Kavli Institute for Theoretical Physics
University of California, Santa Barbara

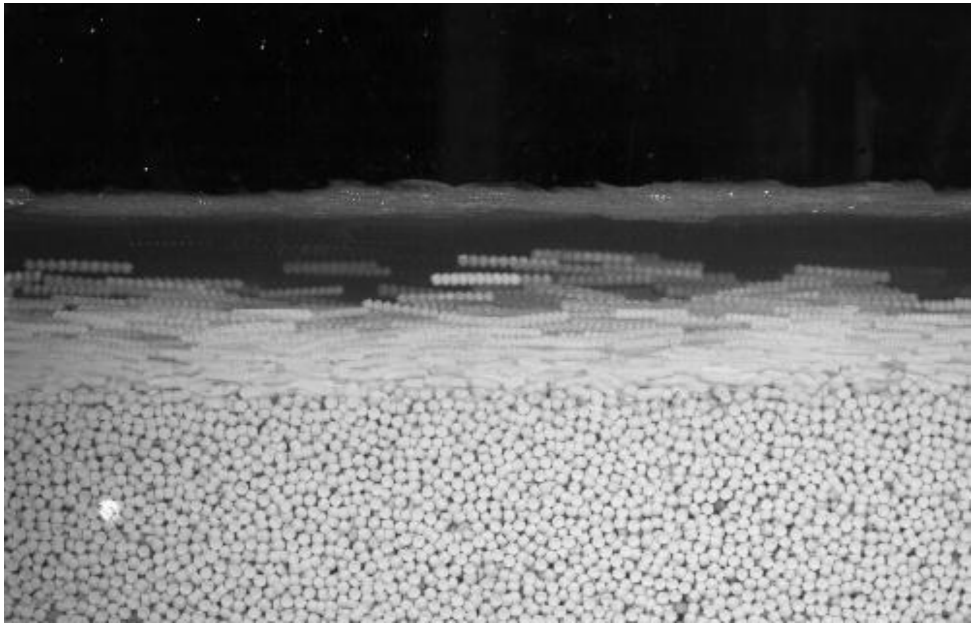
Fluid-Mediated Particle Transport in Geophysical Flows

Sep 23, 2013 - Dec 20, 2013

Intense Bed Load and Surroundings

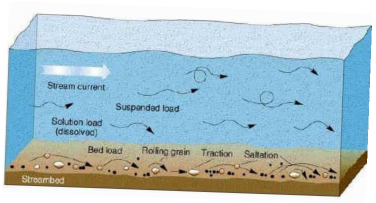
luigi fraccarollo

University of Trento, Italy



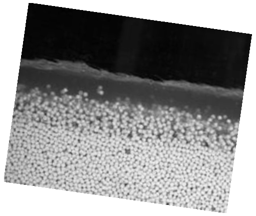
Focus on two-phase fluid on coarse mobile bed

ordinary bedload



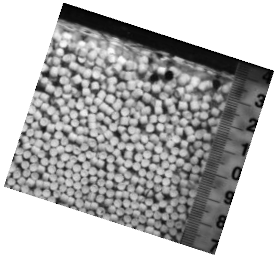
Shields<0.3

Intense bedload



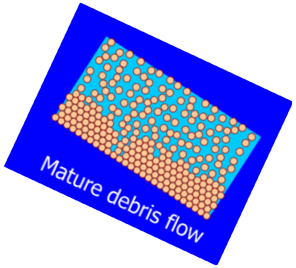
0.3<Shields<3

suspended sheet-flow



Shields>3

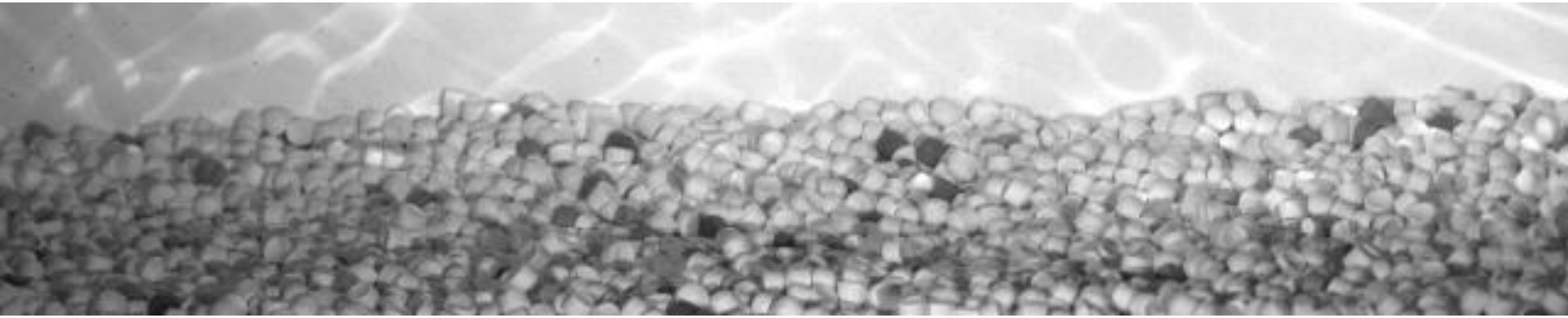
debris-flow



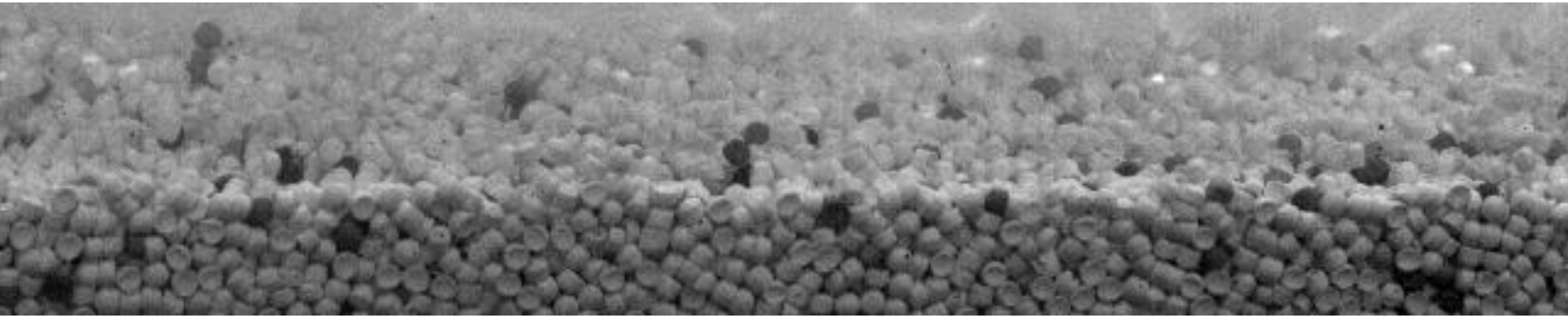
Shields>3

SHIELDS

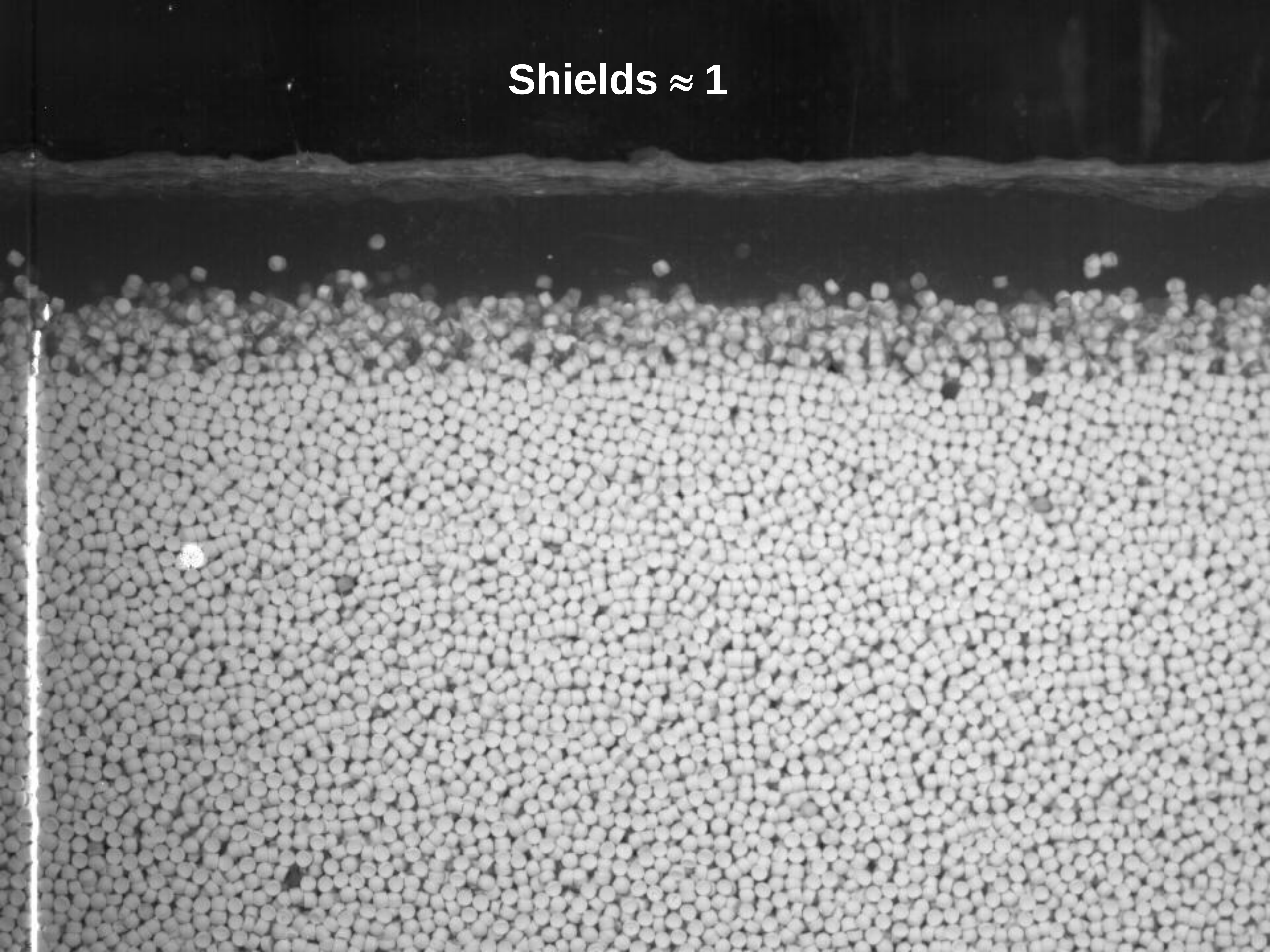
Ordinary bed-load at Shields ≈ 0.1



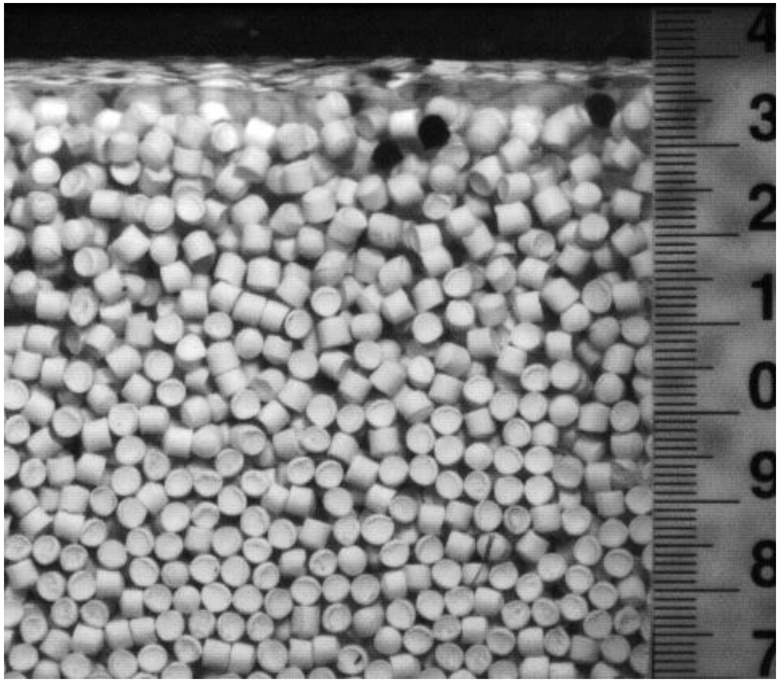
Ordinary bed-load at Shields ≈ 0.3



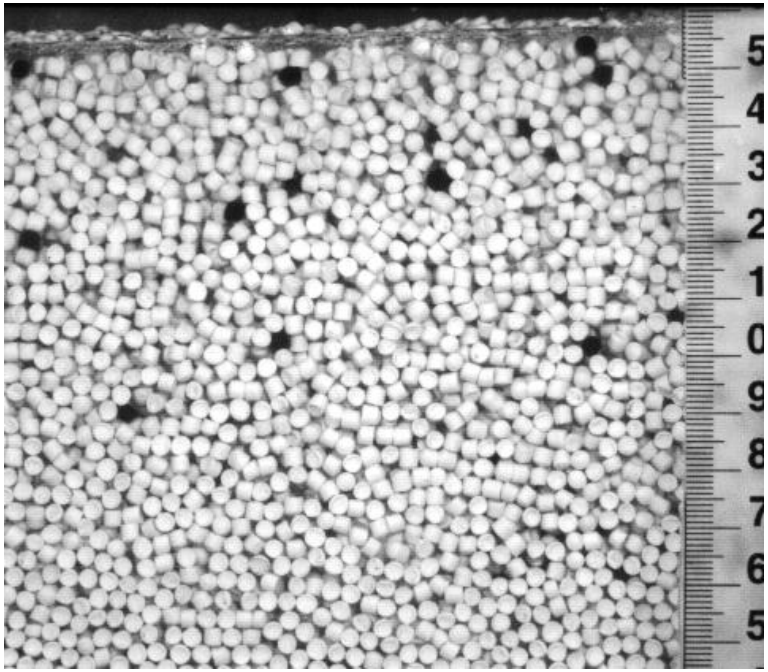
Shields ≈ 1



debris flows on loose bed

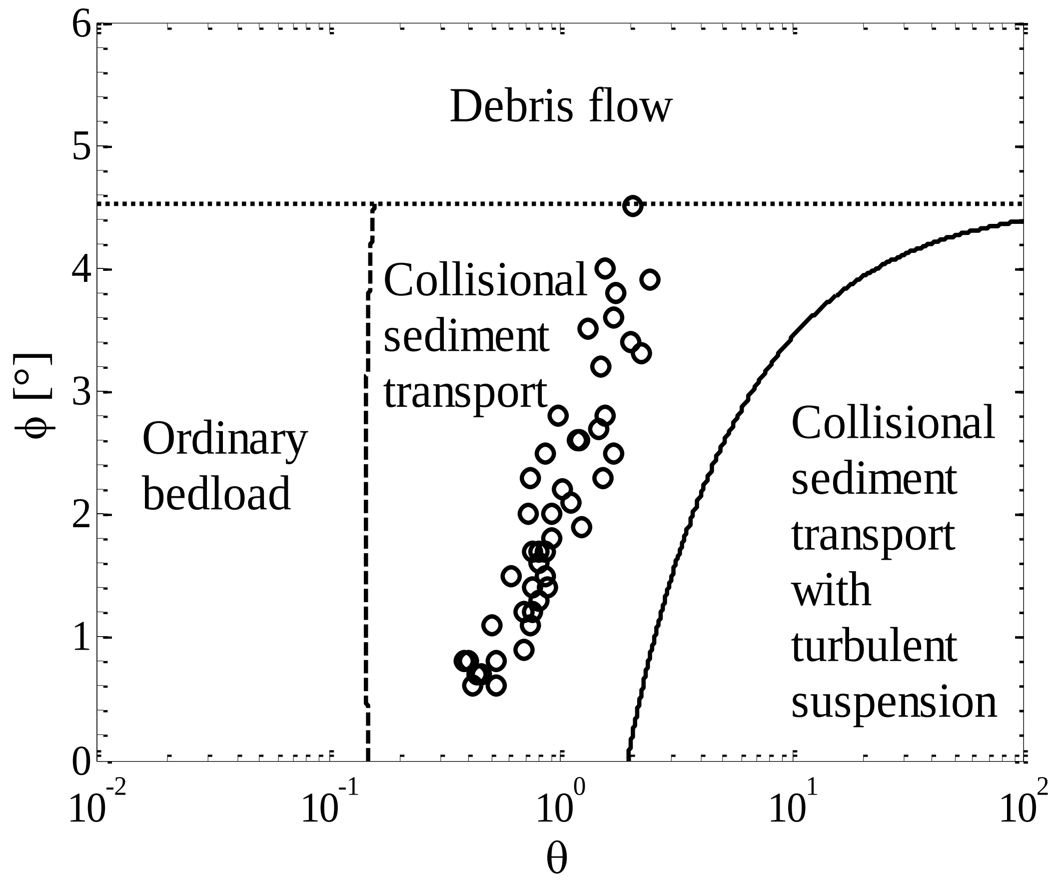


Shields ≈ 10

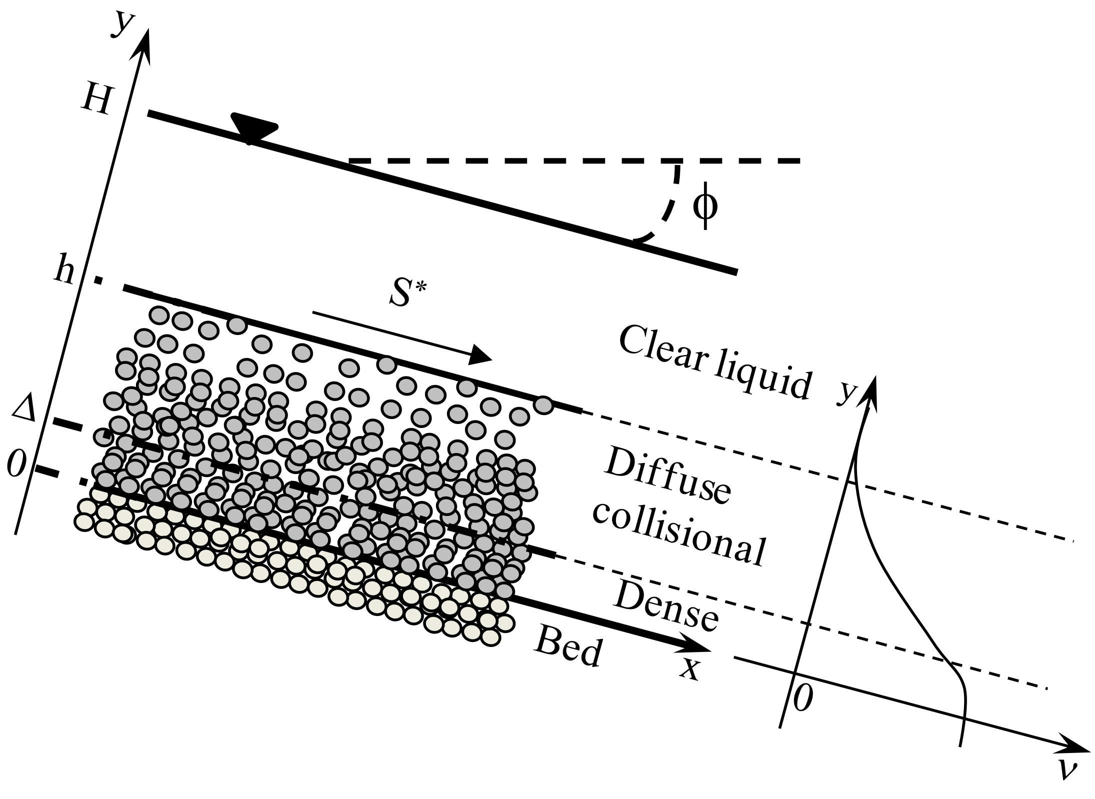


Shields ≈ 50

Rheological-phase diagram (from theory #2)



