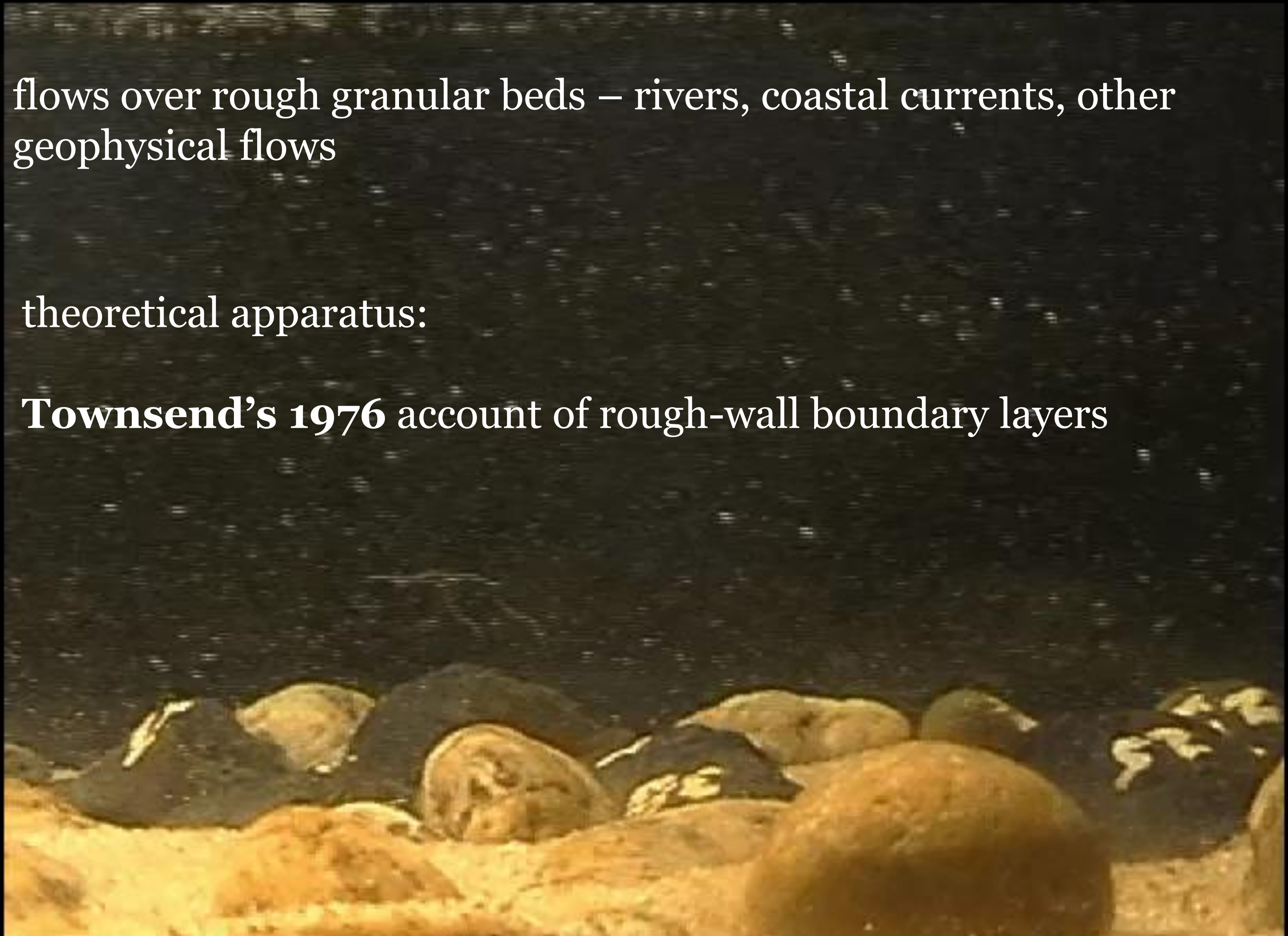
EGU: General Assembly 2020, 4-8 May 2020 | GM3.5

Turbulent open-channel flows over mobile granular low-tortuosity beds: velocity distribution and friction factor

Rui M.L. Ferreira[1]; Daniela Santos[2]; Rigden Y. Tenzin[1]; Ana M. Ricardo[2];

(1) CERIS – Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal
(2) CERIS, Lisboa, Portugal

Motivation



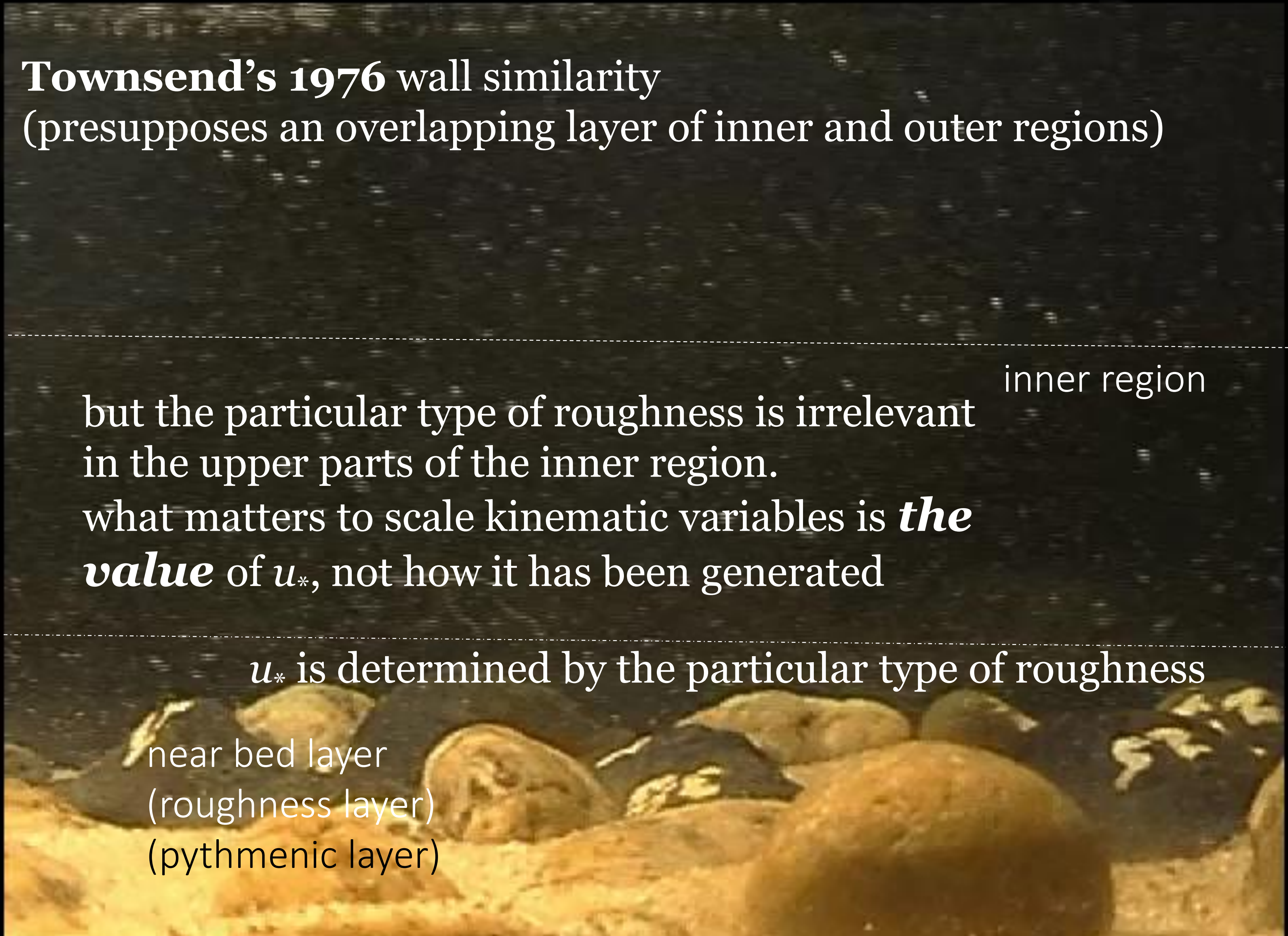
flows over rough granular beds – rivers, coastal currents, other geophysical flows

theoretical apparatus:

Townsend's 1976 account of rough-wall boundary layers

TÉCNICO LISBOA

Motivation



Townsend's 1976 wall similarity
(presupposes an overlapping layer of inner and outer regions)

