Internal dynamics of a free surface viscoplastic flow down an inclined plane : experimental results throught PIV measurments

Perrine FREYDIER, Guillaume CHAMBON, Mohamed NAAIM

Irstea , UR ETGR (Snow avalanche engineering and torrent control research unit)

perrine.freydier@irstea.fr

Introduction

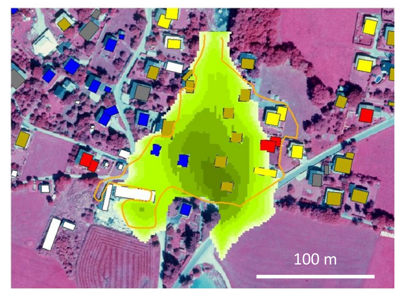

Fig 1 : Simulation of the propagation of a real debris flows crossing a French Alps city.

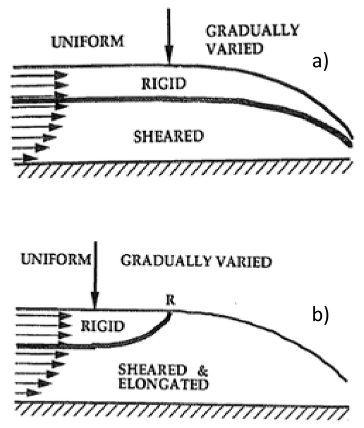

Fig 2 : Flow regimes for a gradually varied flow, [3].

- Natural muddy debris flows can be modeled as non-Newtonian **viscoplastic** fluids [*1, 2*].
- We need to develop **models** that are able to predict accurately hydraulic properties of debris flows.
- These complex flows are generally represented using models based on a momentum integral approach (**shallow water).**
- These models take into account closure terms depending on the shape of the velocity profile inside the flow.
- Free surface flows of yield stress fluids have unsheared regions (plug).
- Most of these models are based on the lubrication approximation (Fig. 2a) leading to the following plug thickness :

$$hp = \frac{\tau_c}{\rho g sin\theta\left(1 - cot\theta \frac{\partial h}{\partial x}\right)}$$

The aim of this work is to acquire experimental results documenting the internal dynamics of a free surface viscoplastic flow down an inclined channel.

Experimental set-up and fluid properties

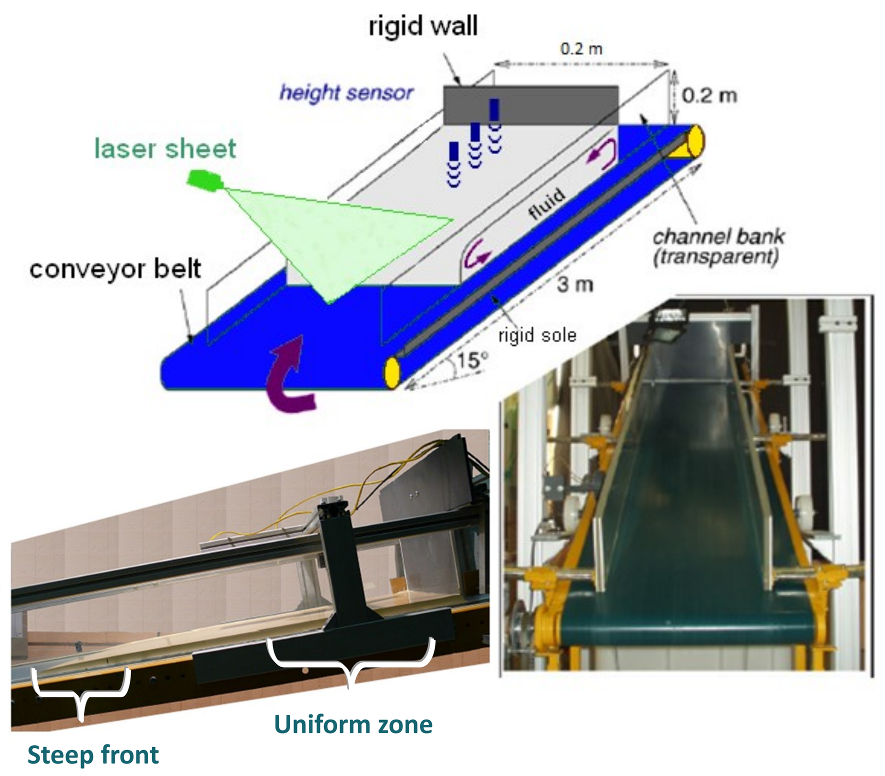

Fig 3: Flume set up, including laser sheet location. The velocity belt u_b can vary from 0 to 1 .5 m.s^{-1}, [4].