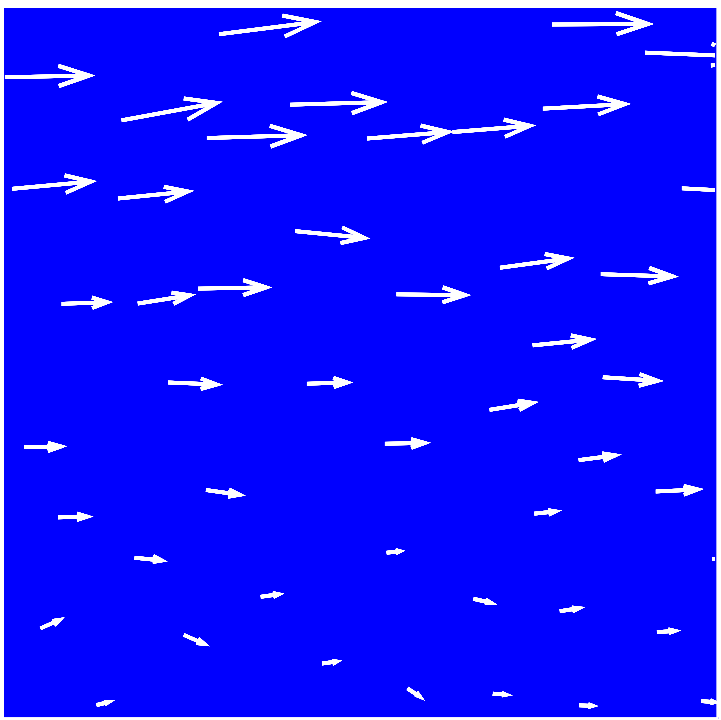
Sheet flow (0.3<Shields<3)



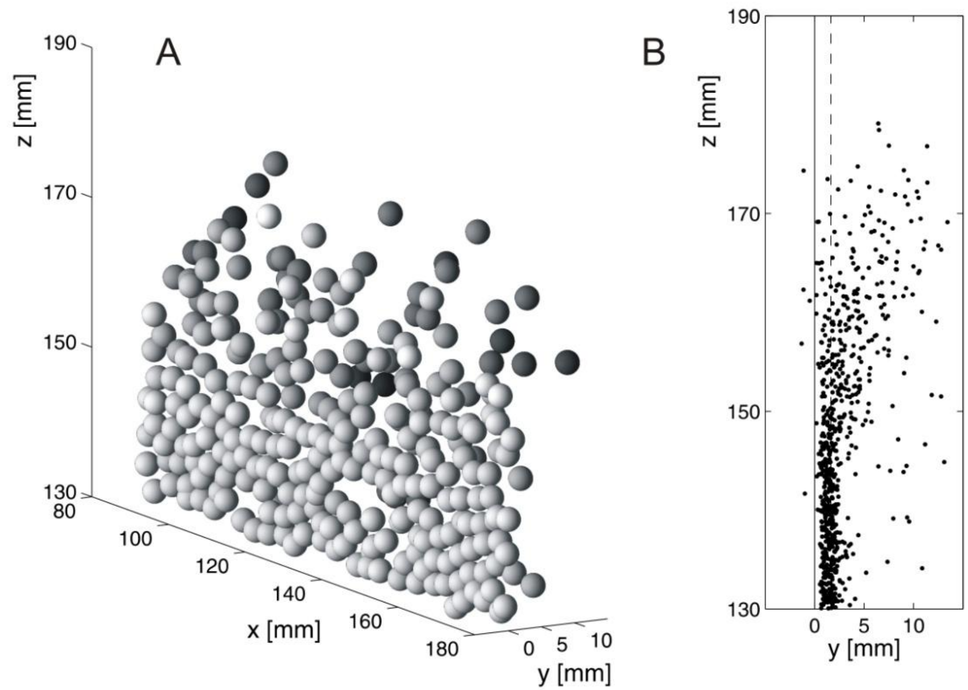
Measurements

Image technique for both velocity and concentration

particle velocity

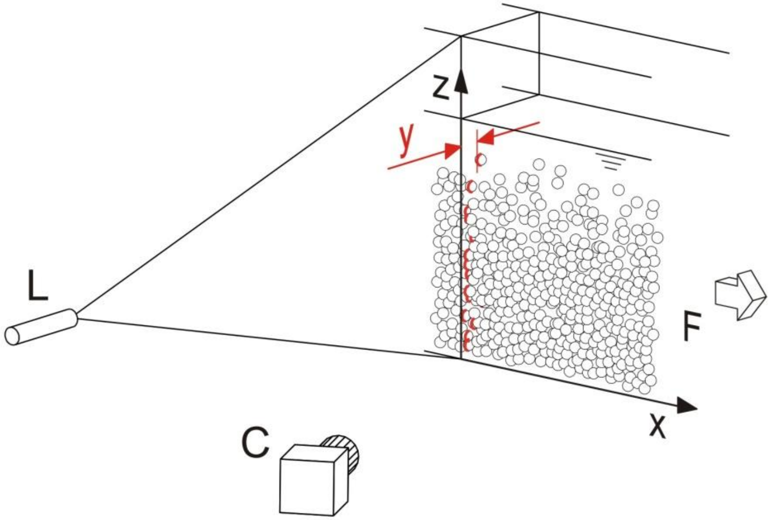


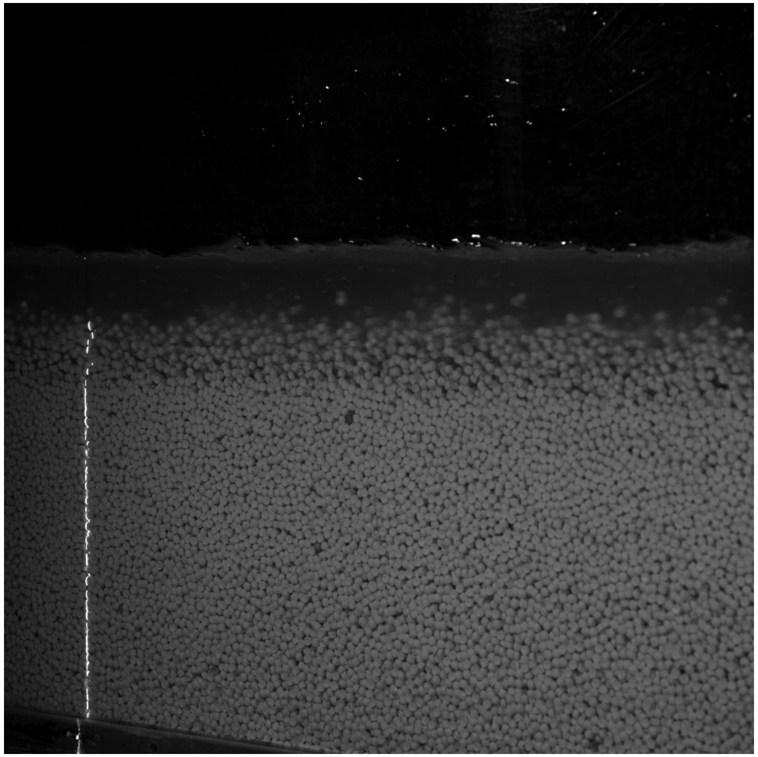
and concentration

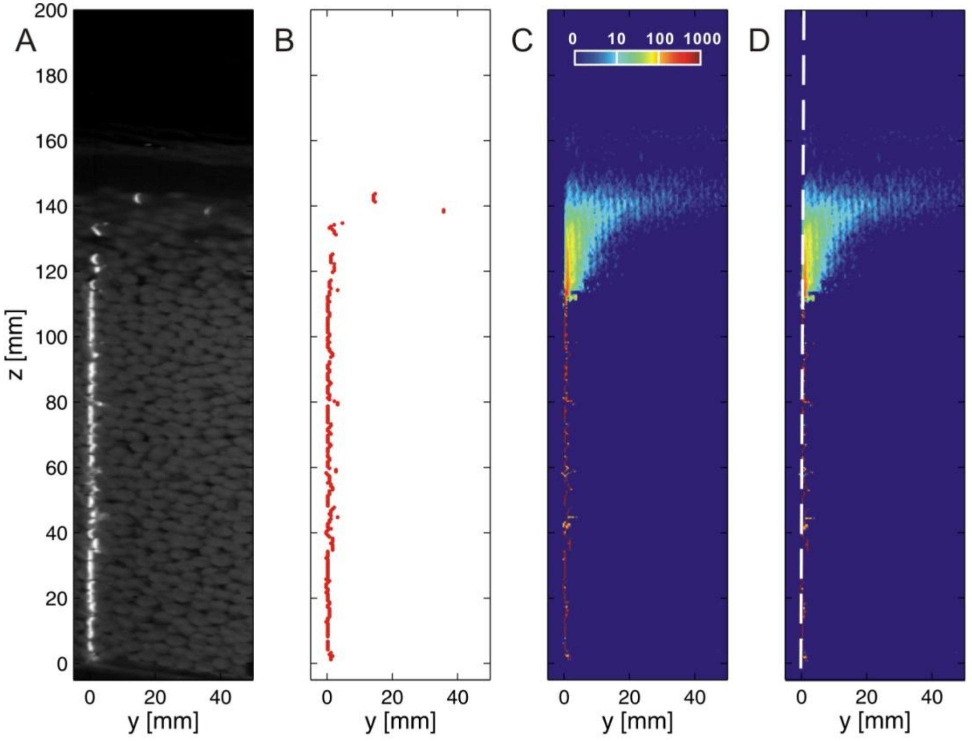


Laser stripe measurements: a new, simple and robust imaging method allowing concentration measurements in granular flows

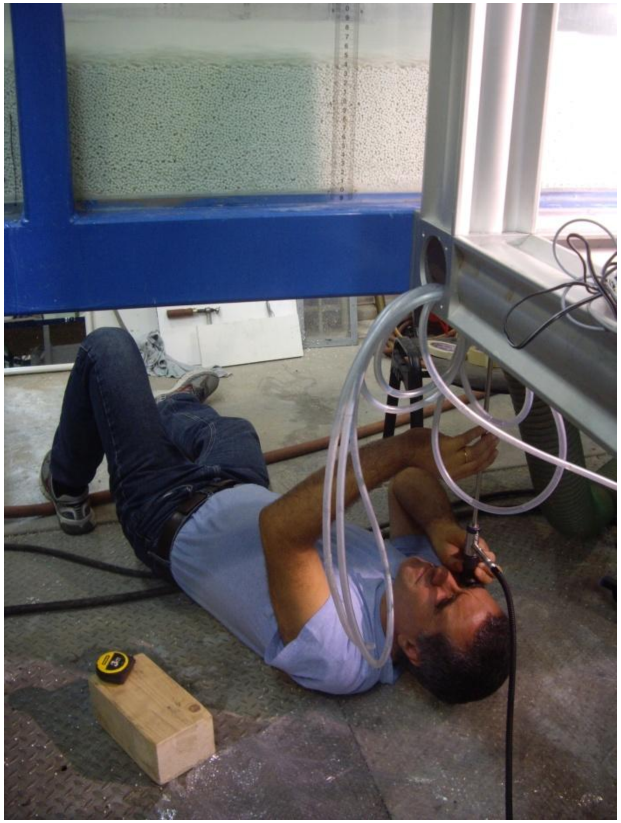
Spinewine, Capart, Fraccarollo, Larcher, Exp. in Fluids, 2011.





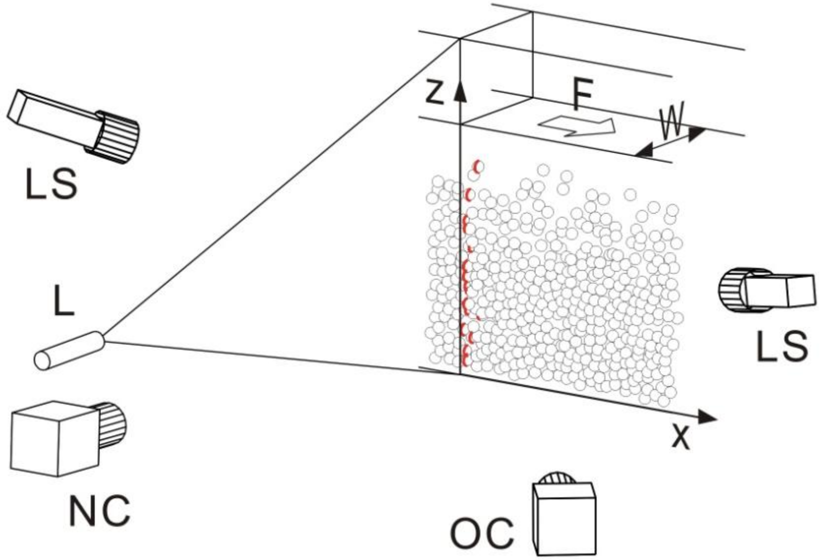


Sheet flow, or intense bed-load (0.3<Shields<3)

