

Turbulent Boundary Layers over Rough and Sediment Beds

Laboratory session on the tilting flume

Auteurs : Rémi CHASSAGNE and Oriana YON-CAMPANER

Contact : oriana.yon-campaner@univ-grenoble-alpes.fr

M2 Turbulence, Methods and Applications

Duration: 3 hours (laboratory session)

How this session is organized:

This session is entirely experimental and takes place at the LEGI tilting flume. **No numerical processing is done during the 3 hours:** you record raw readings, reason qualitatively, and sketch expected shapes on paper; the quantitative treatment (regressions, spectra, etc.) happens afterwards, on the dedicated session, using the formula sheet in Section 5. The whole session concerns **velocity and the turbulent quantities that follow from it** (Reynolds stresses, turbulent kinetic energy, spatial spectra, integral scales).

1 Context and objectives

The apparatus is the variable-slope, free-surface flume of LEGI/ENSE3 (rectangular cross-section, width $b = 35$ cm, length ≈ 11 m). The object of study is the **structure of the turbulent boundary layer** that develops over a fully rough, PMMA bed ($d_{50} = 3$ mm, Nikuradse-type monolayer), and how that structure changes once the same bed is covered by **mobile sediment transport**. All concepts used below follow the notation and presentation of Pope, *Turbulent Flows* (2000): Reynolds decomposition and Reynolds stresses (Ch. 4), the scales of turbulent motion, spectra and two-point correlations (Ch. 6), and wall-bounded turbulent flows, the law of the wall and wall roughness (Ch. 7).

By the end of the session you should have acquired the data needed to:

- characterize a steady, uniform, rough-wall turbulent open-channel flow (discharge, slope, mean depth);
- measure a mean-velocity and Reynolds-stress profiles with an ACVP over the fixed rough bed (**clear-water, CW**, configuration);
- Turbulence statistics (TKE) and **spatial power spectra** can later be extracted;
- repeat acquisition once the flow is seeded by sediment (**sediment-laden, SED**, configuration);
- compare, qualitatively, the CW and SED velocity/turbulence structure.

2 Instrumentation

2.1 The flume and the discharge weir

Flow rate is monitored using a thin-wall triangular weir at the downstream tank, calibrated as

$$Q = 1.35 h_{\text{lue}}^{5/2}, \quad h_{\text{lue}} \text{ in m, } Q \text{ in m}^3\text{s}^{-1}, \quad (1)$$

reproduced in Fig. 1. Slope is set through the downstream jack (set by the demonstrator); the readout at the jack, combined with the pivot-to-jack distance $L = 7.95$ m, gives the bed slope $\sin \theta \approx \tan \theta = \Delta z_f / L$.

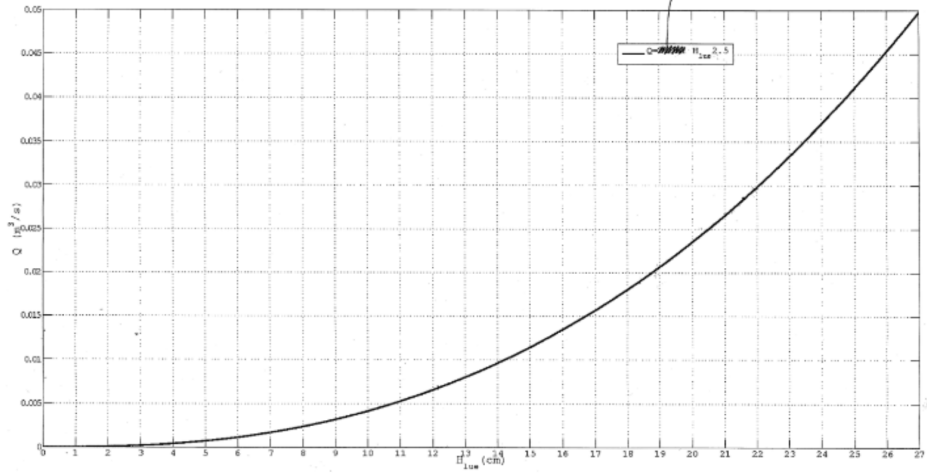


Figure 1: Calibration curve of the downstream triangular thin-wall weir, $Q = 1.35 h_{\text{lue}}^{2.5}$.

