Aeolian sand transport over rigid bed :

Field and laboratory

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OUTLINE

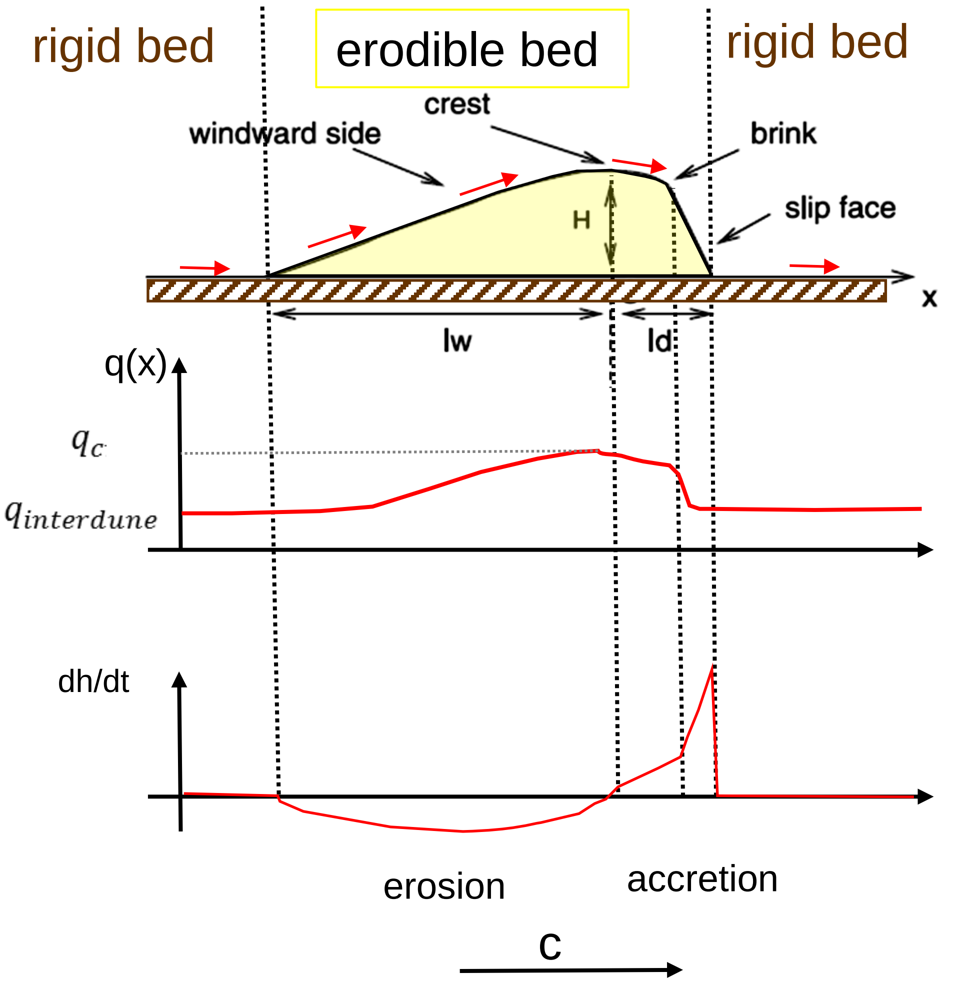
Objectives:

1-Report field study of sand transport and dune dynamics
2-Highlight expected improvement and open questions
3-Understand the effect of varying boundary conditions on transport

Outline :

1-**Field study**
    -issue of barchane dynamics under general sand flux
    -materiel and method
    -results and discussion
2-**Wind tunnel esperiment**
    following the A. Ould el Moctar’s presentation on erodible bed
3-**Open questions** and future work

FIELD STUDY – TRANSPORT OVER BARCHAN



boundary condition

topography

horizontal flux

net erosion

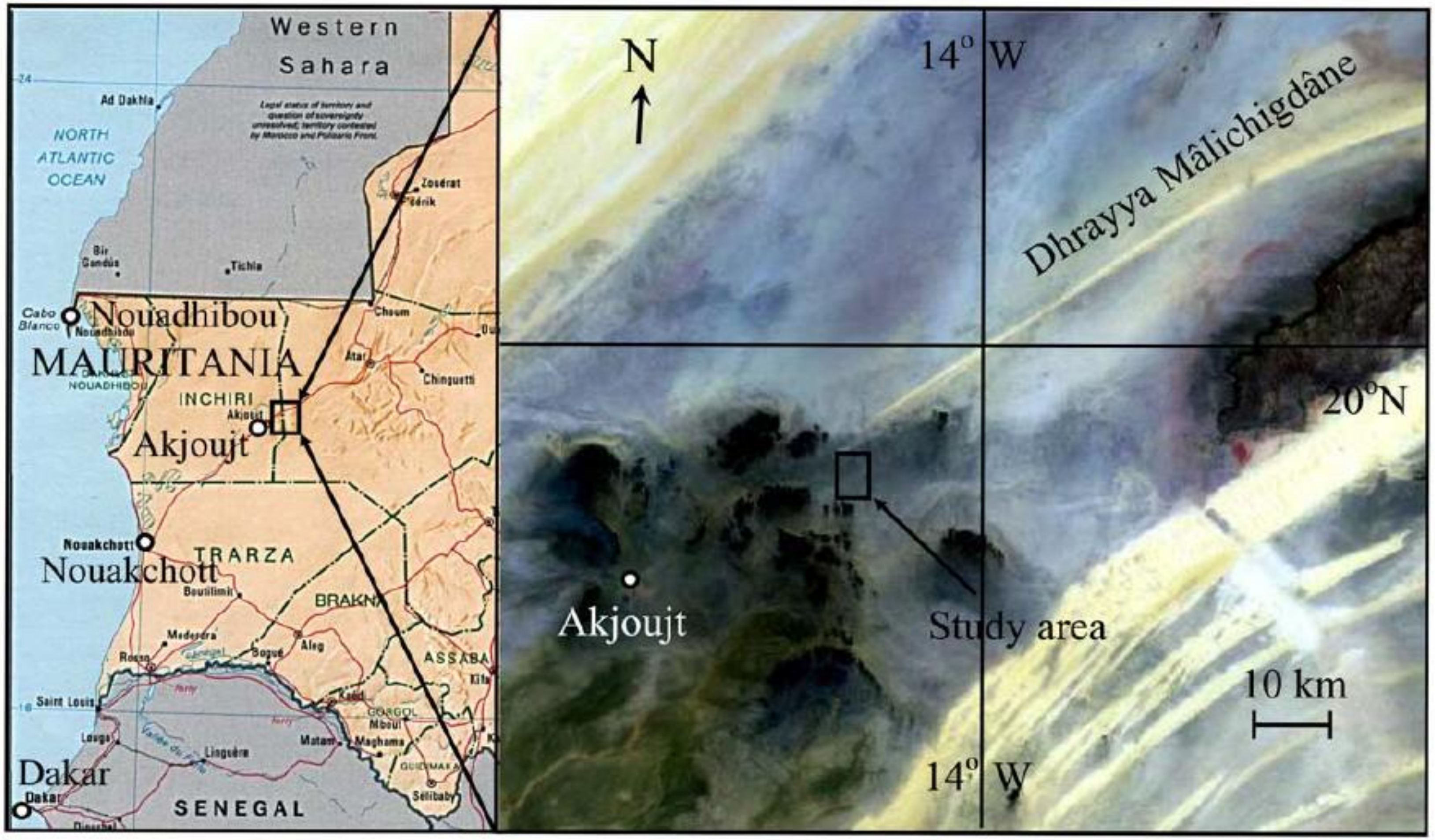
dune celerity

$$\rho . H . C = q_{trap} = q_c - q_{interdune}$$

Saltation over rigid bed is one of the component of barchan dynamics

FIELD STUDY

Mauritanian Desert: The end of Dhrayya Mâlichigdâne



=> No humidity, no salinity, flat ground

FIELD STUDY - PHOTOS

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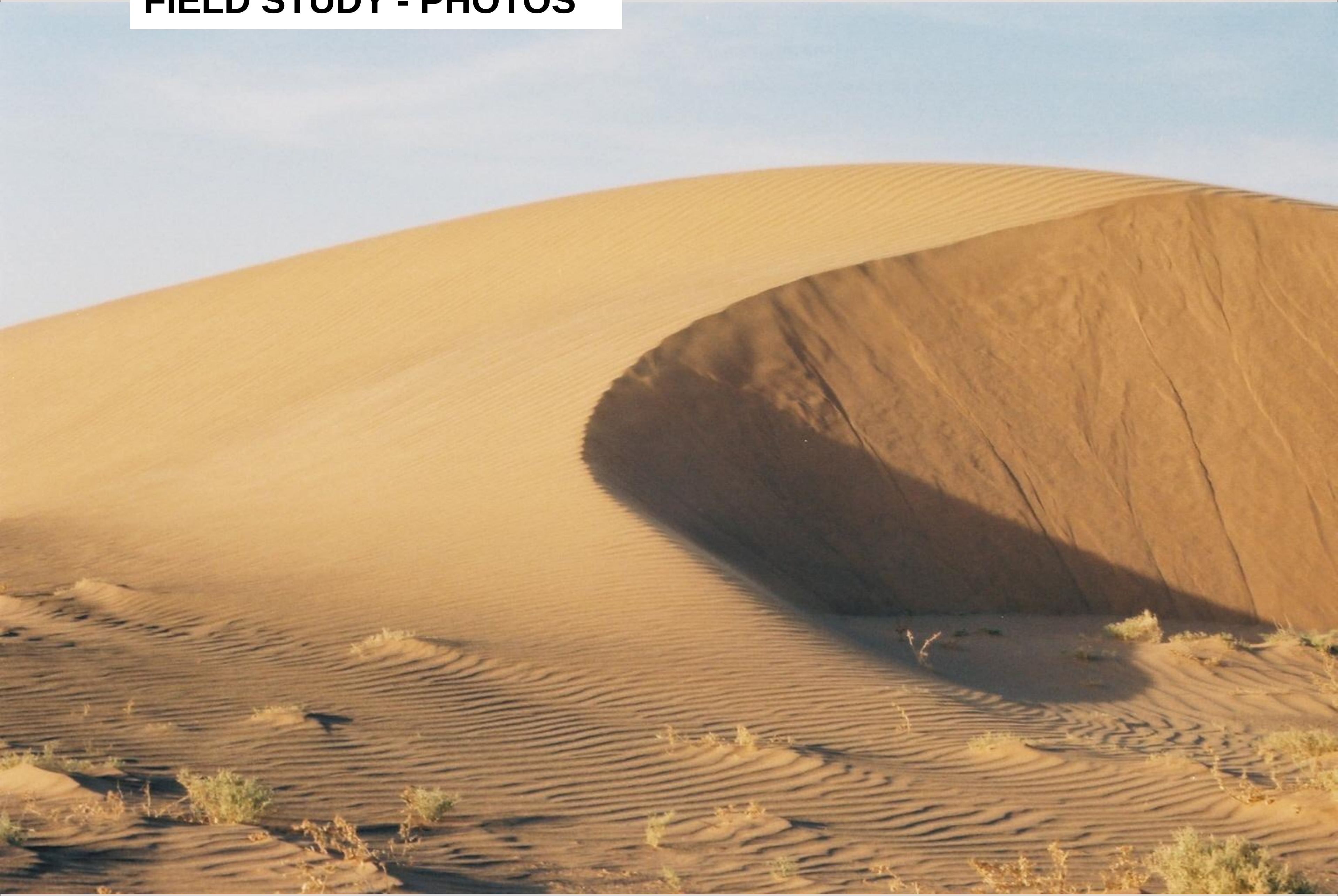
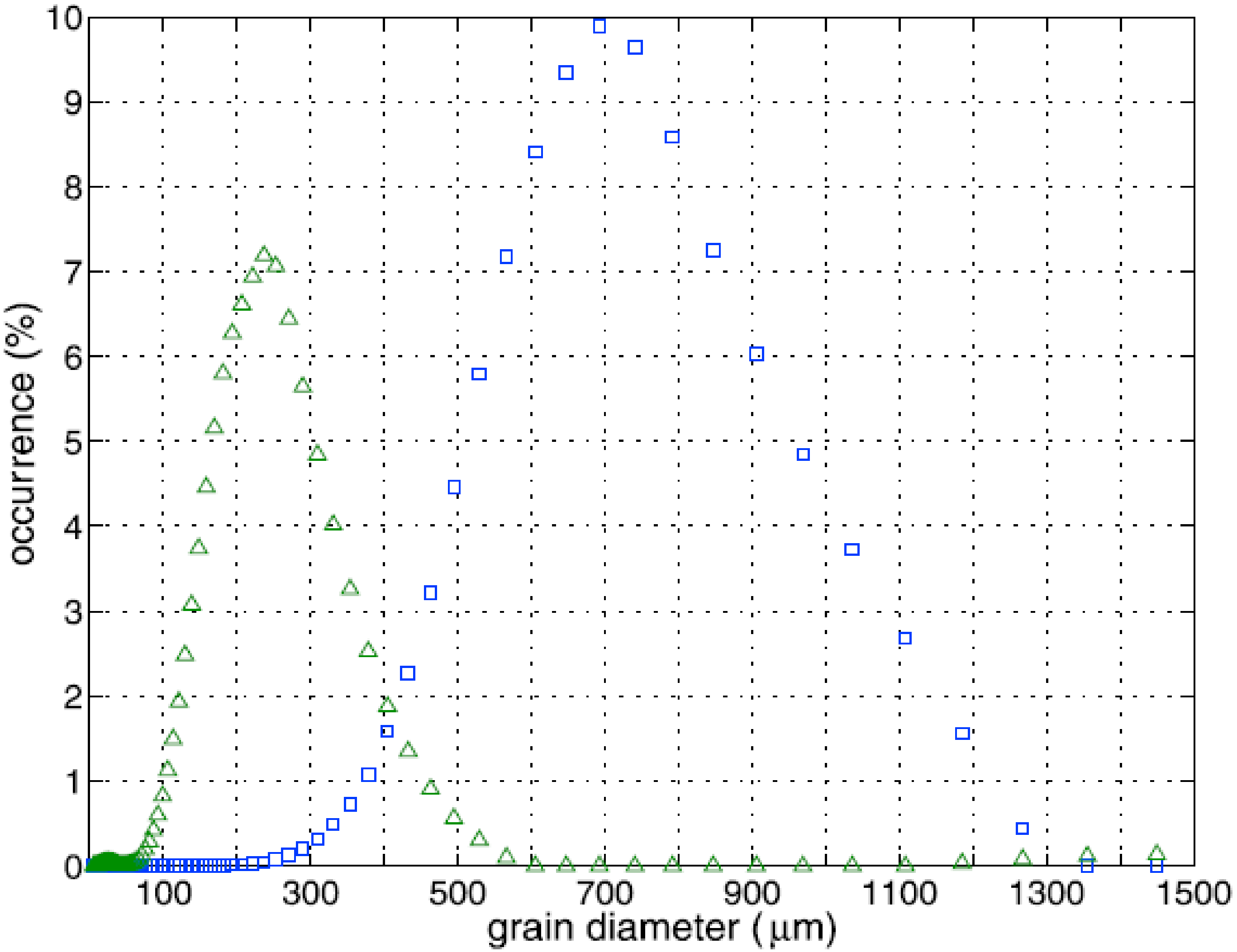


FIELD STUDY - PHOTOS

FIELD STUDY - PHOTOS

FIELD STUDY-MEASUREMENTS

Granulométrie



FIELD STUDY

Meteorological mast in the interdune area

FIELD STUDY - MEASUREMENTS

Air velocity and direction at 10 meters

Air velocity at 5 meters

Temperature and humidity

Air velocity and direction at 2 meters

Air velocity and direction at 1 meters

Acoustic sand flux probe

Continuous measurement of wind, friction and transport every minute

FIELD STUDY – FLUX MEASUREMENTS

Acoustic particle flux probe (from snow application)