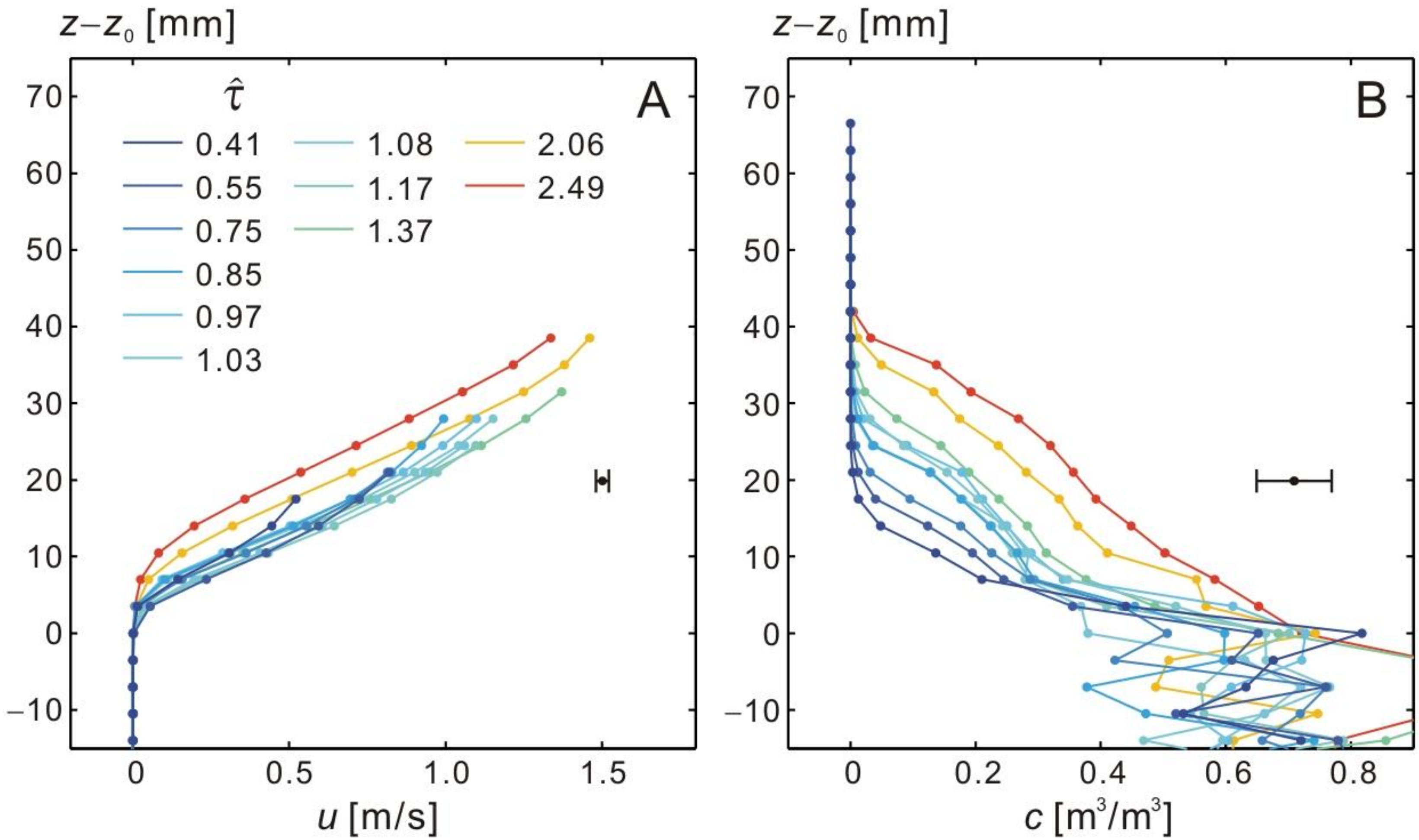


Aug-Sept 2009

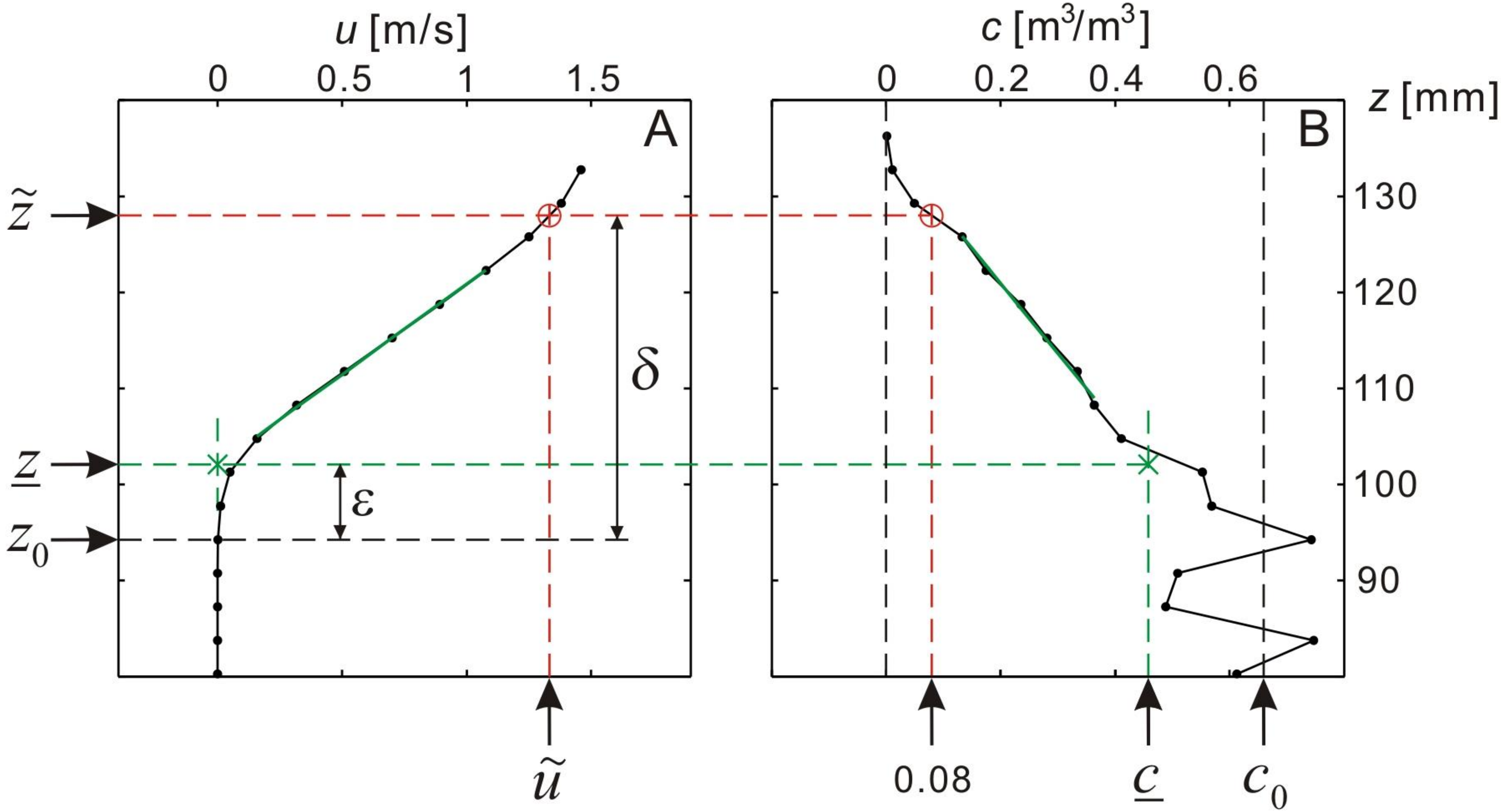
Lab set-up



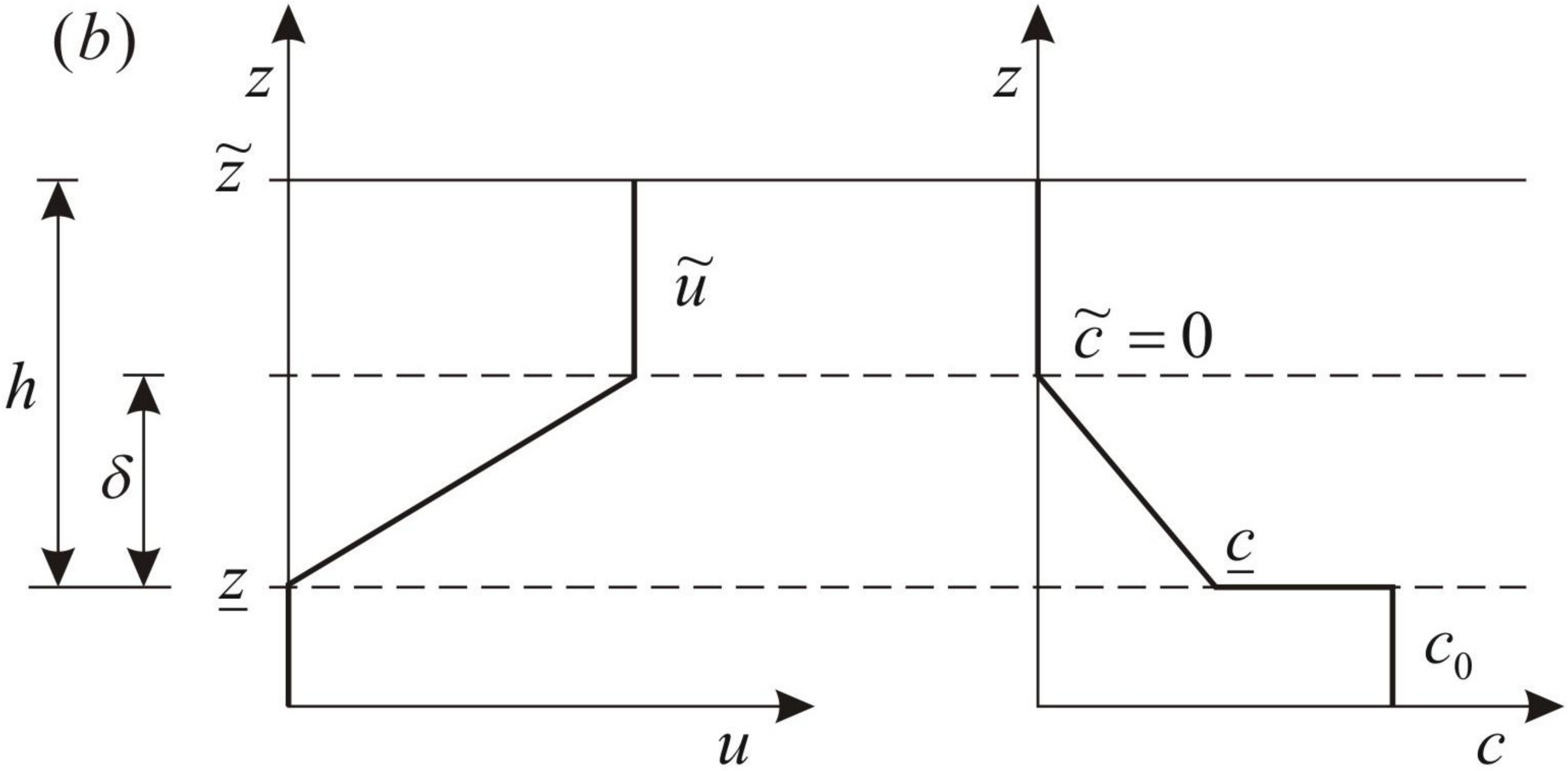
Measured profiles



Layer-structure variables



Layer-structure variables (idealized)



theory #1

Capart, H., Fraccarollo, L. (2011), Geophysical Research Letters

theory #2

Berzi, D. and Fraccarollo, L. (2013), Physics of Fluids

Main features of the theory #1

$$G = \frac{-g\cos\beta \,\mathrm{d}\rho/\mathrm{dz}}{\rho_W(\mathrm{d}u/\mathrm{dz})^2} = 0.058$$

$$\hat{\tau} = \tfrac{1}{2} R\underline{c}\hat{\delta}$$ ← Coulomb yield criterion $R = \tan\alpha_0$

$$\hat{u} = \sqrt{2/(GR)}\,\hat{\tau}^{1/2}$$

Kinetic theory

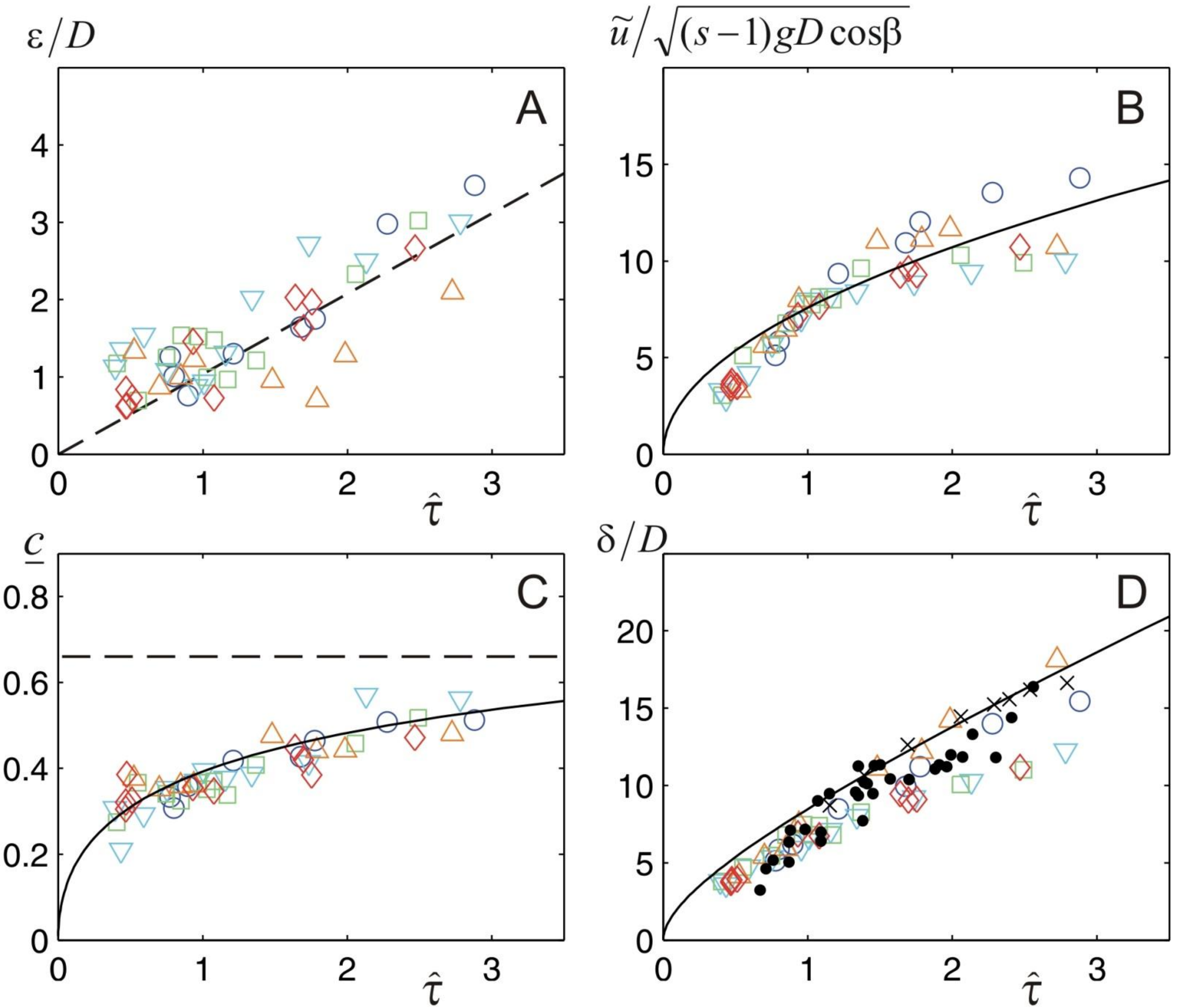
$$\hat{q}_S = \tfrac{1}{6}\underline{c}\hat{\delta}\hat{u} \qquad \hat{\delta} = \frac{\delta}{D} = \frac{f(\underline{c})}{R}\sqrt{\frac{2(s+a(\underline{c}))}{G}}$$

$$\hat{q}_S = \hat{\omega}\hat{\tau}^{3/2}$$

$$\hat{\omega} = (2/(9GR^3))^{1/2} \approx 4.2$$

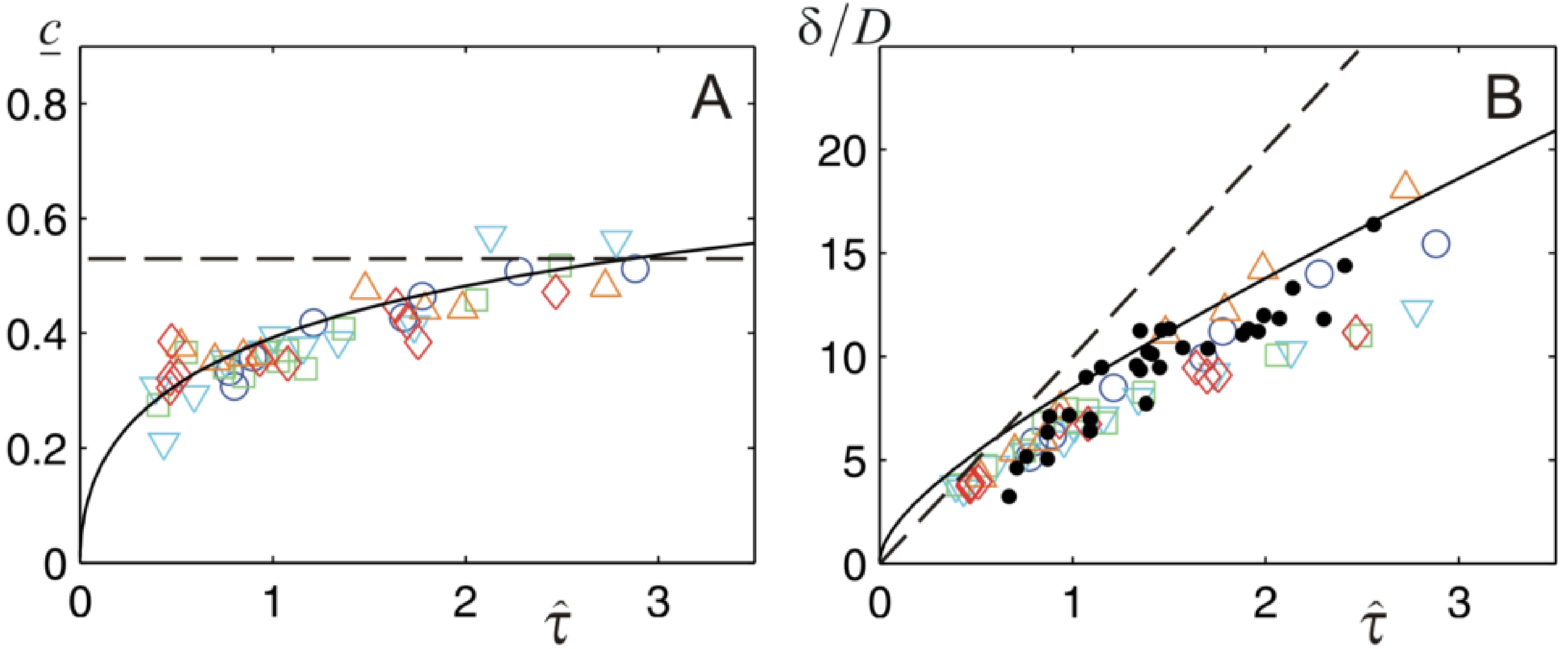
close to the value obtained by *Wong and Parker* [2006]

Main outcomes of the theory #1



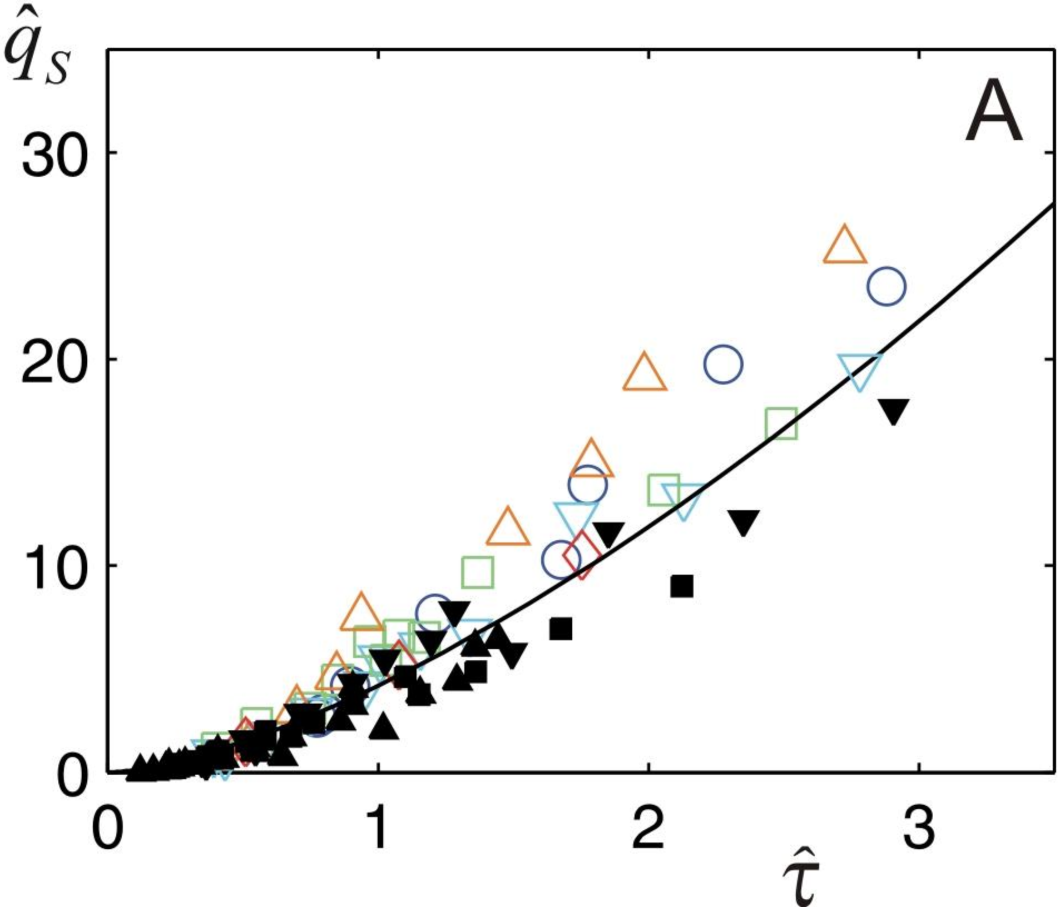
Main outcomes of the theory #1

Comparison with Bagnold (1956)