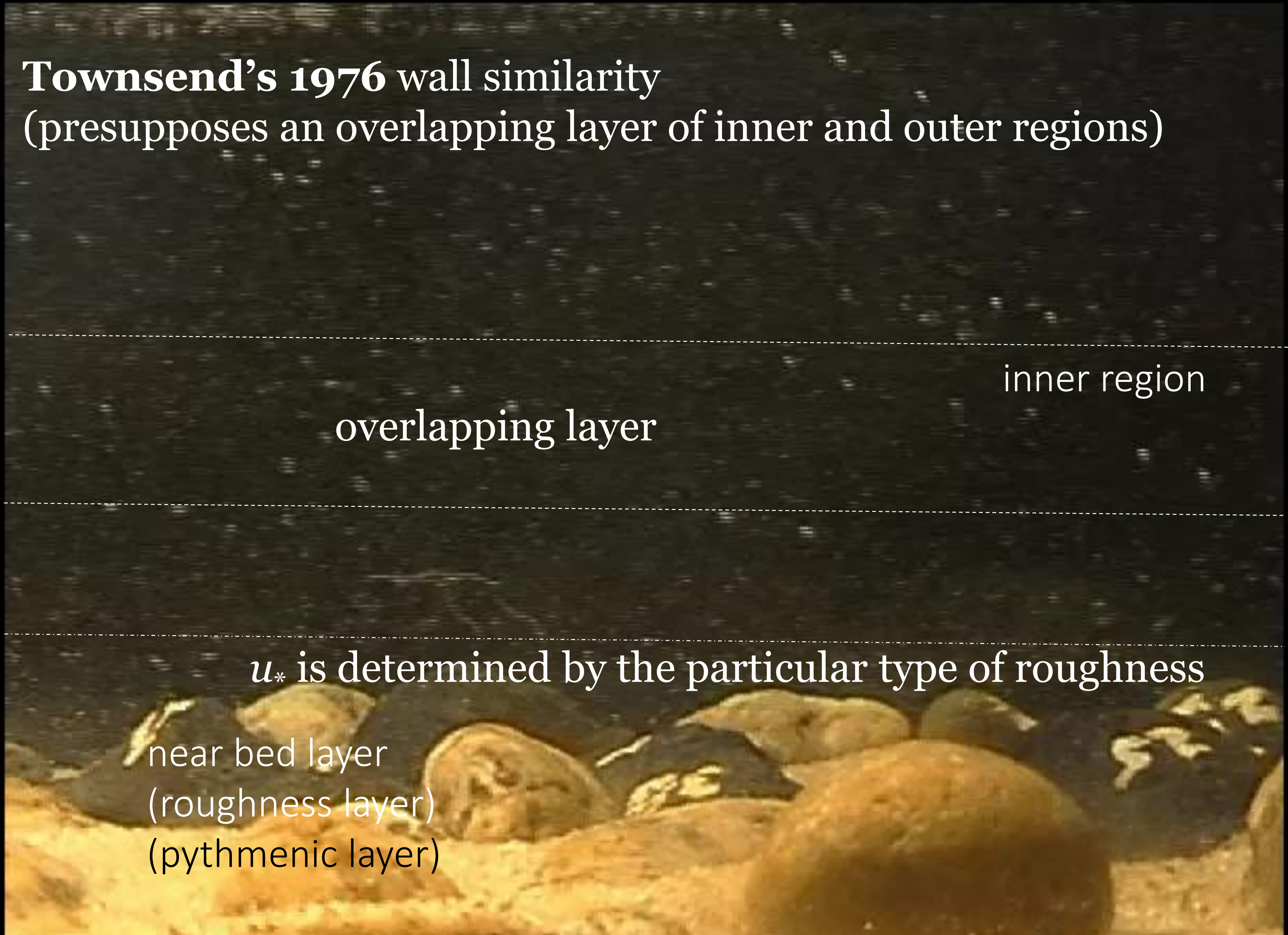
inner region

but the particular type of roughness is irrelevant in the upper parts of the inner region.
what matters to scale kinematic variables is ***the value*** of u_*, not how it has been generated

u_* is determined by the particular type of roughness

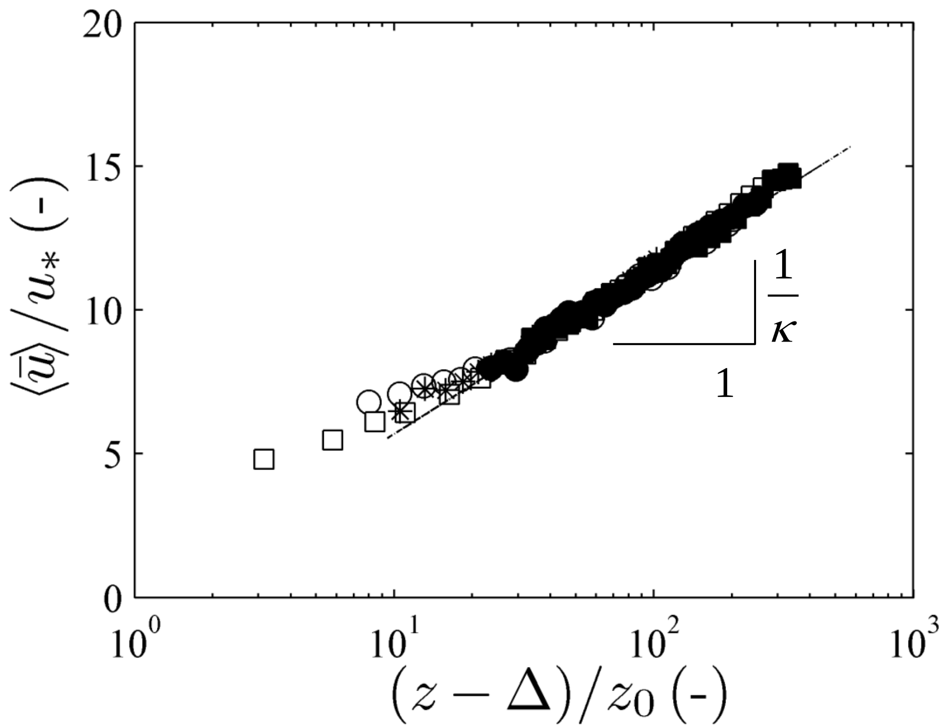
near bed layer
(roughness layer)
(pythmenic layer)

Motivation


Townsend's 1976 wall similarity
(presupposes an overlapping layer of inner and outer regions)
inner region
overlapping layer
u_* is determined by the particular type of roughness
near bed layer
(roughness layer)
(pythmenic layer)

Motivation

the wall-normal distribution of the longitudinal velocity



$$z\partial_z \{u\} = u_* A$$

A **is empirically determined;**
Re independent? universal?

$$z\partial_z \{u\} = u_* A$$

$\kappa = 1/A$ *von Kármán parameter*

Drag reducing flows: $A = 1/\kappa$ **is larger for the same normalized shear rate (lower u_*)**

Motivation

Ferreira 2015: why would the von Kármán parameter express drag reducing flows in flows over rough mobile beds?

influenced by flow anisotropy

$$\kappa \propto \frac{1}{8}\left(\frac{\ell_{0w}(z)}{z}\right)\left(\frac{u_*^2/k}{k/\overline{w'^2}}C_{2w}\right)$$

influenced by larger flow scales?

k – turbulent kinetic energy
$\overline{w'^2}$ – Wall normal turbulence intensity
ℓ_{0w} – transverse integral scale
C_{2w} – constant of transverse 2nd order structure function

Landau remark concerning C_{2w}

the Landau remark: C_2 is not flow-independent when the production range is modulated by a wide range of (roughness-influenced) scales

Motivation

Ferreira 2015: why would the von Kármán parameter express drag reducing flows in flows over rough mobile beds?

whatever the change in the structure of turbulence (very large scales and/or RS anisotropy)

there must be a cause for that change

in this work we investigate

the role of surface-hyporheic exchanges that should depend on **hydraulic conductivity** of the bed

$$\kappa \propto \frac{1}{8}\left(\frac{\ell_{0w}(z)}{z}\right)\left(\frac{u_*^2 / k}{k / \overline{w'^2}} C_{2w}\right)$$

k – turbulent kinetic energy

$\overline{w'^2}$ – Wall normal turbulence intensity

ℓ_{0w} – transverse integral scale

C_{2w} – constant of transverse 2nd order structure function

Objectives

The general objective of this work is to study the effect of the ***hydraulic conductivity*** on open-channel *turbulent flows* of viscous fluids over mobile and hydraulically rough beds of cohesionless sediment.