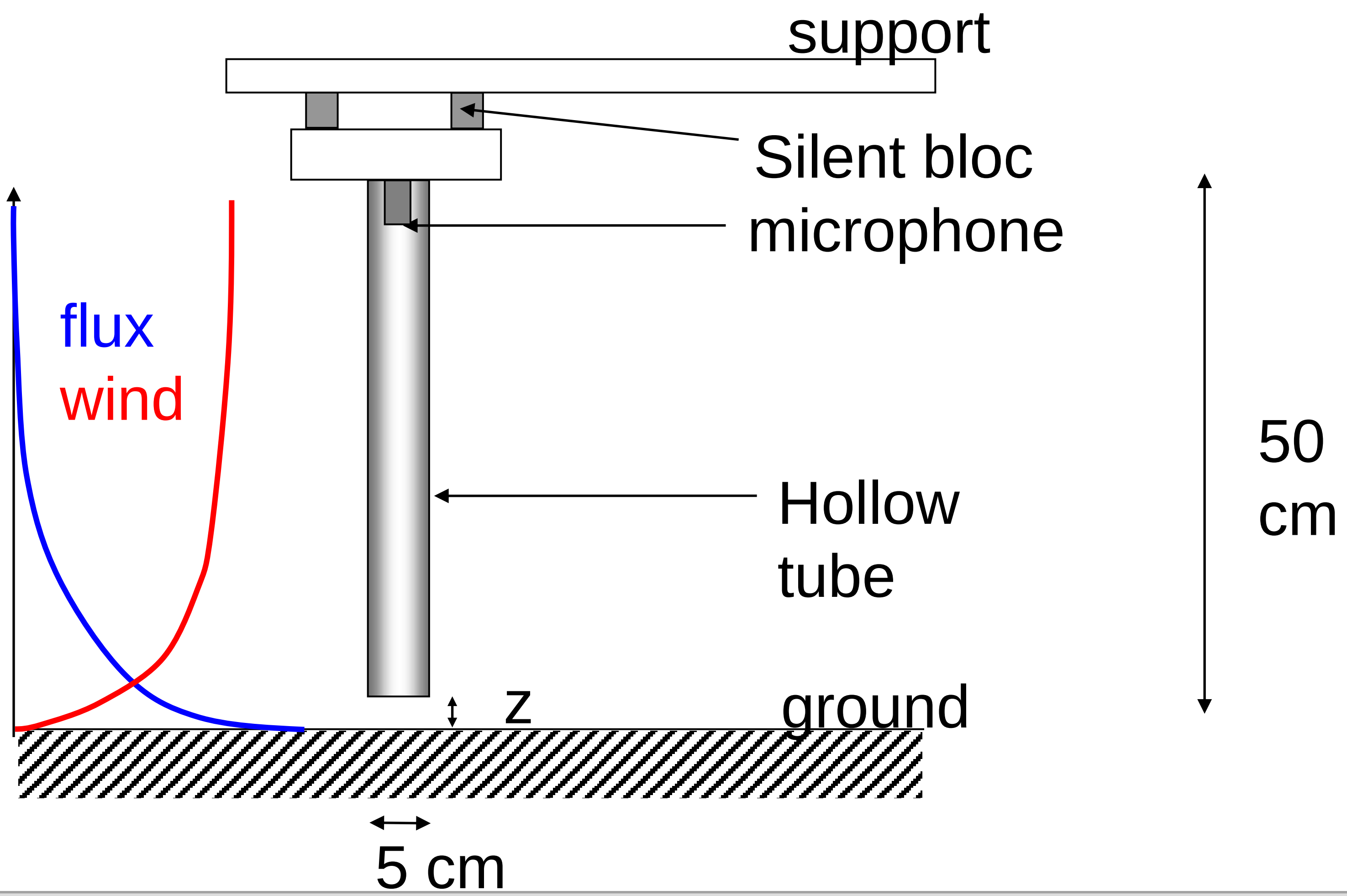
Designed and calibrated during the PhD of **Jean-Luc MICHAUX** supervised by **Mohamed NAAIM from CEMAGREF - Grenoble:**

Sum up :

- Linear response with a lot of scattering in the measures
- Influence of the particles, density, diameter…
- Small influence of noise from the wind below 12 m/s,
- Signal response to a grain impact depend upon the impact position on the probe,
- Time response for 1 seconde
- Robust and easy to manage

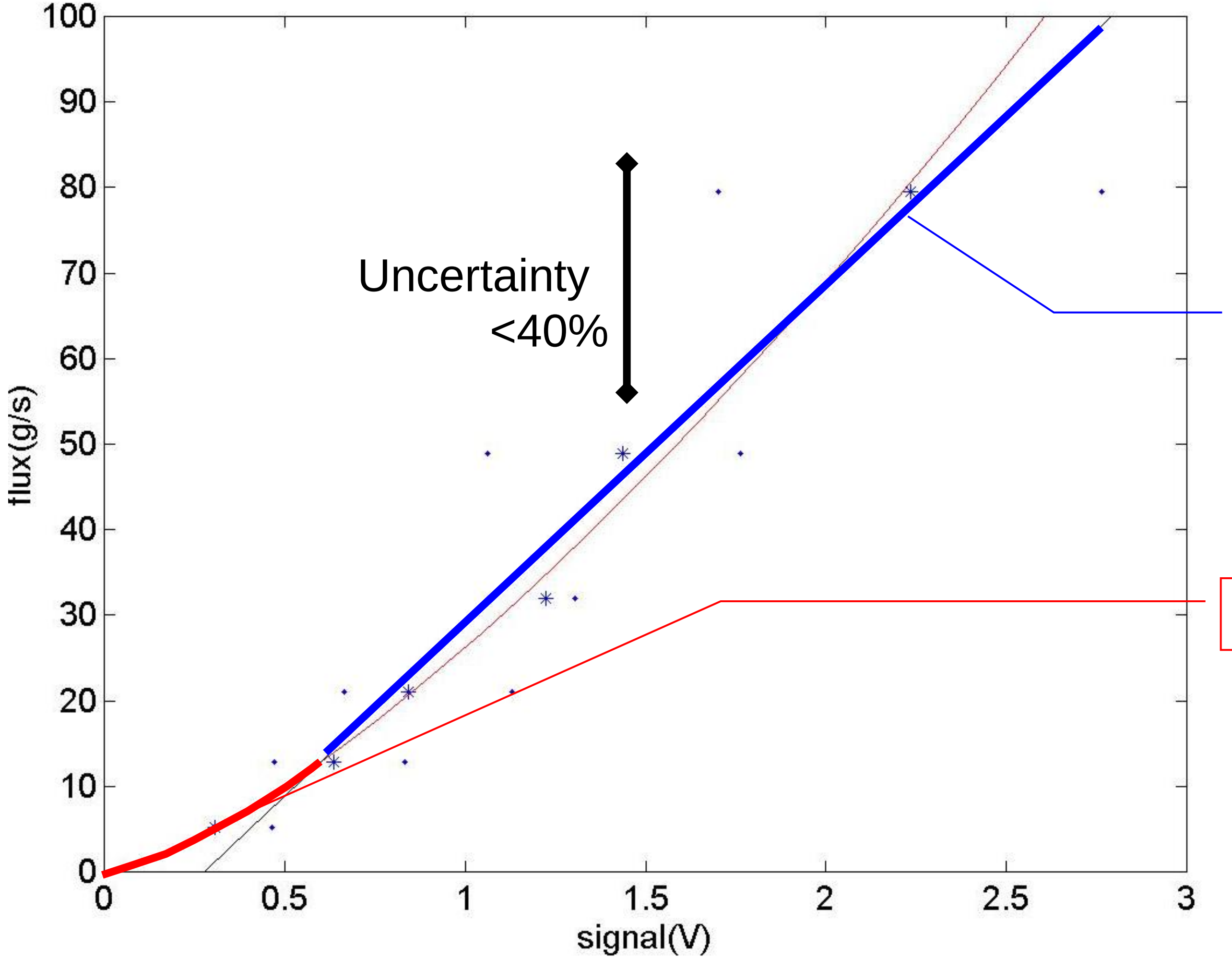
FIELD STUDY - SAND FLUX MEASUREMENTS

Calibration in the nice wind tunnel of K.R. Rasmussen in Århus with stationnary conditions different grain diameter, shear stress, elevation *z*:



FIELD STUDY - SAND FLUX MEASUREMENTS

Calibration results



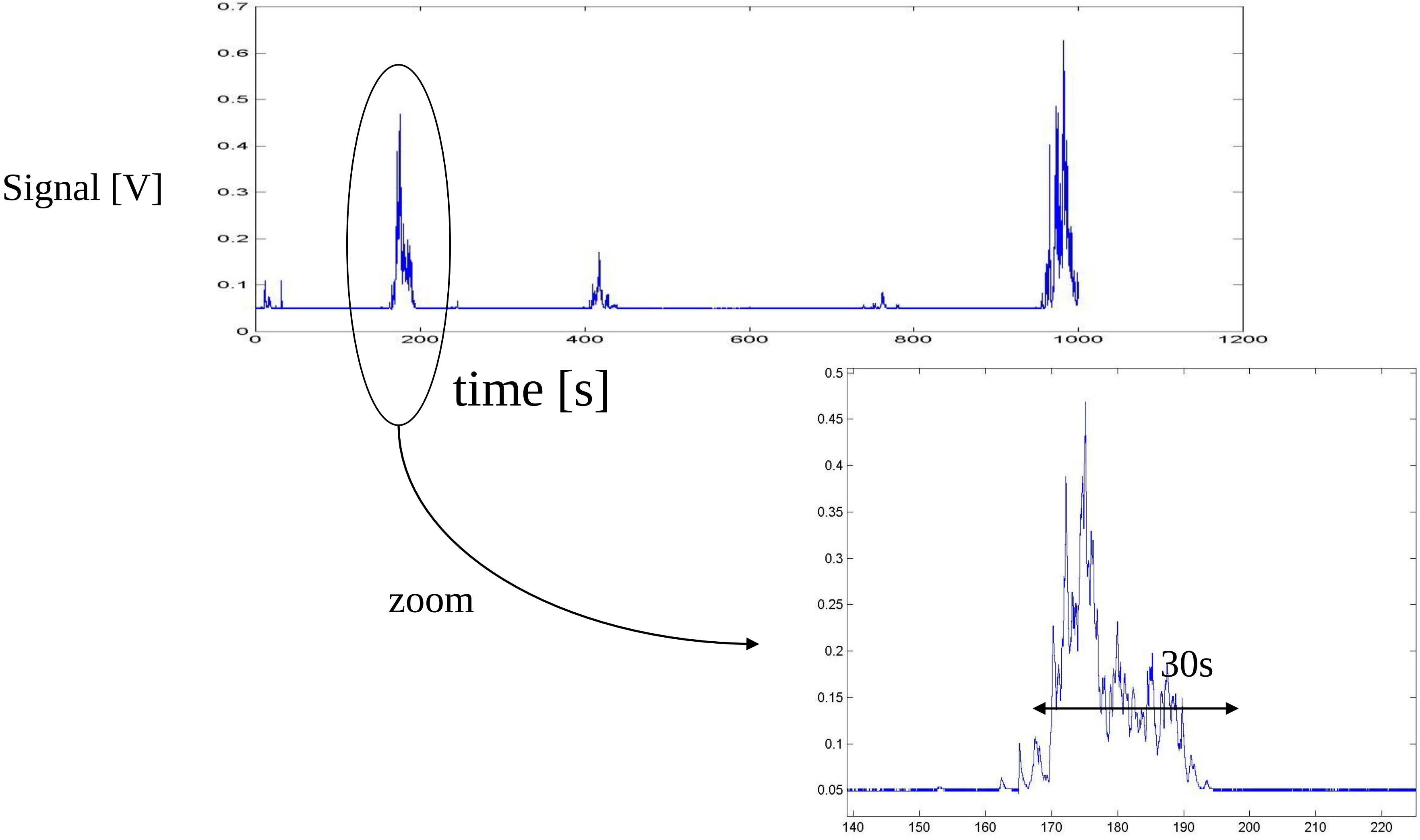
$Q=39,8*(E_2\text{-}Ofset)-11$

$Q=26,2*(E_2\text{-}Ofset)^{1,4}$

"acceptebable" precision…

FIELD STUDY - SAND FLUX MEASUREMENTS

Exemple of a record with intermittent transport



Good time caracteristic

FIELD STUDY – WIND PROFILE

Stationnary turbulent boundary layer condition:

- Without transport:

  $U(z)=2.5\ U^* \,.\, \ln(z/z_0)$

  Avec

  $U^*=(\tau/\rho)^{1/2}$ friction velocity

  $Z_0=d/30$ aerodynamic roughness

- With transport:

  « focus point » model of Bagnold

$$u(z) = \frac{u_*}{\kappa} ln\left(\frac{z}{z_f}\right) + u_f$$

FIELD STUDY – TRANSPORT LAW

Dimensional Transport law

- Bagnold

$$q = C_B \frac{\rho}{g} u_*^3$$

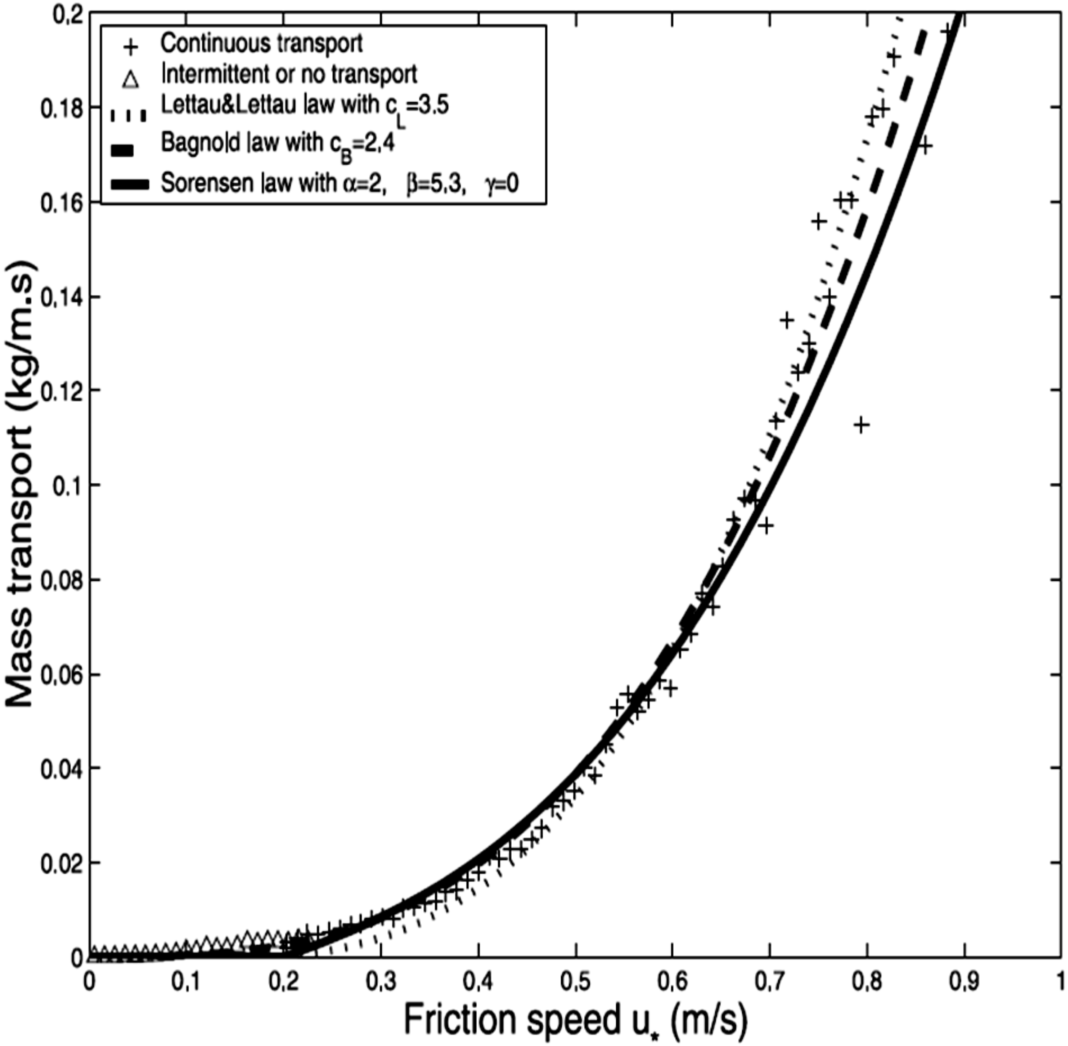
- Lettau & Lettau

$$q = C_L \frac{\rho}{g} u_*^2 \left(u_* - u_*^c \right) \quad \text{for} \quad u_* > u_*^c$$