Main outcomes of the theory #1

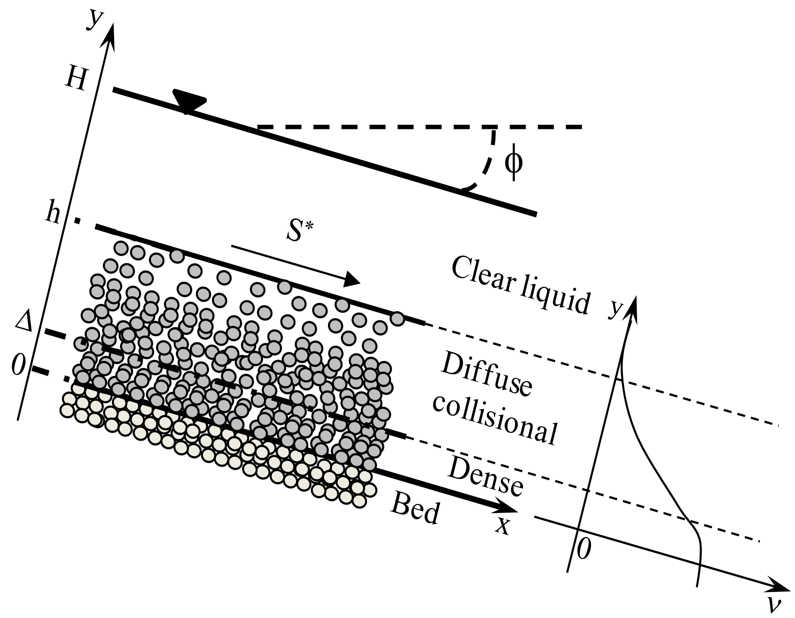
Transport relation

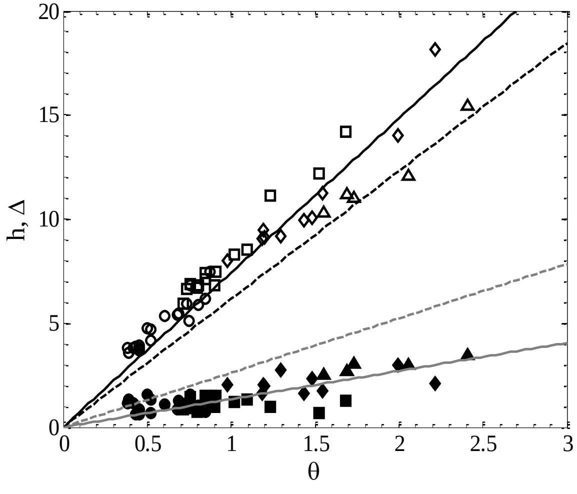


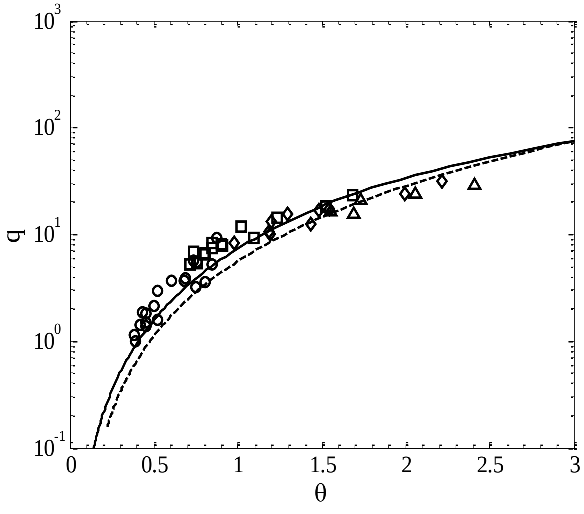
Main features of the theory #2

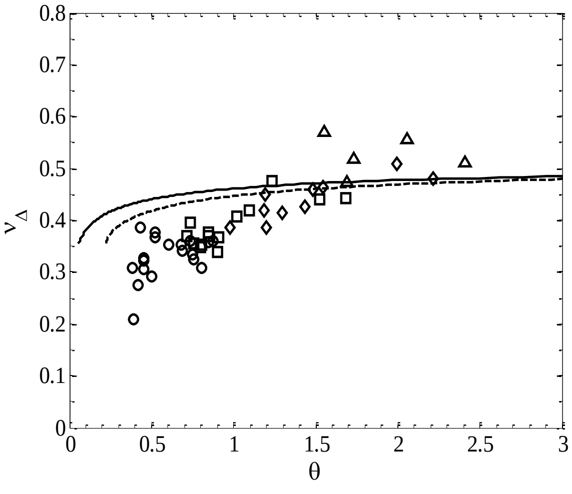
We removed any assumption on G

$$\frac{s_\Delta}{p_\Delta} = k_\Delta = \left(\frac{24 J_\Delta}{5\pi} \frac{1 - e_\Delta}{1 + e_\Delta} \right)^{1/2}$$



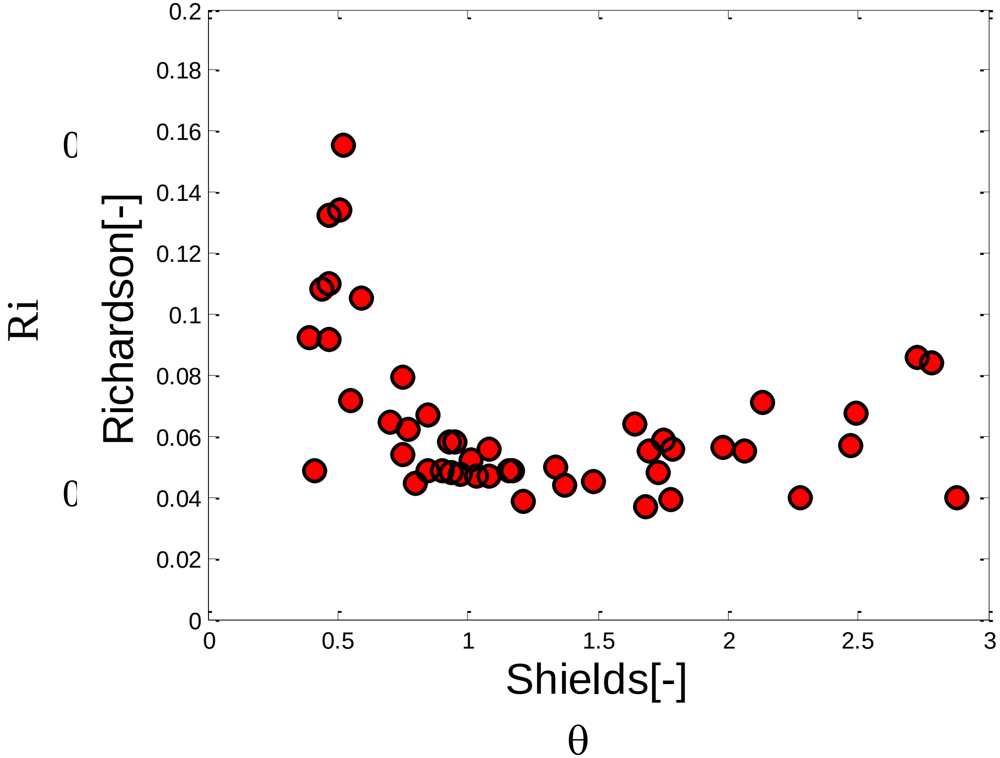




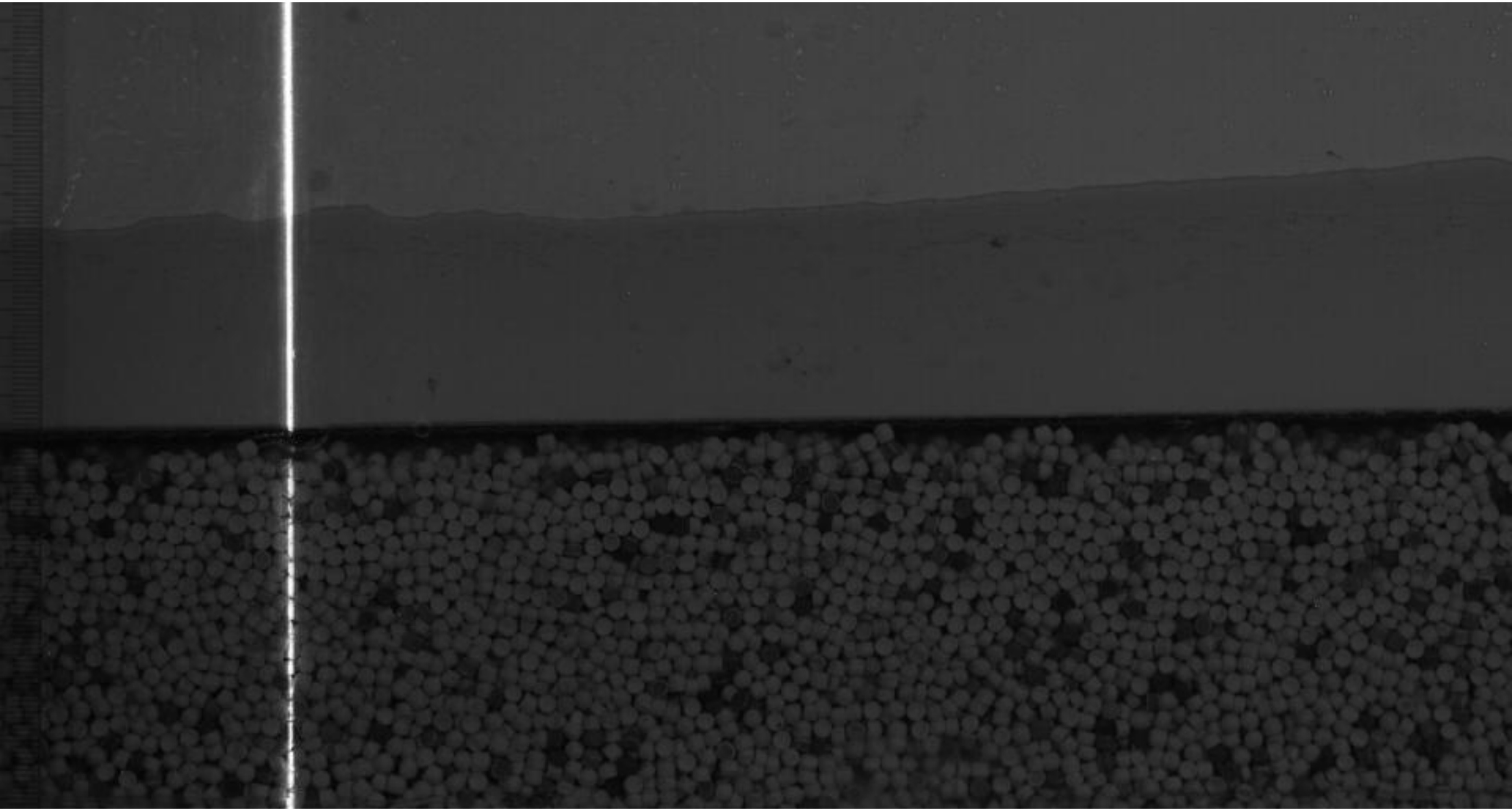


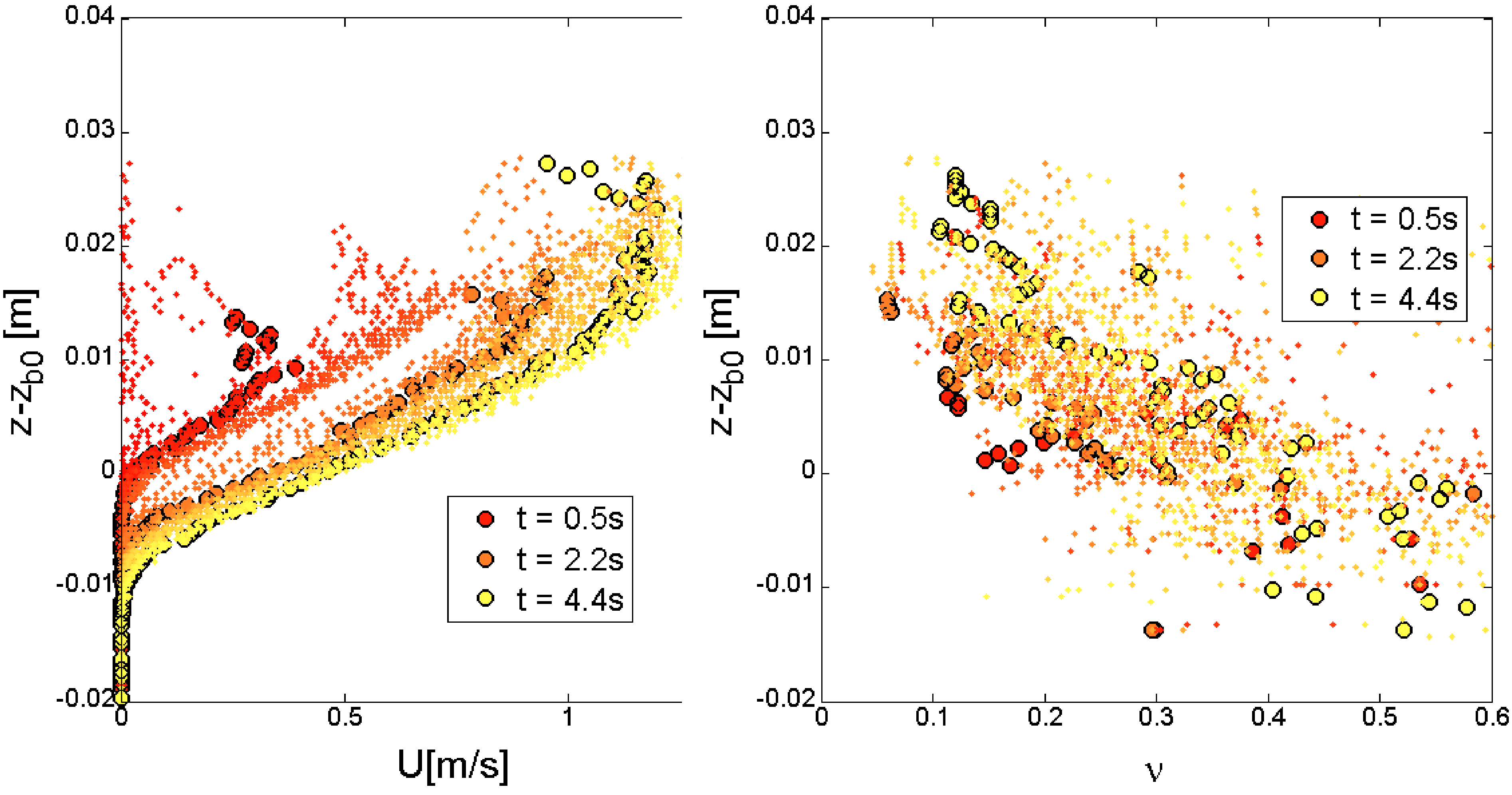
Let’s have a look at Richardson #, it increases as Shields decrease

By theory #2 (no assumption on Richardson), we get



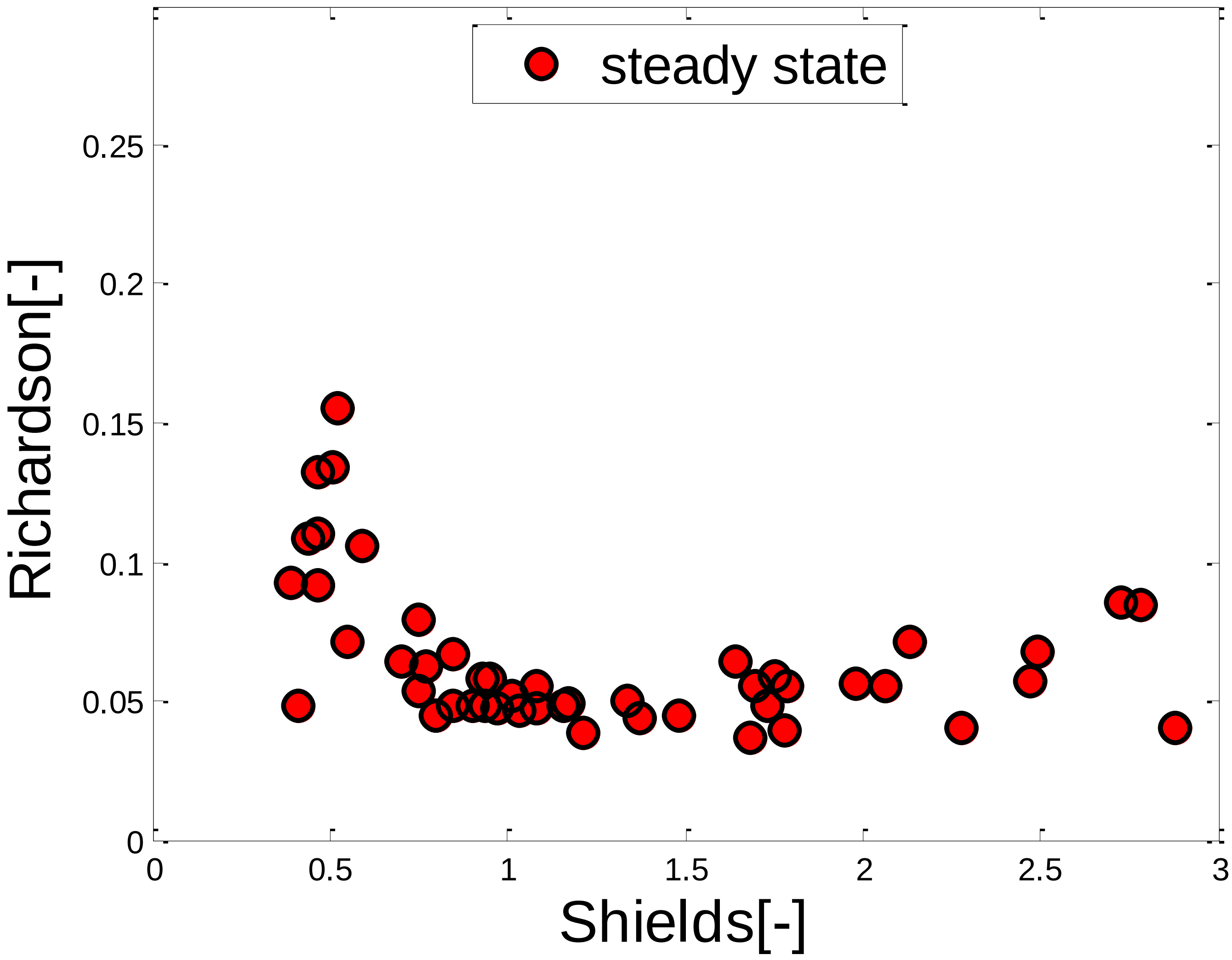
Uniform unsteady flow provides more info about G at low Shields



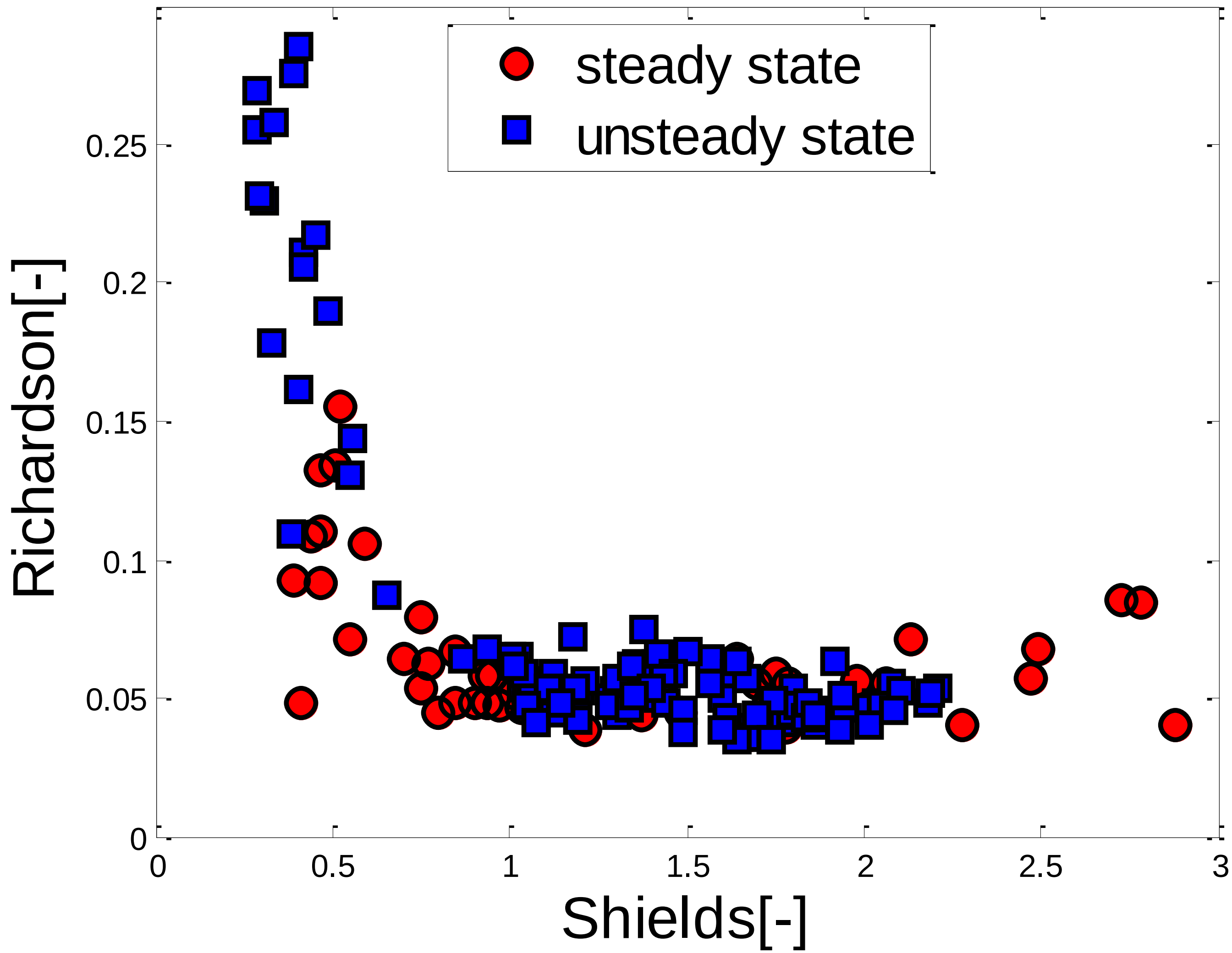


0.04
0.03
0.02
0.01
0
-0.01
-0.02
0
0.5
1
z-z_b0 [m]
U[m/s]
t = 0.5s
t = 2.2s
t = 4.4s
0.04
0.03
0.02
0.01
0
-0.01
-0.02
0
0.1
0.2
0.3
0.4
0.5
0.6
z-z_b0 [m]
ν
t = 0.5s
t = 2.2s
t = 4.4s

