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Velocity and Turbulence Measurements for Assessing the Stability of Riverbeds: a Comparison between UVP and ADVP

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ABSTRACT: Maintaining the overall stability of active riverbeds requires a deep understanding of the complex interactions between turbulent flow forces and forces stabilizing the riverbed. Standard approaches do not properly take into account the turbulence fluctuations in non-uniform flows, while these are of primary importance in the mechanisms determining the stability of stones. In a new approach, the flow forces are quantified by means of parameters combining explicitly the velocity and turbulence distributions over a certain water depth above the riverbed. In this paper, as an onset for using these newly developed bed stability parameters, we report on new experimental measurements of velocity and turbulent kinetic energy based on acoustic methods, whereas all previous uses at the new bed stability parameters relied on Laser PIV Techniques. For quasi-uniform and non-uniform flow conditions, velocity measurements were conducted with two complementary devices: an ultrasonic velocimeter probe (UVP) and an acoustic Doppler velocimeter profiler (ADVP). The results are compared and discussed in detail. A general consistency between the two types of measurements is obtained, while some discrepancies are highlighted close to the bed and tentative explanations are given.

Keywords: Velocity profiles, Turbulent kinetic energy, Open channel flow, Inception of motion, Stability parameters, Mobility parameters, Transport rate, UVP, ADVP, Gravel

1 INTRODUCTION

For evaluating the stability of stones under a fluid flow, the most widely used conceptual framework relies on the stability threshold concept (Buffington and Montgomery 1997). It assumes that the inception of sediment motion occurs once the stability parameter, the ratio between the flow forces acting on the stones and the stabilizing forces, exceeds a threshold value. The Shields stability parameter (Shields 1936), which is by far the most widely used, is based on the bed shear stress, which does not properly take into account the turbulence fluctuations in the flow, except in the case of a uniform flow, while turbulent fluctuations are of primary importance in the mechanisms determining the stability of stones (Dwivedi et al. 2012, Hoffmans 2012). Particles often get moved as a result of bursting flow motions, i.e. the presence of turbulent fluctuations adjacent to the bed. This process is best captured by means of parameters characterizing explicitly the turbulence in the flow. Therefore, a new approach was introduced recently. It quantifies the flow forces by means of a new set of parameters which combine explicitly the velocity and turbulence distributions over a certain water depth above the riverbed (Hoan et al. 2011, Hofland 2005). Although very promising results were already obtained, there is a need for more experimental verifications, supported by high quality turbulence measurements.

In this paper, as an onset for using the newly developed bed stability parameters, we report new experimental results involving profiles of velocity and turbulent kinetic energy, which are precisely the two inputs necessary to evaluate the new bed stability parameters. Experimental tests were performed and detailed under both quasi-uniform and non-uniform flow conditions. Velocity measurements were conducted with two complementary devices: an ultrasonic velocimeter probe (UVP) and an acoustic Doppler velocimeter profiler (ADVP). The results are compared and discuss in detail. A general consistency between the two type of measurements is obtained, which makes them nonetheless highly complementary since their measurements ranges are different. Some discrepancies are also highlighted close to the bed and tentative explanations are given.

2 EXPERIMENTAL SET-UP

Laboratory experiments were undertaken in a horizontal flume 6 m long and 15 cm wide, using uniform sediments representing an armor layer or a riverbed protection, following two configurations. First, the entire bottom of the flume was paved with stones of uniform diameter (8 or 15 mm), leading to quasi-uniform flow conditions, configuration 1 (C1). Second, the flume bottom was smooth upstream of the zone of measurement while the downstream part was covered with gravels, leading to a sudden smooth-to-rough transition, configuration 2 (C2) (Figure 1).