- Sorensen

$$\frac{gq}{\rho u_*^3} = \left(1 - r^{-2}\right) \times \left(\alpha + \beta r^{-2} + \gamma r^{-1}\right)$$

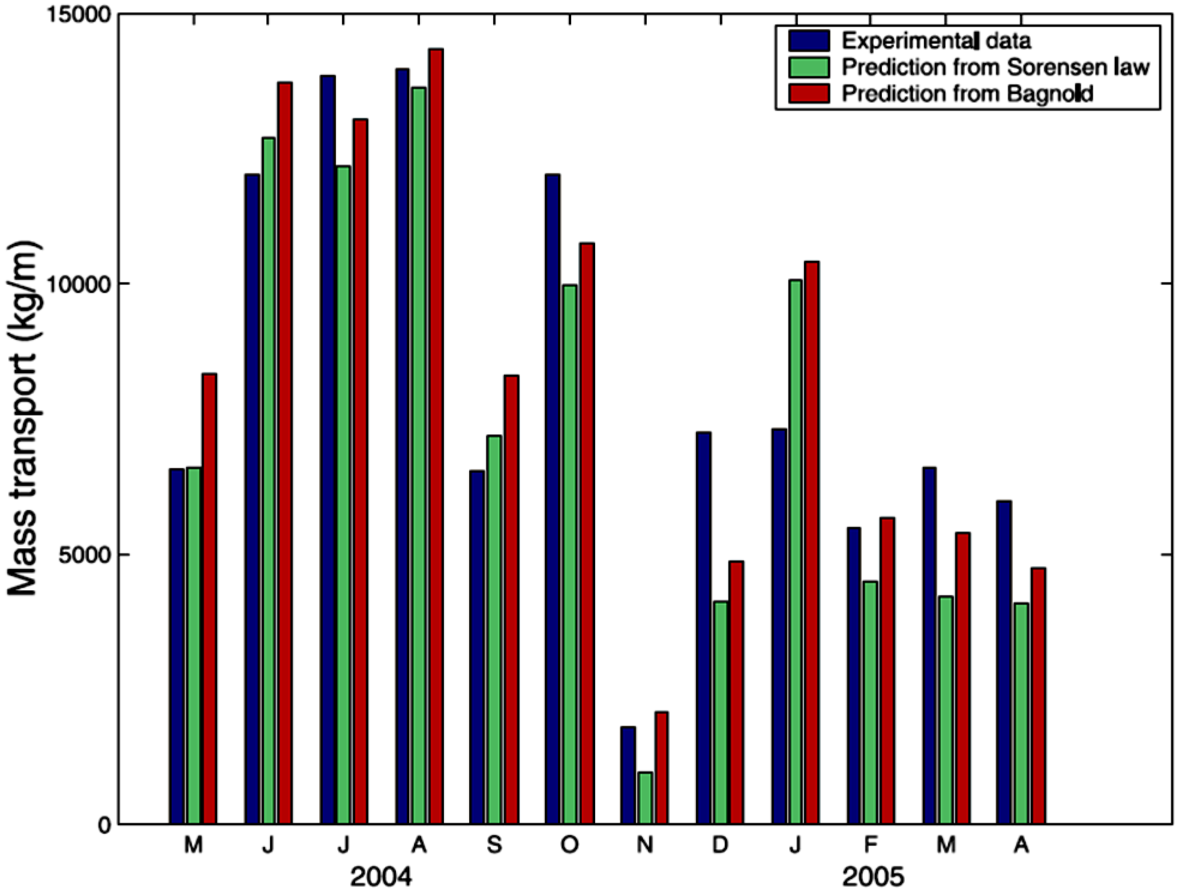
with $r = \frac{u_*}{u_*^c}$



Interdune transport similar to saturated flux over erodible bed in wind tunnel

FIELD STUDY - ANNUAL TRANSPORT

Interdune cumulative mass flux

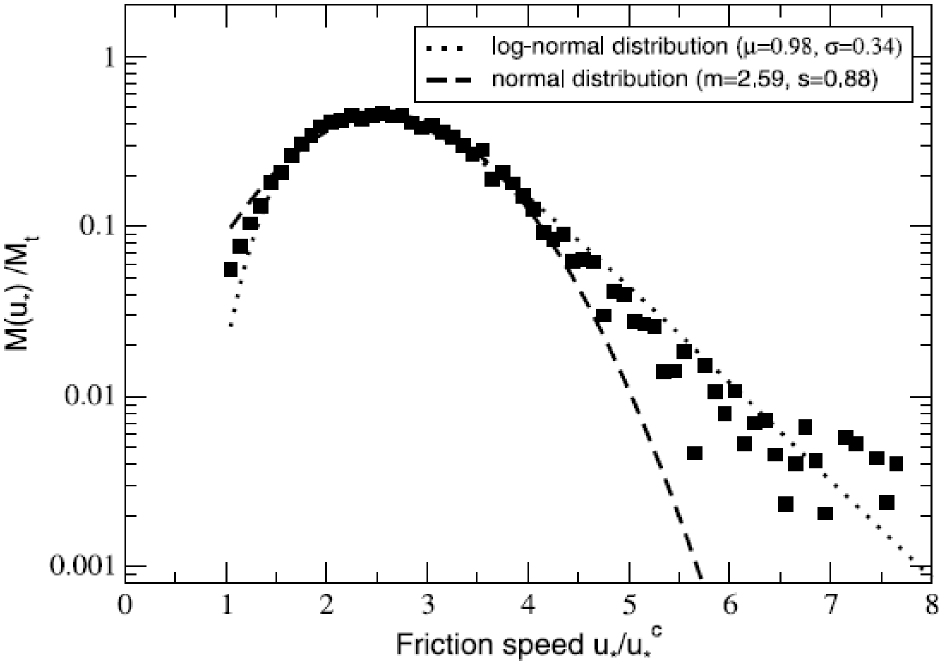


Mean interdune transport : $Q_{interdune} = 18 \text{ m}^3 / \text{m.yr}$

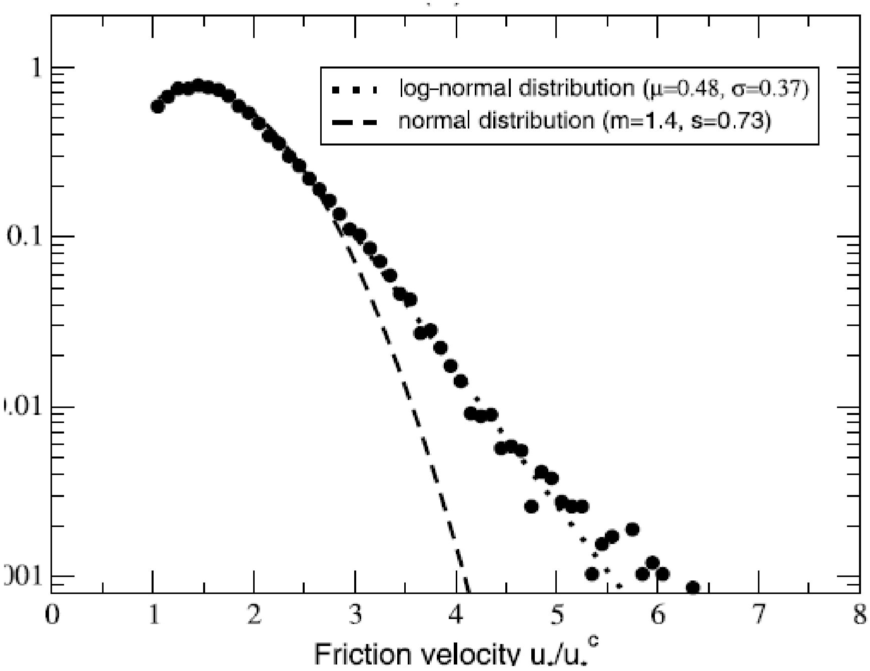
FIELD STUDY – ANNUAL TRANSPORT

Density probability functions of mass transport events:

mass transport



friction velocity



Moderate shear are responsible for the annual transport

FIELD STUDY – DUNE MOBILITY

Absolute topography

Dune celerity:

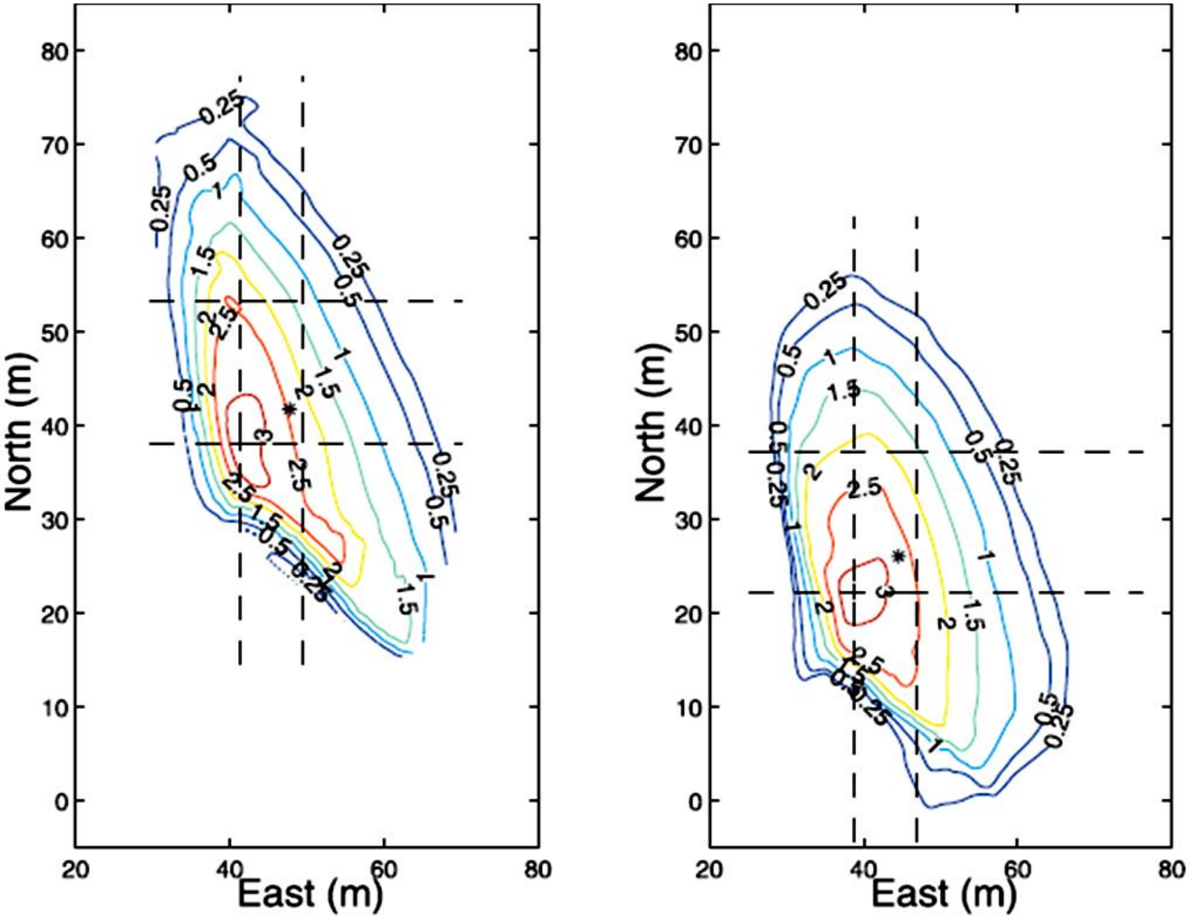
$$c = 16 \text{ m/yr}$$

Mean trapped flux

$$\bar{Q}_{trap} = 38 \text{ m}^3/\text{m.yr}$$
$$= 2\,Q_{interdune}$$

Mean crest flux

$$\bar{Q}_c \simeq 56 \text{ m}^3/\text{m yr}$$
$$\simeq 3\,Q_{interdune}$$



Trapping efficiency of the dune is around 66%

Interdune saltation is one the key points?

FIELD STUDY – PARTIAL CONCLUSIONS

All results are valid in one place and one year…

Open questions on dune mobility :

- How does variability of the direction of the wind modify the barchan shape? i.e. how is the time scale response of the barchan?

  Idea : film& measure the barchan every day…

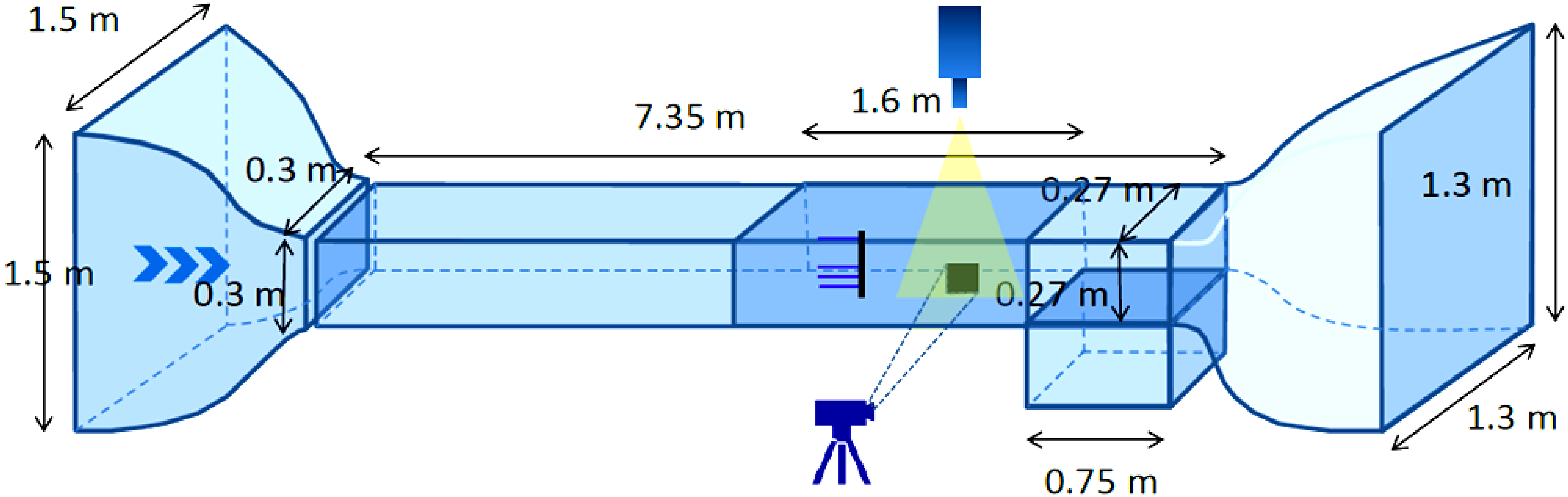
- How does its shape modify its trapping efficiency? Is the slip face criterion enough?