2.2 The ACVP

The Ubertone Acoustic Doppler Velocity Profiler UB-Lab 3C (Fig. 2) emits short ultrasonic pulses (carrier frequency of order 1 MHz) from a central emitter; four passive receivers, each looking along a different oblique axis, receives the pulse scattered by natural micro-diffusers (bubbles, suspended particles) advected by the flow. The Doppler shift on each receiver axis gives one velocity component along that axis; combining the axes yields the 3D (streamwise, spanwise, vertical) velocity vector at each range gate along the vertical, at acquisition rates high enough to resolve the energetic turbulent fluctuations. In this session we use only the velocity output of the instrument, not the scattered amplitude, so everything you measure and later process is a velocity, or a statistic built from velocity.

3 In-lab protocol (3 h) – with reflection questions

Record every reading directly in your notebook (essential parameters in Section 4) as you take it, and answer each ► Reflection question, these are short (a few sentences or a sketch).

0. Safety briefing and flume start-up – 15 min

- Demonstrator briefing.
- Allow the flow to reach steady conditions before any measurement.

1. Hydraulic characterization (clear water) – 20 min

- Read the weir head h_{lue} at the downstream tank; repeat 3 times over the next 20 min to check steadiness. (Eq. 1).

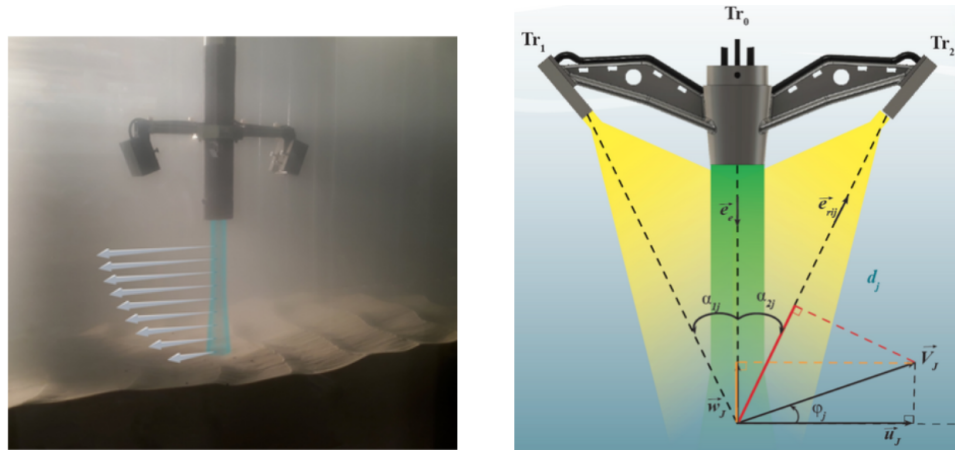


Figure 2: Left: ACVP head above the rough/sediment bed. Right: principle sketch and reconstruction of the velocity vector $\vec{V}_j$ at range gate j .

- Read the jack position and note Δz_f ; record the slope readout.
- Measure the mean water depth h at several points to check uniformity. If uniformity is not reached, or the water depth is not sufficient, use the sluice gate to find the optimal configuration.

► **Reflection – while the flow settles**

- Q1. Write a force balance on a slice of fluid in this steady, uniform flow. What quantity plays the role of the bed shear stress τ_0 , and how is the **friction velocity** u_τ defined from it?
- Q2. u_τ can later be estimated from your data in (at least) three independent ways. Name two of them just from what you already know you will measure in this session (you will meet the third one in Reflection 5).

2. ACVP set-up over the fixed rough bed – 20 min

- Position the ACVP carriage at the chosen measurement station.
- With the demonstrator, set: acquisition frequency f_{acq} , number of range gates, and acquisition duration.