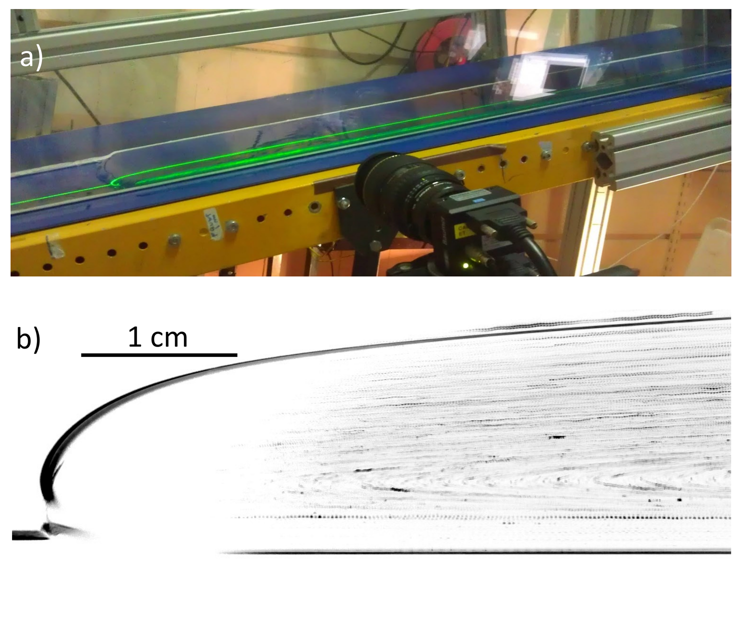

Fig 4 : a) High-speed camera location (Baumer with Nikkon 100 mm macro lens) filming from the side . b) Example of stream lines observed with a carbopol gel sample (u_b = 171 mm.s^{-1}) images resolution is 38 µm/pix .

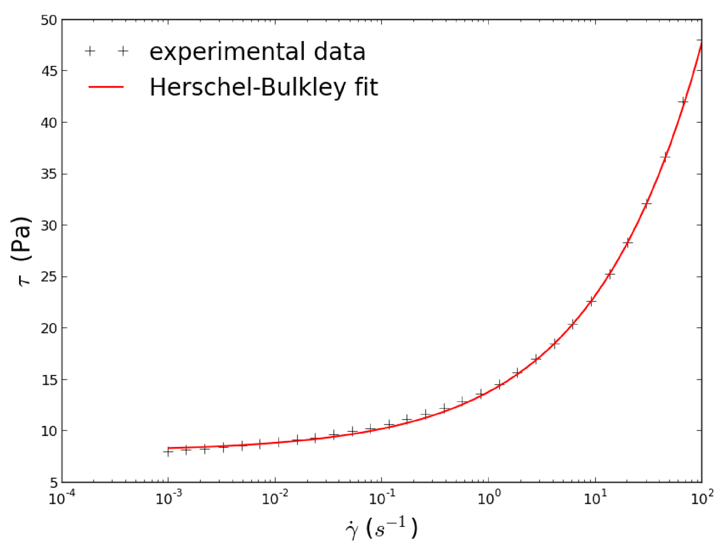

Fig 5 : Typical steady-state flow curves determined on Carbopol sample c1. Red curve represents best adjustments by the Herschel-Bulkley viscoplastic law.

Carbopol sample	τ_c	K	n
c1	8	5.7	0.42

Tab. 1 : Carbopol sample name and rheological properties, determined with a rotational parallel plate rheometer.