- Does the strength of the transport influence strongly this dynamics?

- What is the accuracy of our measurement of $Q_{interdune}$?

WIND TUNNEL EXPERIMENTS-APPARATUS

Same materiel and methods as presented by Ahmed Ould el Moctar



Velocimetry:

- air: Pitot tubes, z = 10, 20, 40 et 130 mm
- particles: Optical methods (PIV, PTV)

PulsedLaser (Δt ~ 10 -200 µs)
CCD camera: resolution2048 x 2048 pixel

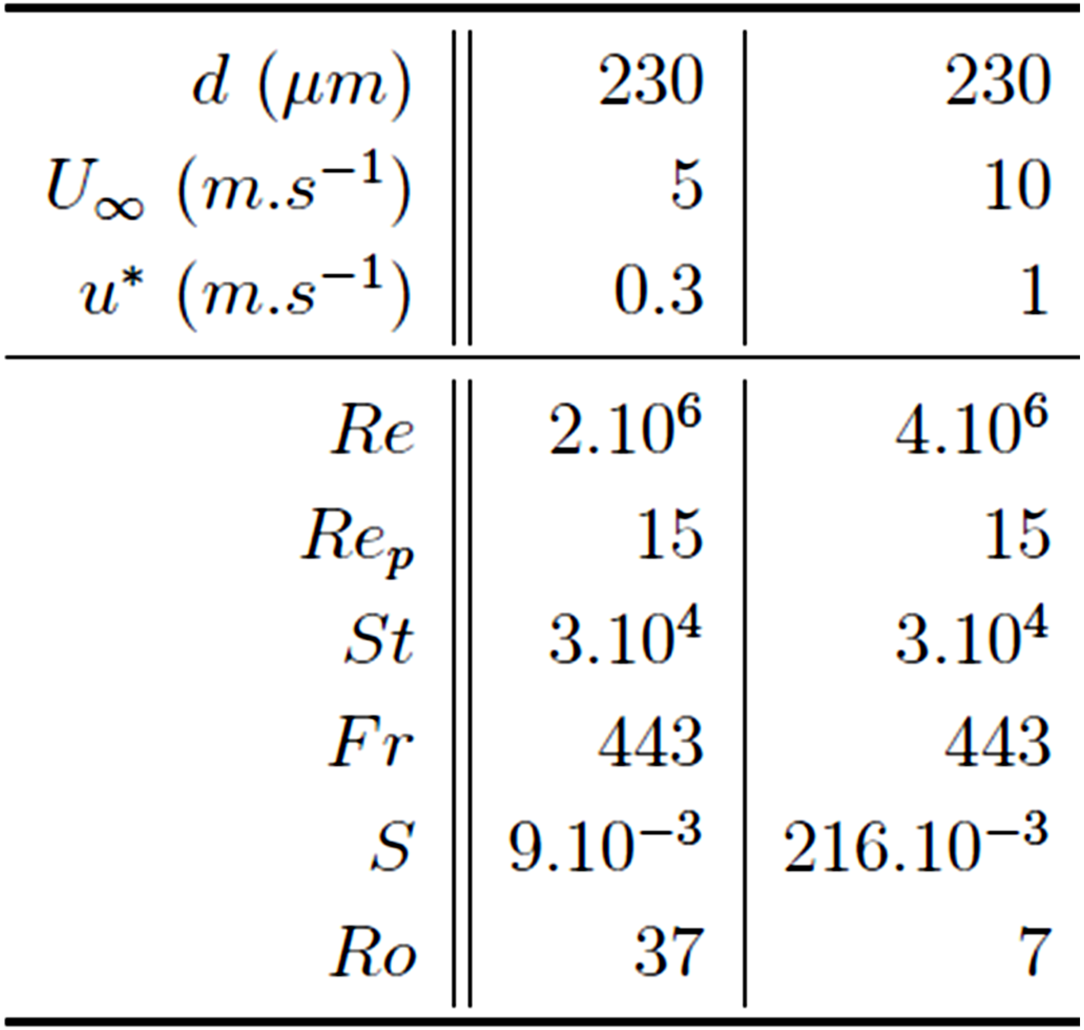
Erodible bed is replaced by a rigid one : no mobile sand at the beginning

WIND TUNNEL EXPERIMENTS-MEASUREMENTS

Physical Parameters	Method	Obtained Quantities
Air Velocity	Pitot Tubes	u^*, z_0 , U_f , z_f
Particule Velocity	PTV	$u(z)$, $v(z)$, u_0 , v_0 (ascending and descending)
Distribution Laws		$P(\xi_x)$, $P(\xi_z)$ (ascending and descending)
Concentrations	Counting	$f(z)$, l_f , f_0
Mass Flux Density	-	$q(z) = \rho_p * f(z) * u(z)$
Total Mass Flux	-	$Q_{PTV} = \int q \, dz$

WIND TUNNEL EXPERIMENTS-MEASUREMENTS

Dimensionless numbers

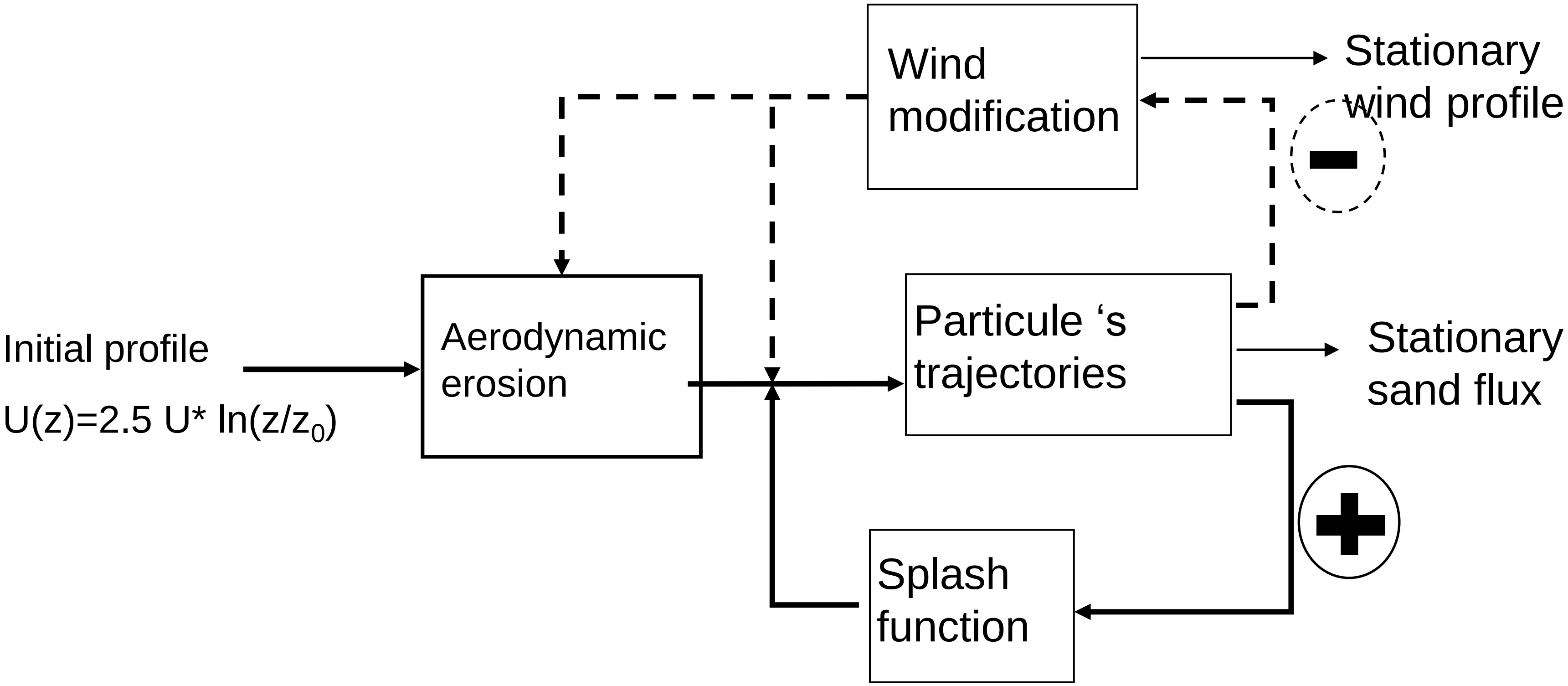


$d\ (\mu m)$	230	230
$U_\infty\ (m.s^{-1})$	5	10
$u^*\ (m.s^{-1})$	0.3	1
Re	2.10^6	4.10^6
Re_p	15	15
St	3.10^4	3.10^4
Fr	443	443
S	9.10^{-3}	216.10^{-3}
Ro	37	7