► **Reflection – before you press start**

- Q3. The instrument emits pulses at ~ 1 MHz. Estimate the wavelength of this ultrasound in water ($c \approx 1500$ m/s), and the round-trip time of a pulse over the ~ 10 – 20 cm profiling range. What does this round-trip time limit?
- Q4. What, physically, should set the acquisition duration of a turbulence measurement? Think in terms of the size of the largest energy-containing eddies in this flow and how long they take to turn over. You do not need a number yet, just the reasoning; you will get the actual number later from your own velocity time series (Reflection 7).

3. ACVP acquisition – clear water (CW) – 40 min

- Launch one full-depth acquisition. Note the file name, start time and instrument settings in the notebook.
- Do a live visual sanity check of the monitor plot (correlation/SNR by range gate) with the demonstrator, accept or repeat the acquisition.

► **Reflection – while the acquisition runs**

- Q5. Sketch, freehand, the shape you expect for the time-averaged velocity $u(z)$ from bed to free surface, labelling the near-wall region and the region you expect to look linear in u vs. $\ln z$ (Pope, Ch. 7). You will compare this sketch with the processed profile later.
- Q6. Define the Reynolds stresses from the Reynolds decomposition $u_i = \bar{u}_i + u'_i$ (Pope, Ch. 4), and write the correlation coefficient R_{xz} of u', w' . What sign do you expect for $\overline{u'w'}(z)$ in this flow, and why?
- Q7. Sketch the shape you expect for $-\overline{u'w'}(z)$ over the depth, and for the full 3D turbulent kinetic energy $k(z) = \frac{1}{2} (\overline{u'^2} + \overline{v'^2} + \overline{w'^2})$ you can build from the ACVP's three resolved components.
- Q8. According to Kolmogorov's theory (1941), what slope do you expect for the velocity power spectrum in the inertial subrange when plotted in a log-log scale? How can you convert a frequency spectrum $E(f)$ into a wavenumber spectrum $E(k_x)$?
- Q9. Once the acquisition on one range gate has produced a velocity *time series* $u(t)$, what single-point statistical tool would let you extract a turbulence **time scale** from it (Pope, Ch. 6)? What extra assumption is needed to turn that time scale into a **length scale**?

4. Transition to sediment transport – 20 min

- Under demonstrator supervision, set the conveyor belt to a chosen value. Estimate the duration of your acquisition to have a constant sediment feeding (Fig. 3)
- Re-measure and record the weir head, and mean depth exactly as in step 1.

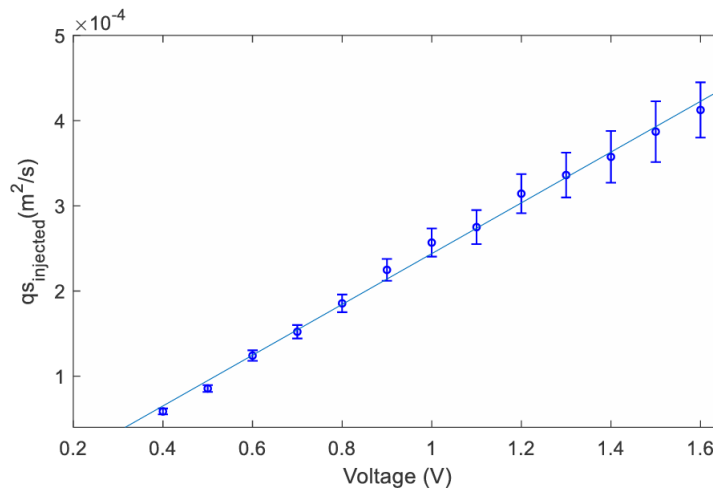


Figure 3: Calibration of solid-load (with $dp=3mm$) as function of voltage on the conveyor belt system.