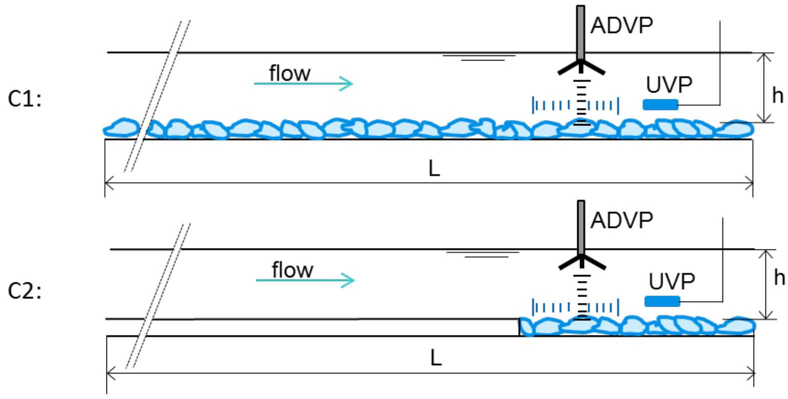


Figure 1. Laboratory flume sketch.

The discharge was measured with a flowmeter and increased by steps of 1 l/s from one test to another. The water level was measured with ultrasonic sensors placed every meter along the flume. The studied range of mean velocity was from 700 mm/s up to 830 mm/s.

Each test was done in two steps. First, the stones were arranged and the hydraulic conditions fixed. After 2 hours the amount of stones which moved was noted. Second, the entire layer was glued on the flume bottom and proper measurements of instantaneous velocity were carried out with two devices: UVP and ADVP probes.

3 VELOCITY MEASUREMENT DEVICES

The velocity was measured by two complementary devices. Both probes are capable to measure an entire profile along its axis, but the UVP records one velocity component and ADVP records all three velocity components. Due to its dimensions of 40 mm in length and 16 mm in diameter, the UVP was placed horizontally for measuring the streamwise velocity component in different flow sections. By changing the probe position, velocity profiles with the water depth were recorded. The ADVP probe was placed vertically, recording measurements in only one section of the flow.

The ADVP probe, Nortek Vectrino II, has a 4-transducer orthogonal plane bistatic geometry which reduces the Doppler noise in velocity estimates (Hurther and Lemmin 2001). It provides for profiling over a 3 cm range interval, 4 cm below of the transducer head, allowing direct measurement of the special structure of the flow. Due to the fact that the most accurate measurement is done in a sampling volume placed at 5 cm below the transducer head, we decided to restrict the measurement interval at 1 cm around this point. In order to measure an entire velocity profile along water depth, the instrument was positioned in steps at different levels. Ten minutes of data were collected at each position, which means 60,000 instantaneous velocity values per series. Data were sampled at a frequency of 100 Hz over a 1 mm range, in 10 cells, with 1.3 m/s velocity range and a pulse-to-pulse interval of 88 µs.

The UVP probe was set to acquire data with a sampling frequency of 100 Hz, in over 30 cells of 2.96 mm each. The instrument was moved vertically in order to obtain a full velocity profile along the water depth. For each position, series of 20,000 values were recorded for about 3 minutes.

For both probes, preliminary tests were undertaken in order to confirm that the length of the measured time series was sufficient.

4 RESULTS

4.1 *Velocity Profiles*

During each experiment, the velocity profiles were recorded with both probes. The evolution of the velocity profiles along the X-axis was checked from the measurements obtained with UVP probe. As can be seen in figure 2, the flow is quasi-uniform, in configuration 1, along the studied window, of 100 mm. The maximum error between the spatial-averaged profile and the profile taken in one cross-section is less than 1.5% for configuration 1, and 12% for configuration 2, no matter the tests.