In particular, we:

- characterize the parameters of log-law (novel database of a high hydraulic conductivity bed),
- discuss the differences observed in the log-law parameters between high and low conductivity beds and,

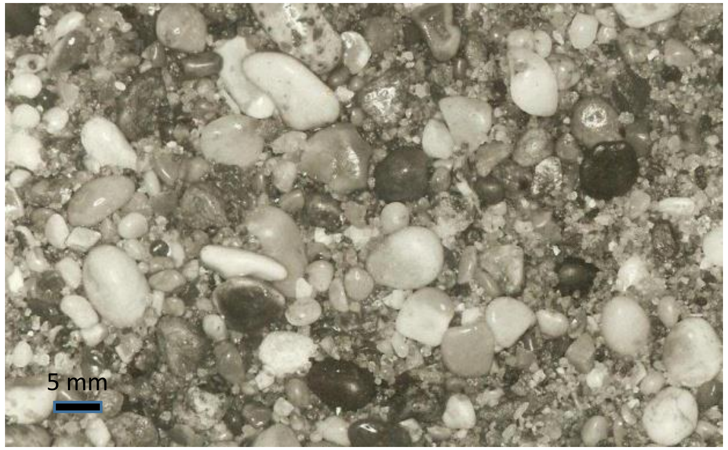
TÉCNICO LISBOA

Macroscopic properties of granular beds

Two databases in a similar flume:

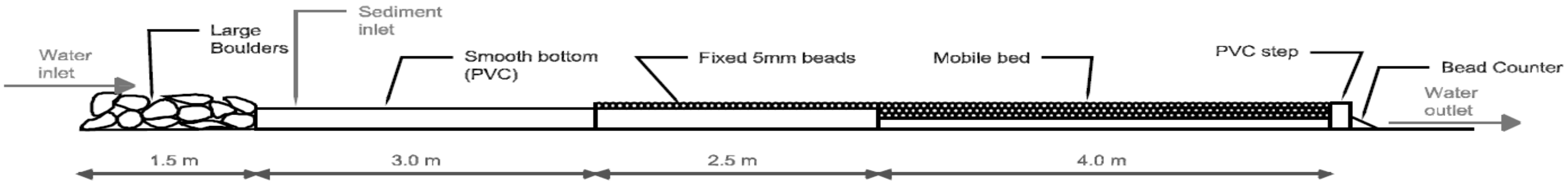
- Under same range of values of Shield parameters
- In the mobile bed cases, under equilibrium transport conditions
- In all cases, under uniform flow conditions
- approximately the same d_{84}
- Different porosity (n), tortuosity (T), permeability (k) and **hydraulic conductivity** (K))

Tests	High conductivity bed (lattice-arranged)	**High conductivity bed (random)**	Low conductivity bed (Existing database)
d_{84} (mm)	4.97	4.97	5.40
ρ (kg/m^3)	2607	2607	2590
n (-)	0.325	0.369	0.301
T (-)	0.88	1.34	9.96
k (m^2)	3.E-08	5.E-09	3.E-10
K (m/s)	3.E-01	6.E-02	4.E-03



The Laboratory

Flume at the Laboratory of Hydraulics Environment of Instituto Superior Técnico, Lisbon



Flow characterization: Lattice arrangement

Mean flow variables characterizing the experimental tests

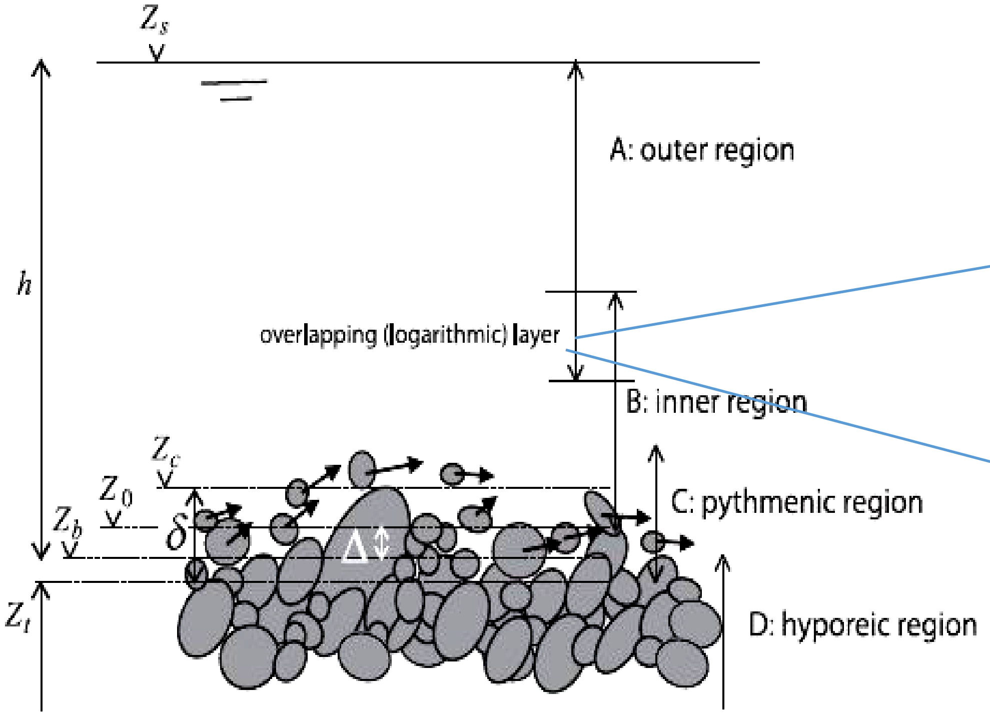
Tests	Q (l/s)	slope (-)	h_u (m)	U (m/s)	R_h (m)	$\tau_0^{(1)}$ (N/m^2)	$u_*^{(1)}$	bead rate	$\tau_0^{(2)}$ (N/m^2)	$u_*^{(2)}$
1	14.98	0.00317	0.0714	0.518	0.0528	1.639	0.041	0.00	1.603	0.040
2	15.90	0.00404	0.0703	0.559	0.0522	2.067	0.046	0.33	2.180	0.047
3	16.67	0.00456	0.0684	0.068	0.0511	2.287	0.048	6.23	2.187	0.047
4	20.83	0.00623	0.0744	0.691	0.0544	3.325	0.058	21.12	3.080	0.056
5	21.35	0.00714	0.0696	0.757	0.0518	3.628	0.060	28.72	3.223	0.057

Flow characterization: Random arrangement

Mean flow variables characterizing the experimental tests

Tests	Q (l/s)	slope (-)	h_u (m)	U (m/s)	R_h (m)	τ_0 (N/m^2)	u_*	bead rate
IM	14.10	0.00221	0.0786	0.4431	0.0566	1.2261	0.0350	0.16
LF	13.37	0.00112	0.0650	0.5081	0.0492	0.5406	0.0233	0.00
ST	10.10	0.00192	0.0710	0.3512	0.0526	0.9901	0.0315	0.00
B5	15.42	0.00224	0.0830	0.4581	0.0589	1.2936	0.0360	0.03
S1	16.83	0.00400	0.0810	0.5130	0.0579	2.2703	0.0476	5.00
S2	20.92	0.00592	0.08200	0.62993	0.05837	3.38959	0.05822	90.00
S3	16.7	0.00520	0.0810	0.5091	0.0579	2.9514	0.0543	14.00

The logarithmic law of the wall



Idealized bed configuration (adapted from Ferreira et al., 2012)

$$\frac{\langle \bar{u} \rangle}{u_*} = \frac{1}{\kappa} \ln\left(\frac{z - \Delta}{k_s}\right) + B$$

$$\frac{\langle \bar{u} \rangle}{u^*} = \frac{1}{\kappa} \ln\left(\frac{z - \Delta}{z_0}\right)$$