Inertia of grains is dominant

WIND TUNNEL - ERODIBLE BED

Steady transport process



Initial profile

$U(z)=2.5\ U^{*}\ \ln(z/z_0)$

Aerodynamic erosion

Wind modification

Stationary wind profile

Particule ‘s trajectories

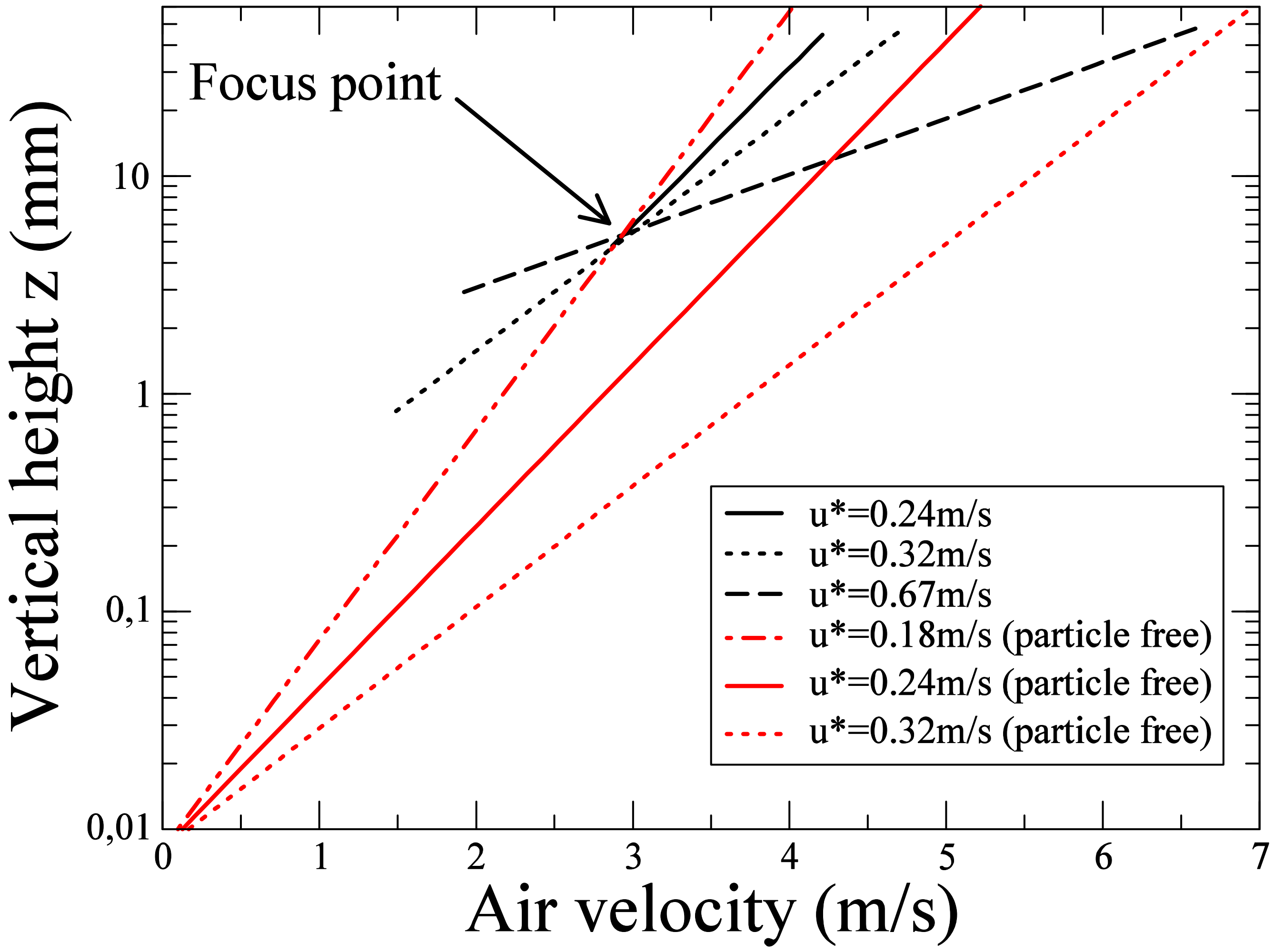
Stationary sand flux

Splash function

Mass transport is the result of a saturated boundary layer

WIND TUNNEL - ERODIBLE BED

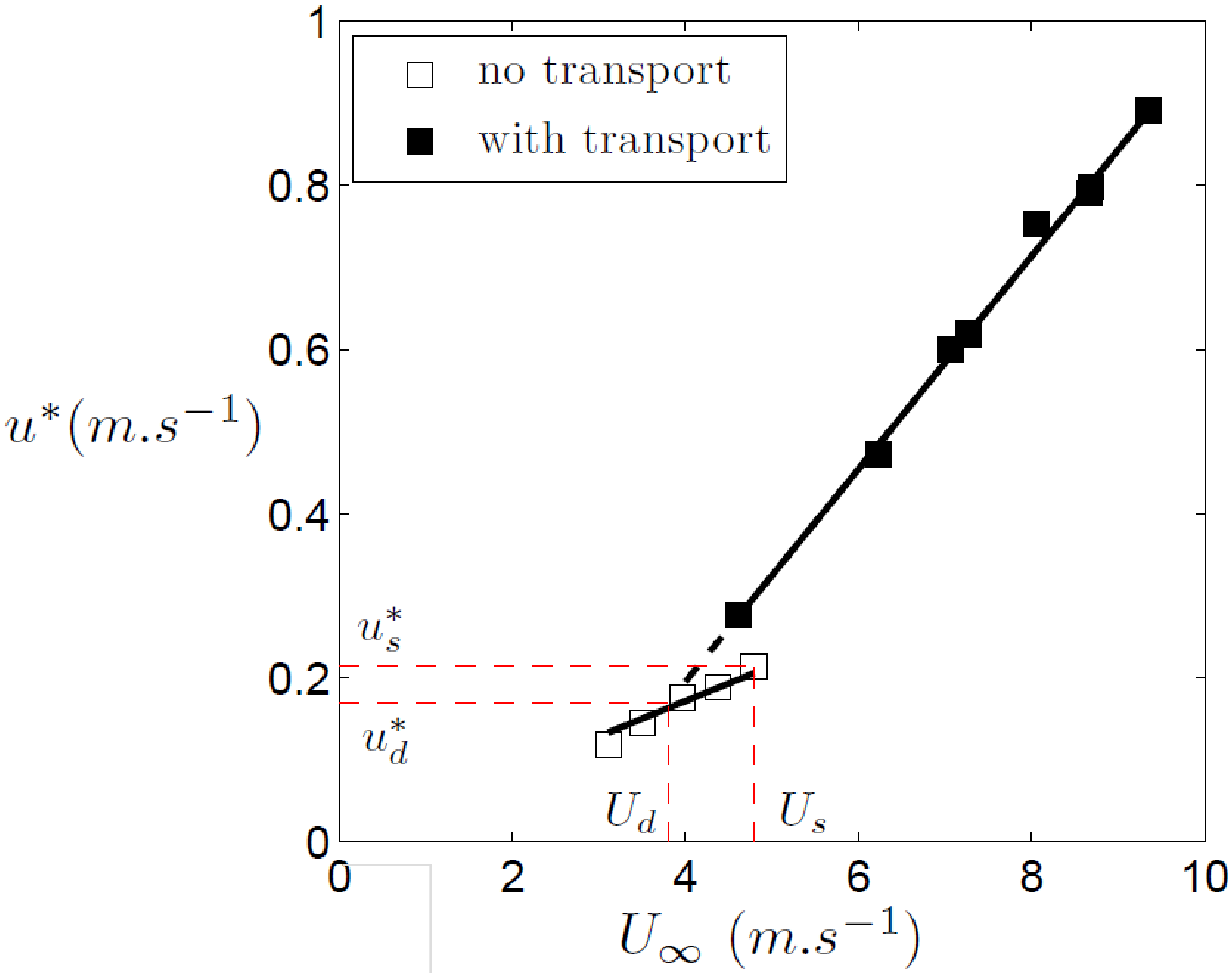
Wind profile



Focus point : z_f=8mm=35d; u_f=2.8m/s=60.$(gd)^{1/2}$

WIND TUNNEL - ERODIBLE BED

Static and dynamic thresholds



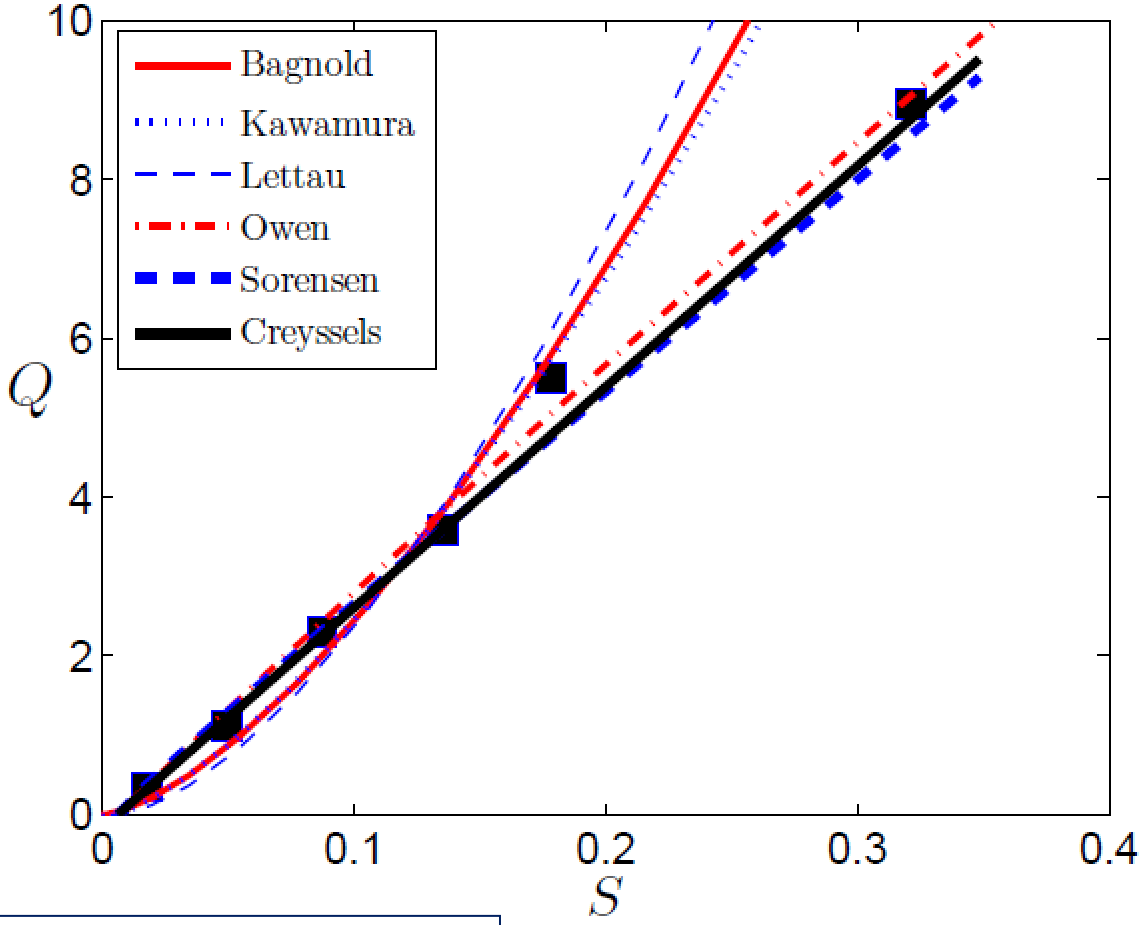
Dynamic threshold is more precise : S_d**=0.0062**

WIND TUNNEL - ERODIBLE BED

Mass flux transported by saltation over erodible bed

$$Q = C_b \sqrt{\frac{d}{D_r}} \frac{\rho_f}{g} u^{*3}$$

$$S = \frac{\tau_*}{\rho_p . g . d} = \frac{u_*^2}{\frac{\rho_p}{\rho_f} g . d}$$



$$\boxed{Q = \alpha_Q \rho_p d \sqrt{gd}\,(S - S_d)}$$

Scaling law differ from the classic ones

WIND TUNNEL - ERODIBLE BED - PARTIAL CONCLUSION

COMPARISONS BETWEEN FIELD AND LABORATORY MEASUREMENTS

- Similar sand flux around S=0.1

- Different scaling law with the shear
  - Laboratory: $Q \propto u^{*2}$ or S
  - Field : $Q \propto u^{*3}$ or $S^{3/2}$

Potential explanation:

- Larger roughness in the field
- Higher level of turbulent ra te and wider frequency range
- Larger poly-dispersity

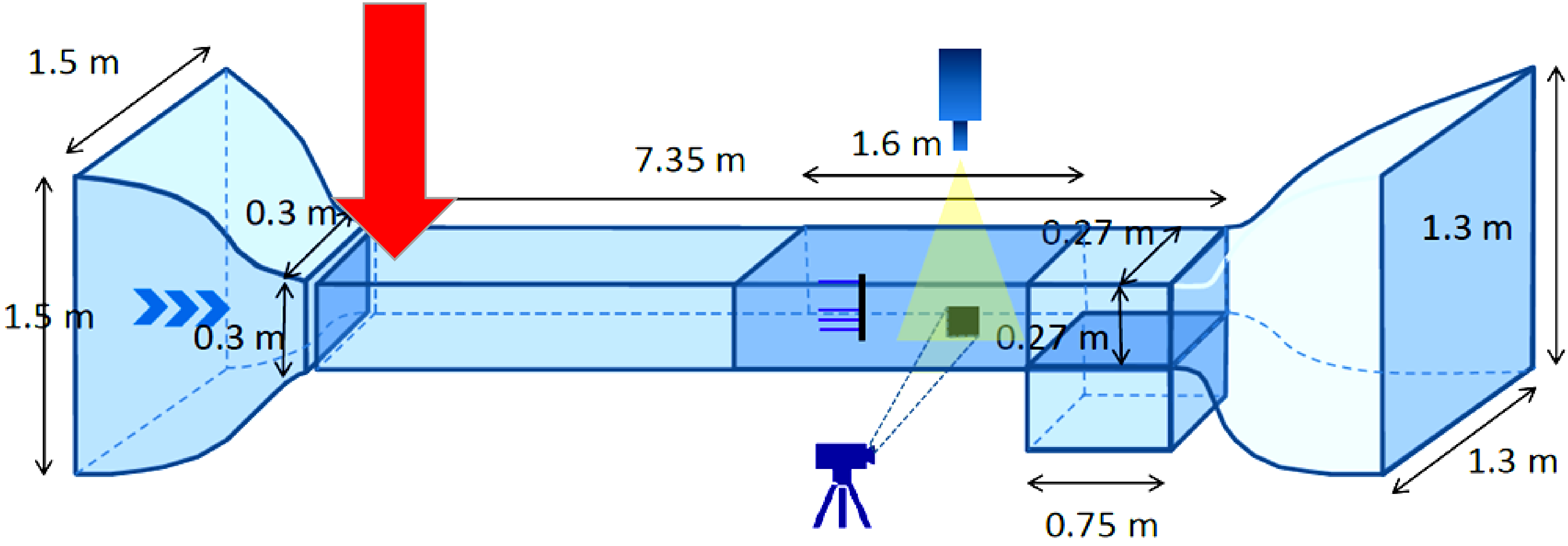
- **Interdune flux should differ from saturated flat case**
- **Rigid bed condition in the field**

WIND TUNNEL - RIGID BED

Mass flux is not a result of the system anymore

Sand input

Q_{in}



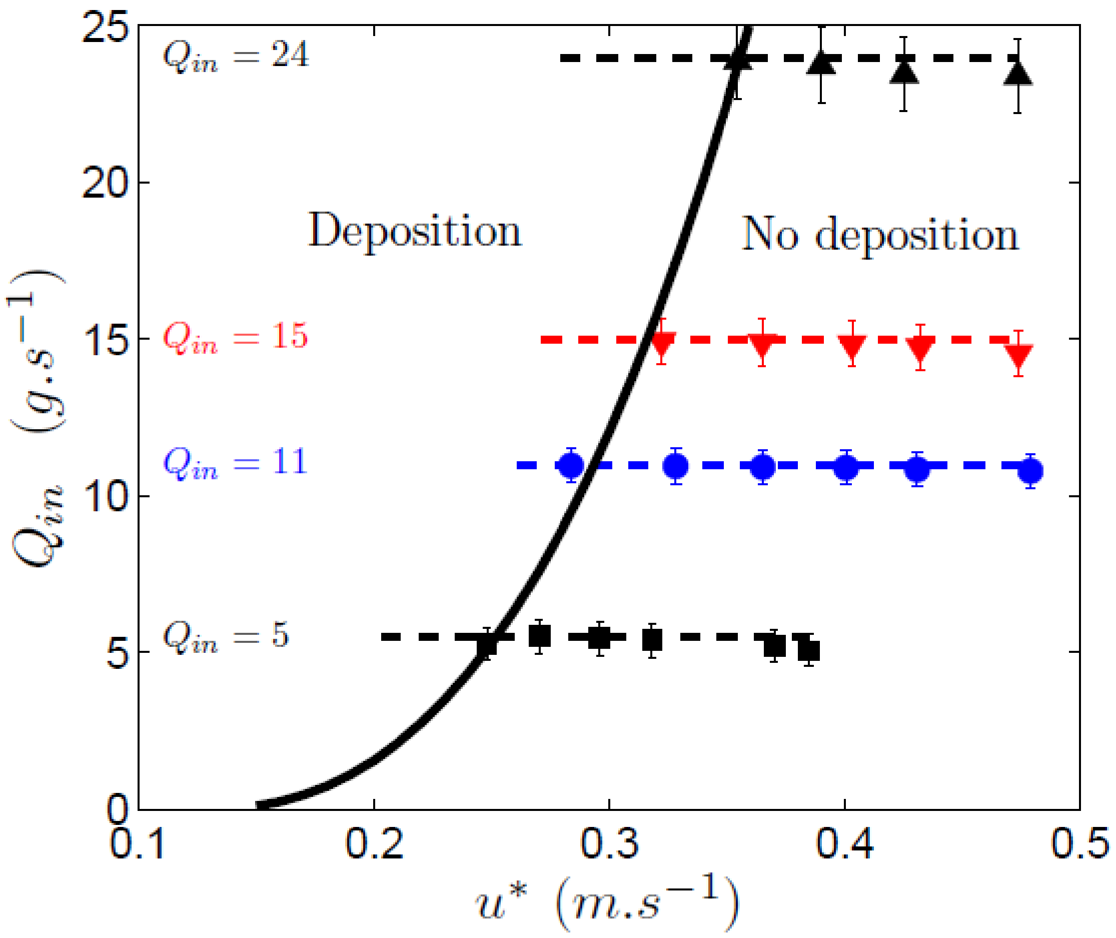
Two independent controlled parameters :

