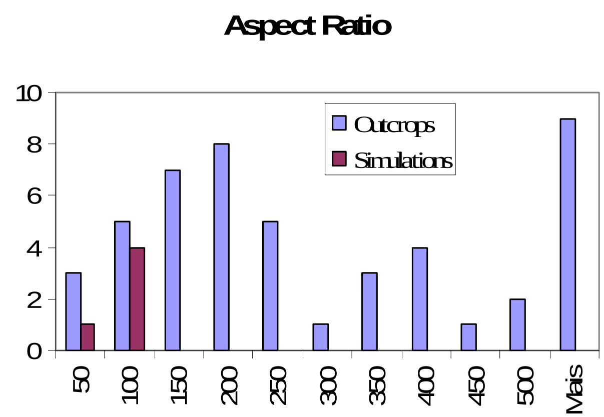
7 – CASE STUDIES

FRONTAL SPLAYS



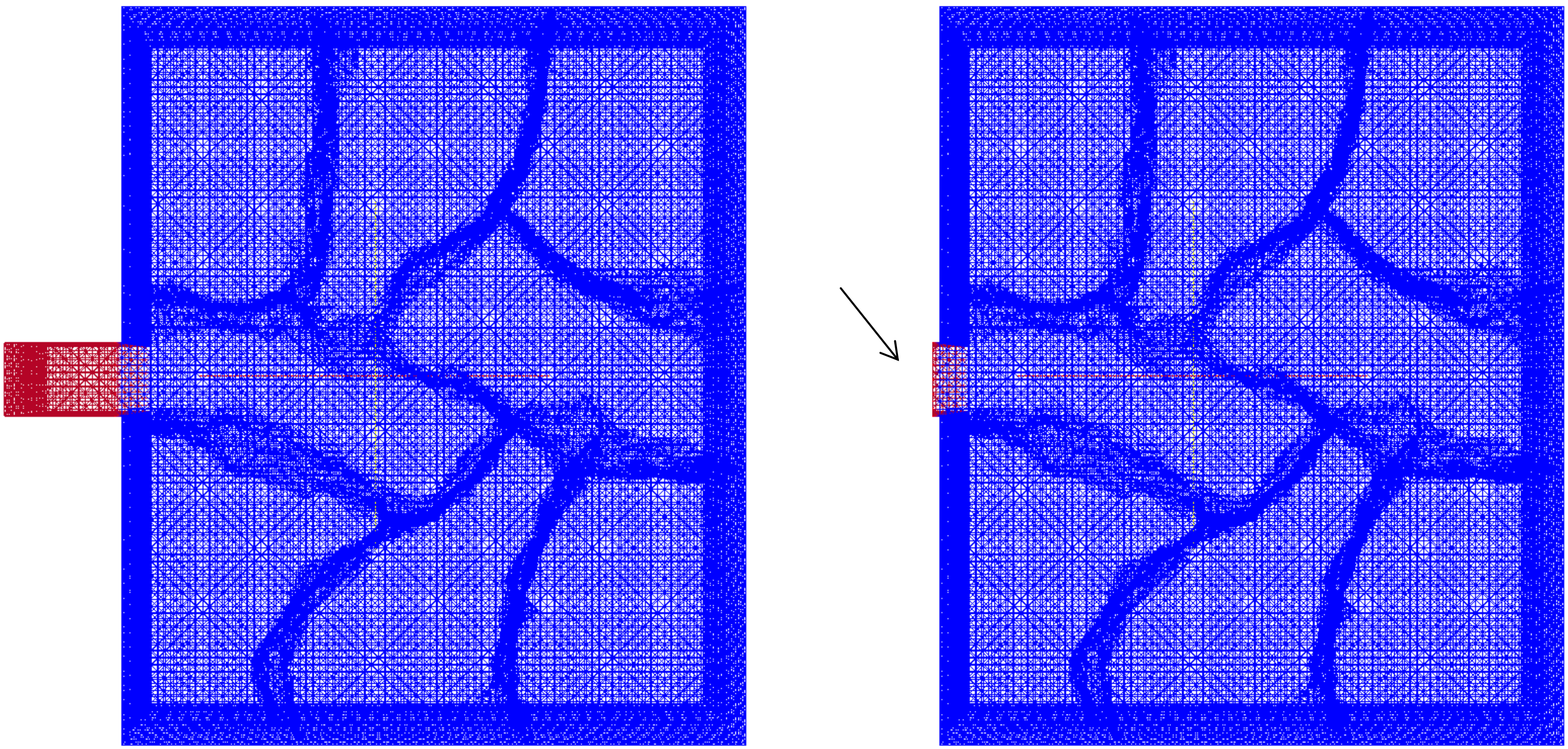






7 – CASE STUDIES

FRONTAL SPLAYS – PULSE - CONTINUOUS FLOW



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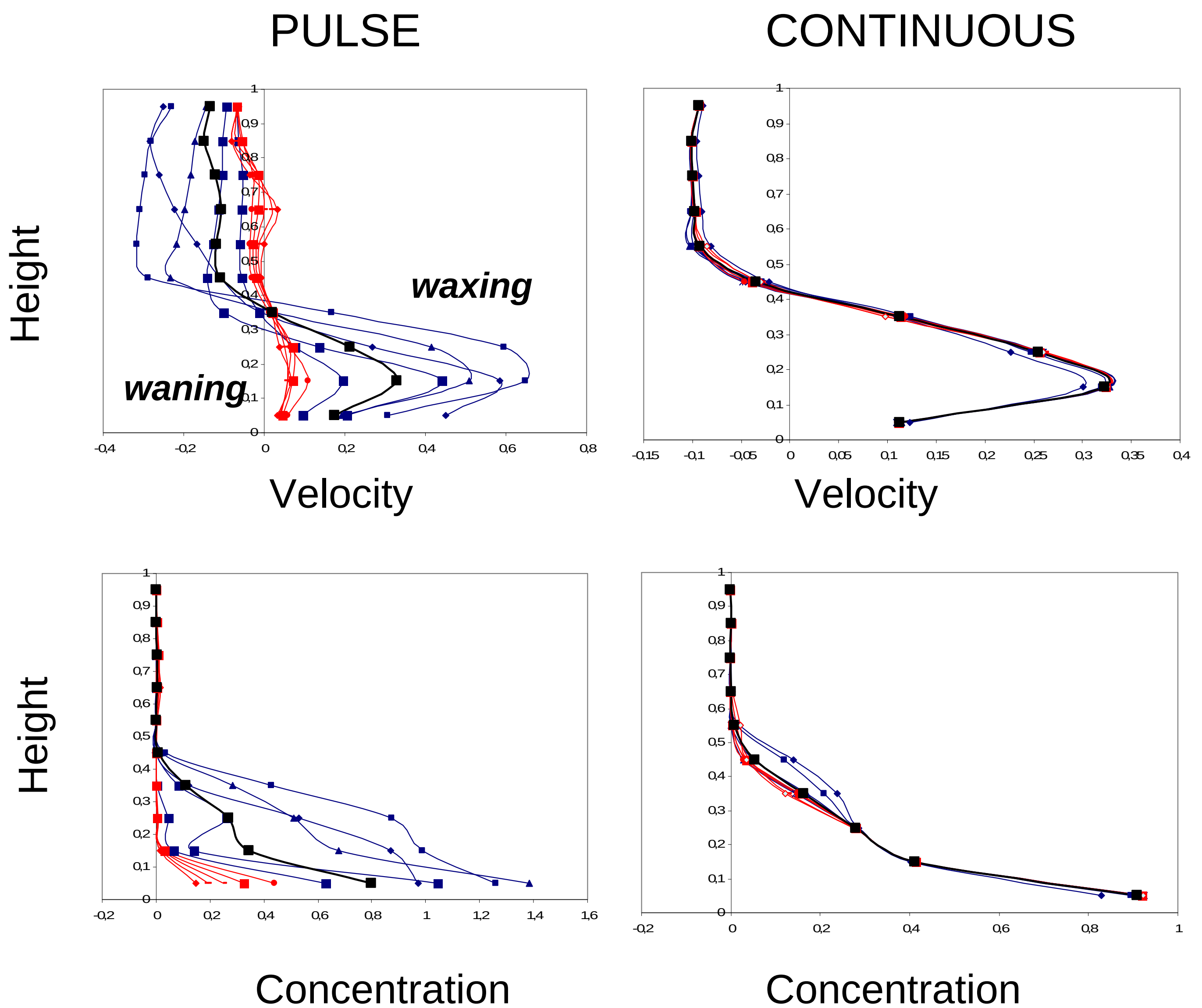