κ : von Kármán parameter

Δ : displacement height

k_s : geometric scale of the roughness elements

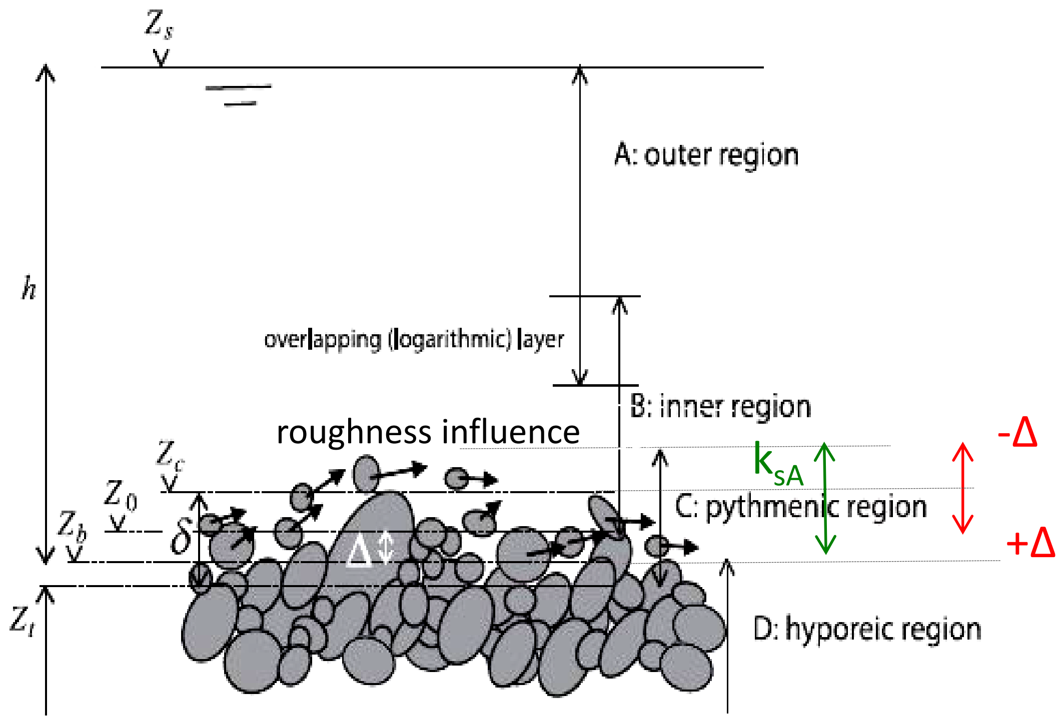
z_0 : roughness height $z_0 = k_s e^{-\kappa B}$

Introduction
Motivation
Objectives
Experimental facilities & procedures
The Laboratory
Flow characrterzation
Macroscopic properties
Methodology
Data treatment
Methods of calculation
Results and discussion
Conclusions and future work
Acknowledgement

Scenarios – definitions of log-law parameters for rough walls

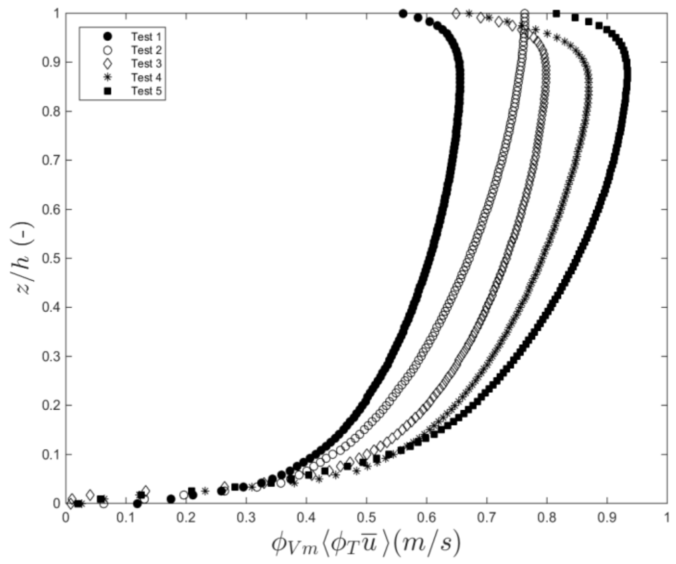
(New high-conductivity databases)	Existing database of Ferreira et al. (2012)
Scenario (sB): bed zero: Z_c, $\kappa \neq 0.4$, B=8.5 and the roughness scale k_s is computed from roughness function	***scenario s2:*** Z_c, $\kappa=0.4$, B=8.5 and ks is computed from roughness function
Scenario (sA): Z_c. $\kappa \neq 0.4$. The roughness scale k_s and the normalized flow velocity B are subjected to fitting procedures	***scenario s3 :*** Z_t, $\kappa \neq 0.4$, ks and B is subjected to best fit procedure

Definitions of log-law parameters for rough walls

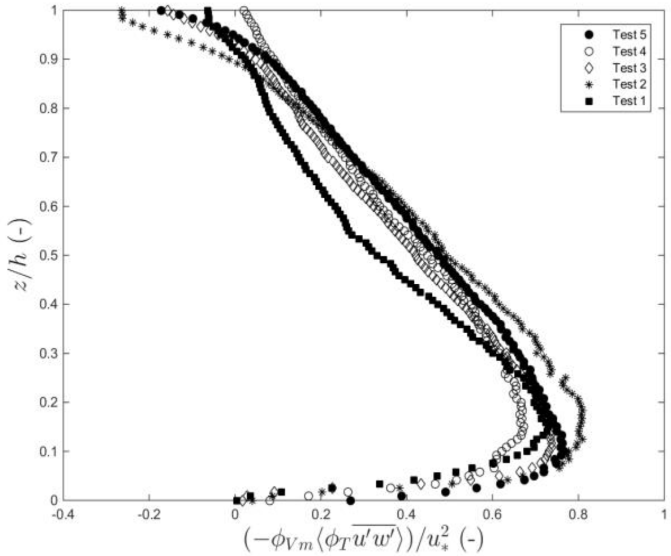


Idealized bed configuration (adapted from Ferreira et al., 2012)

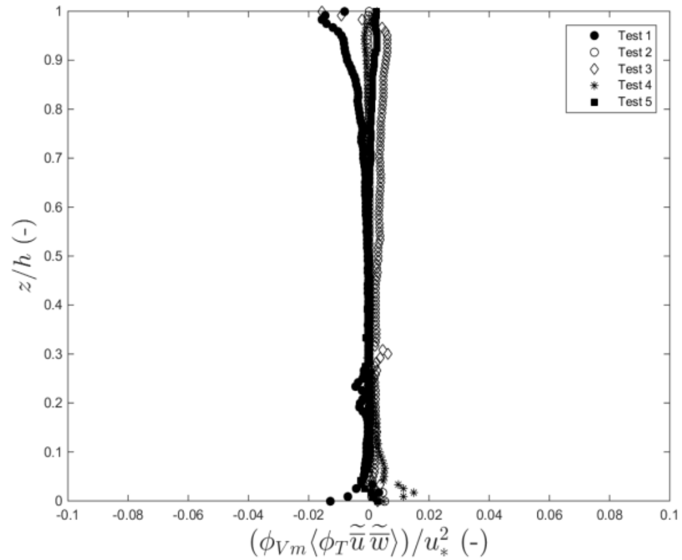
Results and discussion-double-average (DA) quantities