Let's consider G dependence on Shields in both the steady and unsteady stages of the flow

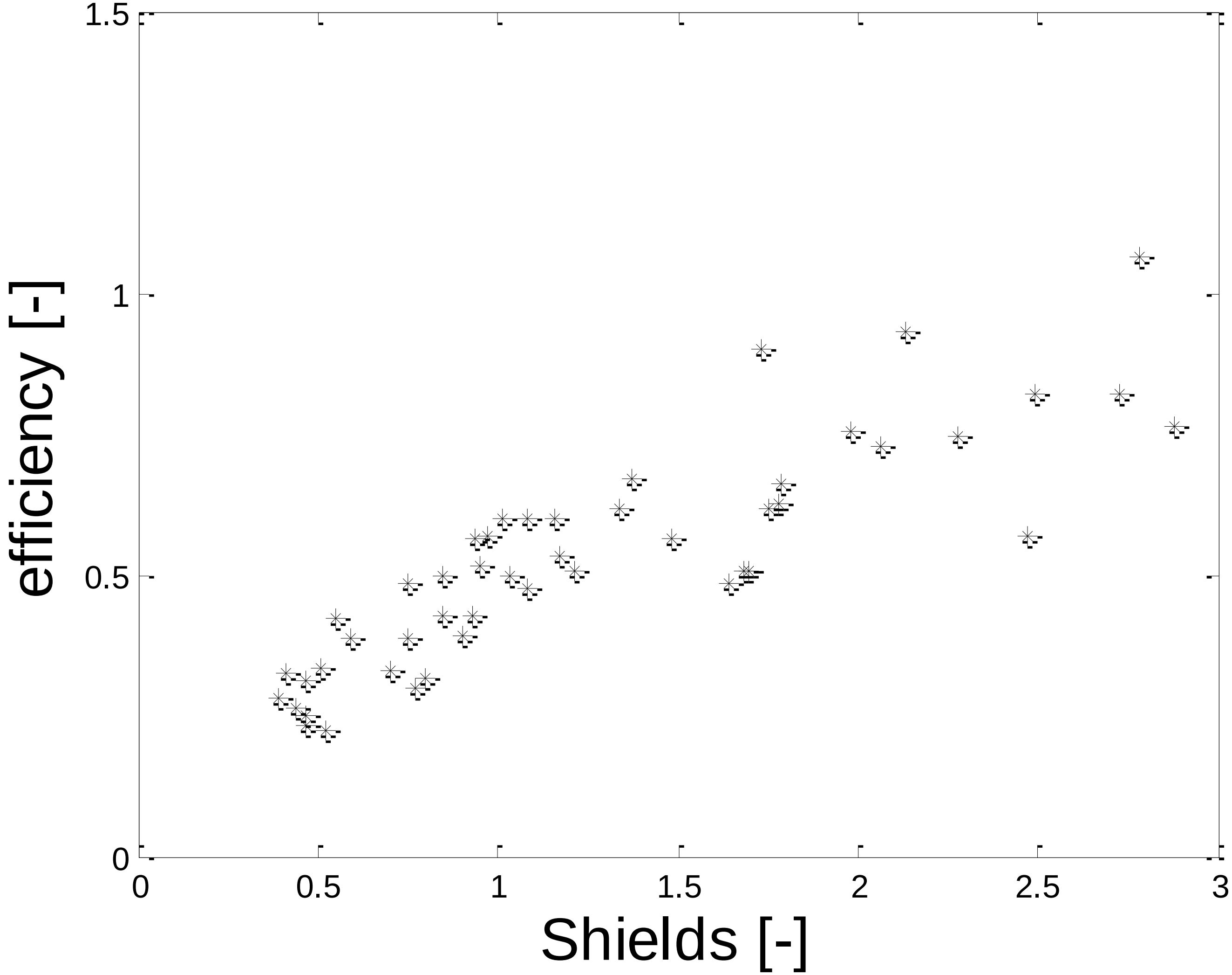


Let's consider G dependence on Shields in both the steady and unsteady stages of the flow



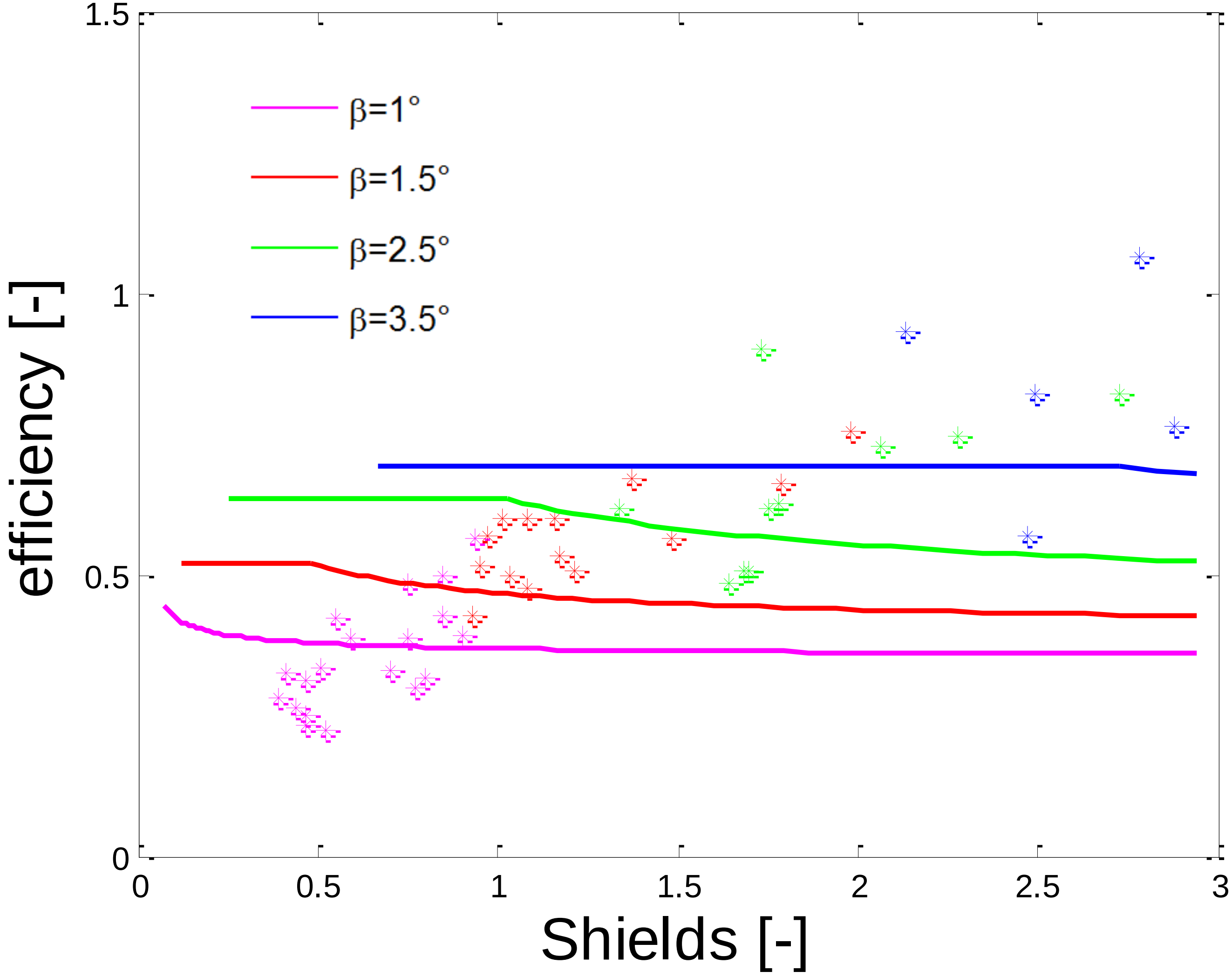
Further global predictors

efficiency ... q_L $\tan\beta$



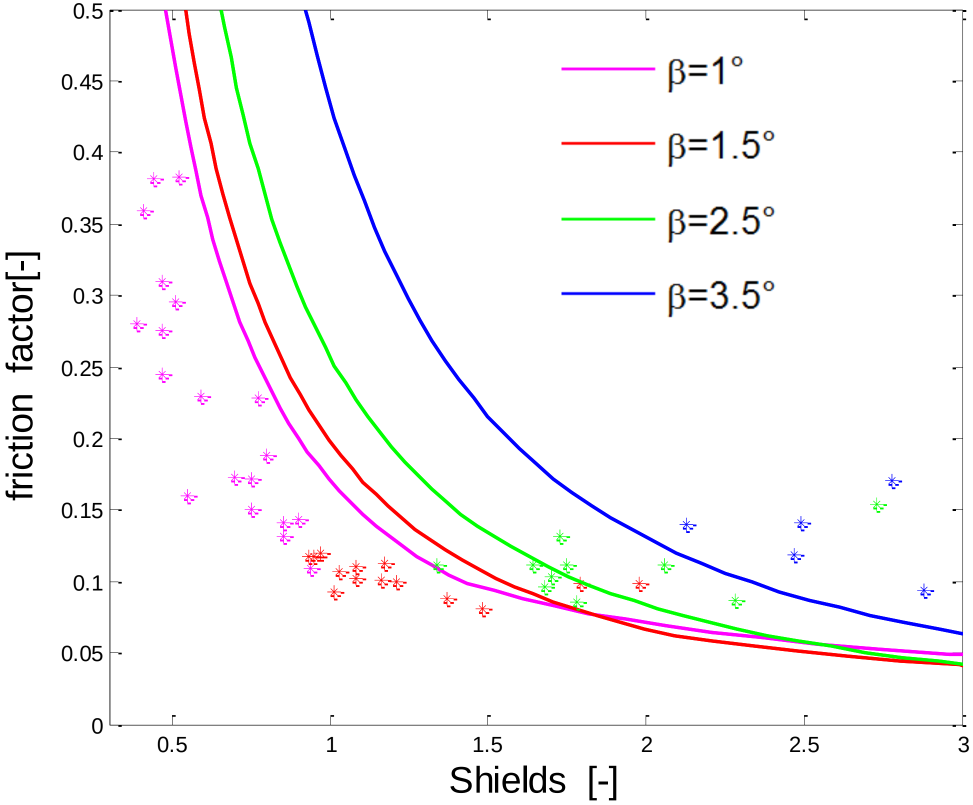
efficiency

$$e_b = \Delta \frac{q_b}{q_L} \frac{\tan \alpha_0}{\tan \beta}$$



Resistance function

$$f = 8\left(\frac{u_*}{u}\right)^2$$



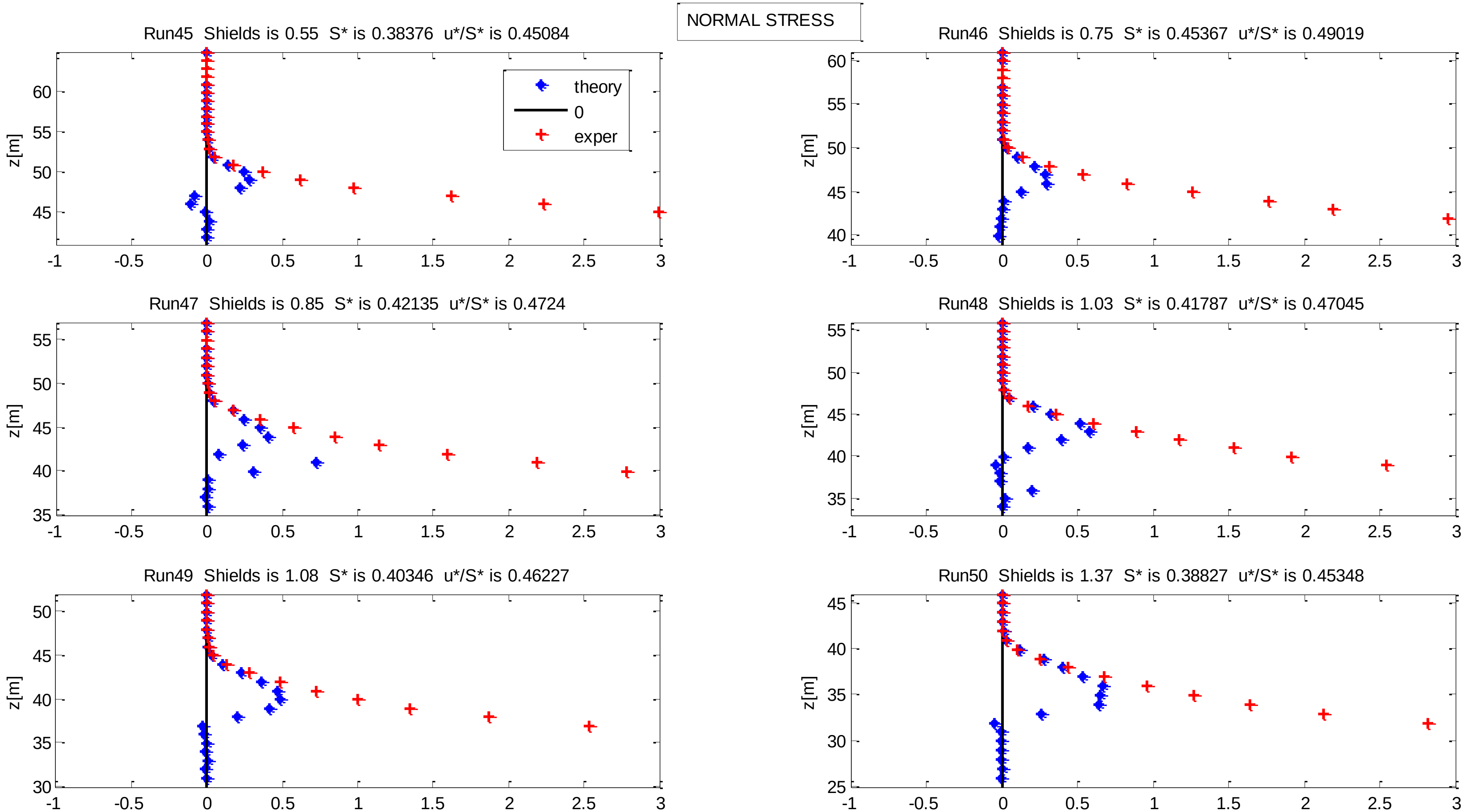
Look at the distributions and local information

$$p = 4\nu GFT$$

$$F = \frac{1+e}{2} + \frac{1}{4G}$$

$$e = \varepsilon - 6.9\frac{1+\varepsilon}{St}$$

$$\frac{\partial p}{\partial z} = \nu(\rho_s - \rho) g \cos\beta$$

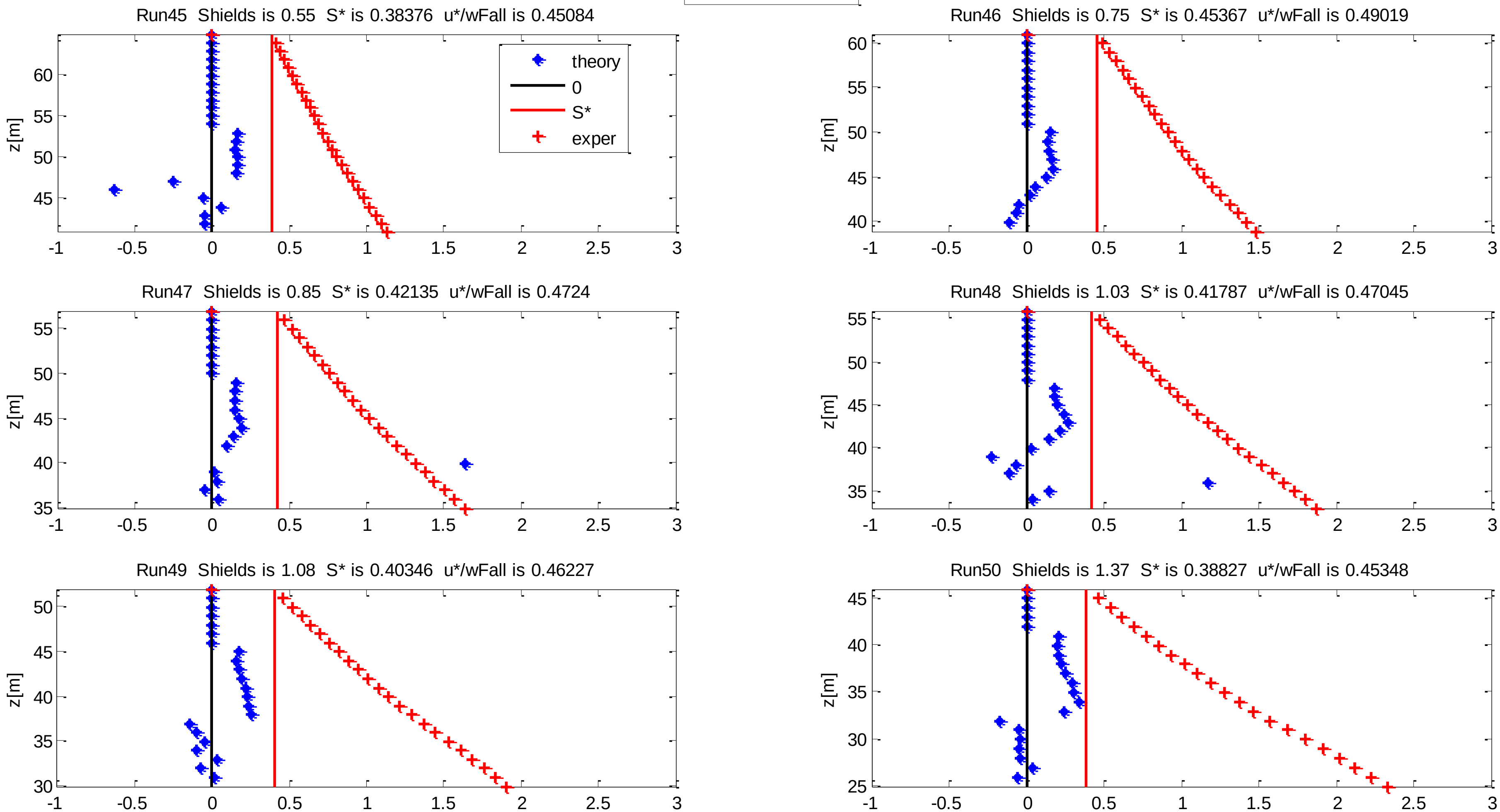


$$s = \frac{2J}{5\sqrt{\pi}} \frac{p}{F\sqrt{T}} \frac{\partial u}{\partial z}$$

$$J = J(\nu, T)$$

$$\frac{\partial s_{tot}}{\partial z} = [\nu(\rho_s - \rho) + \rho] g \cos\beta$$

SHEAR STRESS



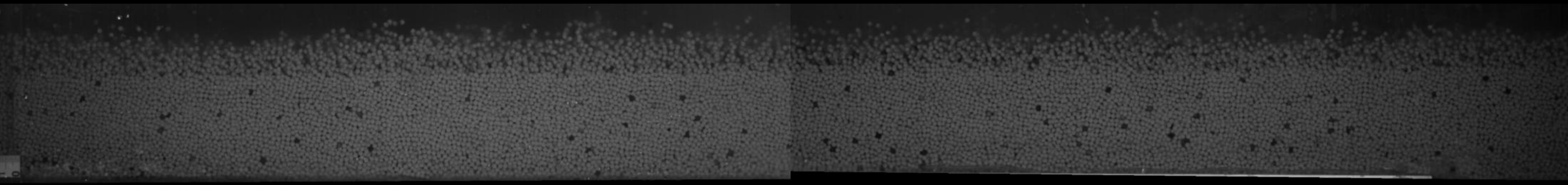
What about the kinematics?

