Influence of the shear stress on fine sediment exchanges with the substrate using UVP measurements

Romain Dubuis[1], Giovanni De Cesare[1]
[1] Hydraulic Platform LCH, ENAC, École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland

The dynamic of fine sediment in rivers is closely related to the interactions between fine particles, the riverbed and the flow conditions. The accumulation of fine sediment in the riverbed reduces vertical water exchanges and can have detrimental effects on the ecosystem of rivers. The conditions needed for the deposition of suspended sediment on the surface or inside the riverbed depend on the local flow conditions and have only been little studied. To explore this aspect, flow velocity measurements were performed using a UVP probe to evaluate the shear stress and asses the accuracy of the measurement in locations with different flow conditions along a flume. The shear velocity was inferred from the velocity profiles using the log-law equation. These results were then compared to the estimation of the shear stress using a simple backwater curve model. Results show that the shear velocity can be well evaluated when the flow conditions are not disturbed by protruding grains, even though gravel induce some variability in the results. The use of UVP to measure the shear stress with small relative water depth in comparison with bed roughness still represents challenges that might be addressed in future work.

Keywords: Fine sediment deposition, UVP, Shear velocity, Surface clogging, Velocity profile

1. Introduction

The excessive accumulation of fine sediment in the pores of riverbeds results in a reduction of vertical exchanges which can have detrimental effects on fish and benthos [1], as observed in numerous channelized or regulated Alpine rivers. The deposition of fine sediment transported as suspended load on riverbeds results in surface clogging when the flow conditions are unable to wash fine sediment deposited on top of the riverbed surface. Inner clogging can also take place when these fine particles are filtered inside the substrate but cannot deposit on the surface. [2]. When the shear stress of the flow mobilizes the riverbed, fine sediment trapped in the substrate is released, a process called declogging. As such, flow conditions have an important influence in the dynamics of fine sediment in rivers, in addition to other factors. Given the high variability of flow conditions in a river and the spatial dynamic of transported fine sediment, it is relevant to establish a relation between the local flow conditions and the type of clogging observed. The shear stress applied by the flow on suspended and deposited particles must be determined to understand correctly the process taking place. Ultrasonic velocity profilers (UVP) can be used to measure the local shear stress based on the velocity profile, and avoid complex numerical simulation in spatially varying flow conditions. However, the accuracy of the measurement using this method has first to be compared with theoretical values. In this context, the accuracy of shear stress measurement using a UVP is compared with theoretical values obtained from a simple eddy curve model, in the case of a bed of gravel and suspended sediment.

UVP probes have the advantage to allow for the measurement of the velocity profile with a limited impact on the flow. The turbid environment provided by the presence of suspended sediment in the case of clogging experiments is also adapted to this method [3].

2. Experimental setup and instruments

2.1 Flume

The deposition of fine sediment and the clogging process were analyzed using a 6.25 m long, 15 cm wide flume filled with a 31 cm thick layer of substrate (Fig. 1, see also [4]). The substrate was composed of a wide grain-size distribution of sand and gravel, ranging from 0.1 to 8 mm, with a small armoring of the surface layer, which had a geometric mean diameter d_{50} of 4.9 mm. A false bottom allowed an infiltration flow to be established through the substrate layer. Fine sediment in suspension was composed of quartz silt ranging between 0.1 and 63 μm, at a concentration ranging between 0.8 and 1 kg/m^3. A continuously varying flow depth was set to analyze the type of deposition with varying flow conditions, with a discharge of 2.24 L/s and a water depth h_w ranging between 3.8 and 14.2 cm. The quantification of the clogging process was done by observing the chan-

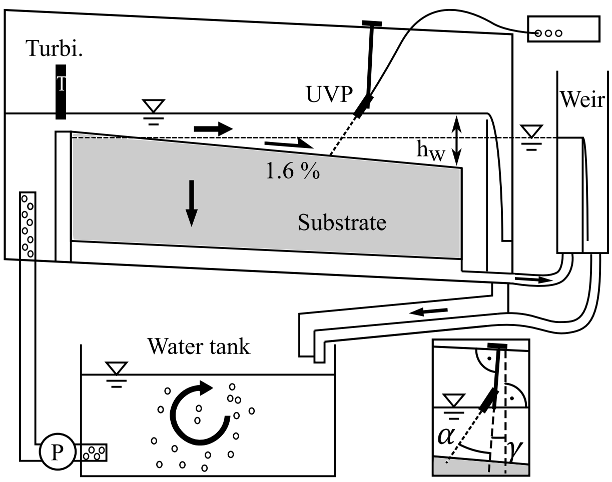

Figure 1: Experimental setup with regularly varied water depth and bed shear stress, equipped with a UVP probe.

ge in suspended fine sediment concentration, the final surface covered by fine sediment, samples of the substrate as well as through the change of the substrate permeability.