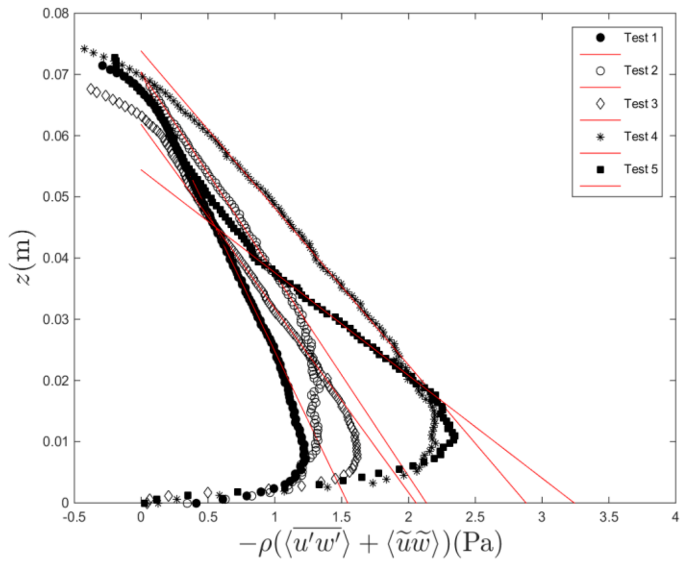
DA-longitudinal velocities



Reynolds shear stresses



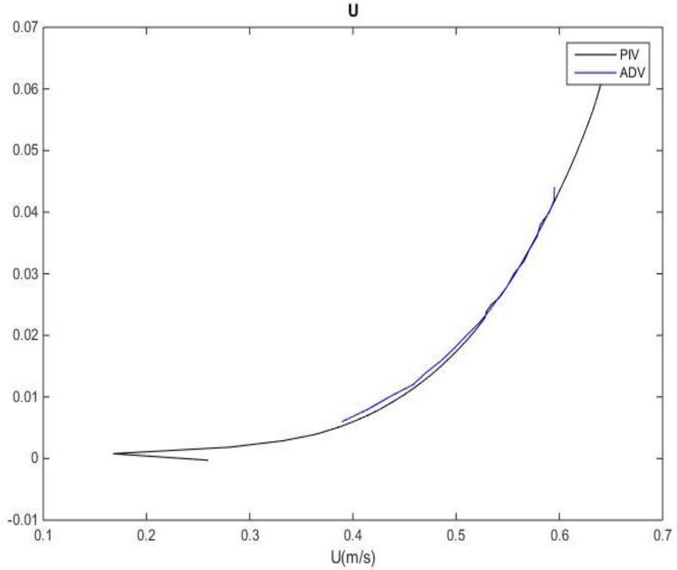
Form-induced shear stresses



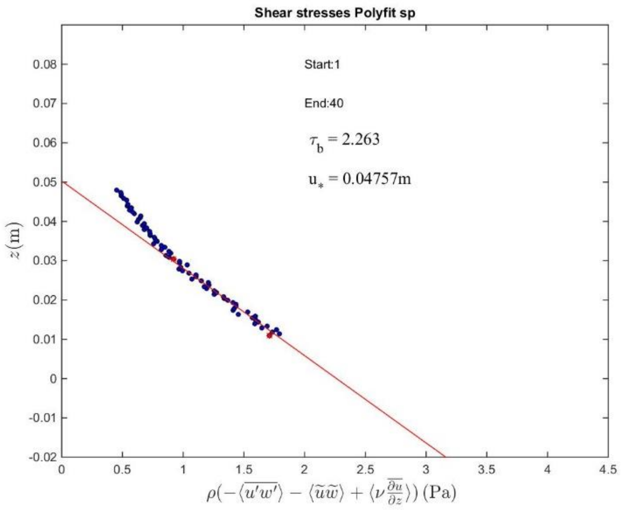
Bed-shear stresses

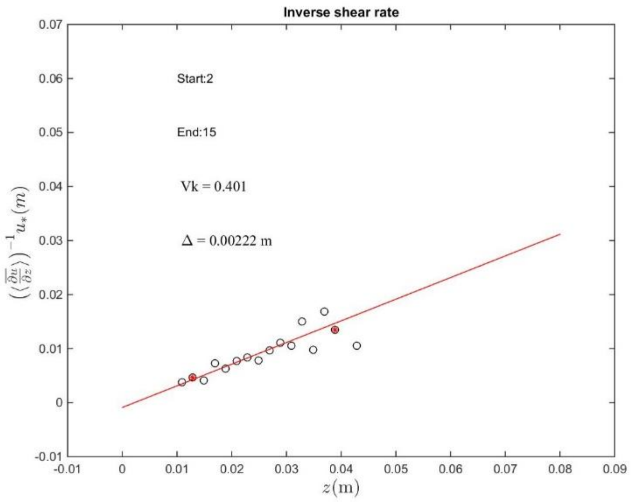
Validation of PIV measurements

PIV and ADV – fixed rough bed

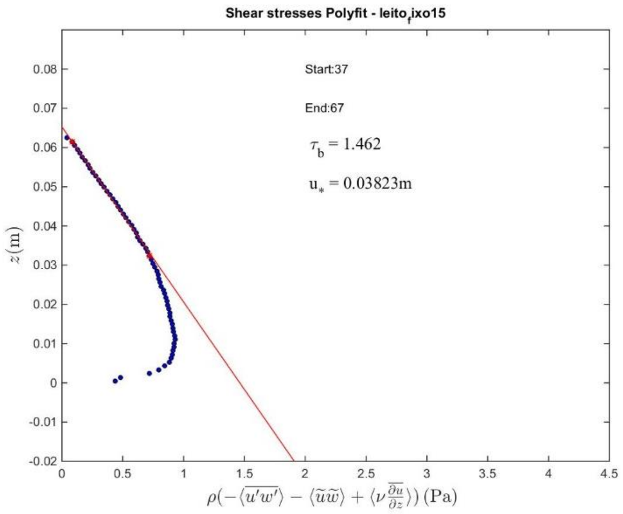


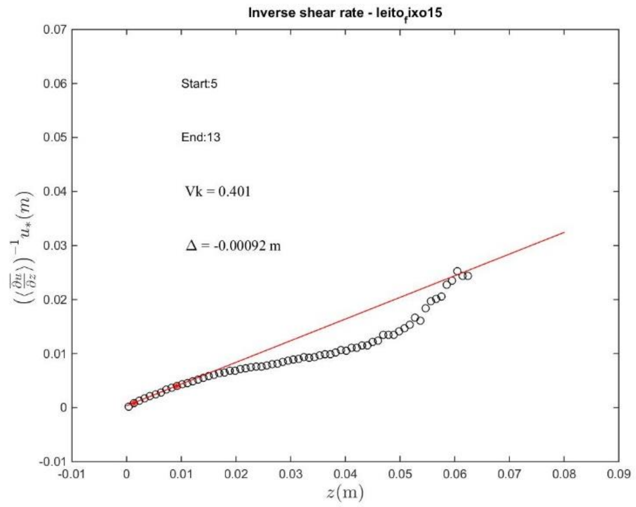
ADV



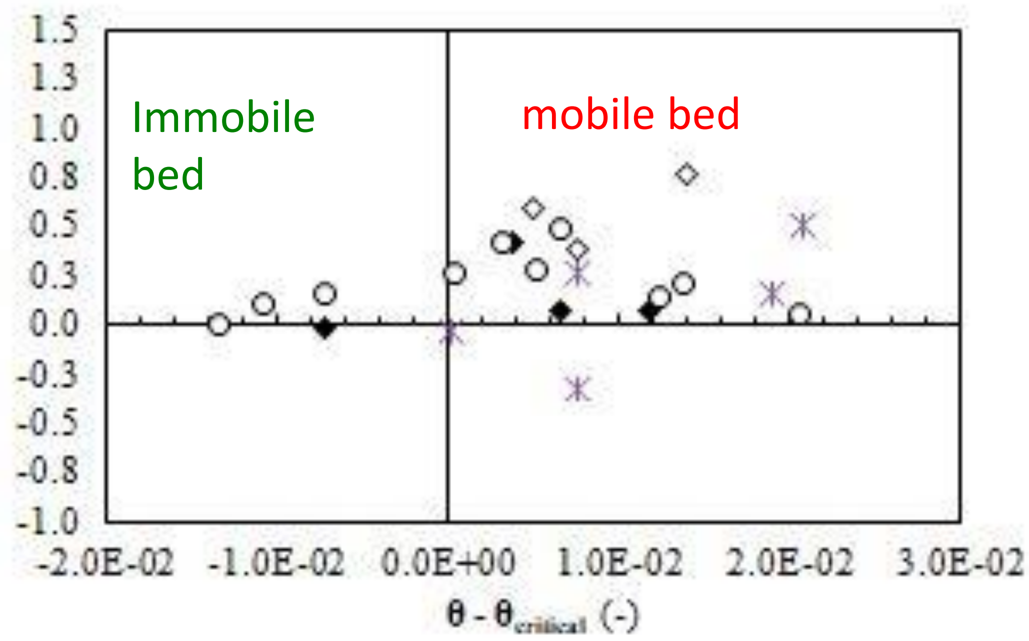


PIV





Results and discussion



Ferreira et al. (2012)

- ○ Gravel mixture
- ◇ Sand-gravel mixture subjected to water-work till armouring level
- ◆ Sand-gravel mixture

New high conductivity database

- ✳ Monosized spherical glass beads -Lattice arrangement
- + Monosized spherical glass beads - random arrangement

•Shield parameter: $\theta = \dfrac{\tau_0^{(2)}}{(s-1)\rho g d}$

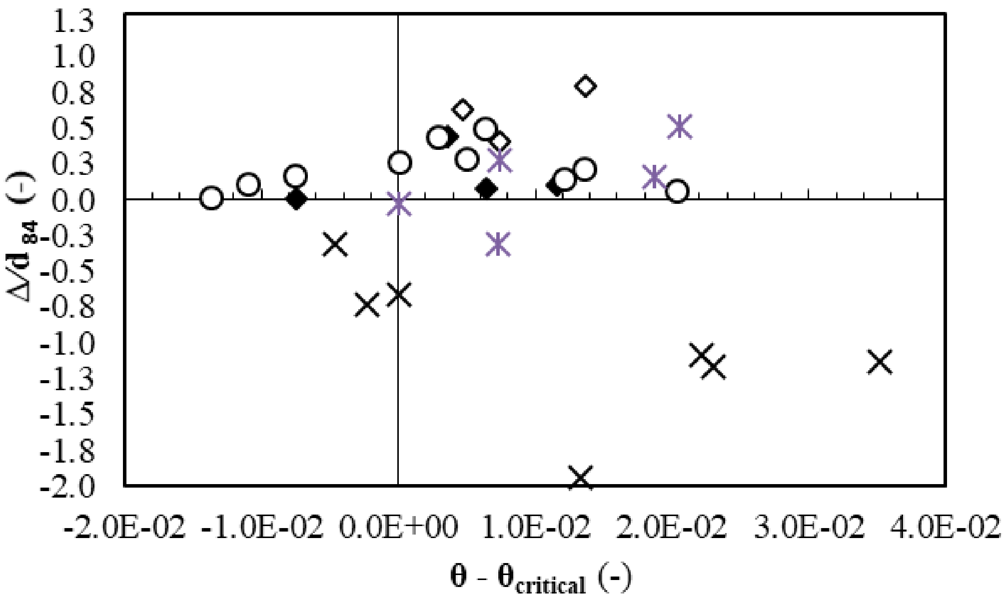
• Kramer criterion for critical Shields parameter (generalized incipent motion)