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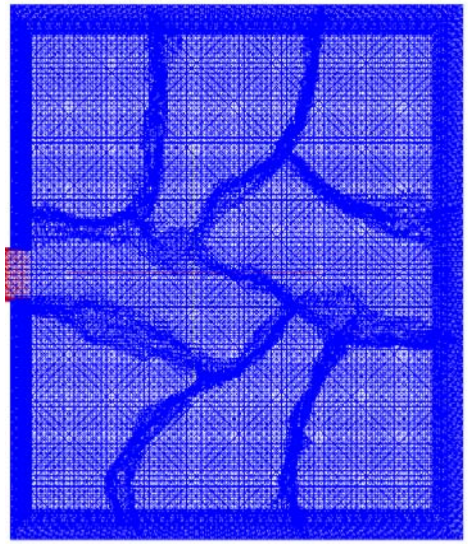

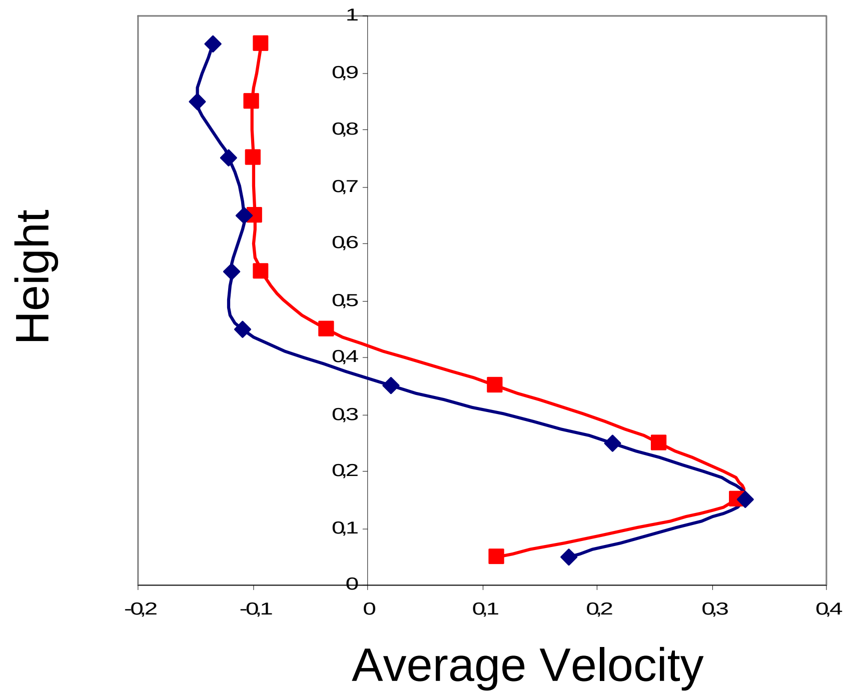

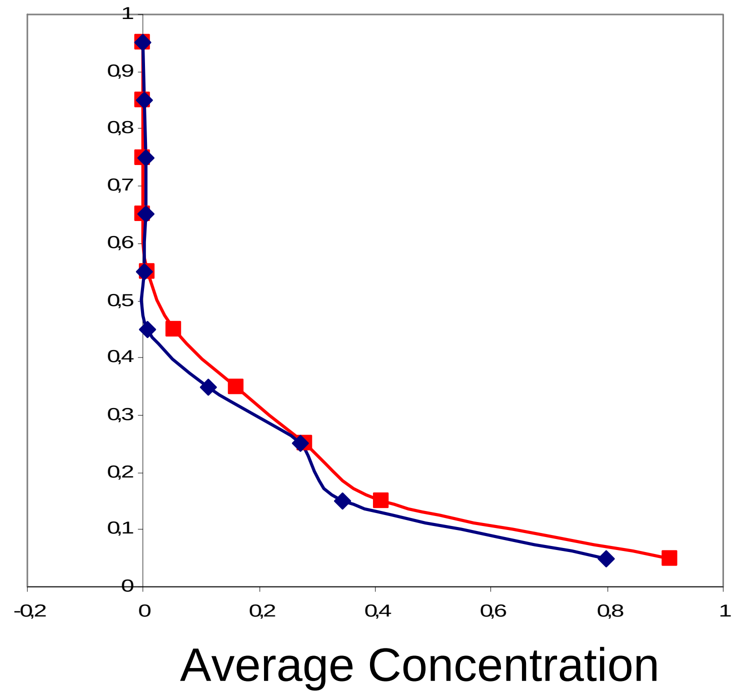

7 – CASE STUDIES

FRONTAL SPLAYS – PULSE - CONTINUOUS FLOW

	PULSE	*CONTINUOUS*
Percentage of deposit material	0.81	0.50
Concentration of material in suspensio	0.030	0.046
Distance of deposit	2.14	1.23

7 – CASE STUDIES

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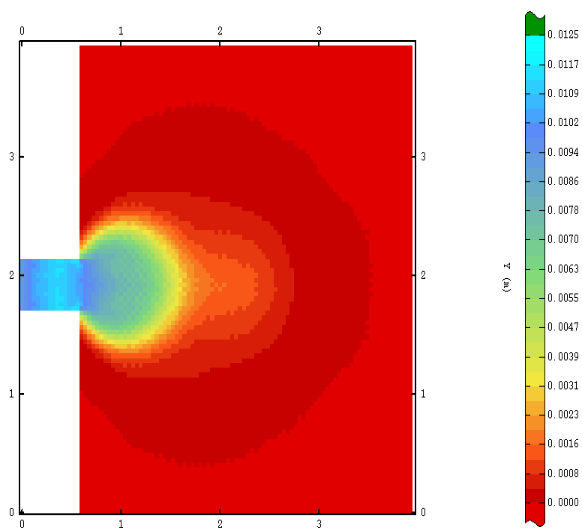
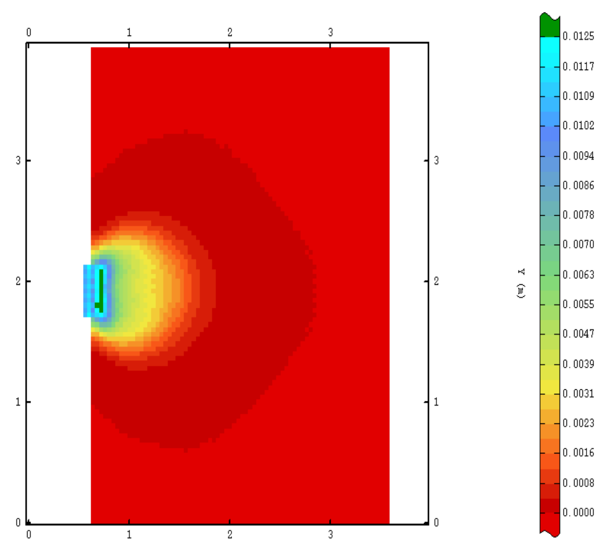


waning



7 – CASE STUDIES

Click to view movie.