2.2 Ultrasonic Velocity Profiler

The flow conditions were measured in different locations along the flume by measuring the velocity profile at the center of the cross-section. To this effect, a Met-Flow 4 MHz UVP was used. The UVP probe was placed in the opposite direction of the flow, at an angle α of 30° to the perpendicular of the flume top slope (Fig. 1). The direction of the flow was assumed to be parallel to the flow surface. The flow velocity U was therefore inferred from the averaged measured velocity $\bar{v}_m$ using the following relation:

$$U = \frac{\bar{v}_m}{\sin(\alpha + \gamma)} \tag{1}$$

Where γ is the angle between the surface flow and the top structure of the flume (see Fig. 1, detail).

3. Methodology

3.1 Data acquisition

Experiments were conducted to evaluate the deposition of fine sediment at the limit between surface clogging and inner clogging by observing the surface of the riverbed covered by fine sediment at the end of the experiment. The continuously decreasing shear stress provided by the increase of the water depth along the flume had to be determined to link the observed phenomena with the flow conditions. Velocity profiles were measured at 13 locations along the flume, distant of 50 cm each.

The tip of the UVP probe was positioned right below the water surface, at a distance x from the inlet. Silt particles in suspension, which are responsible for the clogging of the bed, were used as seeding to reflect the signal. The longitudinal position of the probe was occasionally shifted by a few centimeters when local flow disturbances due to the irregular bed surface resulted in a velocity profile that deviated significantly from the theoretical log-law profile.

The UVP was set to measure points from 5 mm from the probe, with one measurement point every 0.74 mm, which corresponds to a vertical resolution of 0.64 mm. A total of 200 velocity profiles were measured in each location, with 256 repetitions for each profile. The voltage was set to 60 V, and the echo gain started at 3 and ended at 6.

3.2 Processing of the data

The raw data were then processed to obtain the shear velocity, in a similar way to the method used by [3] or [5]. The logarithmic law of the wall defines the velocity profile as [6]:

$$U = \frac{u_*}{\kappa} \ln\left(\frac{z}{z_0}\right) \tag{2}$$

Where κ is the von Karman's constant, taken as 0.41, u_* is the shear velocity and z_0 the bed roughness dimension. Assuming a rough turbulent flow, the bed roughness can be defined as $z_0 = k_s/30$, where k_s is Nikuradse's roughness, situated in the range $2d_{50} \leq k_s \leq 3d_{90}$ [5], and resulting, for the composition of the bed surface, in $d_{50}/12 = 0.38\,mm \leq z_0 \leq d_{90}/10 = 0.75\,mm$. In a similar way to [5], no form drag correction was applied since the bed is flat. A linear regression between the velocity profile and the logarithm of the dimensionless depth z/z_0 was used to find the shear velocity. The regression was restricted to measurements situated in the interval $0.7 \cdot d_{50} < z < 0.25 \cdot h$, with h the water depth, as suggested by [7], to stay within the log-law region and avoid influence of the bottom particles.

4. Results

4.1 Velocity profiles

The regression of the velocity measurements within the selected interval are presented in Figure 2, at 13 different locations along the flume. The regression was performed using $z_0 = 0.38\,mm$, a value situated at the lower end of the proposed range.