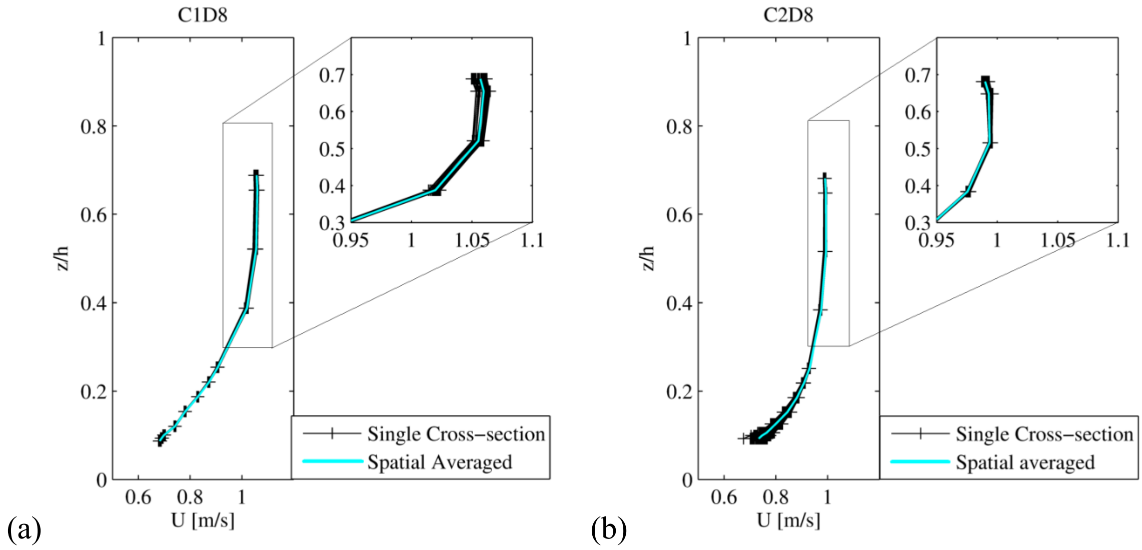


Figure 2. Streamwise velocity in different flow sections along 100 mm, recorded with UVP for a discharge of 18 l/s and a stone diameter of 8 mm: (a) Configuration 1, (b) Configuration 2.

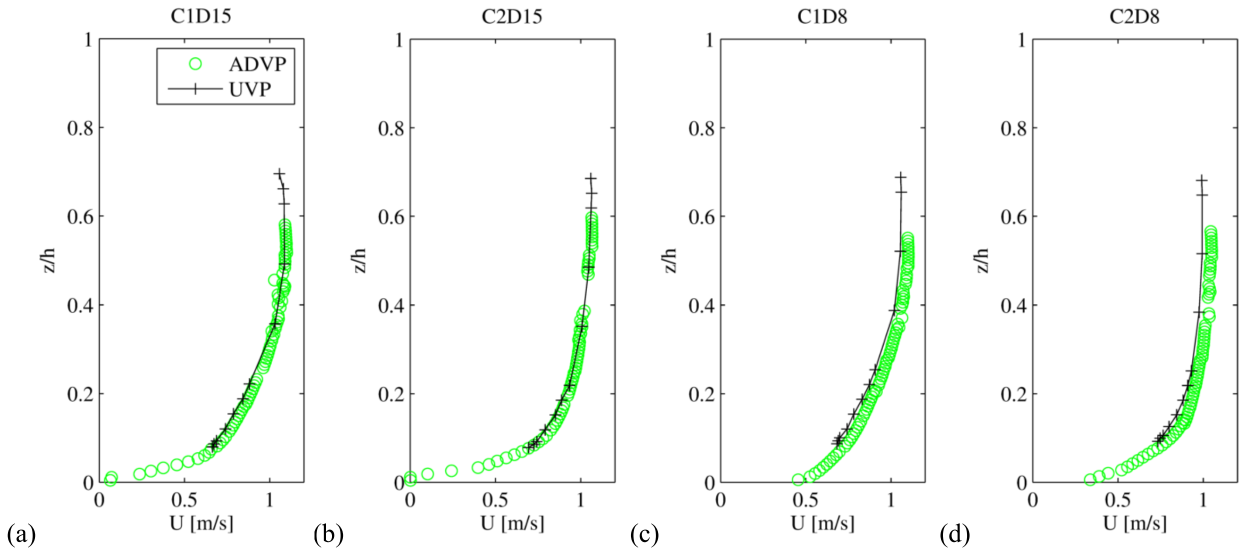


Figure 3. Mean streamwise velocity for a discharge of 18 l/s, in configuration 1(a,c) and 2(b,d), for grain size of 15 mm (a,b) and 8 mm (c,d).