•All results plotted as a function of $\theta - \theta_{crit}$

TÉCNICO LISBOA

Results and discussion

Displacement height Δ



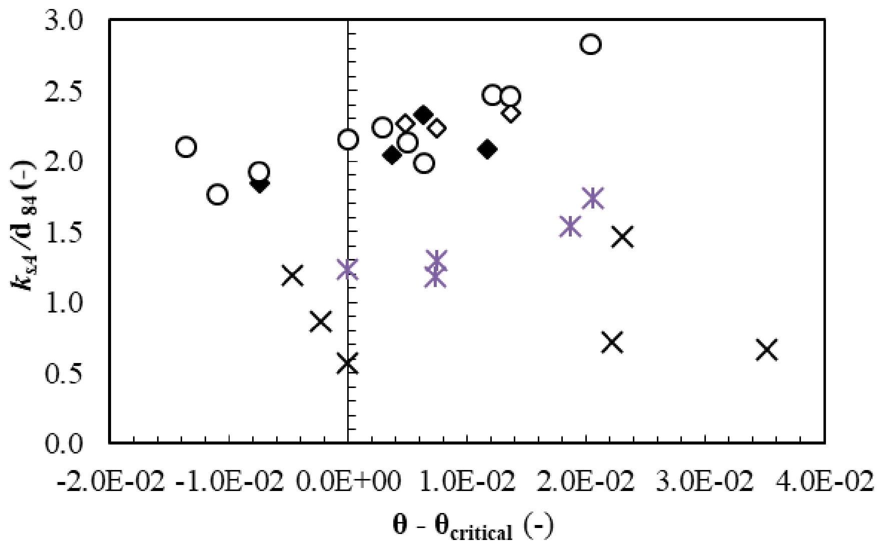
•Location of the zero-plane of the log-law.

•**The zero plane of the log-law is not dependent of hydraulic conductivity.**

•Tests with higher bed morphology diversity or higher bed load transport will have the log-law higher above the plane of crests (but data dispersion is high).

Results and discussion

Geometric roughness scale k_{sA}



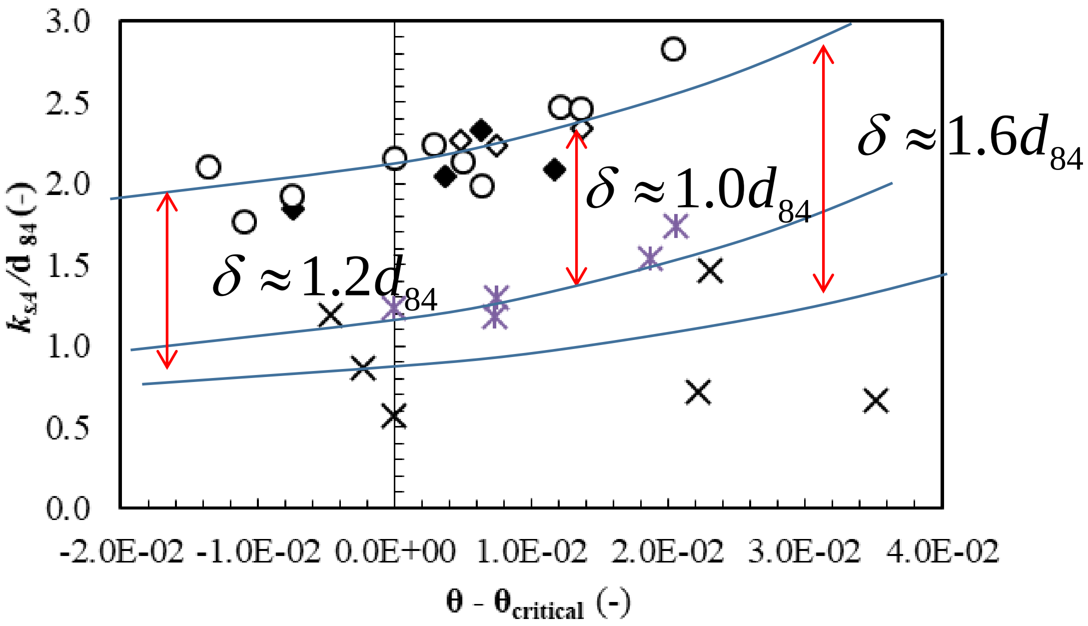
•**In all high conductivity beds**, the **total thickness of roughness is lower than in the low conductivity bed**.

•It shows the influence of conductivity but essentially of bed micro-topography (in fact because the former needed the later)

•It seems to increase with bedload rate

Results and discussion

Geometric roughness scale $k_{sC} = k_{sA} - \delta$



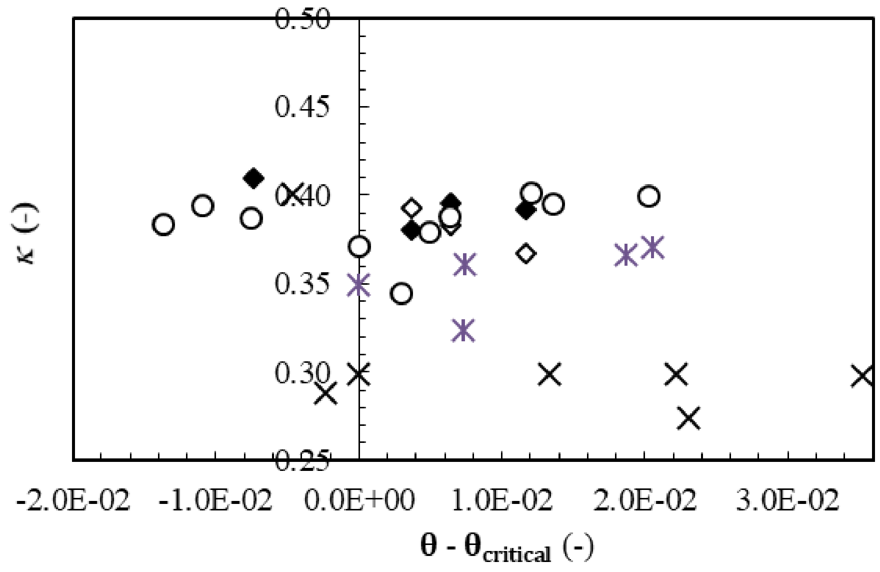
•However, note that the **thickness of the bed is *lower* for the higher conductivity beds**

•So, the **effects of the roughness *above the plane of the crests* extend for the same distance** approximately.

•In other words, in the high conductivity cases **the bed is thinner, but the effects of the roughness above the crests extends over a region of the same magnitude.**

Results and discussion

von Kármán constant κ



•Contrarily to Ferreira et al. (2012) there was no possibility to adjust a theoretical curve with VK approx 0.4.

•The **high conductivity** beds have κ ***consistently lower*** than that of the low conductivity beds.

•This indicates **that higher conductivity may lead to a change in turbulence structure in the inner region (Ferreira 2015).**

•In the lattice-arranged high-conductivity case, κ may increase with the transport rate.

TÉCNICO LISBOA

Conclusion, Impact

The main findings can be summarized as follows:

i) hydraulic conductivity does not affect the location of the zero plane of the log-law or the thickness of the region above the crests where the flow is determined by roughness.

ii) increase of hydraulic conductivity has *no impact* on roughness influence *above the crests* – ***between troughs and crests there seems to be seems a "disconnected" flow*** in natural beds.

iii) higher hydraulic conductivity is associated to a structural change: higher near-bed velocity and higher shear-rate in the inner region. In dimensional terms this means a same u_* is achieved with a flow with larger mass rate – thus a lower friction factor $f = (u_*/U)^2$.

TÉCNICO LISBOA

Conclusion, Impact

The main findings :

iv. So flows over high conductivity beds appear drag-reducing even if *geometric* roughness parameters do not change appreciably.

v. Within the high conductivity case, higher tortuosity leads to different results – lower value of VK constant, lower overall roughness.

Impact

i) Modellers need to incorporate properties of near-bed turbulence in their wall functions

ii) Sheds light on why simple granular beds are more mobile – forces on the bed particles (scale with U^2) are larger in high conductivity beds for the same u_*.

Thank you!