FRONTAL SPLAYS – PULSE - CONTINUOUS FLOW

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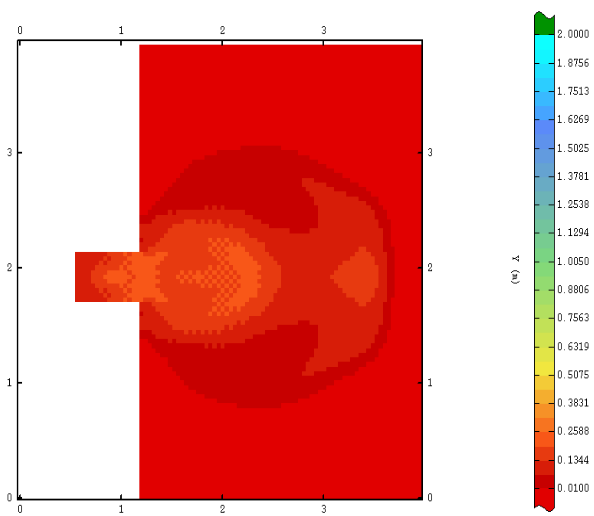

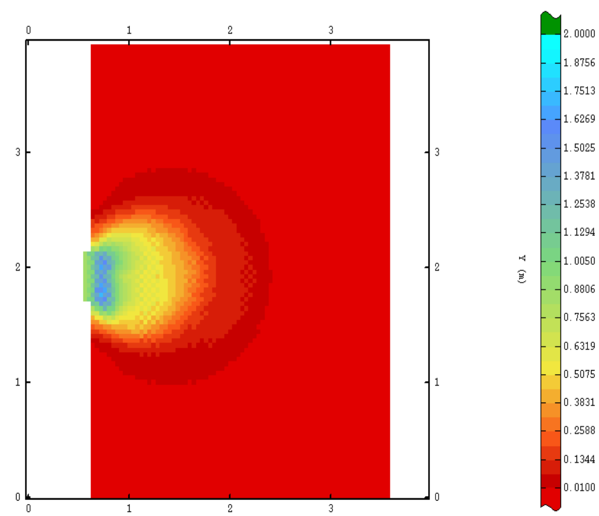

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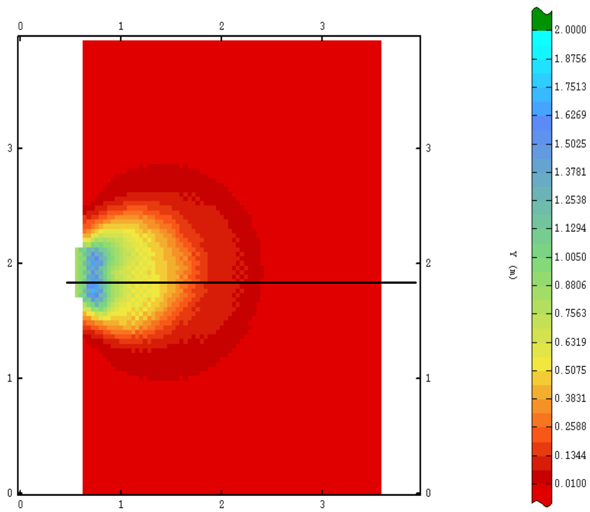
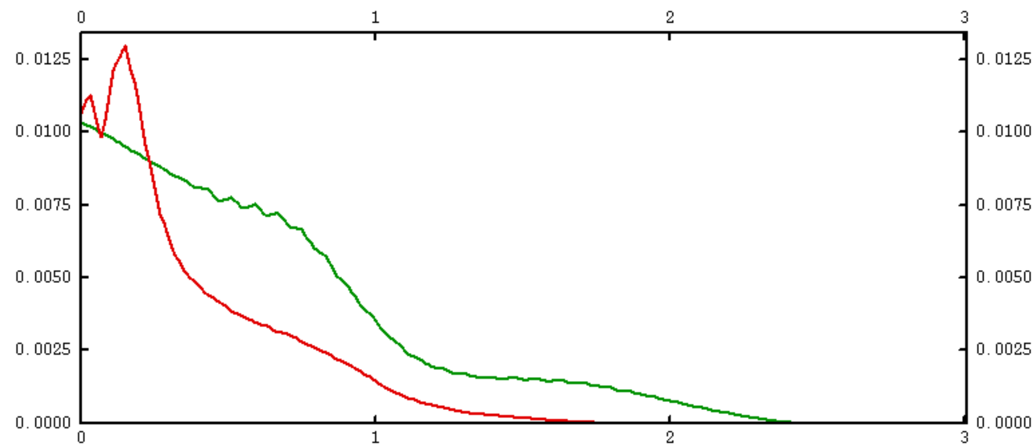
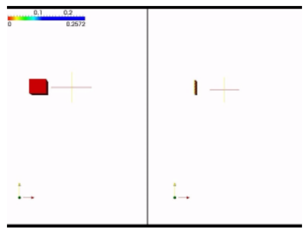