Therefore, it is relevant to compare the averaged velocity profile measured by UVP with those measured by ADVP. Such a comparison is shown in figure 3 for one representative case, corresponding to a discharge of 18 l/s in both configurations and for the two considered grain sizes. The velocity profiles obtained from the two different instruments are remarkably consistent. Their complementarity is well demonstrated by figure 3, as the ADVP offers a higher resolution vertically and enables measurements close to the bottom, while the UVP gives access to data closer to the free surface. A slight shift is observed between the profiles from the two instruments in figure 3(c) and (d). This results probably from a small difference in the inflow discharge, as both series of measurements were not performed simultaneously, in order to avoid the interference. Interestingly, all profiles obtained with both devices combine very smoothly, so that the overall profile does not show any effect of the vertical step used to perform the measurements.

4.2 *Turbulent Kinetic Energy*

Both instruments can be used to derive turbulent kinetic energy profiles, but with some additional input for UVP as it measures only one velocity component. Turbulent kinetic energy is defined as:

$$k = \frac{1}{2}\left(\overline{u'^2} + \overline{v'^2} + \overline{w'^2}\right) \tag{1}$$

where $u'$is the velocity fluctuation in the streamwise direction, v' the velocity fluctuation in the transversal direction, and w' the velocity fluctuation in the vertical direction.

As ADVP records all three velocity components, the corresponding turbulent kinetic energy profile could be directly derived from equation 1. In contrast, for data obtained with the UVP probe, the Nezu's coefficients (Nezu and Nakagawa 1993) were used in order to consider the influence of vertical and transversal fluctuations:

$$\overline{v'^2} \simeq 0.3025 * \overline{u'^2} \text{ and } \overline{w'^2} \simeq 0.5041 * \overline{u'^2} \tag{2}$$

These are empirical results, normally valid only in uniform conitions.

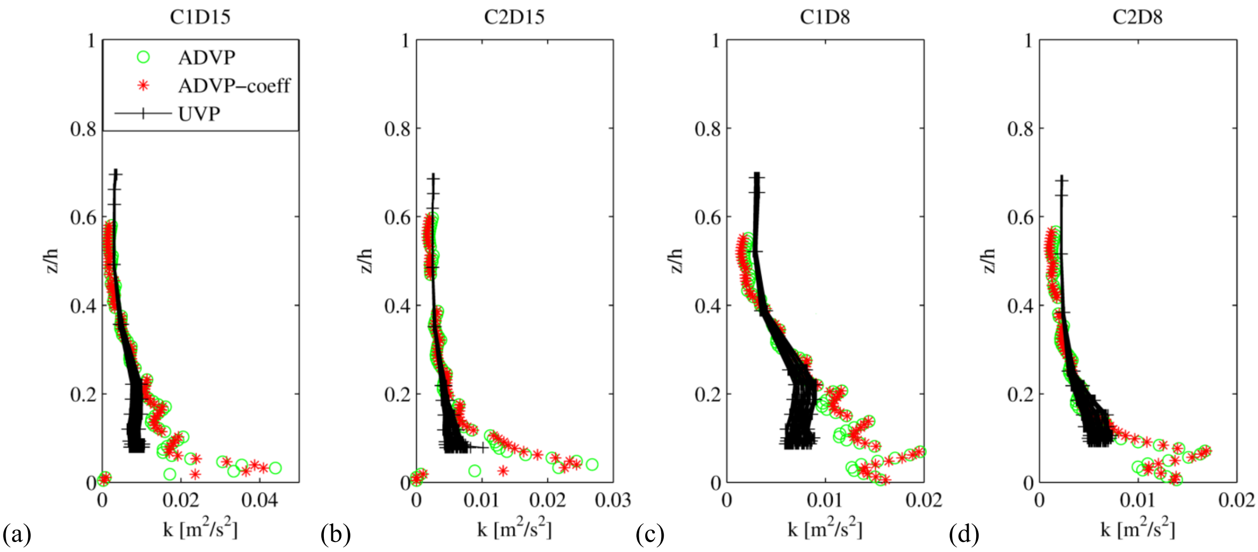


Figure 4. Turbulent kinetic energy profiles for a discharge of 18 l/s, in configuration 1 (a,c) and 2 (b,d), for grain size of 15 mm (a,b) and 8 mm (c,d).