- **Carbopol** gel is used as a transparent homogeneous **viscoplastic fluid.**

Experimental results in the uniform zone

Theoretical framework

Expression of the velocity profile (1) :

$$u(y) = \begin{cases} \frac{n}{n+1} y_0^{\frac{n+1}{n}} \left(\frac{\rho g sin\theta}{K}\right)^{\frac{1}{n}} \left[1 - \left(1 - \frac{y}{y_0}\right)^{\frac{n+1}{n}}\right] & if \quad y < y_0 \\ \frac{n}{n+1} y_0^{\frac{n+1}{n}} \left(\frac{\rho g sin\theta}{K}\right)^{\frac{1}{n}} & if \quad y \geq y_0 \end{cases}$$

$y_0 = h - hp$ denotes the thickness of the sheared layer below the plug.

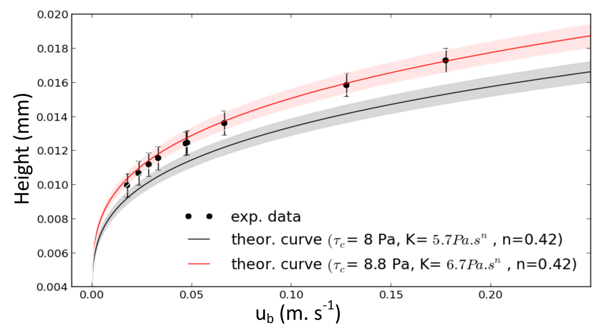

Fig 6 : Evolution of flow height H in the uniform zone as a function of belt velocity u_b of the tested Carbopol Sample c1.

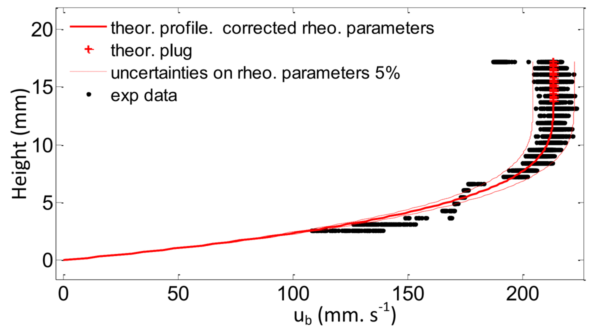

Fig 7 : Horizontal velocity derived from PIV as a function of vertical coordinate . Theoretical profile is computed using Eq. 1 with rheological parameters determined at the flow scale.

- We observe a systematic discrepancy between experimental data and theoretical predictions accounted for by increasing the yield stress τ_c by 11% and the consistency K by 19 %.
- **Rheological parameters have to be determined at the flow scale** and data about **velocity profiles in the uniforme zone** are necessary to determined accuratly the correction to apply to the rheological parameters measured with a rheometer, [5] .

Experimental results in the front zone

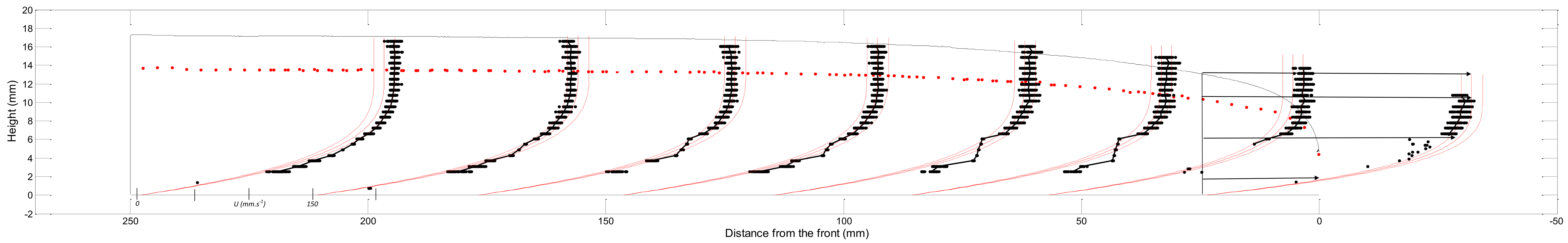

Fig 8 : Flow depth and velocity profiles for the carbopol sample c1 (Tab. 1), θ= 15 °, u_b = 171 mm.s^{-1}. Theoretical yield surface is represented in red dotted line, theoretical profiles are represented in red line with 5% uncertainties on the rhelogical parameters. Theoretical profiles are computed using the theoretical free surface provided by lubrication approximation and the rheological parameters determined at the flow scale.