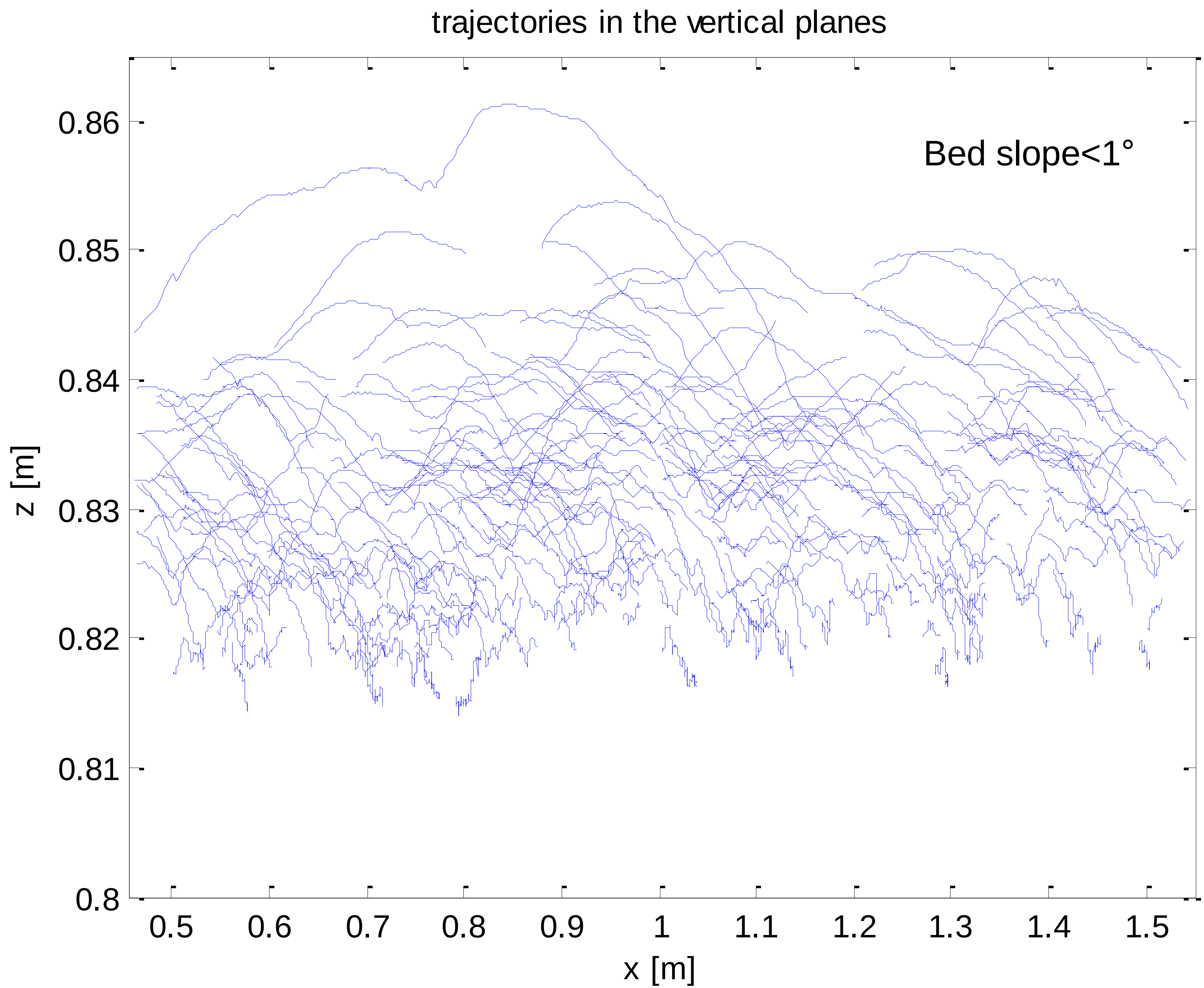
Let's have a look at the trajectories

At low Shields values ($\Theta<0.1$) we observe a few grains moving in a random way

At moderate Shields values ($\Theta\approx1$) we have the following sheet flow and relevant trajectories

Shields ≈ 1




trajectories in the vertical planes
Bed slope<1°
z [m]
x [m]
0.86
0.85
0.84
0.83
0.82
0.81
0.8
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
1.4
1.5

What about the kinematics?

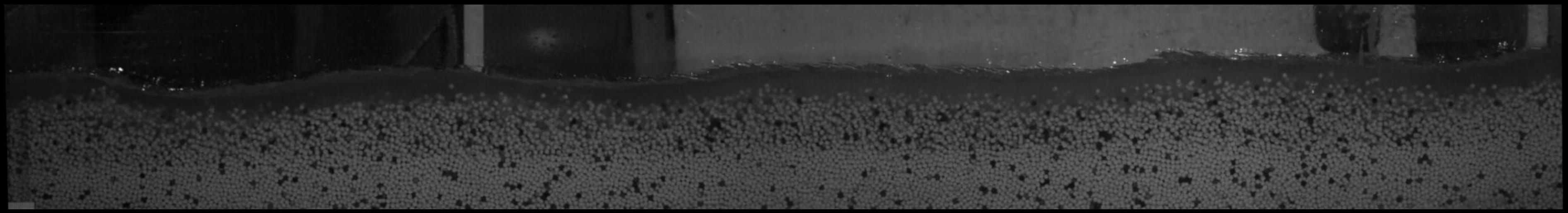
Let’s have a look at the trajectories

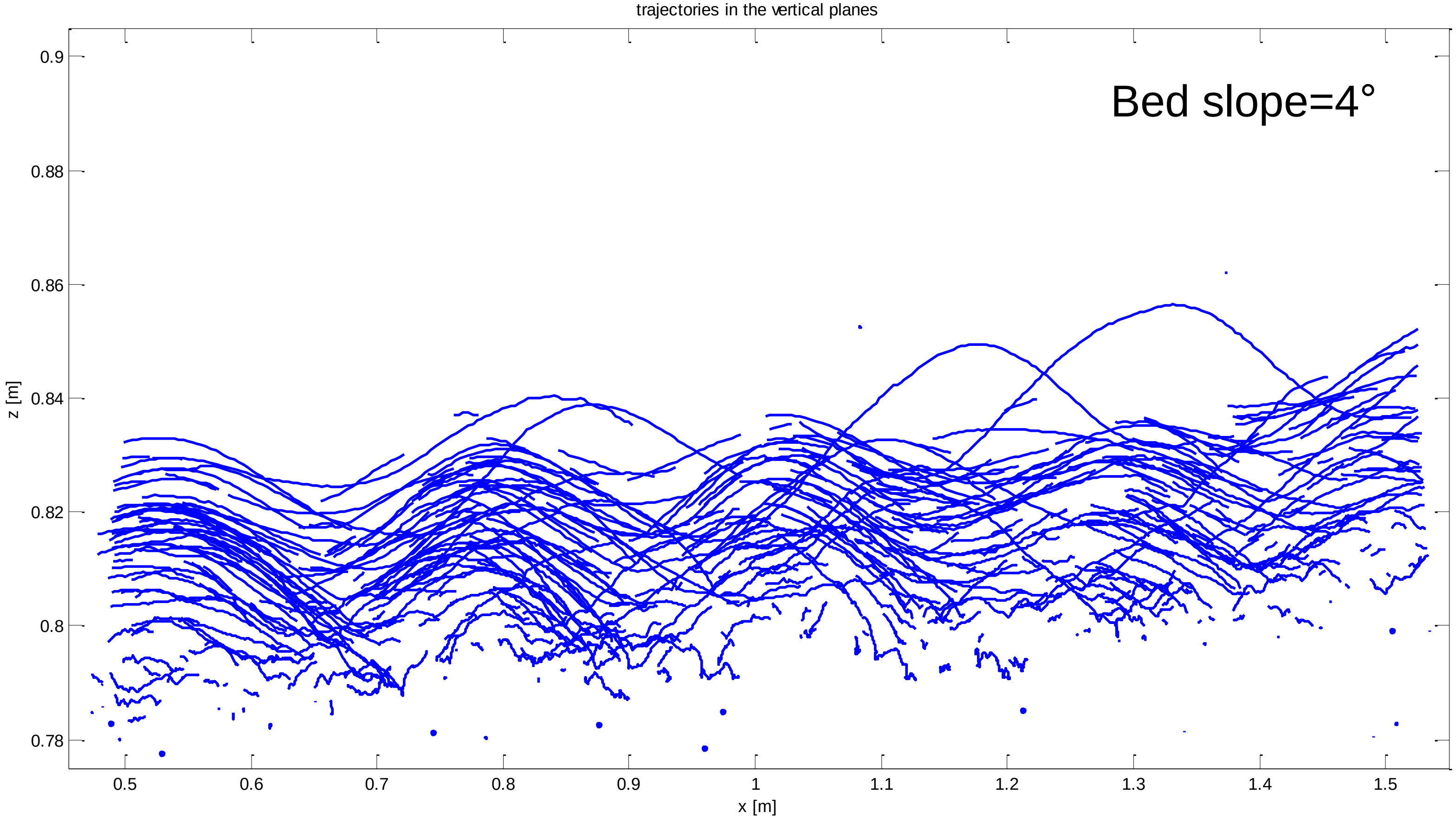
At low Shields values (Θ<0.1) we observe a few grains moving in a random way

At moderate Shields values ($\Theta \approx 1$) we have the following sheet flow and relevant trajectories

Increasing Shields up to the limit of sheet flow range ($\Theta \approx 3$), flow and trajectories present new features

Shields ≈ 3

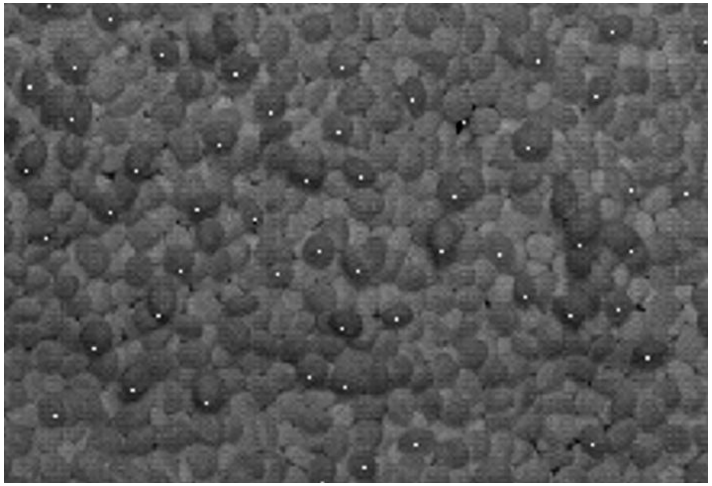


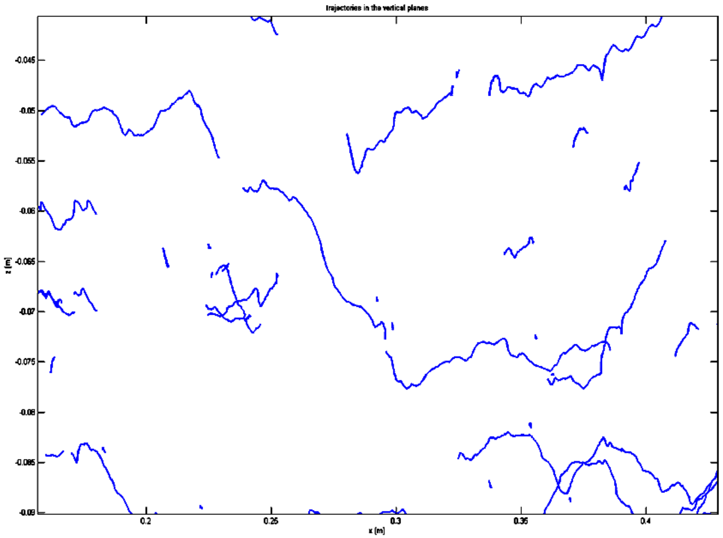


trajectories in the vertical planes
Bed slope=4°
z [m]
0.9
0.88
0.86
0.84
0.82
0.8
0.78
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
1.4
1.5
x [m]

Imaging technique applied to ordinary-bedload runs

Problems with trajectory reconstruction: interruptions





less than 10% of trajectories are complete

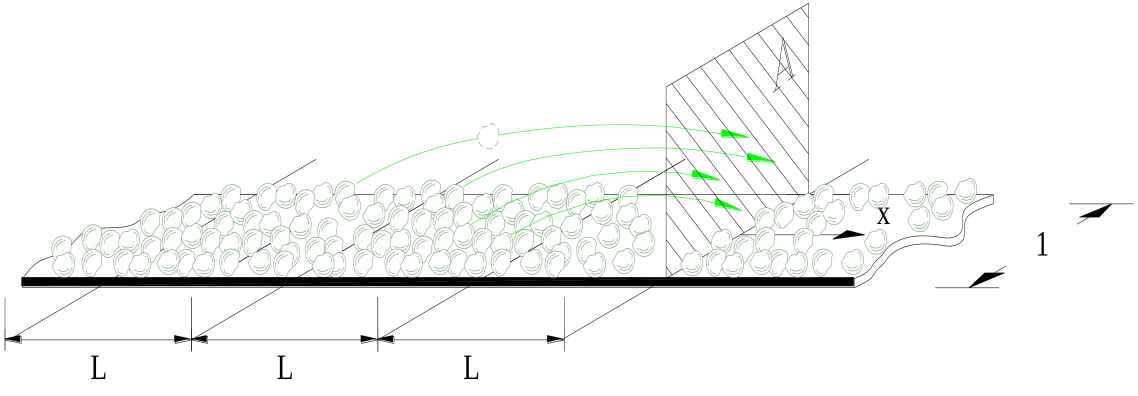
What the images may tell without the trajectories?

EINSTEIN [1937]

$$q_S = E_b L_S \forall_p$$

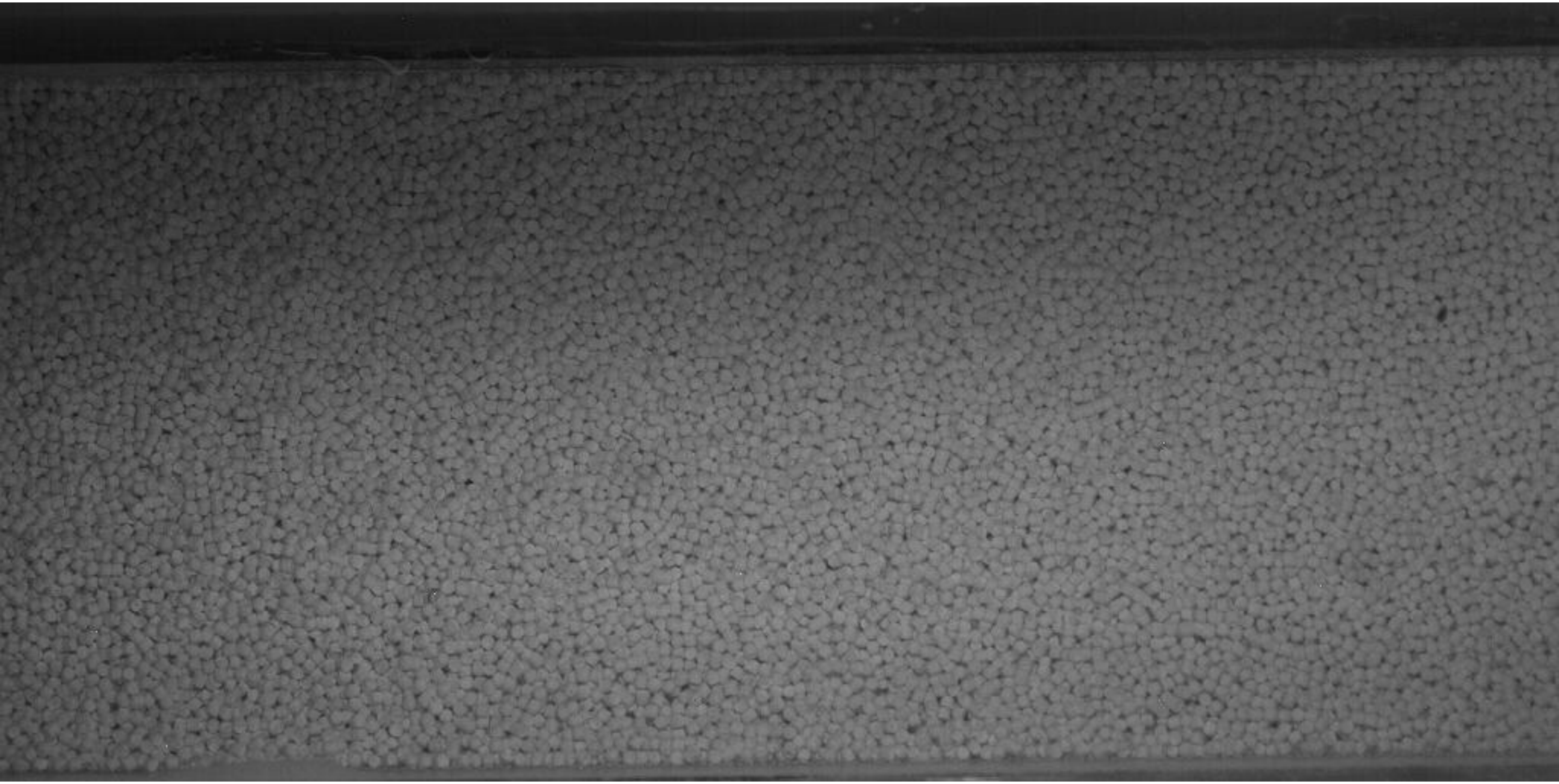
E_b is the number rate per unit bed area at which particles are entrained from the bed into bed load motion;