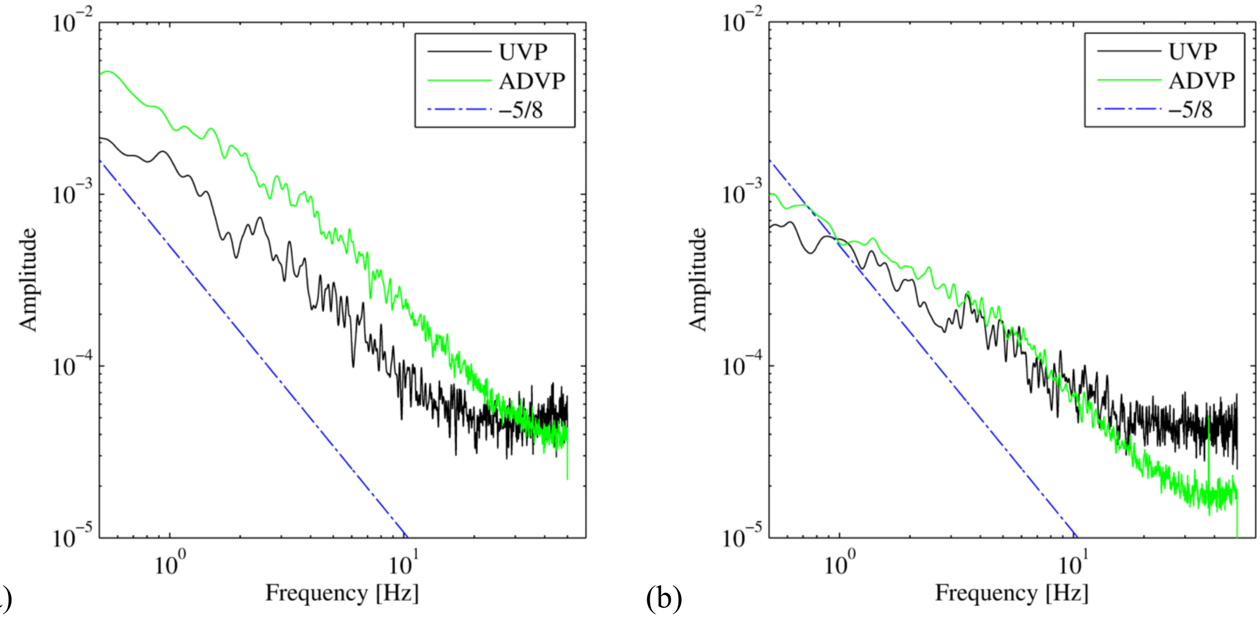
Figure 4 shows a comparison in-between the turbulent kinetic energy profiles obtained with both instruments. The UVP results reveal that the flow is not fully uniform from the turbulence point of view The maximum error between the spatial-averaged profile and the profile taken in one cross-section is about 23% for configuration 1, and 30% for configuration 2, no matter the tests. This indicates that the length of 5 m upstream of the measurement window is not enough to ensure a fully developed flow in configuration 1.