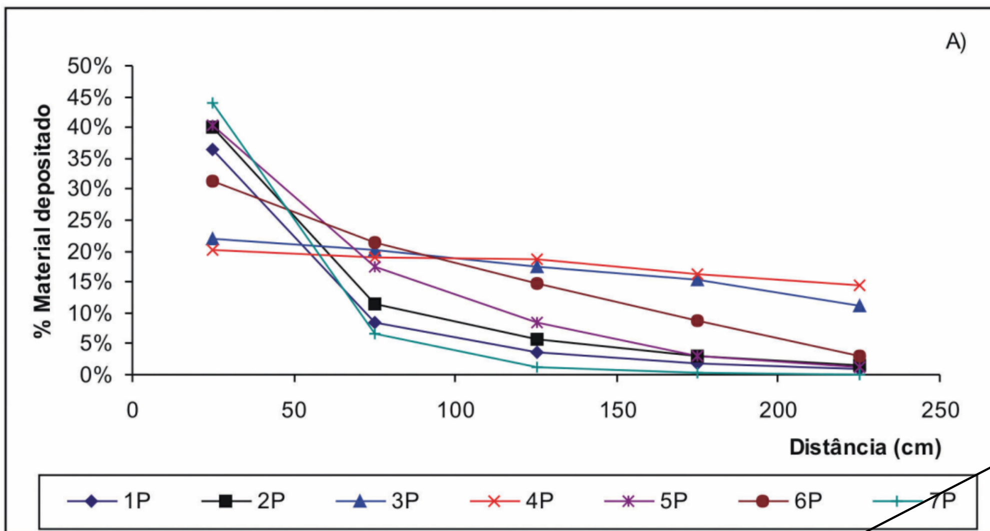
waxing



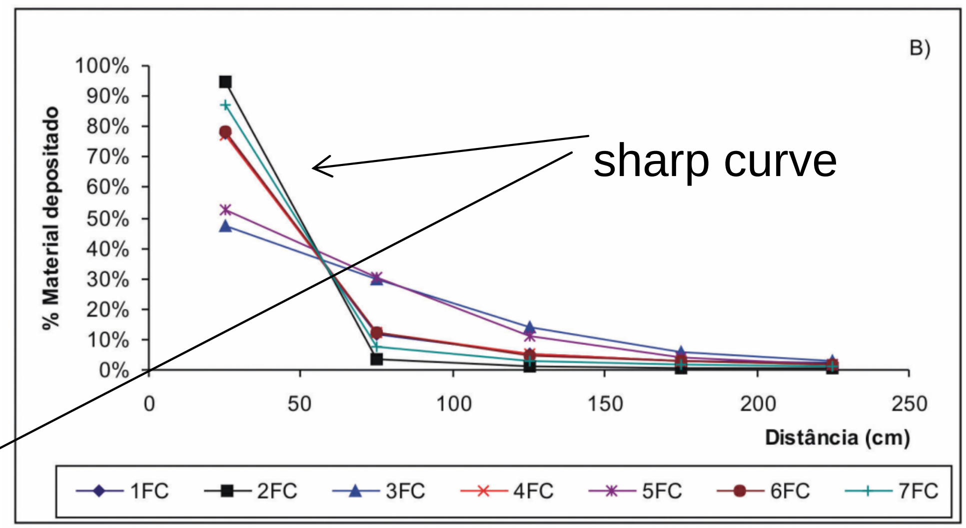


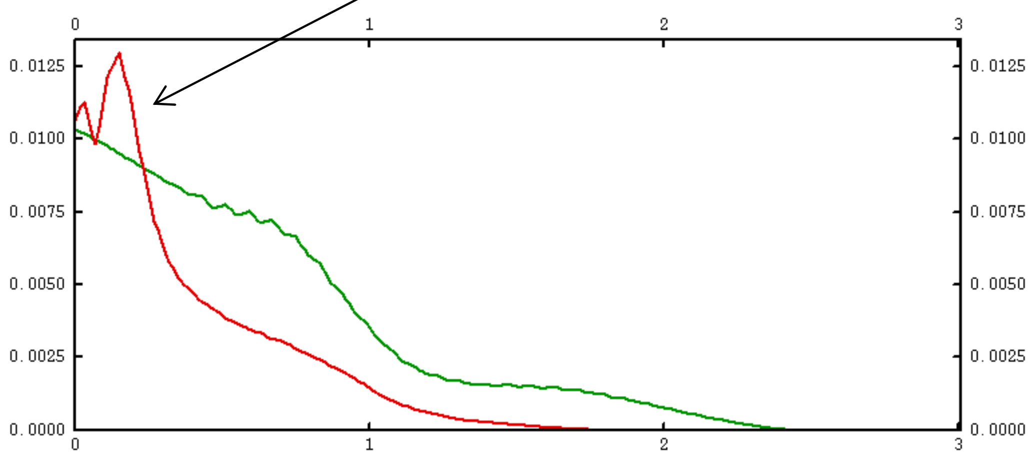
FRONTAL SPLAYS – PULSE - CONTINUOUS FLOW

pulse flume experiments

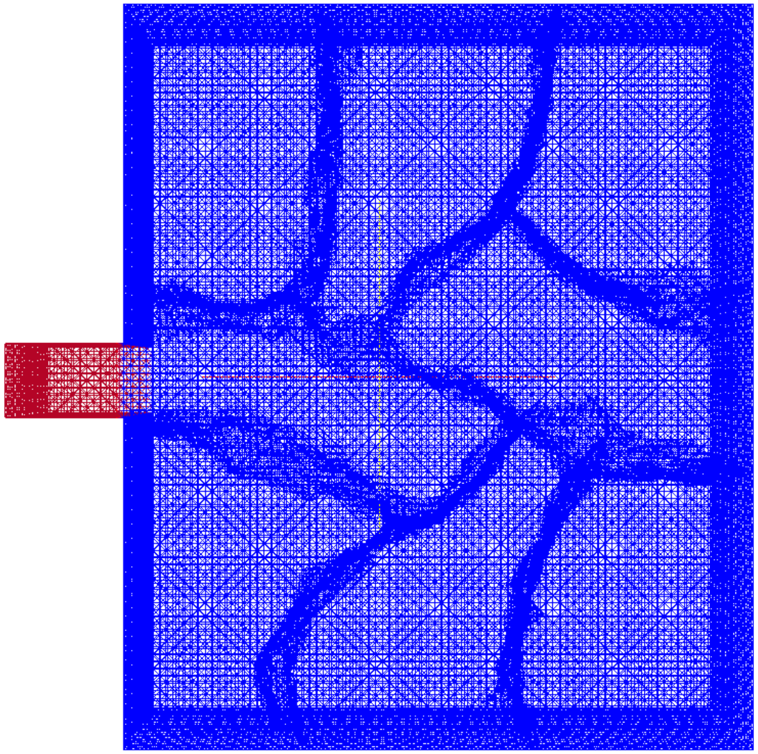


continuous flume experiments





LEVEE CONSTRUCTION



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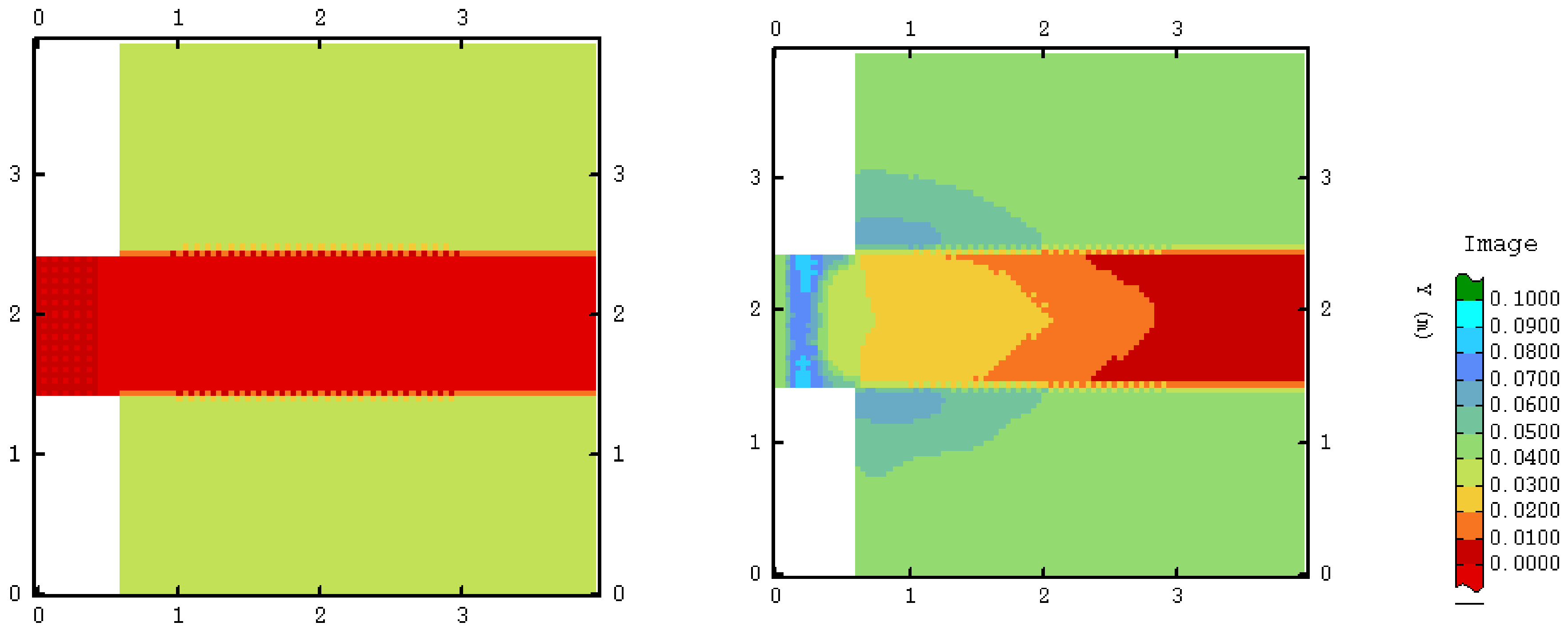