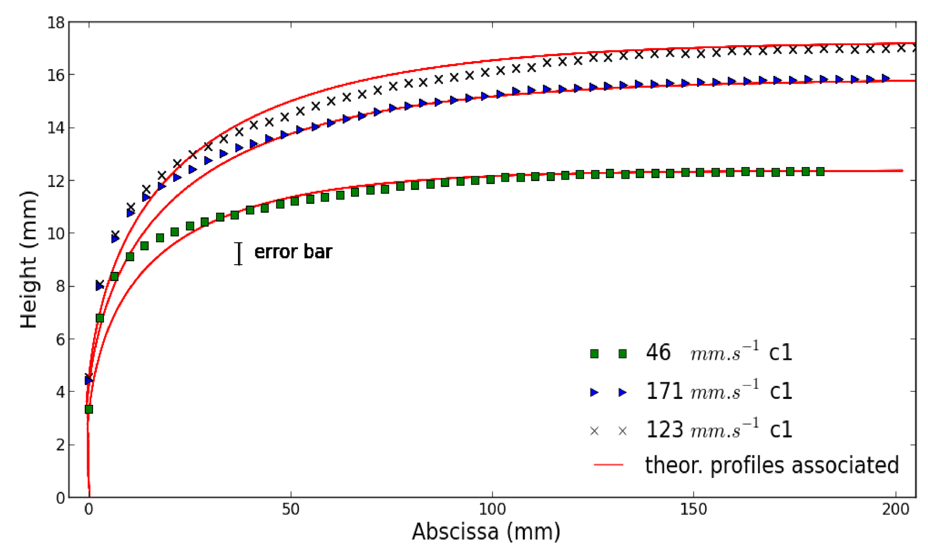

Fig 9 : Flow height *H* versus abscissa for Carbopol sample c1 and different belt velocities *ub* . Theoretical curves are provided by lubrication approximation.

- Similar experiments have been performed, with velocity varying from 45 to 171 mm.s^{-1} : Fr = [0.13 – 0.42] , G =[0.20 - 0.28], Hb = [0.50 – 0.76] are respectively the Froude number, the non dimensionnal yield stress and the Herschel Bulkley number.
- Sufficiently far from the front (x > 30 mm), lubrication theory provides a good approximation to predict velocity profiles.
- A difficulty resides in finding an efficient way to determine the position of the plug from experimental data.
- Theoretical depth profiles (Fig. 9) appear to reproduce the experimental data quite well. In the vicinity of the front, we note a slightly discrepancy.

Conclusion and outlook

- Our experimental set up allows to observe the internal dynamics of a front of a gravity driven flows. Experiences can be conducted with various flume inclinations, velocities and materials (Newtonian, pseudoplastic, viscoplastic).
- Rheological parameters are determined at the flow scale.
- In the front zone (x > 30 mm) results show good agreements with lubrication approximation concerning velocity profiles and free surface shape.
- We need to improve our set up in order to look at the head of the front .

References

1 Coussot P. (1994): Steady, laminar, flow of concentrated mud suspensions in open channel, Journal of Hydraulic Research, Vol. 32, No 4, pp. 535-559.

2 Ancey, C. (2006): Plasticity and geophysical flows: A review, Journal of Non-Newtonian Fluid Mechanics, Vol. 142, pp. 4-35.

3 Piau, J .M. (1996): Flow of a yield stress fluid in a long domain. Application to flow on an inclined plane, Journal of Rheology, Vol. 40, pp.711–723.

4 Chambon, G., Ghemmour, A. and Laigle, D. (2009): Gravity-driven surges of a viscoplastic fluid: An ex perimental study, Journal of Non-Newtonian Fluid Mechan ics, Vol. 158, pp. 54-62.

5 Chambon, G., Ghemmour and Naaim M. (2014): Experimental investigation of viscoplastic free-surface flows in steady uniform regime, Journal of Fluid Mechanics, Vol. 754, pp. 332-364.

Acknowledgment

Financial support by INSU - Programme Terre Solide - ALEAS is acknowledged. Irstea is member of Labex Tec21 and of Labex Osug@2020.