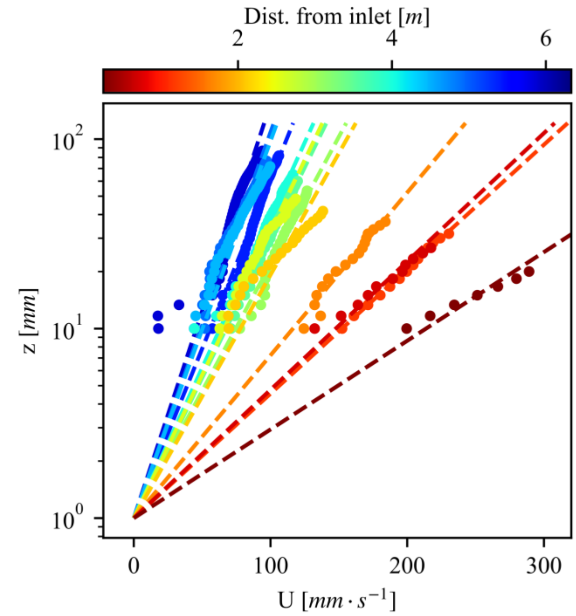

Figure 2: Velocity profiles in the log-law interval as a function of the depth (y-axis), expressed with a log-scale. The dashed lines correspond to the linear regression of each profile.

Outside of the selected interval, the measurement data deviates from the theoretical log-law curve and are therefore not used in the regression. In consequence, the resulting velocity profile obtained from the fit deviates in the upper part of the flow depth, especially for velocity profiles measured at the upstream part of the flume where the flow velocity was higher (Fig. 3).

The R^2 values of the fits for the different regressions lay in the range between 0.81 and 0.99, with the lowest value (<0.9) attributed to a section at the end of the flume (Fig. 2, dark blue) and at around 2.2 m (Fig. 2, yellow).

4.2 Comparison of shear stress with backwater curve model

The low value of z_0 used for the regression allows to obtain shear velocities that correspond approximately to

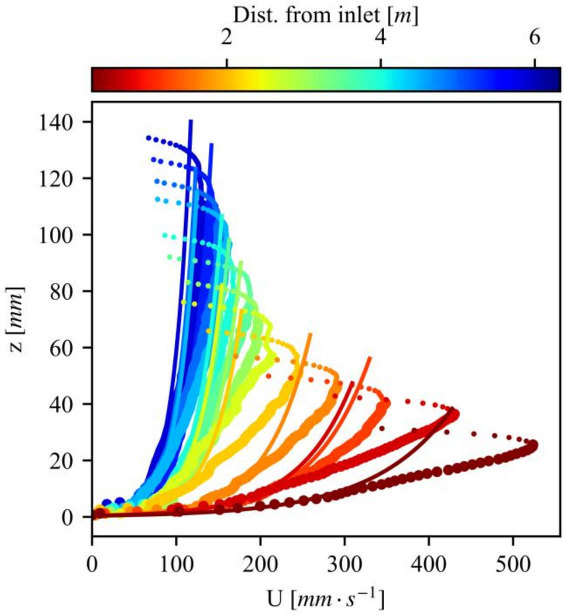

Figure 3: Full velocity profiles in each measured section along the flume (bullets) as a function of the depth (y-axis). The continuous lines correspond to the log-law velocity profile obtained from the regression of Fig. 2 up to the water surface. Small bullets show measurement affected by UVP transducer.

the theoretical shear velocity calculated using a simple backwater curve model, as shown on Figure 4. The backwater curve model was calibrated using water surface and bed level measurements of multiple experiments with the same substrate and wall roughness. Using a more commonly accepted value of $k_s = 3d_{90}$ [8], the values of the shear velocity using the UVP measurements are overestimated in comparison with the theoretical values obtained from the backwater curve model. In this case, the theoretical value is about 70% of the measured shear velocity.

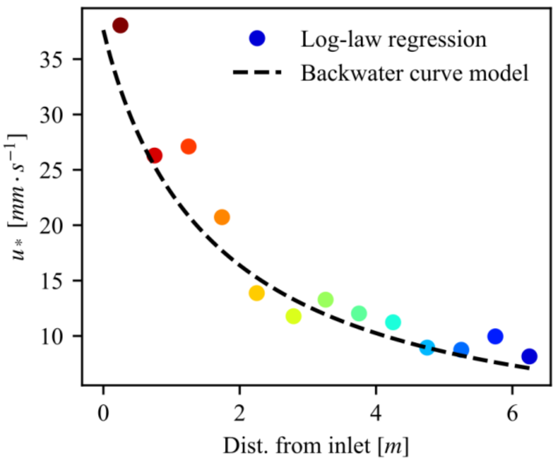

Figure 4: Comparison between the shear velocity obtained by UVP measurements and by the backwater curve model.