L_S is the step length, or distance a particle moves before being re-deposited

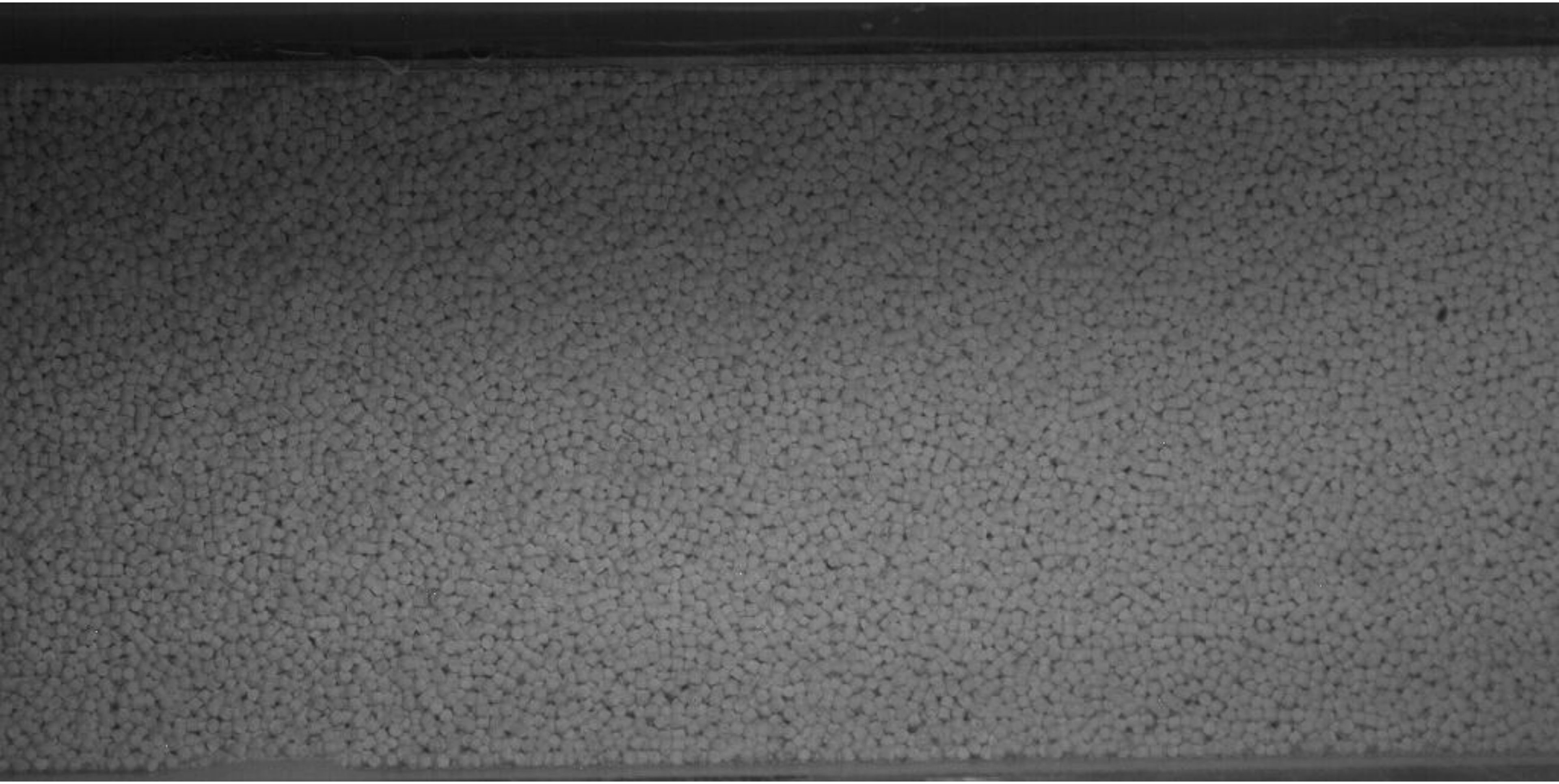


Let’s look at image differences

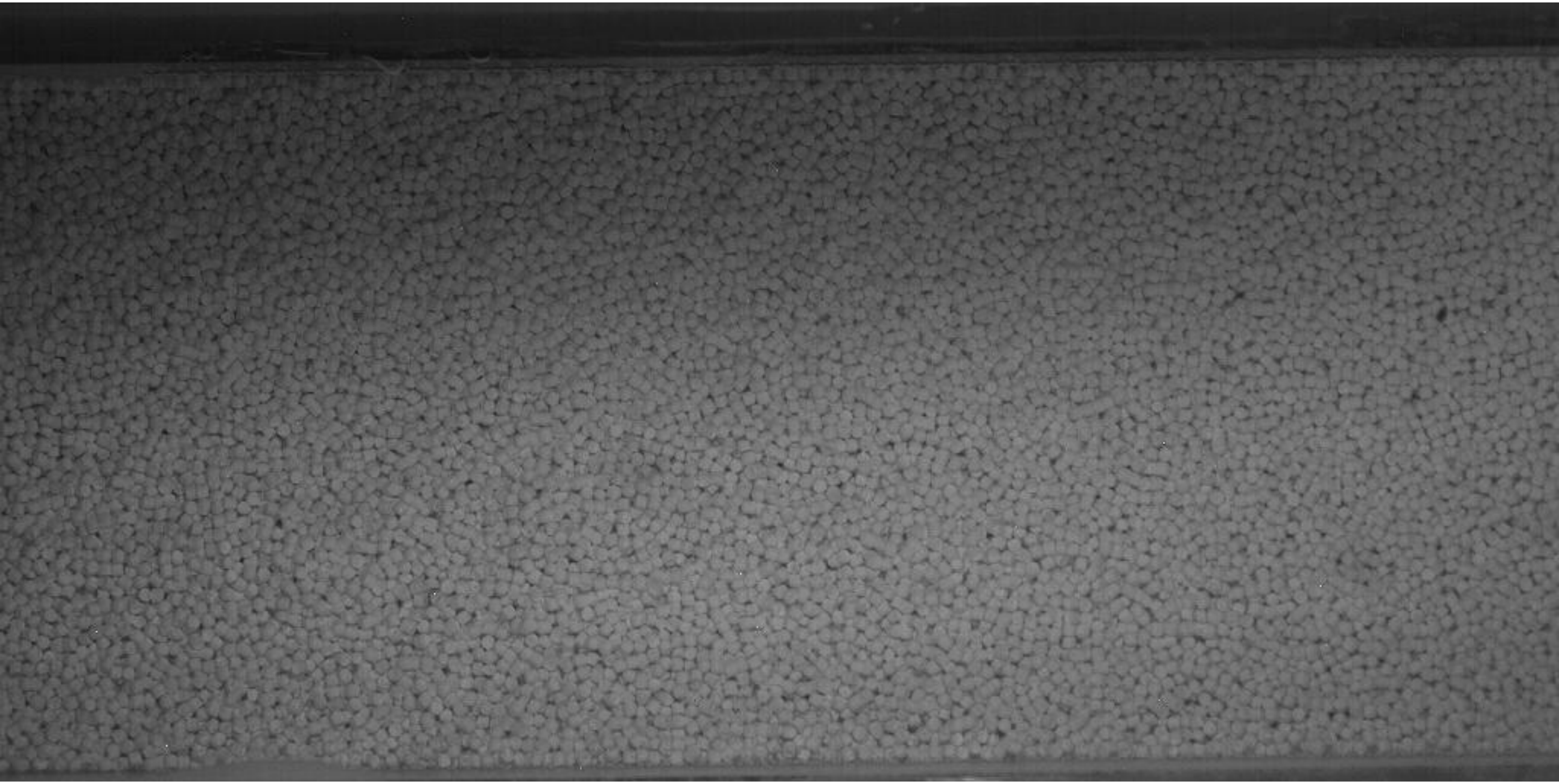
we subtracted pixel-by-pixel the grey scale intensity of the first image from the current image first image