► Reflection

- Q10. The equivalent sand roughness k_s and the friction velocity together define a roughness Reynolds number $k_s^+ = k_s u_\tau / \nu$, which classifies a wall as hydraulically smooth, transitional or fully rough (Pope, Ch. 7). Qualitatively, do you expect the bed to move further into, or out of, the fully-rough regime once sediment are introduced? Justify in one or two sentences.
- Q11. Based on Q1, what do you expect to happen to τ_0 (and hence u_τ) at the *same* discharge if the effective bed roughness increases?

5. ACVP acquisition – sediment-laden (SED) – 50 min

- Repeat the *same* ACVP acquisition protocol as step 3 (same station, same range-gate configuration, mean velocity and time serie), now over the mobile bed.
- Observe and log qualitatively the visual turbulence intensity near the bed on the live monitor.

► **Reflection – while the acquisition runs**

- Q12. Update your sketches for the SED case: how do you now expect $u(z)$ and $-\overline{u'w'}(z)$ to differ from the CW sketches – same near-bed values, a vertical shift, a different slope in the log region? Sketch both on the same axes as before, in a different colour.
- Q13. “Hydraulic” estimate of u_τ : from the force balance of Reflection 1, write u_τ purely in terms of quantities you have already measured in this step (no ACVP data needed). This is the third, independent estimation route you were asked to anticipate in Reflection 2.

6. Side-by-side qualitative comparison – 10 min

- With the demonstrator, display the two live monitor plots (CW and SED) side by side.

► **Reflection – synthesis**

- Q14. Write a short paragraph: did what you actually observed match your theoretical sketches? If not, propose one physical explanation for the discrepancy.

7. Wrap-up and data hand-off – 15 min

- Copy the raw CW and SED acquisition files and the weir/slope/depth reading sheet onto the storage.
- Shut down the flume with the demonstrator (pump off, jack to rest position, ACVP powered down).

4 Lab notebook – fields to fill in

Use one copy of this table per configuration (CW and SED).

Quantity	Raw value(s) recorded
Weir head h_{lue} (3 readings, time-stamped)	
Jack / slope readout, Δz_f	
Depth readings	
ACVP station (distance from inlet)	
f_{PRF} , acquisition duration, # range gates	
File name(s) / acquisition time (profile & time series)	
Live-monitor SNR/correlation check: pass?	
Bed state observation (ripples / sheet flow / none)	
Answers to Reflections (sketches + short text)	

5 Formula sheet for the (post-session) Python processing

Not to be used during the 3-hour session. This is what you need, together with your raw files, to process the data afterwards. Notation follows Pope (2000).

Discharge, bulk quantities

$$\begin{aligned}
 Q &= 1.35 h_{\text{lue}}^{5/2} && \text{(weir calibration)} \\
 U &= Q/A, \quad A = b h && \text{(bulk velocity)} \\
 \sin \theta &\approx \tan \theta = \Delta z_f / L, \quad L = 7.95 \text{ m} && \text{(bed slope)}
 \end{aligned}$$

Uniform-flow bed shear stress and friction velocity

$$\tau_0 = \rho g R_h \sin \theta, \quad R_h = A/P \ (\approx h \text{ if } b \gg h) \quad (2)$$

$$u_\tau = \sqrt{\tau_0/\rho} \quad (3)$$

Reynolds decomposition, Reynolds stresses, TKE (Pope, Ch. 4–5)

$$u_i(t) = \overline{u_i} + u'_i(t) \quad (4)$$

$$\tau_{ij} = -\rho \overline{u'_i u'_j} \quad (\text{Reynolds stress tensor}) \quad (5)$$

$$R_{xz} = \frac{\overline{u' w'}}{\sigma_u \sigma_w} \quad (\text{correlation coefficient}) \quad (6)$$

$$k(z) = \frac{1}{2} \left(\overline{u'^2} + \overline{v'^2} + \overline{w'^2} \right) \quad (\text{Full 3D TKE resolved by the ACVP}) \quad (7)$$

Spatial Power Spectra and Taylor's Hypothesis (Pope, Ch. 6)