4.3 Clogging process at the limit between surface and inner clogging

Based on the analysis of the riverbed surface covered by fine sediment at the end of the experiment, using pictures of the surface [9], it is possible to express the relation between the type of clogging and the shear stress (Fig. 5). The surface covered by fine sediment corresponds to the proportion of white surface (fine sediment) in contrast with the darker substrate, analyzed pixel by pixel.

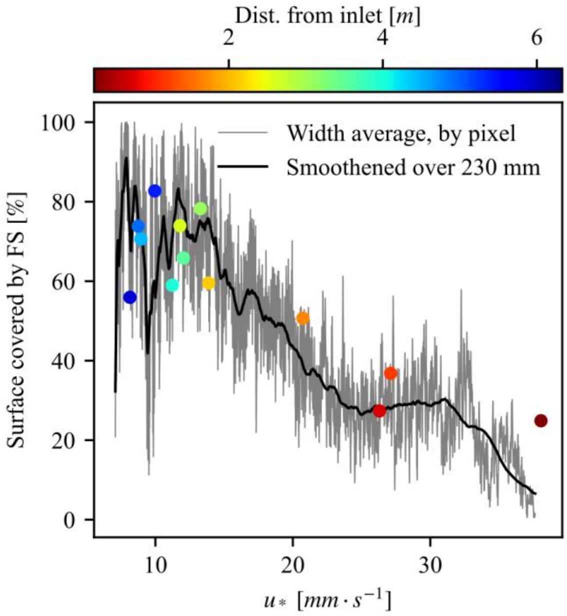

Figure 5: Surface covered by fine sediment as a function of the shear velocity, using theoretical (continuous line, from calibrated backwater curve) and measured (bullets) shear velocity. Pixels used in the analysis of covered surface correspond to a distance of 0.23 mm, longitudinally.

The surface covered by fine sediment decreases regularly with the increase of the shear velocity, without specific threshold, from values of around 80% (Fig. 6c), until the covered surface reaches a value of about 20% for shear velocities over 25 mm/s (Fig. 6a). This last case corresponds to the usual cover observed in experiments with inner clogging.

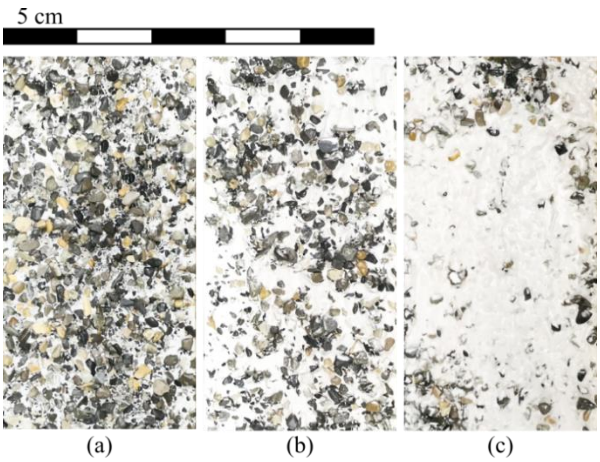

Figure 6: Surface covered by fine sediment in the case of (a) inner clogging, (b) in the transition and (c) surface clogging.

5. Discussion

5.1 Data acquisition

The rough surface of the riverbed, with the largest grains reaching 8 mm, in comparison with the water depth (38 to 142 mm) implies that the velocity profile can change significantly depending on the location of the probe. The arrangement of the grains at the bed surface can modify the flow on an important part of the flow depth, for example in the presence of secondary currents. To this regard, the presence of secondary current could be checked by using a second transducer with a different angle. Alternatively, the ADVP method could provide a more detailed measurement of the local flow [10]. Since the average flow conditons are relevant and secondary currents occurs in a limited area of the bed surface, the UVP method allows obtaining sufficiently detailed results for the studied case. The definition of the bottom of the flow is also a source of errors since the probe may capture the presence of intra-gravel flow when the signal is directed between gravel particles or be affected by the presence of protruding grains. This aspects implies testing different locations to obtain good profiles. The reduced velocity near the surface of the water as observed in Figure 3 can be attributed to the influence of the UVP transducer and does not correspond to the real velocity close to the water surface.

5.2 Estimation of the shear stress

Using the logarithmic law equation to estimate the shear velocity gives accurate results when a well-developed velocity profile can be obtained. This method depends on factors like the bed roughness, which needs to be estimated, and can provide different results depending on the assumptions. The results obtained through this method should be therefore used with precaution, especially when no calibration can be performed to evaluate the best value of the bed roughness, for example.