Since Nezu's coefficients were developed for smooth and uniform conditions, we performed a verification of their applicability in the present case. Indeed, figure 4 also compares the turbulent kinetic energy deduced directly from the ADVP measurements with estimates of turbulent kinetic energy obtained by using the ADVP measurements in the streamwise direction only and the Nezu's coefficients. The consistency between both estimates of turbulent kinetic energy is surprisingly good. This confirms the relevance of using UVP measurements, corrected by Nezu's coefficients, as a proxy for turbulent kinetic energy in the upper layer of the flow where ADVP measurements are not accessible. Moreover, in this region of the flow layer, the agreement between turbulent kinetic energy estimated from UVP data and from direct measurements by ADVP is generally good. Where differences are observed, the UVP measurements are systematically lower than the ADVP measurements. This may be a consequence of the more intrusive character of the UVP probe. In contrast, in the lower layer of the flow, close to the bed, estimates of turbulent kinetic energy from UP and from ADVP measurements diverge. The former is generally twice to three times lower. This may results, again, from the more intrusive nature of UVP device in the measurement area. It also suggests that the UVP instrument is more strongly affected by the vicinity of the bed. In contrast Nezu's coefficient may not be blamed for this discrepancy, as demonstrated by the consistency, aven close to the bed, between the turbulent kinetic energy deduced from the complete set of ADVP measurements and from the streamwise velocity measurements only corrected based on equation (2).

Finally some effects of the vertical step used to perform the ADVP measurements can be noticed in the turbulent kinetic energy profiles, while they were not in the velocity profiles. This feature remained, despite several repetitions of the tests. This is a known issue of this instrument as acknowledged in literature (Zedel and Hay 2011).

4.3 *Velocity Spectra*

To complement the comparison of the two measurement devices, a typical velocity spectra of the streamwise velocity component is represented in figure 5. The two spectra were derived from series recorded with UVP and ADVP at $0.1h$ above the flume bed (figure 5(a)) and $0.4h$ (figure 5(b)), respectively, in the same flow cross-section, for discharge of 18 l/s and a stone diameter of 8 mm.



(a) (b)

Figure 5. Velocity spectra in configuration 1with stones of 8 mm in diameter at: (a) $0.1h$ and (b) $0.4h$ above the bed.

There is generally a good agreement between the slope and level of the spectra. They show a well defined inertial subrange at frequencies below about 20 Hz. For ADVP probe, there is a noise floor close to the Nyquist frequency of 50 Hz. The UVP probe fails to record structures with a frequency greater than 20 Hz. The slight change in-between the two instruments could be due to the intrusive character of the UVP probe, especially near the bed where the velocity values are lower. This can explain the difference in-between the turbulent kinetic energy profile (figure 4). In contrast at a level of $0.4h$, figure 4 and figure 5(b) show consistency in-between the two series of measurements.

5 CONCLUSION

Velocity profiles and turbulent kinetic energy profiles were measured in two configurations (quasi-uniform and smooth-to-rough transition) for two grain sizes. In configuration 1, where the flume bed is entirely covered with stones, after 5m, in measurements window the flow is fully developed, the velocity profiles have a stable shape, so a spatial-average can be done. Two measurement devices were used: UVP and ADVP. The obtained results are consistent, so a final velocity profile can be constructed using data close to the bottom recorded with ADVP and close to the flow surface recorded with UVP, respectively. In contrast, turbulent kinetic energy profiles are not fully developed even in configuration 1, which means that a longer distance should be considered. The UVP probe provides only the streamwise velocity component, which means that the computation of turbulent kinetic energy can not be done directly. Therefore, Nezu's coefficients were used, although they were initially developed for smooth uniform flow conditions. The results appear to be surprisingly good in this situation, even relatively close to the bed. Due to a good agreement of turbulent kinetic energy profiles from ADVP and UVP in the upper layer, both instruments are consider to be complementary in the capture of a full profile of turbulent kinetic energy. In contrast, discrepancies between UVP and ADVP are obtained close to the bottom, where ADVP measurements are claimed more reliable. We believe this is due to its capacity of recording turbulent structures with higher frequencies, but also due to more intrusive character of UVP measurement.

These results will support the use of recently develop turbulence-based bed stability parameters to evaluate towards more advanced, truly process-based and predictive assessment, of riverbed stability.

NOTATION

d	stone diameter
u	streamwise velocity component
u'	velocity fluctuation in streamwise direction
v'	velocity fluctuation in transversal (y) direction
w'	velocity fluctuation in vertical (z) direction
k	turbulent kinetic energy
x	main axis of the flow
y	transversal axis of the flow
z	vertical axis of the flow

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