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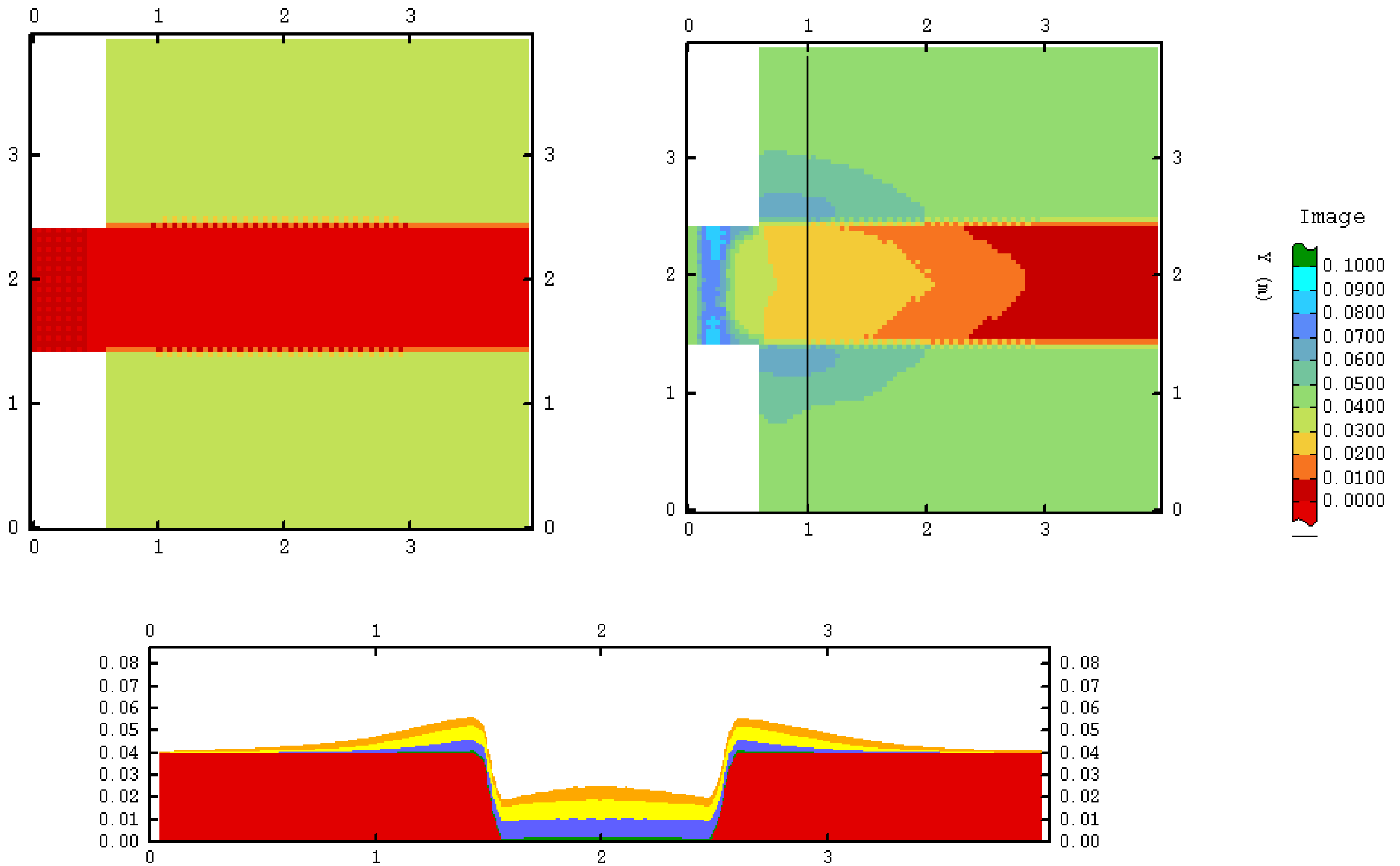
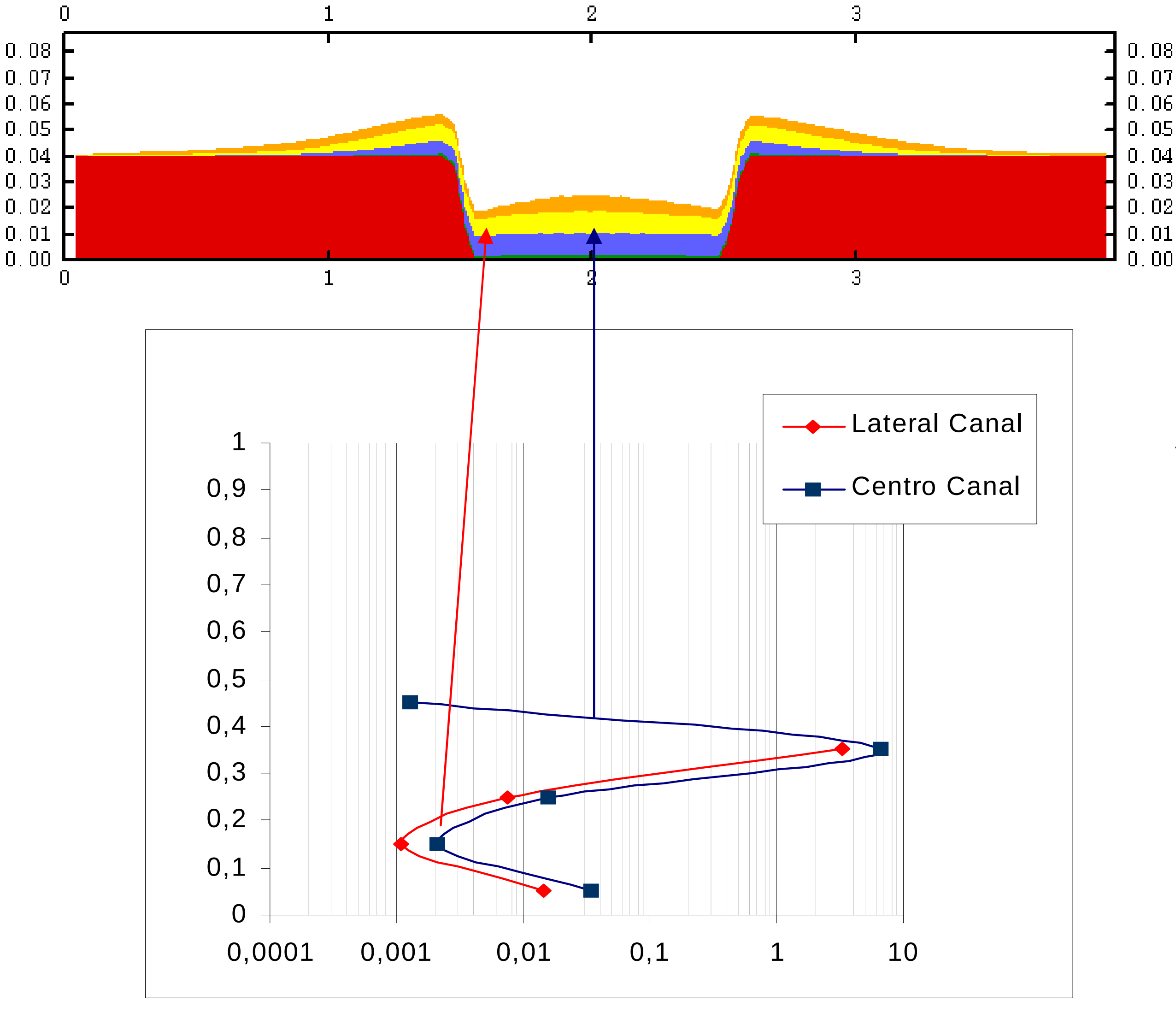