In a similar way to what observed [7], the range over which the log-law regression is applied can be extended to larger values than $z = 0.25 \cdot h$, for instance $0.3 \cdot h$, with a similar quality of the fit, although [7] use an ADVP, providing 3D detailed measurements.

5.3 Type of clogging

The smooth transition between inner clogging and surface clogging observed along the flume during this experiment is attributed to the hiding-exposure effect [5], [11]. Large protruding grains of the substrate can reduce the shear stress in the interstices of the riverbed surface which allows for the deposition of fine sediment reaching these areas. A more systematic examination of flow velocity near the substrate surface would provide a better understanding of how the transition between the two types of clogging is related to the interaction between flow and bed roughness.

The discrete measurement of the shear velocity reveals the relation that exists between the surface covered by fine sediment and the shear velocity. However, assessing the type of clogging depending on a single measurement should be taken with precaution since the local measured value can vary on very short distance.

6. Conclusion

The evaluation of the bed shear stress by using velocity profiles obtained from UVP probes provided similar results to the one obtained on the basis of the flow and geometric characteristics of the flume. Due to the relatively large bed roughness, obtaining usable velocity profiles required to avoid pertubrations of the flow due to protruding grains. This method is able to estimate the shear stress that defines the type of clogging, taking advantage of the suspended material responsible for the clogging process. In larger applications with different bed morphologies, this method would allow estimating the local flow conditions and related type of clogging.

References

[1] J. I. Jones, J. F. Murphy, A. L. Collins, D. A. Sear, P. S. Naden, et P. D. Armitage, « The Impact of Fine Sediment on Macro-Invertebrates », *River Research and Applications*, vol. 28, n° 8, p. 1055-1071, 2012, doi: 10.1002/rra.1516.

[2] R. Dubuis et G. De Cesare, « The clogging of riverbeds: A review of the physical processes », *Earth-Science Reviews*, vol. 239, p. 104374, avr. 2023, doi: 10.1016/j.earscirev.2023.104374.

[3] J.-N. Saugy, A. Amini, et G. De Cesare, « Flow structure and grain motion assessments of large river widening in a physical model using ultrasonic Doppler velocity measurements », *Exp Fluids*, vol. 63, n° 7, p. 115, juill. 2022, doi: 10.1007/s00348-022-03430-9.

[4] R. Dubuis et G. De Cesare, « Influence of Vertical Fluxes on the Clogging of Riverbed by Fine Sediment », in *39th IAHR World Congress*, in IAHR. Granada, 2022, p. 659-666. doi: doi:10.3850/IAHR-39WC2521711920221145.

[5] C. J. McCarron, K. J. J. Van Landeghem, J. H. Baas, L. O. Amoudry, et J. Malarkey, « The hiding-exposure effect revisited: A method to calculate the mobility of bimodal sediment mixtures », *Marine Geology*, vol. 410, p. 22-31, avr. 2019, doi: 10.1016/j.margeo.2018.12.001.

[6] H. Schlichting et K. Gersten, *Boundary-Layer Theory*, 8th revised ed. Springer Science & Business Media, 2000.

[7] F. Bagherimiyab et U. Lemmin, « Shear velocity estimates in rough-bed open-channel flow », *Earth Surface Processes and Landforms*, vol. 38, n° 14, p. 1714-1724, 2013, doi: 10.1002/esp.3421.

[8] G. H. Keulegan, « Laws of Turbulent Flow in Open Channels », *Journal of Research of the National Bureau of Standards*, vol. 21, p. 707-741, 1938.

[9] R. Dubuis et G. De Cesare, « Limits between surface and inner clogging of riverbed by fine sediment », in *proceedings of River Flow 2022*, 2022.

[10] D. Duma, S. Erpicum, P. Archambeau, M. Pirotton, et B. Dewals, « Velocity and Turbulence Measurements for Assessing the Stability of Riverbeds: a Comparison between UVP and ADVP », *Proceedings of the 11th International Conference on Hydroscience & Engineering*, p. 539-544, 2014.

[11] W. Wu, S. S. Y. Wang, et Y. Jia, « Nonuniform sediment transport in alluvial rivers », *Journal of Hydraulic Research*, vol. 38, n° 6, p. 427-434, nov. 2000, doi: 10.1080/00221680009498296.