- Wind strength, u_* or S
- Q_{in}

2D diagram regime

WIND TUNNEL - RIGID BED

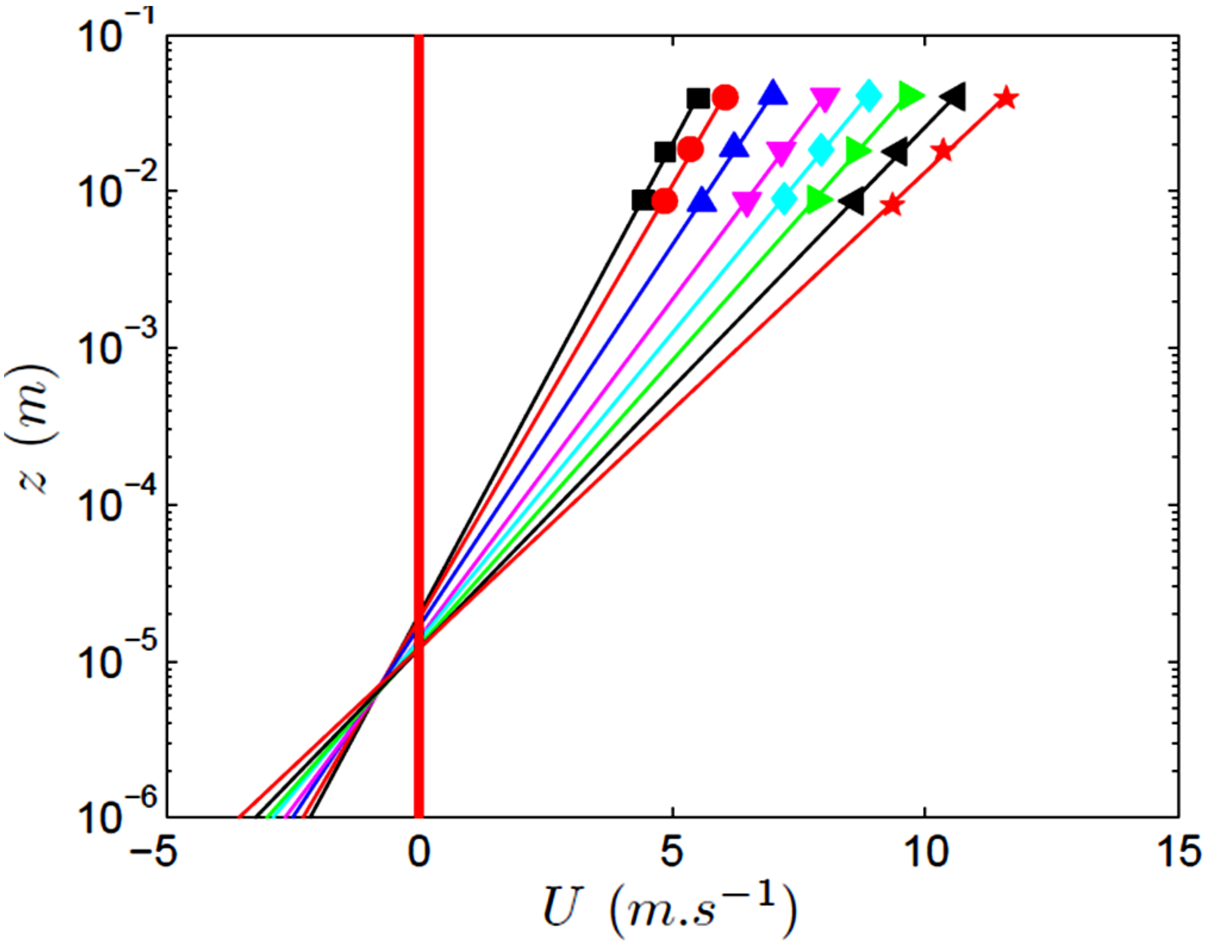
Regime diagram



Maximum capacity of transport

WIND TUNNEL - RIGID BED - AIR VELOCITY

Logarithmic air velocity profile for Q_{in}=15g/s

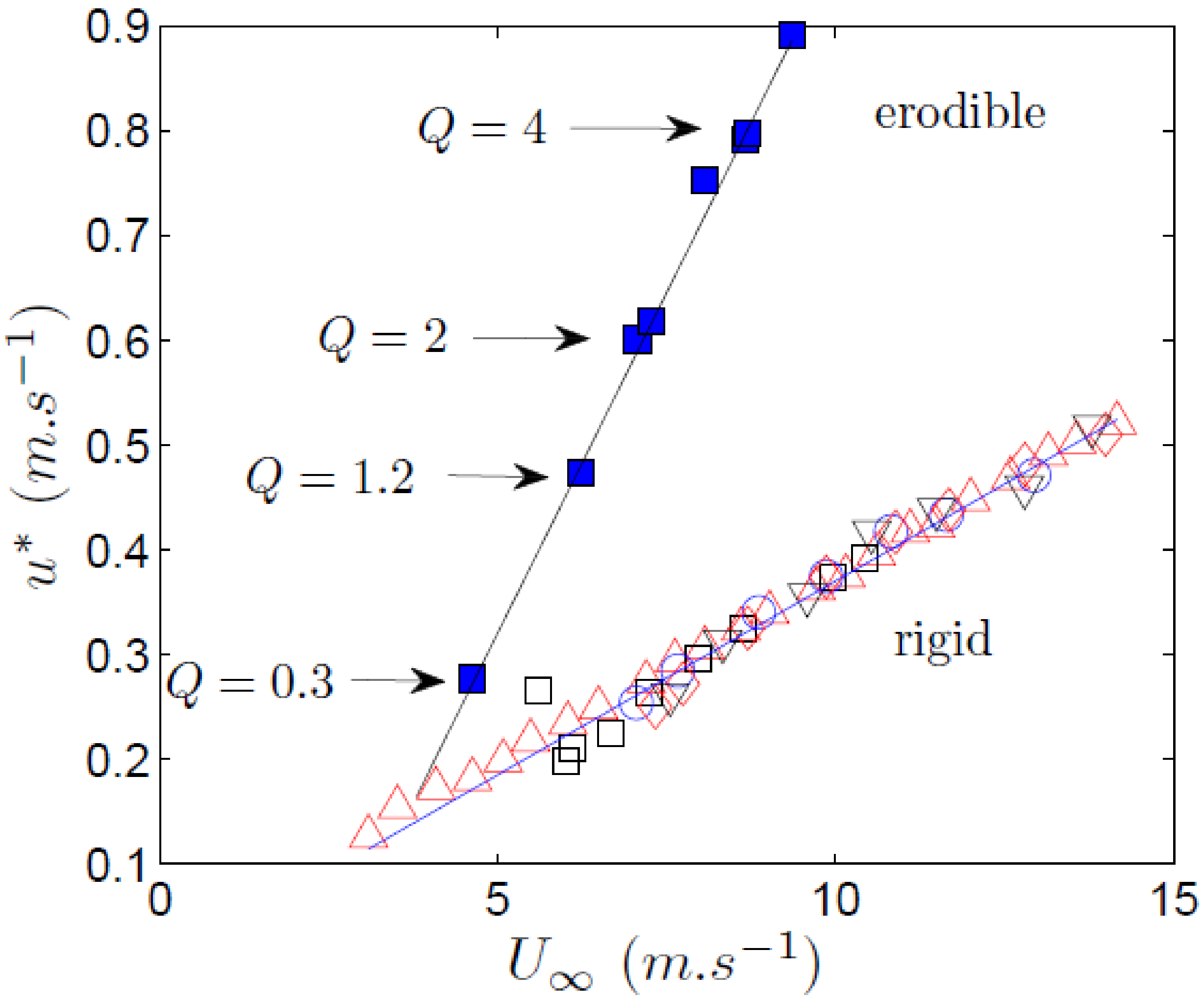


Air velocity profiles for various flow strengths obtained in the case of rigid bed with an incoming rate $Q_{in} = 15\ g/s$: $S = 0.0190$ (■), 0.0223 (●), 0.0288 (▲), 0.0366 (▼), 0.0445 (◆), 0.0515 (▶), 0.0616 (◀), 0.0741 (◆). The profiles exhibit a logarithmic law with the height and converge to a focus point.

Friction should be estimated

WIND TUNNEL - RIGID BED - AIR VELOCITY

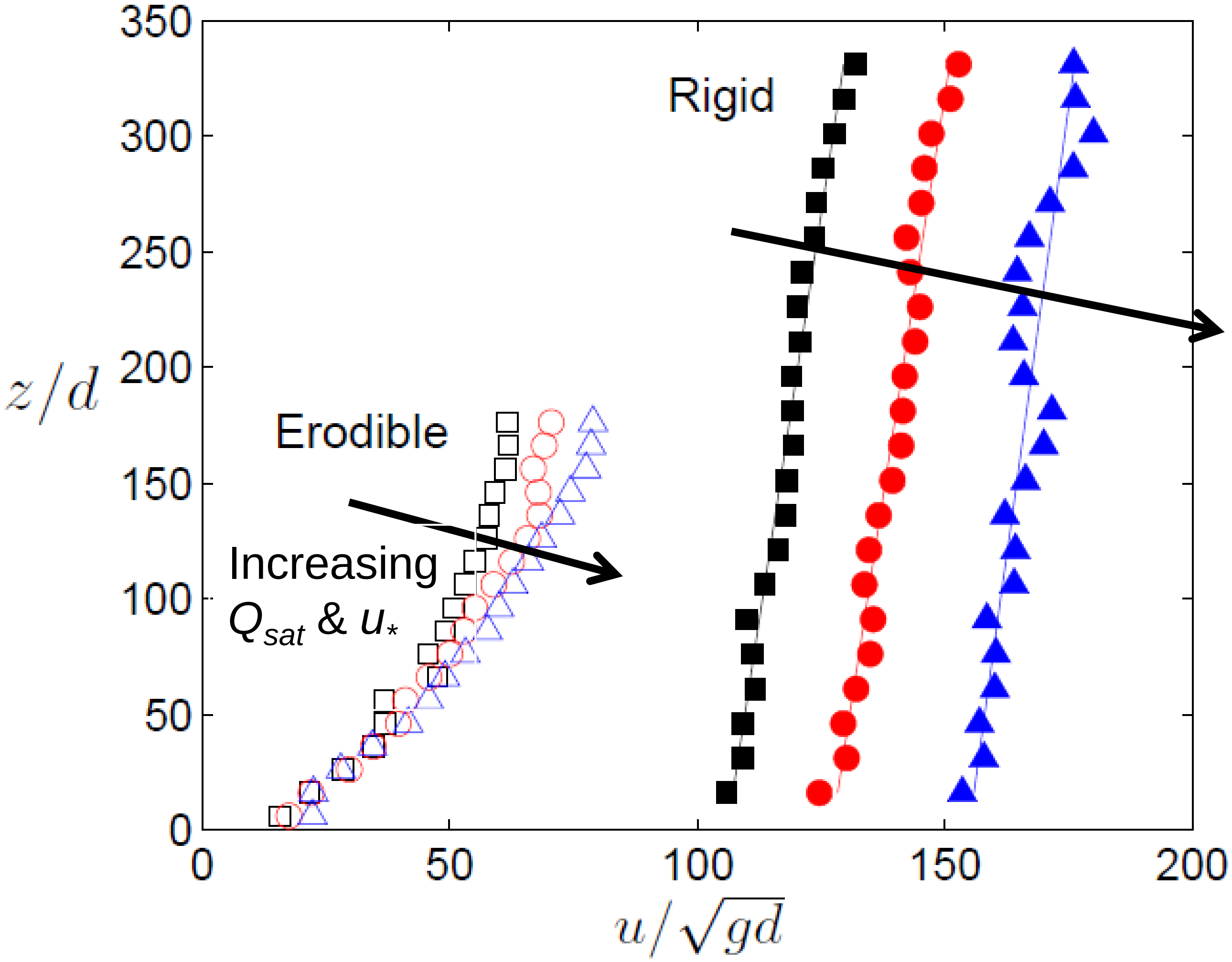
Air friction velocity for $Q_{in} = 0$ (△), $5.5\ g/s$ (□), $11\ g/s$ (○)