7 – CASE STUDIES

LEVEE CONSTRUCTION

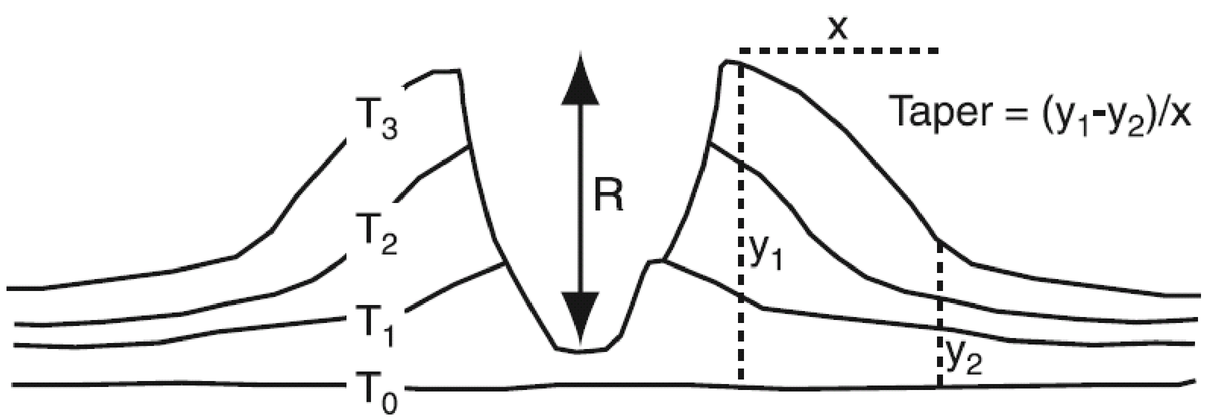


$$Ri = \frac{1}{Fr} \propto \frac{c}{u^2}$$

7 – CASE STUDIES

LEVEE CONSTRUCTION – QUALITATIVE APPROACH

Straub & Mohrig (2008) – Levee Constuction Model



Case B - Main deposition inside the channel
R goes down - Taper goes up

7 – CASE STUDIES

LEVEE CONSTRUCTION – QUALITATIVE APPROACH

Straub & Mohrig (2008)

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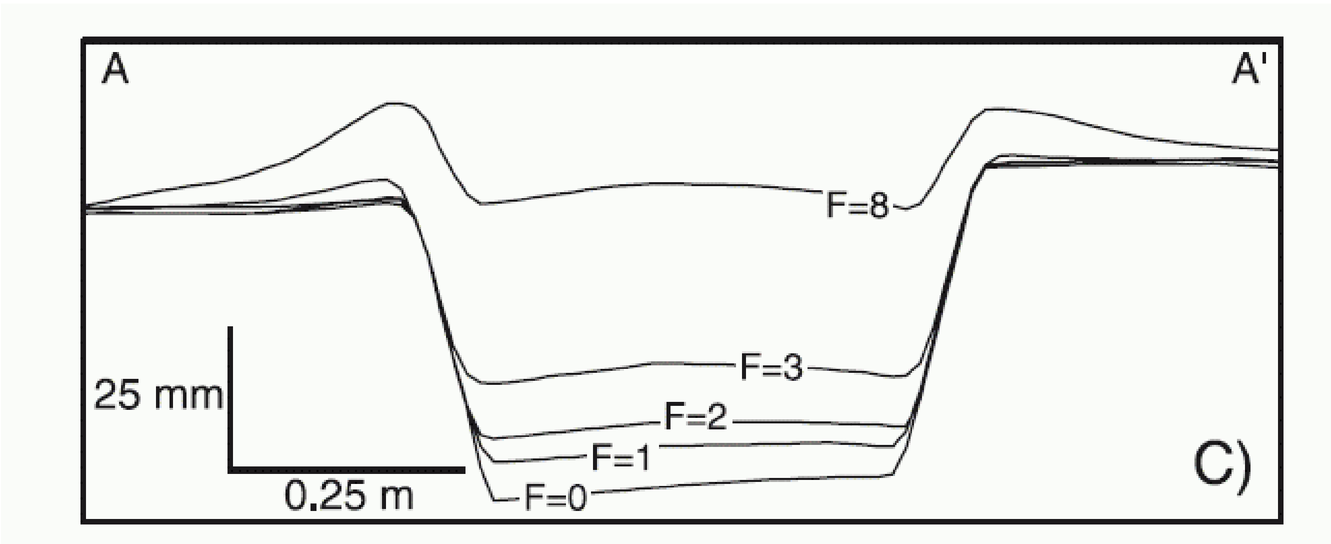

7 – CASE STUDIES

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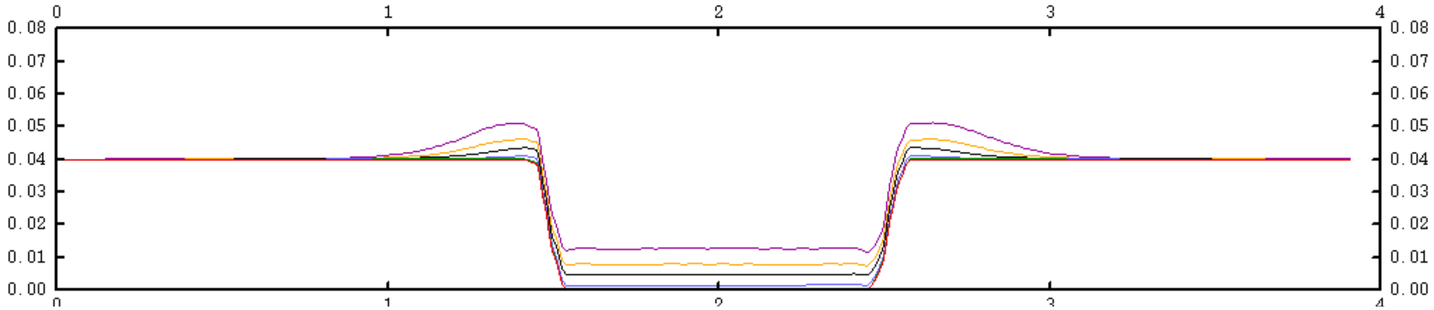
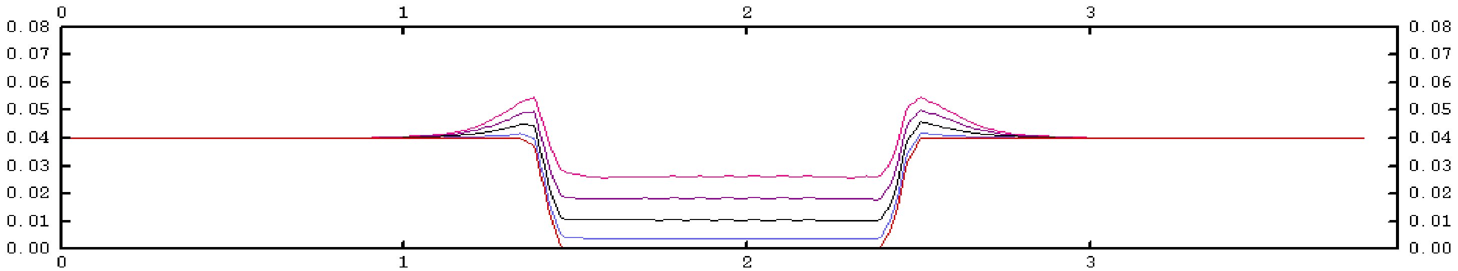
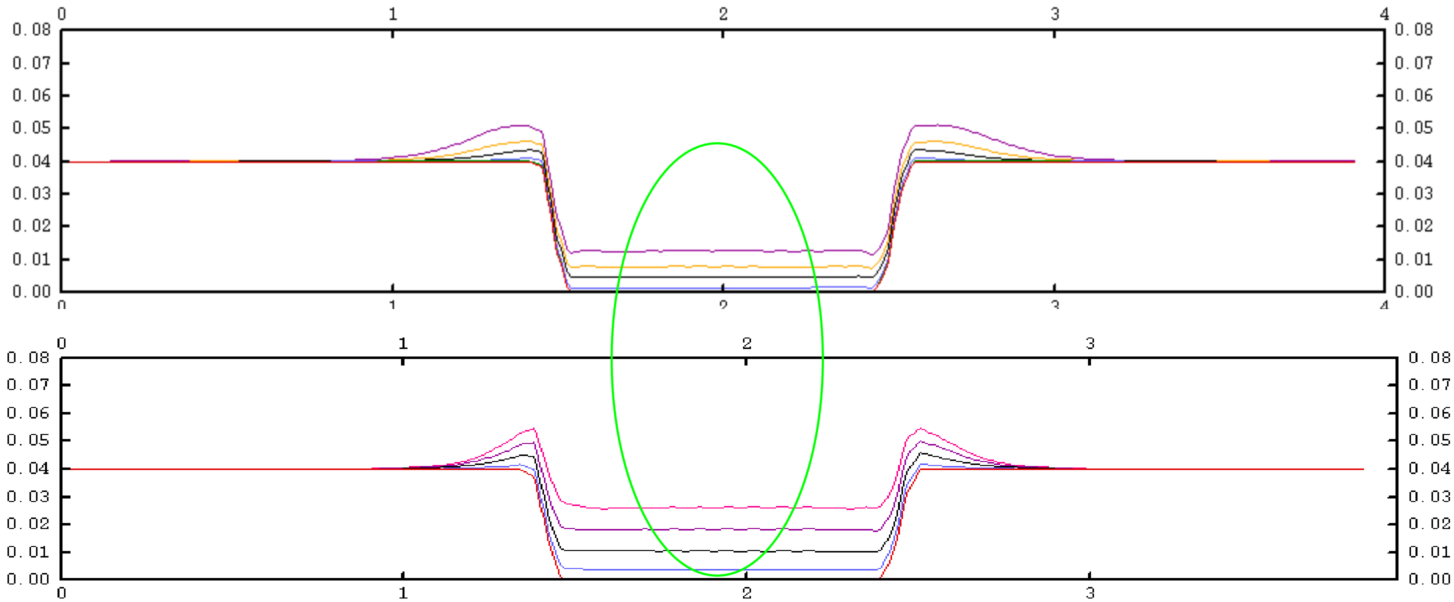