This work was partially funded by FEDER, program COMPETE, and national funds through the Portuguese Foundation for Science and Technology (FCT) project ASHES - PTDC/ECI-EGC/29835/2017

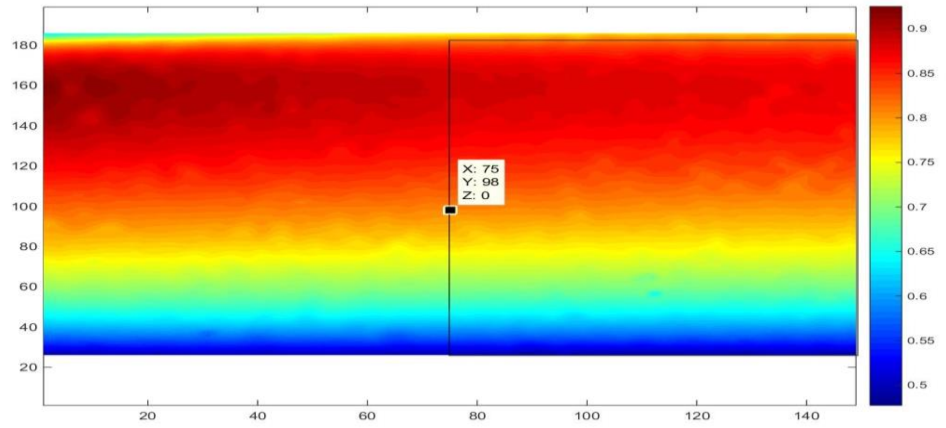
.

20 anos FCT Fundação para a Ciência e a Tecnologia

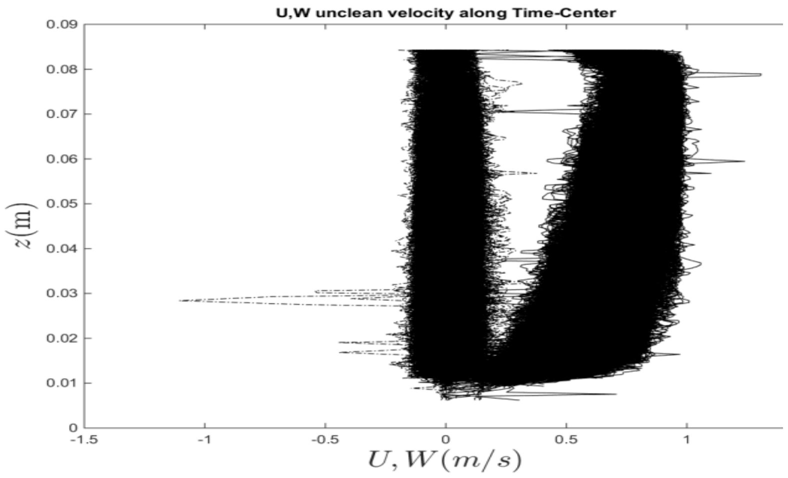
Introduction
Motivation
Objectives
Experimental facilities & procedures
The Laboratory
Flow characrterzation
Macroscopic properties
Methodology
Data treatment
Methods of calculation
Results and discussion
Conclusions and future work
Acknowledgement

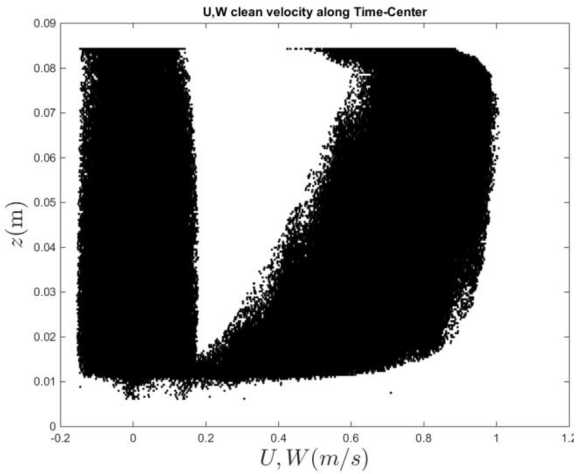
Data treatment

Choosing uniform section

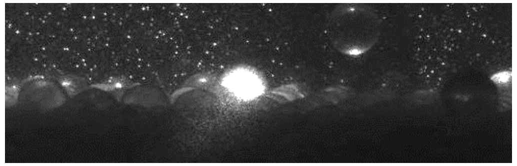


Removal of spurious velocity

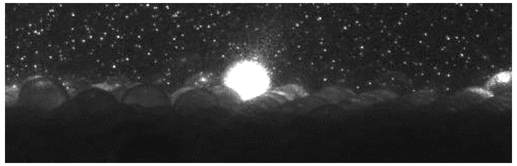




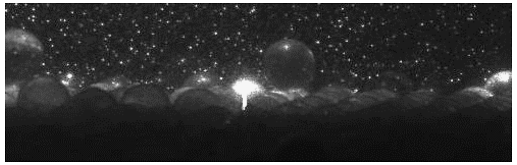
Locating the crests of bed



$t = t_o$



$t = t_o + \Delta t$



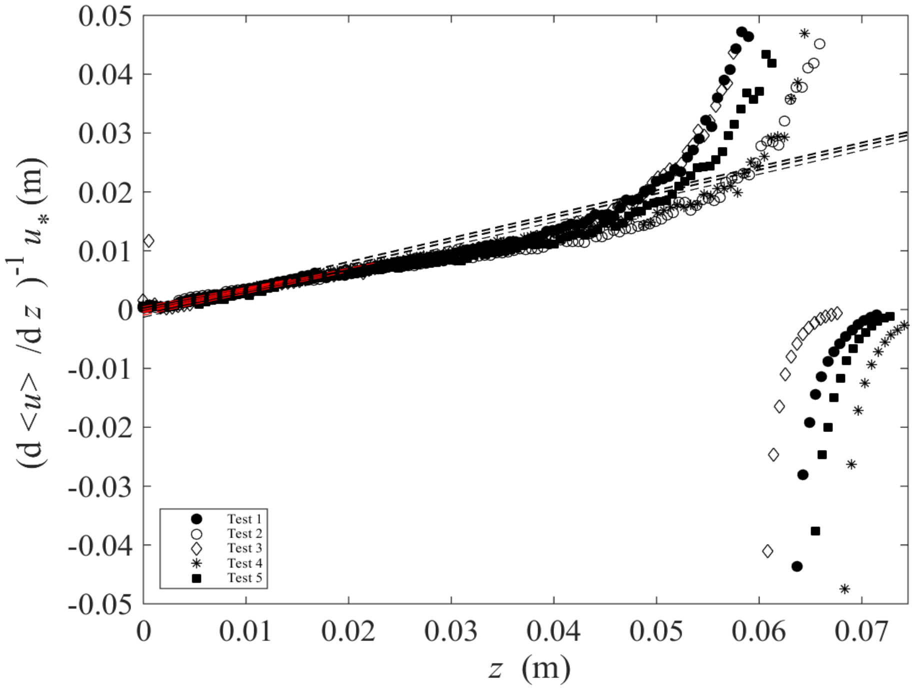
$t = t_o + 2\Delta t$

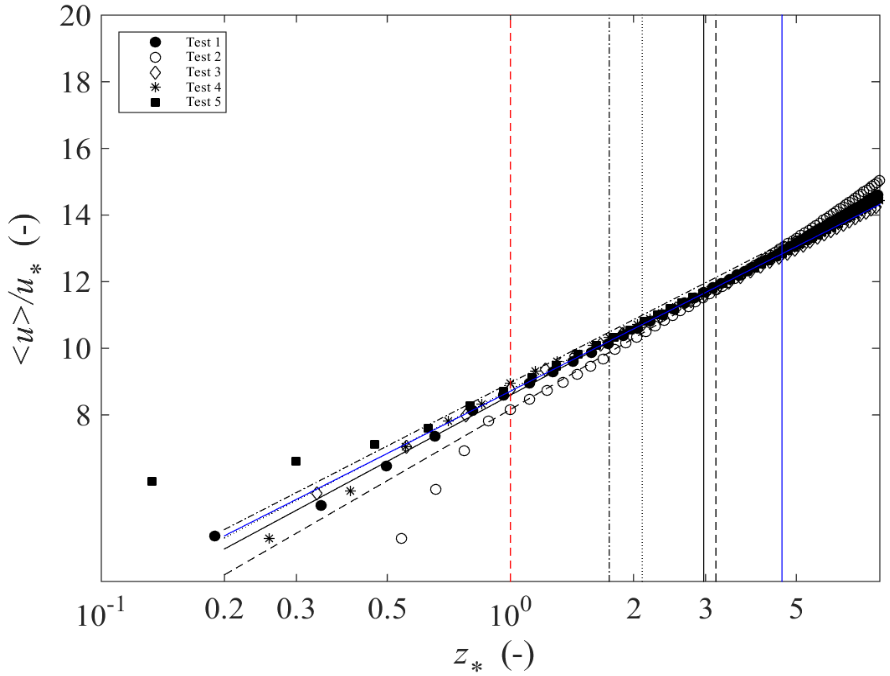
Methods of calculation

Scenario (sA) :

$$u^{*}\left(\frac{d\langle\bar{u}\rangle}{dz}\right)^{-1} = \kappa(z-\Delta)$$

$$\frac{\langle\bar{u}\rangle}{u_{*}} = \frac{1}{\kappa}\ln\left(\frac{z-\Delta}{k_{s}}\right) + B$$