smaller friction over rigid bed and independent on flux

WIND TUNNEL - RIGID BED - GRAIN VELOCITY

Particle horizontal velocity for similar u_*

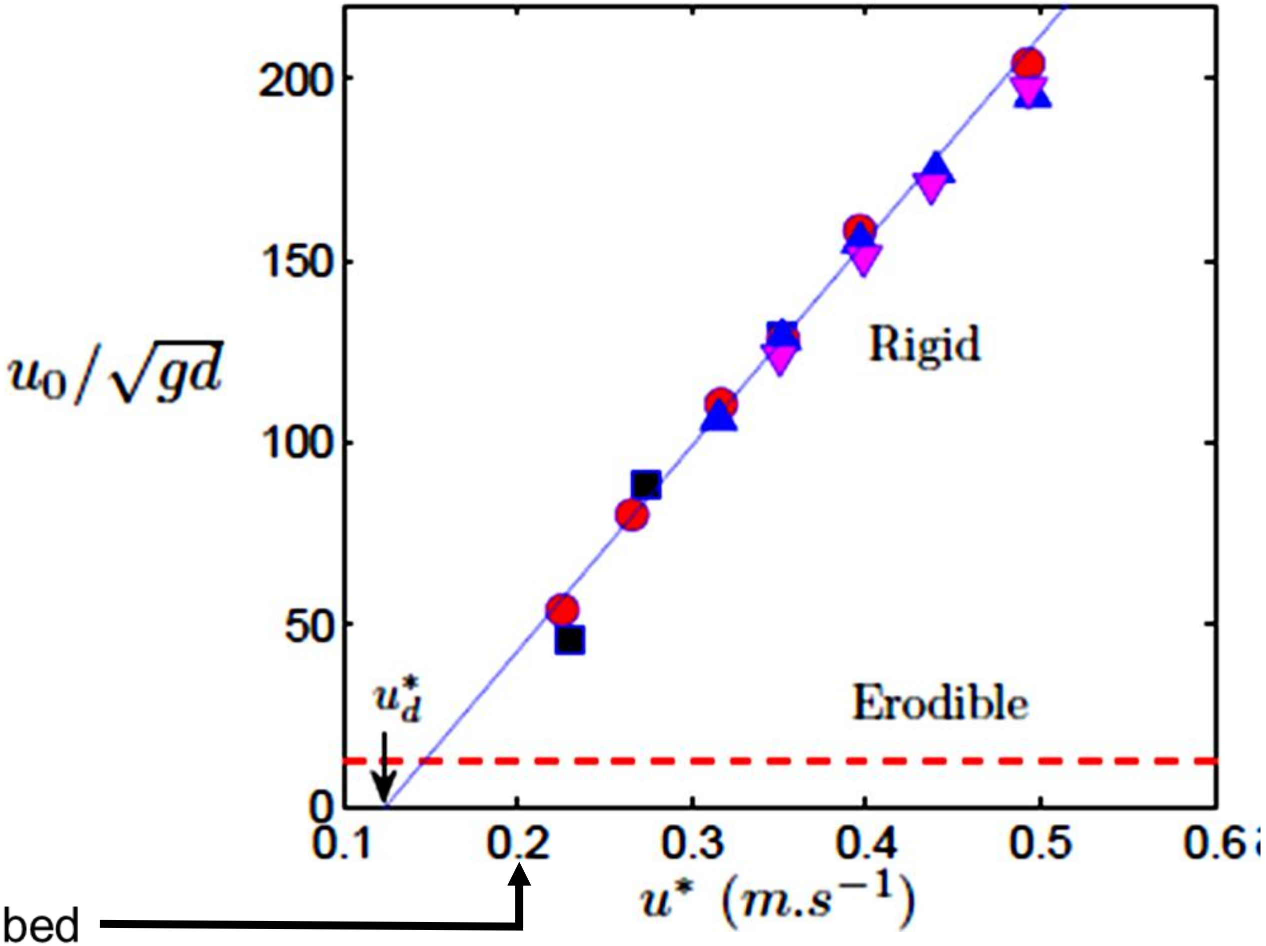


Q_{in}= 15g/s
Increasing u_*

Cloud of particle are in equilibrium with the wind

WIND TUNNEL - RIGID BED - GRAIN VELOCITY

Particle slip velocity for various Q_{in}

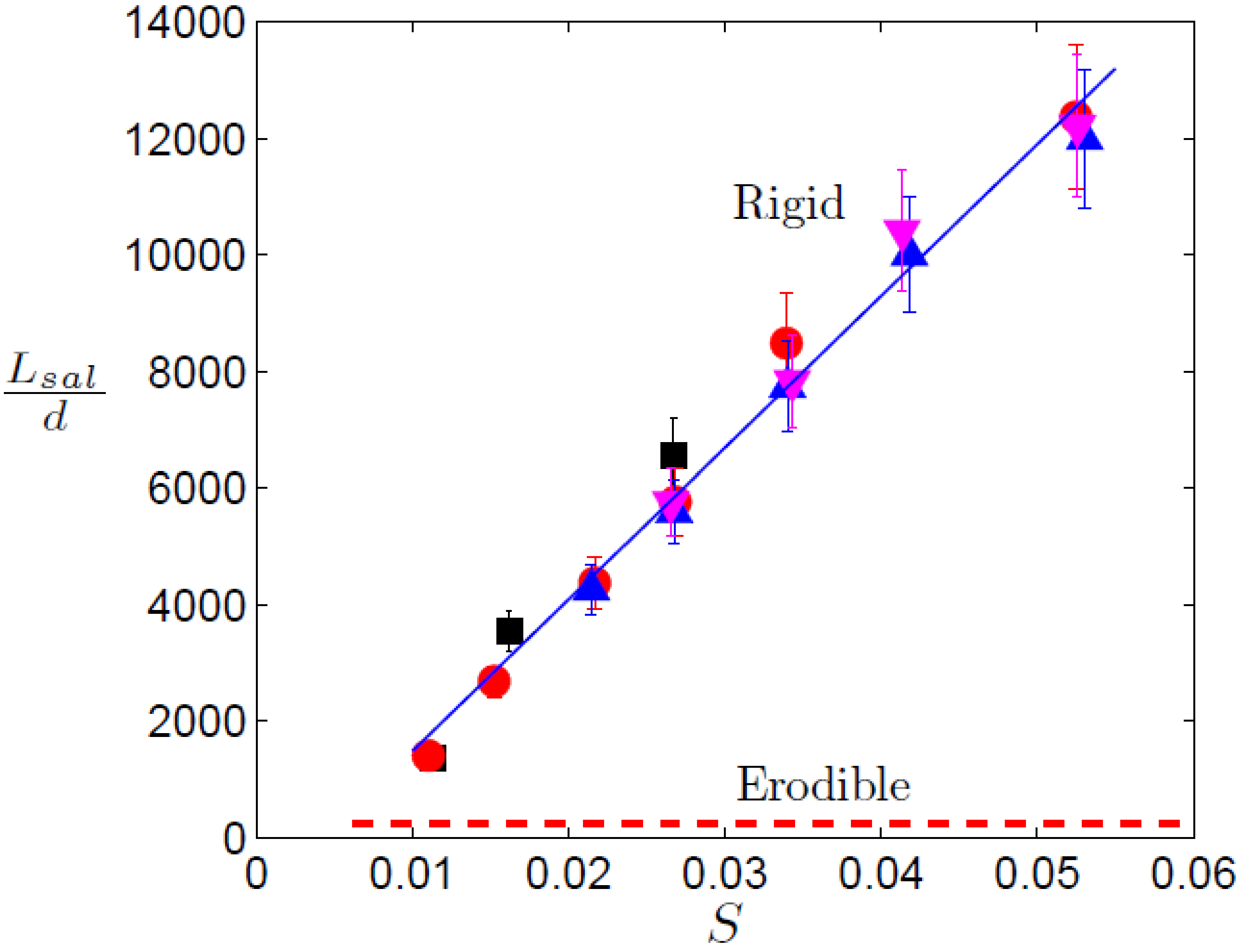


u_d^* erodible bed

Dynamics independent on Q_{in}, threshold below erodible case

WIND TUNNEL - RIGID BED - GRAIN TRAJECTORIES

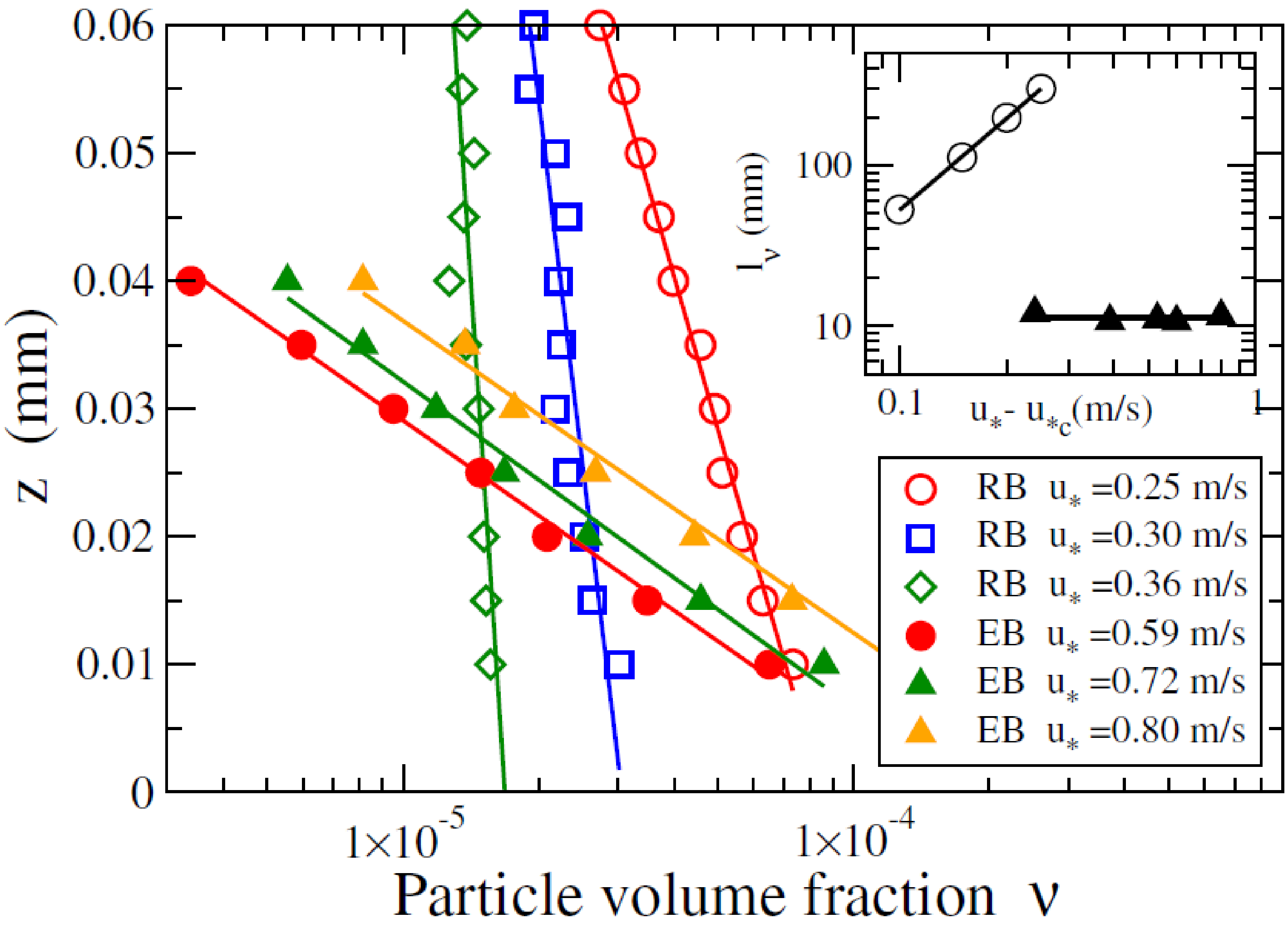
Mean saltation length



Cloud of particle are in equilibrium with the wind

WIND TUNNEL - RIGID BED - GRAIN CONCENTRATION

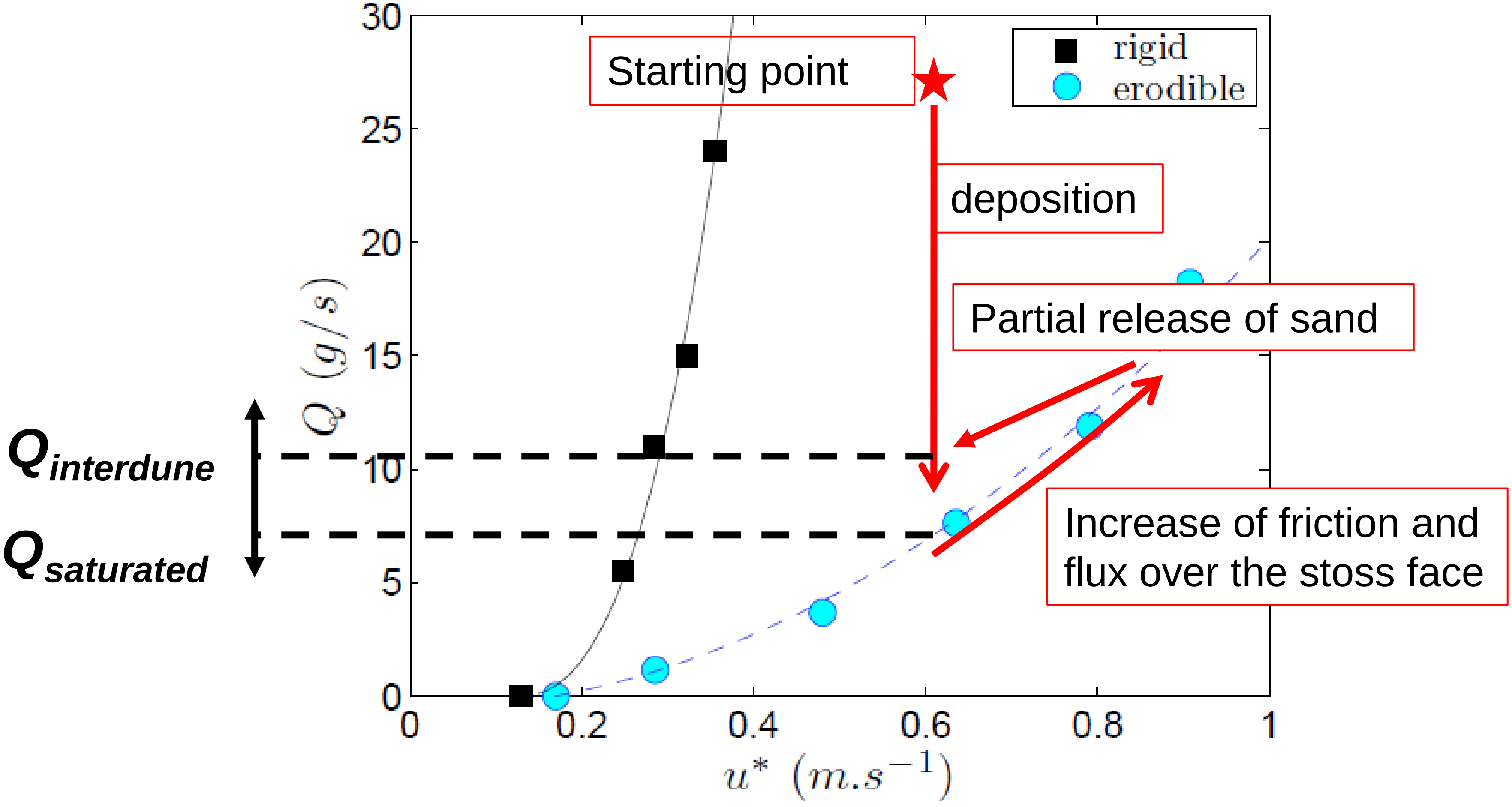
Particle volume fraction profile for similar flux between erodible and rigid case



More rapid but more dilute cloud of particles

CONCLUSIONS

Compared maximum mass flux



Starting point

deposition

Partial release of sand

Increase of friction and flux over the stoss face

$Q_{interdune}$

$Q_{saturated}$

$Q_{interdune}$ is a complex result of partial trapping of the dune

PERSPECTIVES

Laboratory experiment :

- Improve the calibration of the probe on a rigid bed
- For erodible case submitted to high shear rate… (See Diego’s work)

Field experiment :

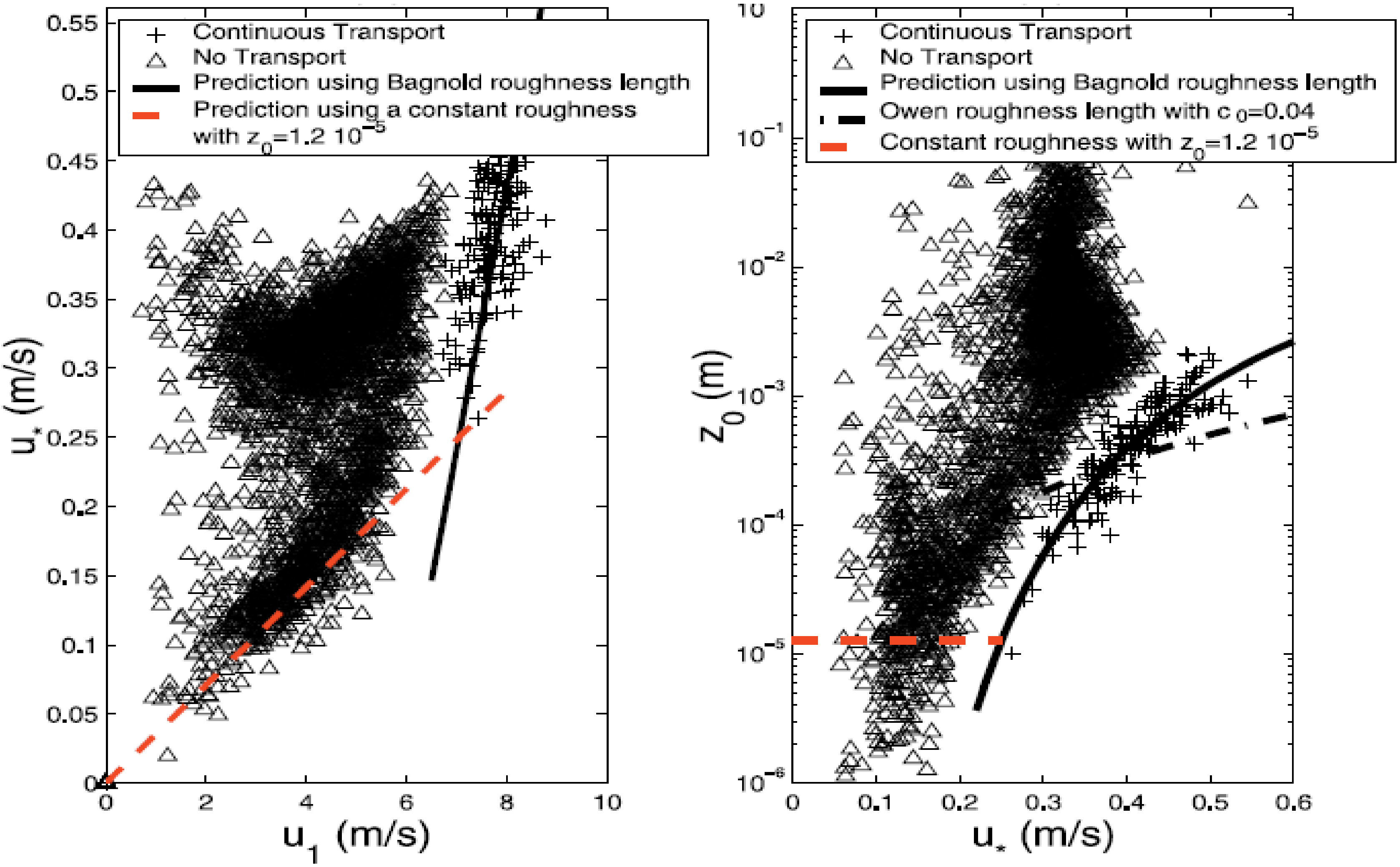
- Compare $\boldsymbol{Q}_{\boldsymbol{interdune}}$ with fluxes on the dune
- Compare trapping efficiency in other situation (N. Le dantec)
- Repeated those measures for various strength and direction of the wind

Extension of this work

- Study intermediate soil quality neither completely erodible nor rigid
    - with bidisperse sand
    - Or sand + humidity + salt (application to costal area).
- Application to abrasion problems with the challange of instantaneous shear stress measurements

SUPPLEMENT

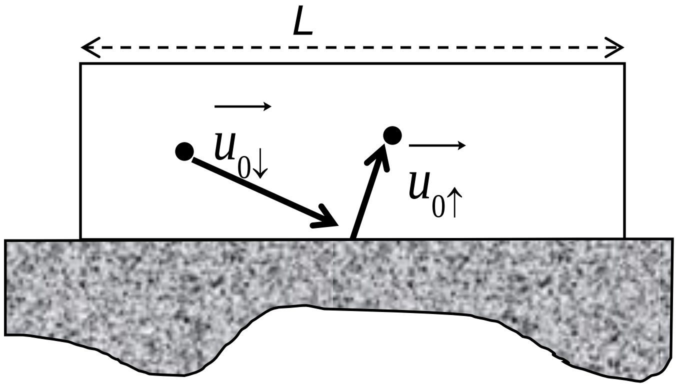
FIELD EXPERIMENTS – WIND SHEAR STRESS



$$z_f = 0.13 \pm 0.05\, m \;\; \text{and} \;\; u_f = 5.8 \pm 0.4\, m/s$$

wind shear stress from this focus point model

SCALING LAWS INTERPRETATION

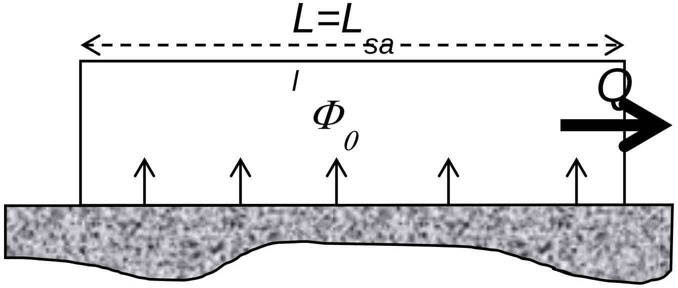


Longitudinal momentum flux lost by the fluid : $L.\tau_{part}$

Longitudinal momentum won by one part: $m.\left(u_{0\downarrow} - u_{0\uparrow}\right)$

Longitudinal momentum flux won by a set of part : $\Phi_0.\left(u_{0\uparrow} - u_{0\downarrow}\right)$