Caso B

7 – CASE STUDIES

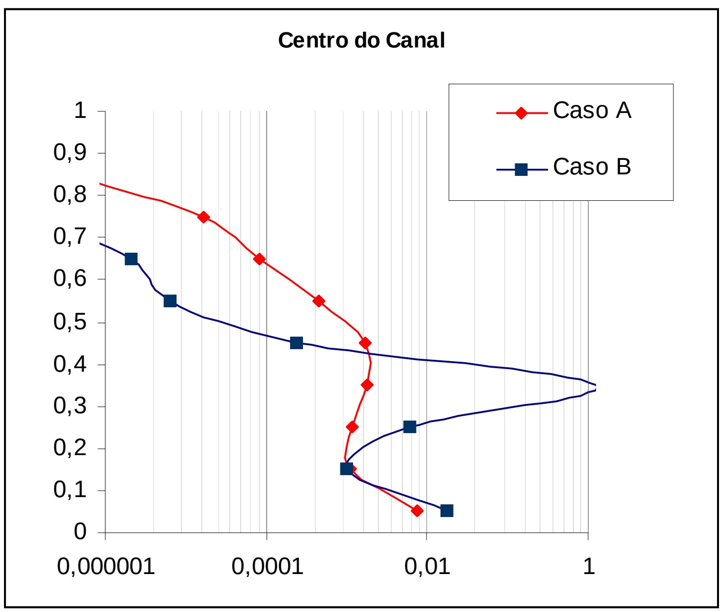
LEVEE CONSTRUCTION – QUALITATIVE APPROACH



Caso A

Caso B

$$Ri = \frac{1}{Fr} \propto \frac{c}{u^2}$$



7 – CASE STUDIES

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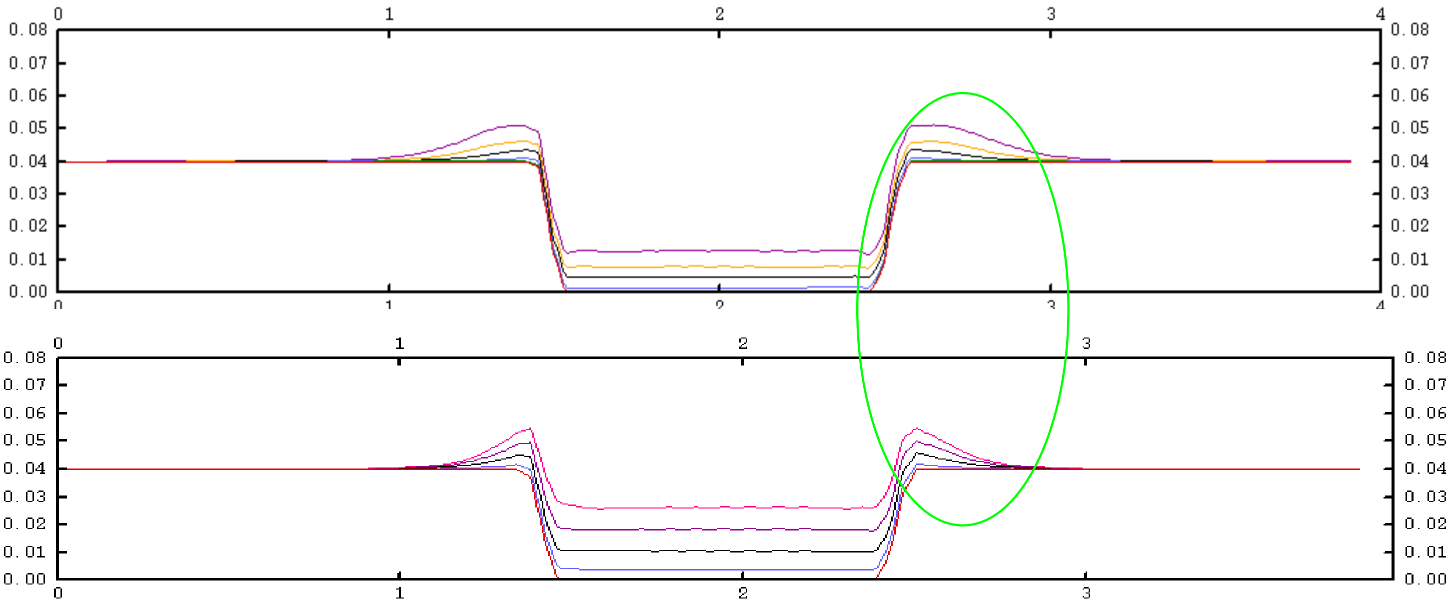

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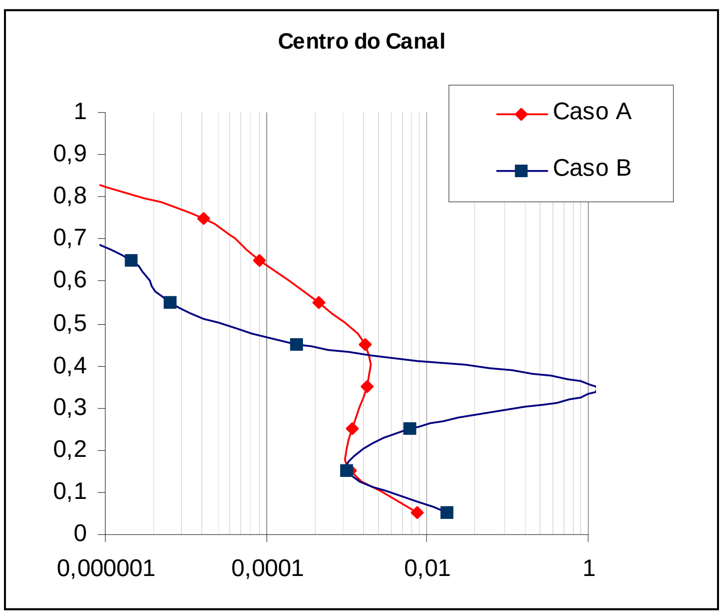