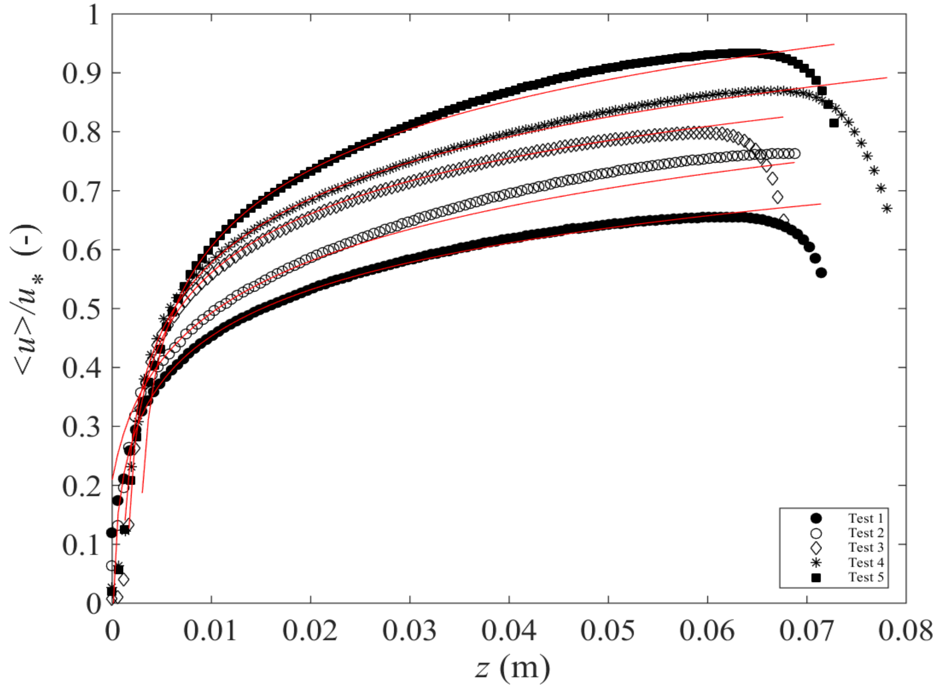
Double-Average longitudinal velocity profiles and regression lines for scenario sA

Methods of calculation

Scenario (sB) :

$$\frac{\langle \bar{u} \rangle}{u^*} = \frac{1}{\kappa} \ln\left(\frac{z - \Delta}{z_0}\right)$$

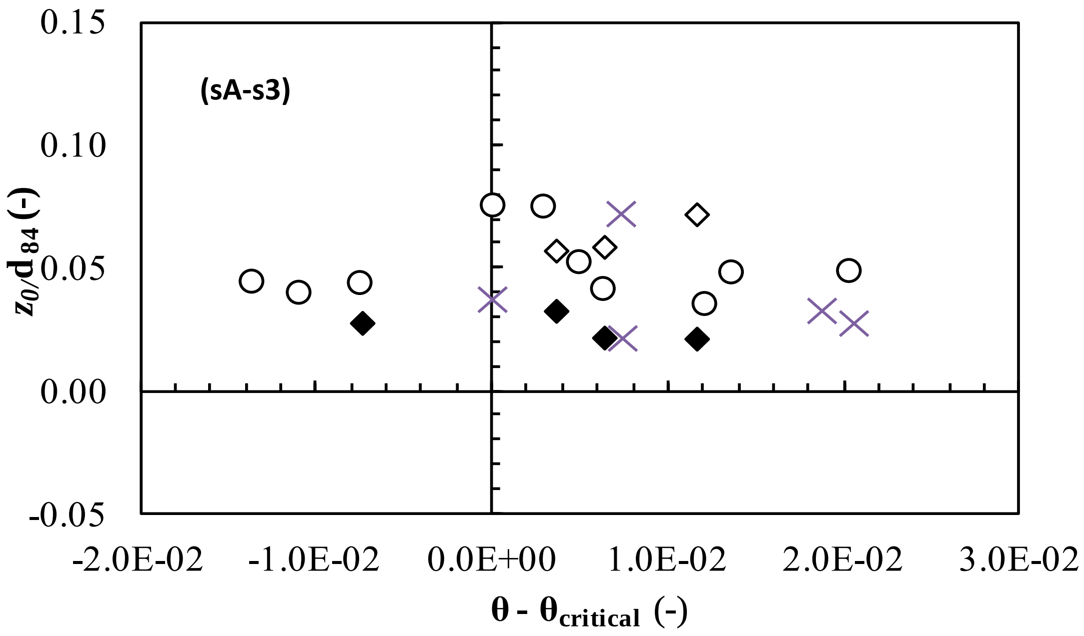
$$k_s = z_0 e^{\kappa\, 8.5}$$



Double-Average longitudinal velocity profiles and theoretical velocity for scenario sB

Results and discussion

Roughness height z_0

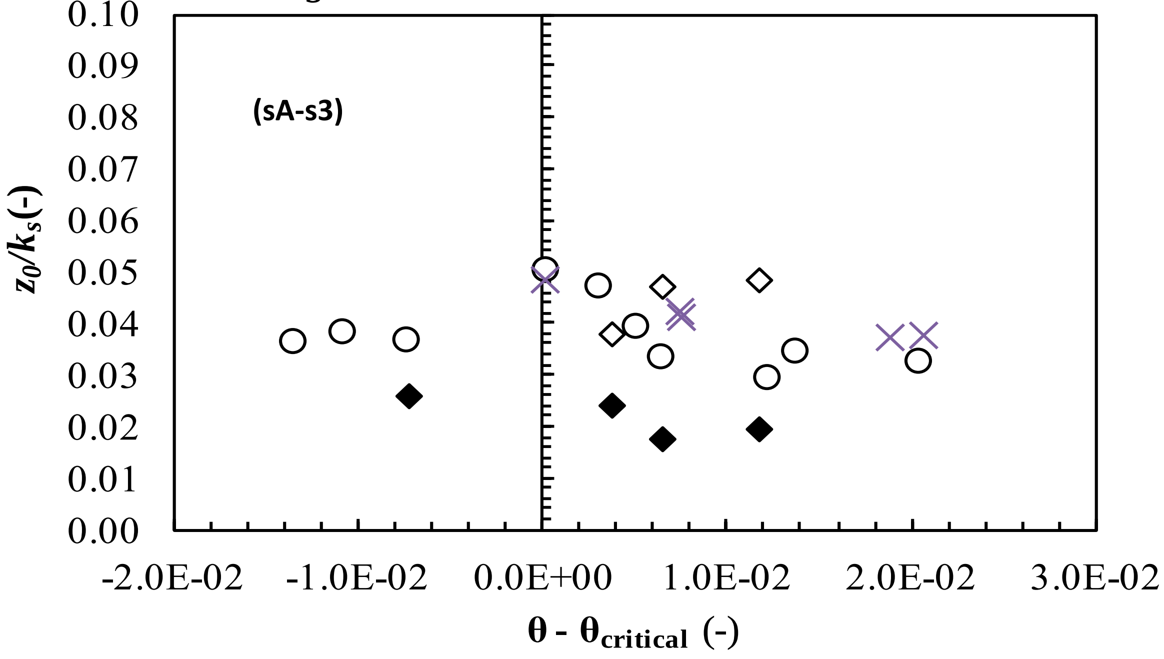


- There is no clear trend of increment of z_0 with respect to Shields number in both cases.
- The addition of sand smoothens the bed (Ferrreira et al. 2012).
- **Conductivity does not appear to change roughness height as the results are similar to the gravel bed**.

Results and discussion

Normalized flow velocity B

$$\frac{z_0}{k_s} = e^{-B\kappa}$$



•the high conductivity bed has the same ratio as the *gravel* low conductivity bed – this shows that **B is larger in the high conductivity bed, compensating a smaller VK parameter**. Together they express a **larger mass and momentum flux for the same u_* - or lower u_* at critical movement conditions in high conductivity beds**

•The presence of moving sand appears to render the bed smoother even if conductivity is low.