Momentum balance gives : $L.\tau_{part} = \Phi_0.\left(u_{0\uparrow} - u_{0\downarrow}\right)$



Mass balance on *L*=*L*$_{sal}$ gives : $Q = L_{sal}.\Phi_0$

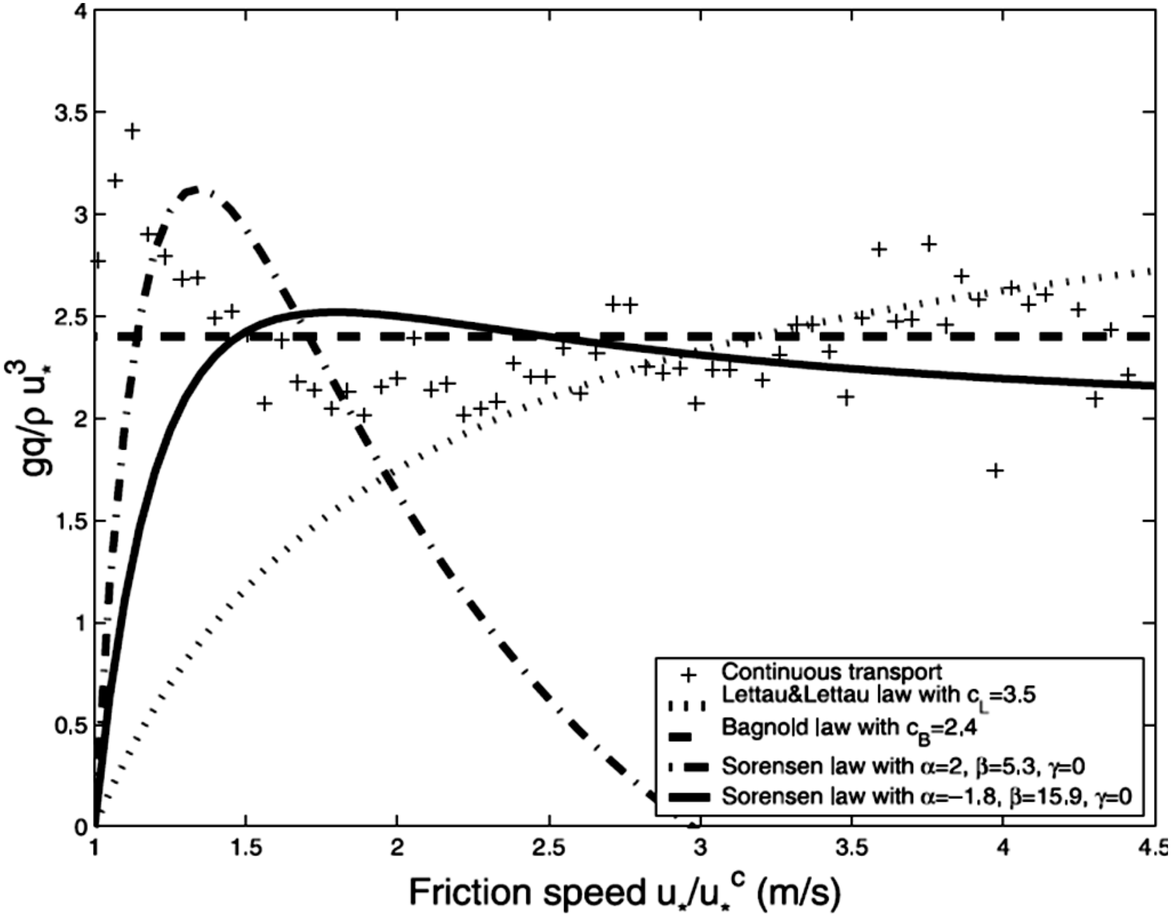
Then : $$Q = \frac{L_{sal}}{\left(u_{0\uparrow} - u_{0\downarrow}\right)}.\tau_{part}$$

Then with a constant Froude number $Fr_{sal} = \frac{u_0}{\sqrt{g.L_{sal}}} = \text{const}$ the saltation length scales $L_{sal} \propto u_0^{\ 2}$

Over rigid bed: $u_{0\uparrow}, u_{0\downarrow} \propto u*$ and then the transport $Q \propto u*^3 \text{ or } S^{3/2}$

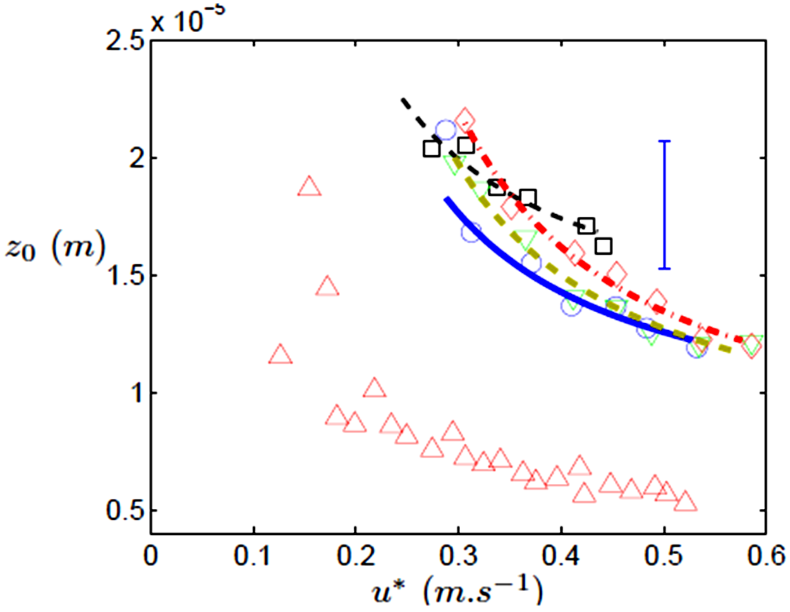
Over erodible bed $u_{0\uparrow}, u_{0\downarrow} = \text{const}$ and then $\boxed{Q \propto u*^2 \text{ or } S}$

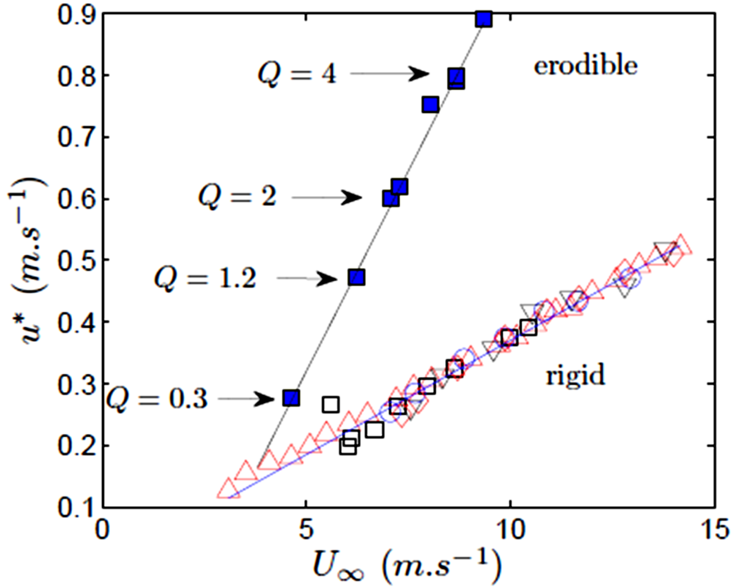
FIELD EXPERIMENTS – TRANSPORT LAW



Classic empirical laws match the trend of the transport law

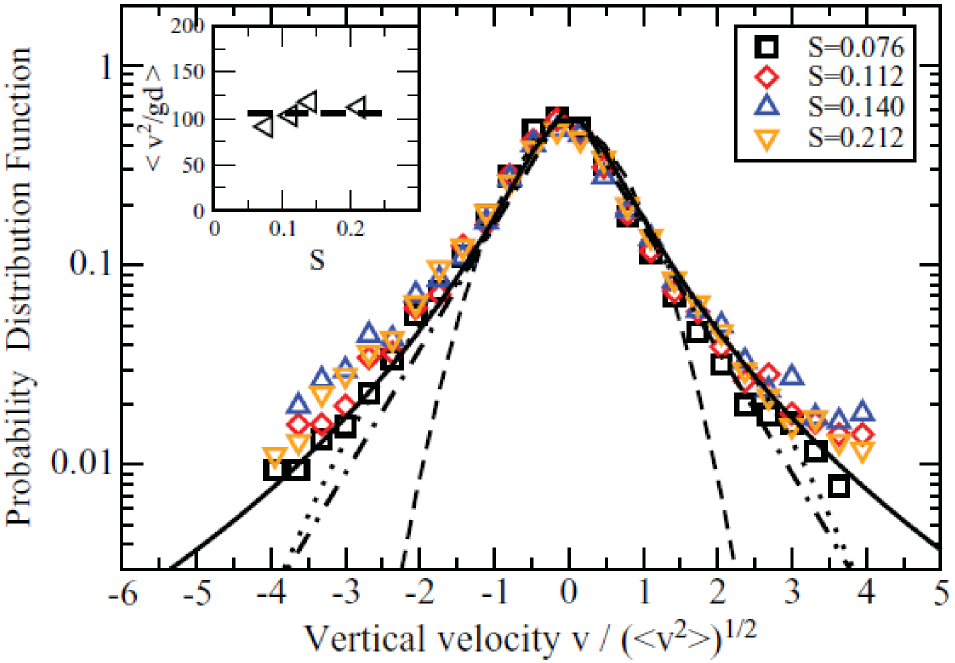
WIND TUNNEL - RIGID BED - AIR VELOCITY

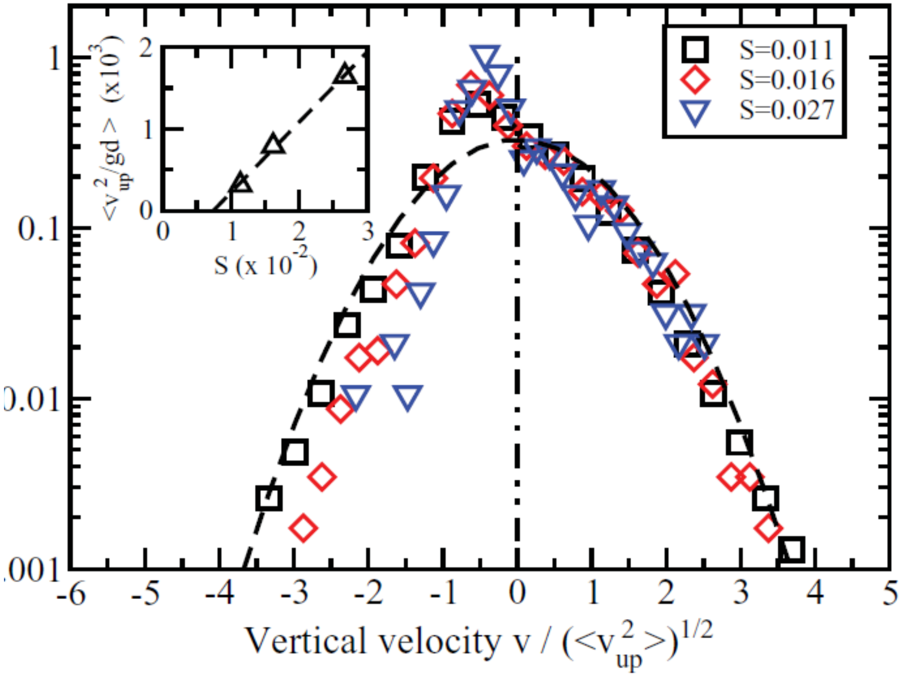




WIND TUNNEL EXPERIMENTS-RIGID BED

Particle velocity distribution

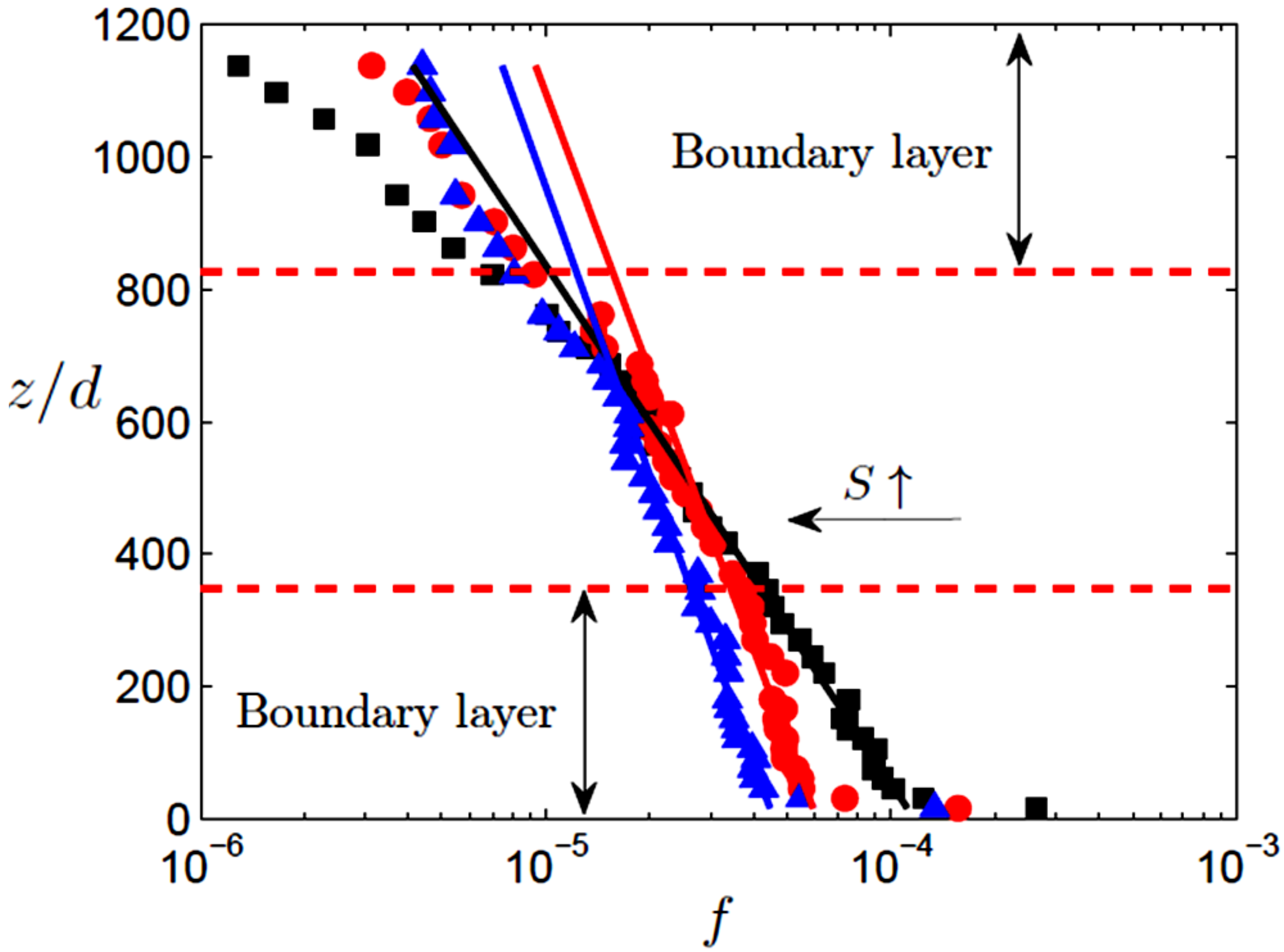




⇨ Fine velocity distributions signe the boundary condition

WIND TUNNEL EXPERIMENTS-RIGID BED

Finite test section height



⇨opposite concentration behaviours

Dune trajectory simulated from april 2004 to april 2005