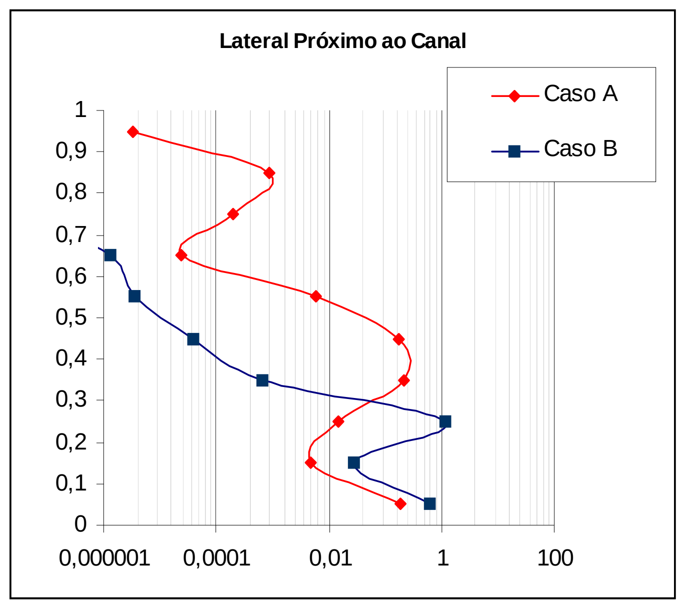

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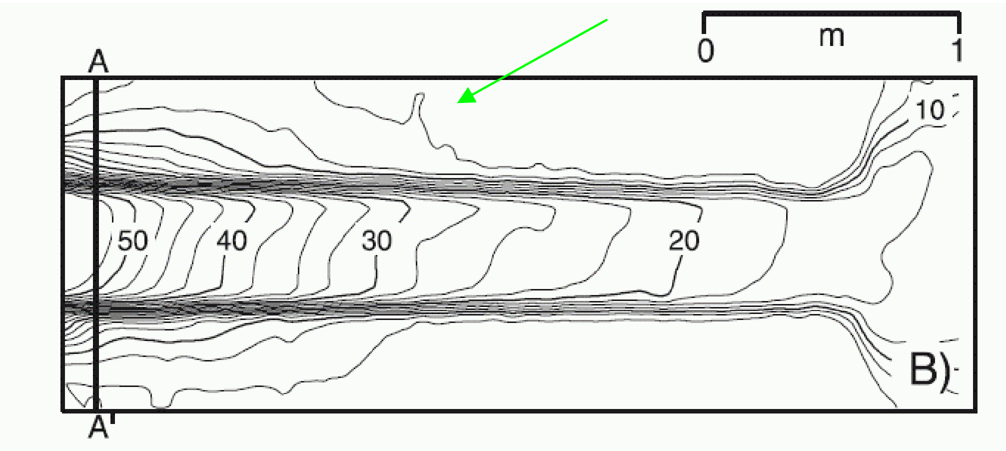

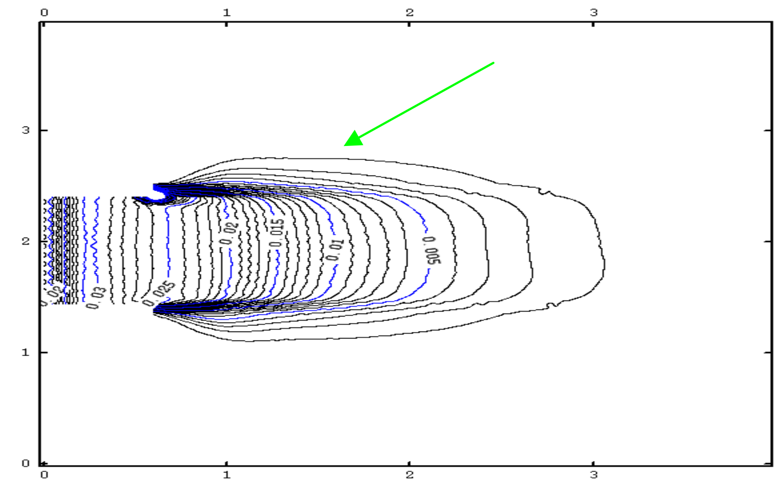

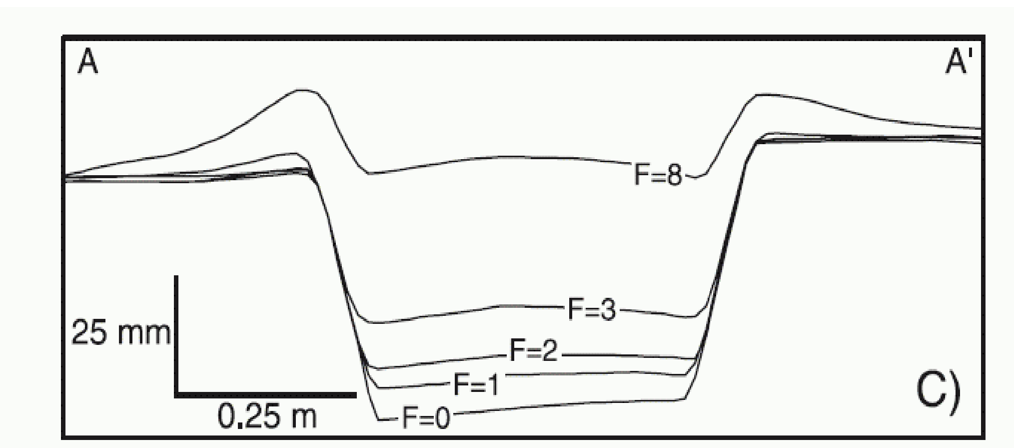

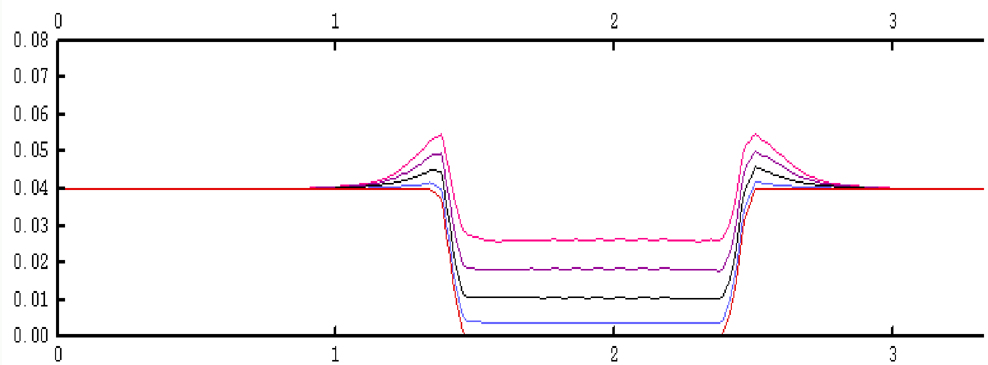

flume experiment

numerical experiment

OUTLINE:

8 – CONCLUSIONS

• LES is less accurate than DNS, as seen in the results, either in the visual inspection or in the more quantitative sedimentation rate and spatial distribution;

• LES could provide very realistic models in simple configurations, in 2 hours time simulation running in less than 25 cores;

• some sedimentological results could be discussed, like different geometries generated by flow characteristics in a levee configurations, as well as a different deposition aspects related to pulse x continuous flows;

• LES, when compared to DNS, proved to be useful for the study of sedimentological characteristics of deposits, for very simple cases;

OUTLINE:

9 – NEXT STEPS

We envisage:

- Simulation of multiple grain sizes;
- Erosional model;
- More precise turbulence models
- A more robust quantitative validation scheme

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- ***Perform processes studies in a reasonable computational time***