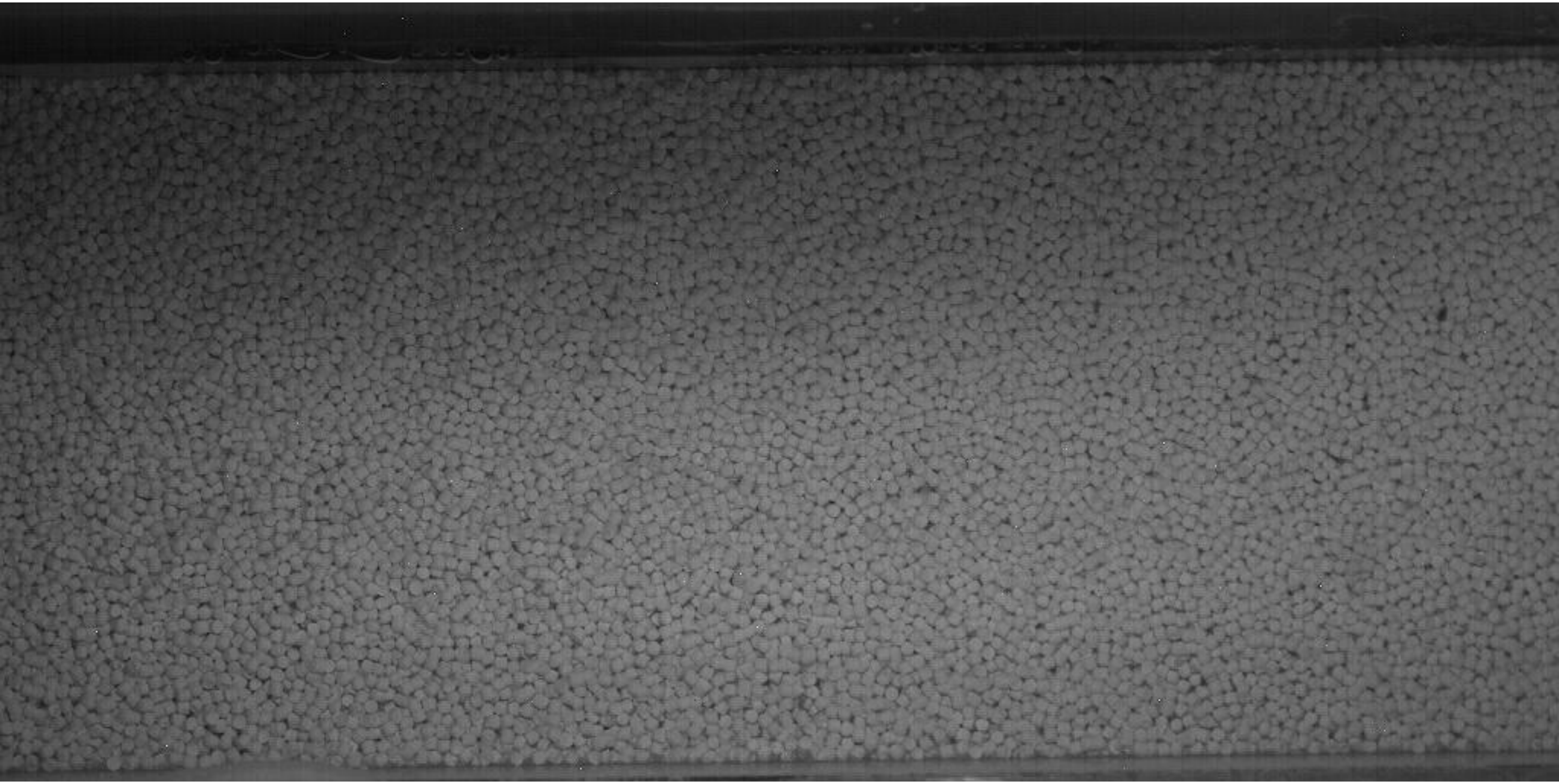
after a few seconds



after a few minutes

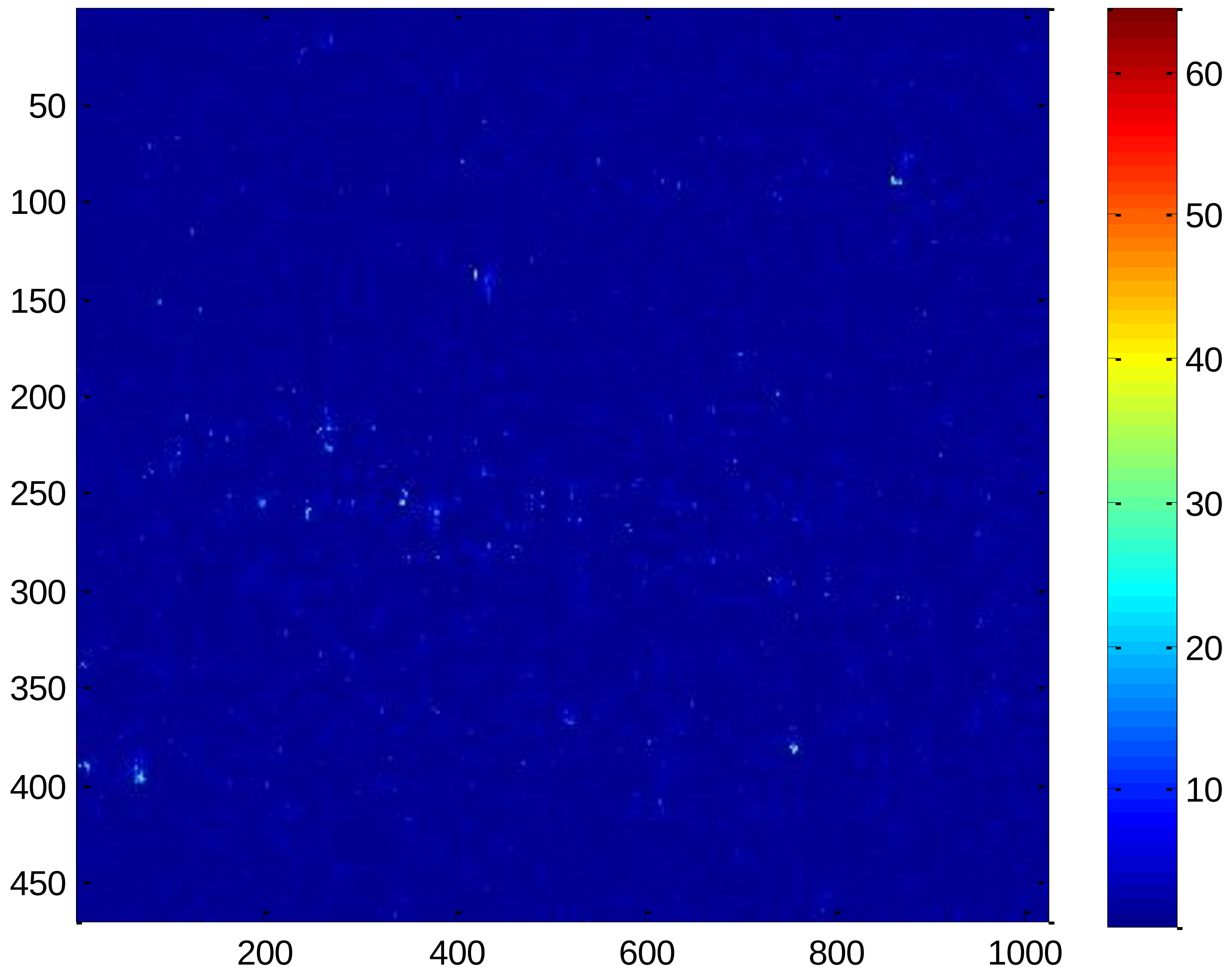


after several minutes

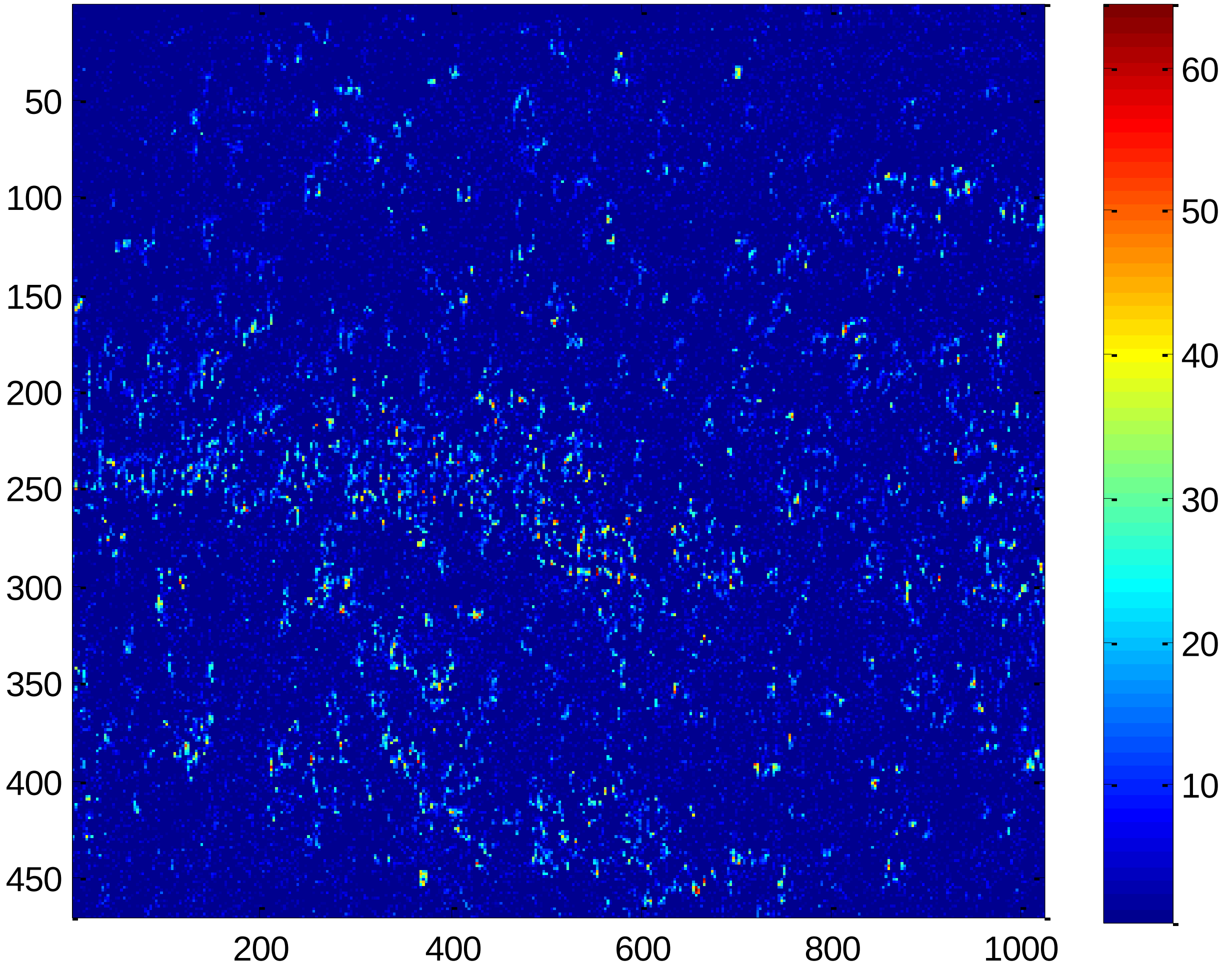


Subtraction of images pixels by pixels

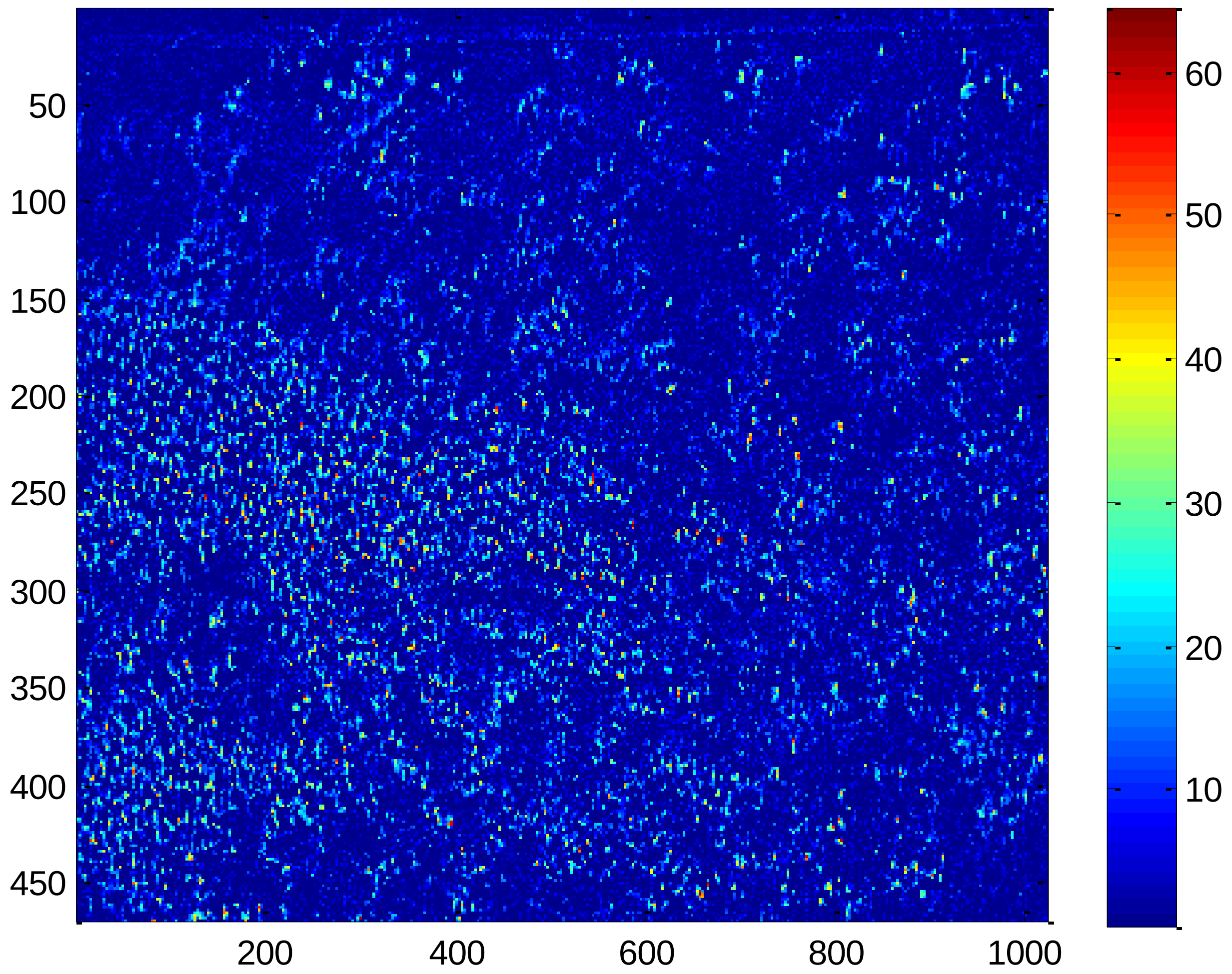
After a few seconds



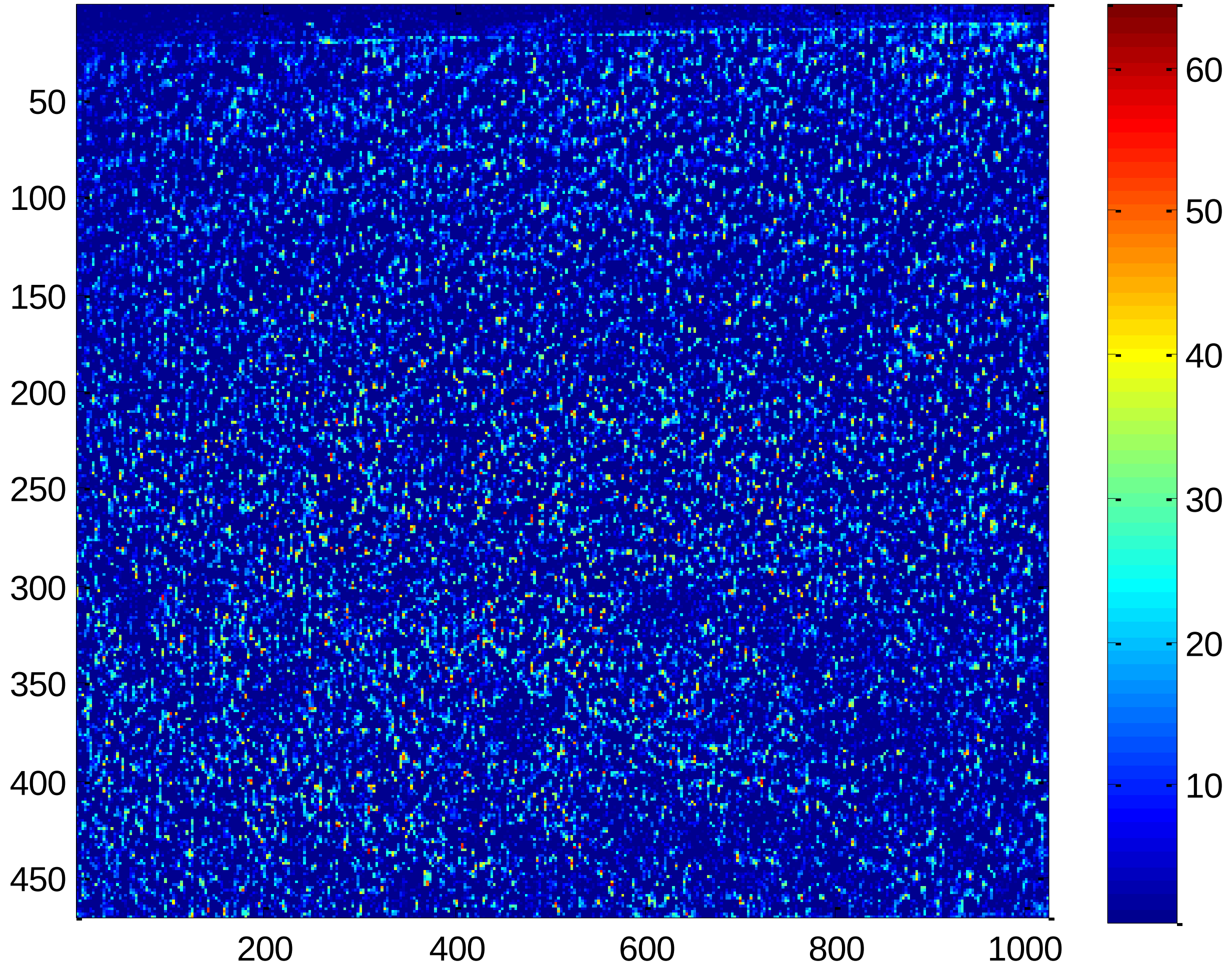
After a minute



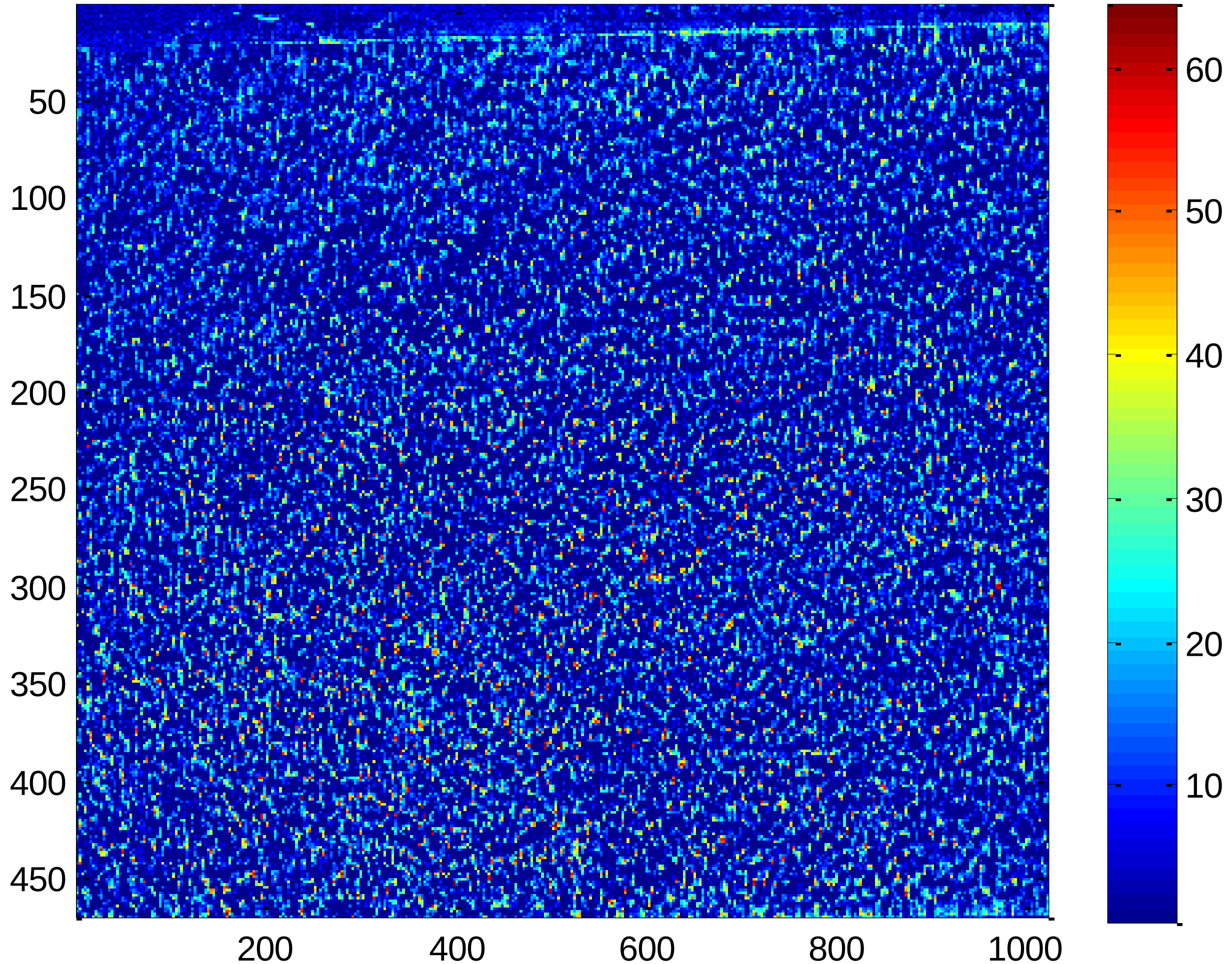
After a few minutes



After several minutes

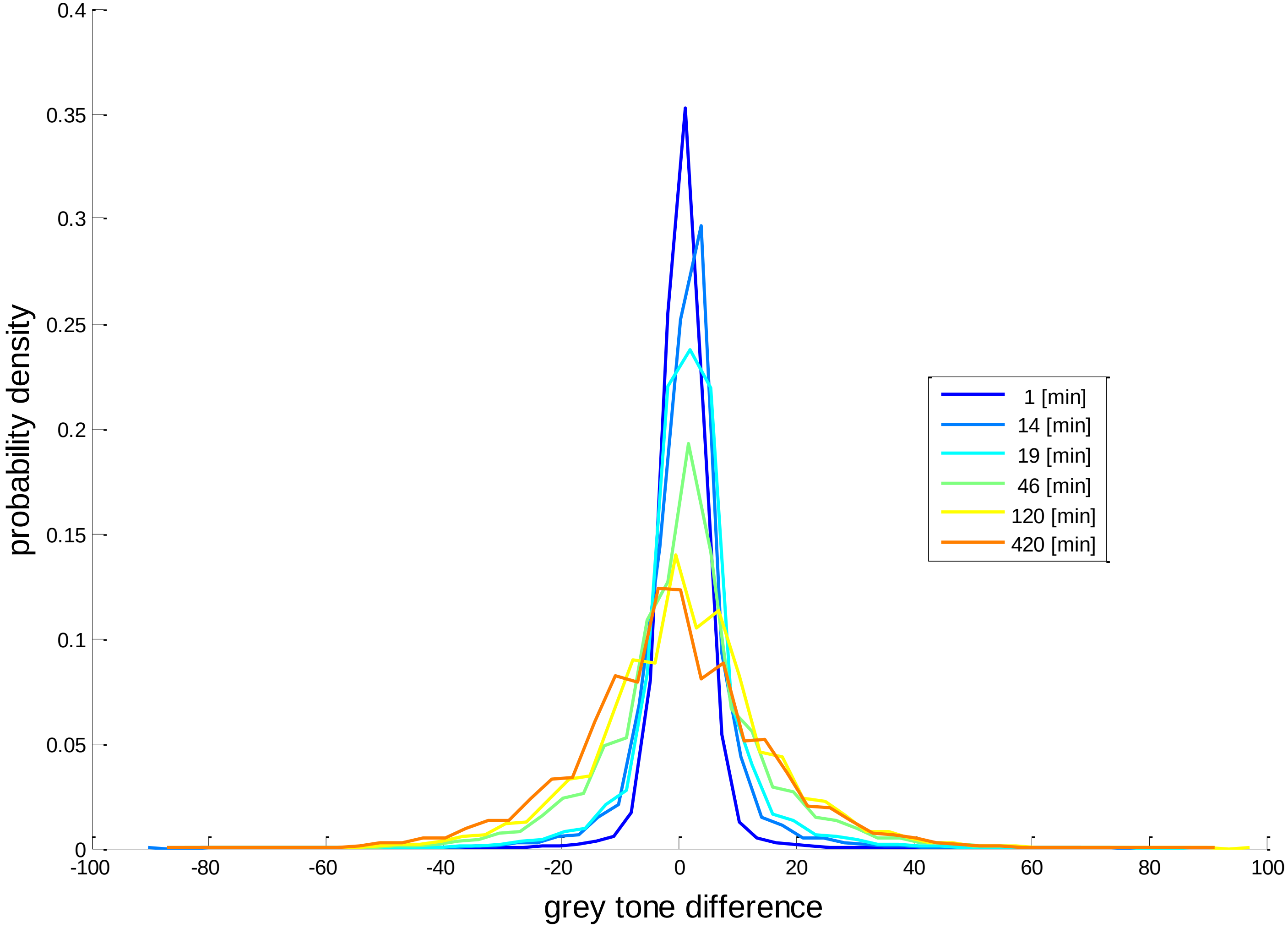


After an hour



Use the pixel image-differences as a random variable

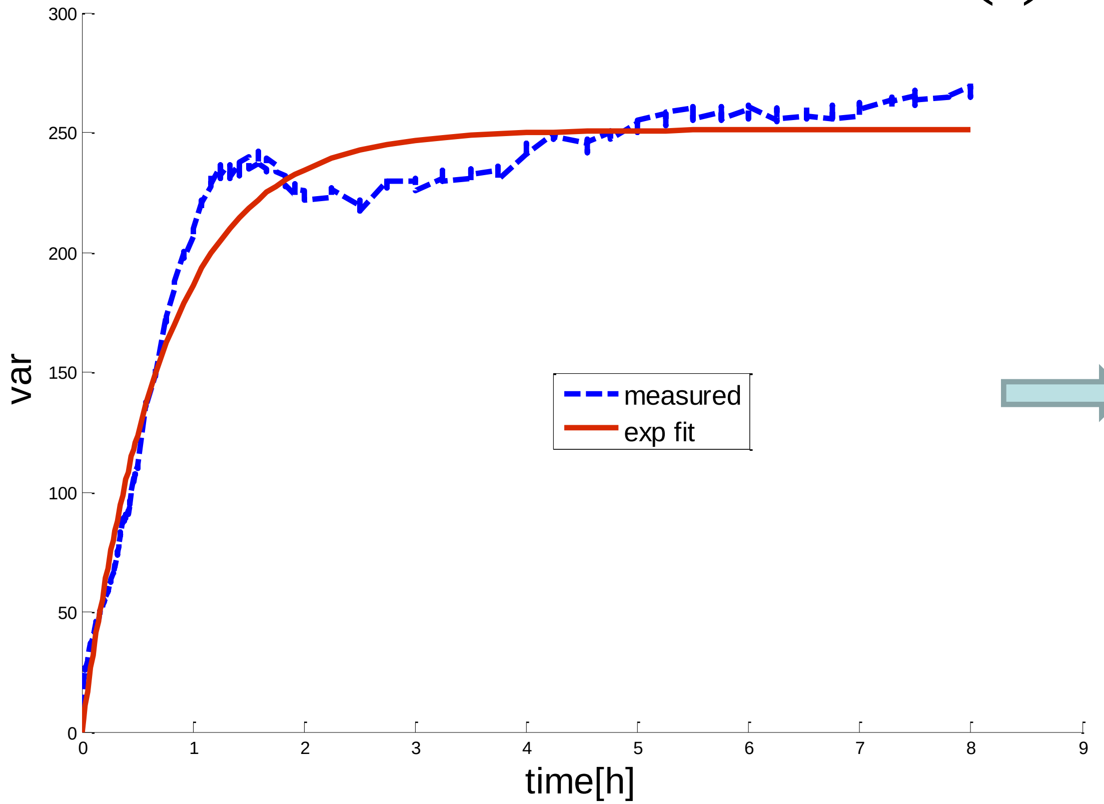
$$\mathrm{var}\,(t) = \mathrm{var}_{noise} + \mathrm{var}_{Q_S} + \mathrm{var}_{E_b}\,(t)$$



Use the pixel image-differences as a random variable

$$\mathrm{var}\,(t) = \mathrm{var}_{noise} + \mathrm{var}_{Q_S} + \mathrm{var}_{E_b}\,(t)$$

A simple theoretical model yields: $\mathrm{var}(t) = \mathrm{var}_{\infty}(1 - e^{-E_b t})$



$$E_b$$

$$L_S = \frac{E_b \forall_p}{q_S}$$

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