To observe the turbulent energy cascade, compute the Power Spectral Density (PSD) in the frequency domain, $E_{uu}(f)$, using a Fourier transform on the velocity time series $u'(t)$. To convert the temporal frequency spectrum $E_{uu}(f)$ into a spatial (wavenumber) spectrum $E_{uu}(k_x)$, apply **Taylor's frozen-turbulence hypothesis** using the local mean velocity $U(z)$:

$$k_x = \frac{2\pi f}{U(z)} \quad (8)$$

$$E_{uu}(k_x) = \frac{U(z)}{2\pi} E_{uu}(f) \quad (9)$$

In the inertial subrange, the spectrum should follow the Kolmogorov $-5/3$ decay law:

$$E_{uu}(k_x) \propto \epsilon^{2/3} k_x^{-5/3} \quad (10)$$

Law of the wall and rough-wall regime (Pope, Ch. 7)

$$u^+ = u/u_\tau, \quad z^+ = z u_\tau/\nu, \quad \delta_\nu = \nu/u_\tau \quad (11)$$

$$\text{Viscous sublayer: } u^+ = z^+ \quad (z^+ \lesssim 5) \quad (12)$$

$$\text{Log law: } u^+ = \frac{1}{\kappa} \ln z^+ + B, \quad \kappa \approx 0.41, \quad B \approx 5.2 \quad (\text{hydraulically smooth wall}) \quad (13)$$

$$\text{Fully rough wall: } u(z) = \frac{u_\tau}{\kappa} \ln \left(\frac{z}{z_0} \right), \quad z_0 = k_s/30 \quad (14)$$

$$\text{Roughness Reynolds number: } k_s^+ = k_s u_\tau / \nu \quad \begin{cases} k_s^+ \lesssim 5 & \text{hydraulically smooth} \\ 5 \lesssim k_s^+ \lesssim 70 & \text{transitional} \\ k_s^+ \gtrsim 70 & \text{fully rough} \end{cases} \quad (15)$$

Integral time and length scales (Pope, Ch. 6)

From the one-point streamwise velocity time series $u'(t)$ at your chosen range gate, compute the autocorrelation function

$$\rho_{uu}(\tau) = \frac{\overline{u'(t) u'(t+\tau)}}{\overline{u'^2}}, \quad (16)$$

and the integral time scale

$$T = \int_0^\infty \rho_{uu}(\tau) d\tau \quad (\text{in practice, integrate up to the first zero-crossing of } \rho_{uu}). \quad (17)$$

Using Taylor's frozen-turbulence hypothesis (valid when turbulence intensity is low compared to the mean advection speed), convert T into an integral length scale

$$L_{11} \approx \bar{u}T, \quad (18)$$

Ultrasound

$$\lambda = c/f, \quad c \approx 1500 \text{ m s}^{-1} \quad (19)$$

$$t_{\text{round-trip}} = 2R/c, \quad f_{\text{PRF,max}} = 1/t_{\text{round-trip}} \quad (20)$$

Suggested comparison plots (CW vs. SED), post-session

- $u(z)$ and $u'(z)$ vs. $\ln z$ with log-law fit, both configurations on the same axes.
- $-u'w'(z)$ and $k(z)$, both configurations.
- Spatial Power Spectral Density $E_{uu}(k_x)$ in a log-log scale, highlighting the $-5/3$ inertial subrange.
- $\rho_{uu}(\tau)$ at the chosen range gate, both configurations; resulting T and L_{11} .
- Table comparing u_τ (three estimations) and k_s (or k_s^+ regime) between CW and SED.

References

1. Pope, S. B. (2000). *Turbulent Flows*. Cambridge University Press. (Ch. 4: Reynolds equations; Ch. 6: Scales of turbulent motion; Ch. 7: Wall-bounded flows.)
2. Chassagne, R. & Barthélemy, E. *T.P. Couche limite*. Plateforme réseau pédagogique IEE, ENSE3/LEGI.
3. Guta, H. (2022). *Etude expérimentale des processus turbulents de transport sédimentaire* (Doctoral dissertation, Université Grenoble Alpes).