Bedload transport assessment on a physical model of a large river widening using ultrasonic Doppler velocity measurements

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The 3rd correction of the Rhône River is the largest flood protection project in Switzerland so far. Covering a length of 162 km, it aims to protect some 100,000 people and prevent flood damages, which could raise up to 10 billion Swiss francs for major events. It also intends to revitalize the river and its surrounding area. A natural or revitalized river presents a dynamic morphology that can be assessed using bathymetric survey, bedload transport and hydrodynamic flow behavior. The present case study aims to investigate the behavior of the bedload transport for the future Rhône at the Verney widening using physical model. A valid bedload assessment requires distributed water depths and velocities. The used dataset consists of Lidar scans and recorded streamwise and crosswise velocity profiles. The analysis is performed at two selected cross sections based on the ultrasound Doppler velocity profile method. The velocity profiles allow assessing the local shear stress on the mobile river bed. The different velocity profiles are compared, and the results discussed.

Keywords: Physical modelling, Bedload transport, Ultrasonic Doppler velocimetry, River revitalization

1. Introduction

Local river widening becomes a common approach in river restoration and flood protection. Such projects have become very common in Switzerland in recent years [1]. In the context of the 3rd correction of the Rhône River, several local widenings are planned [2].

Studies have already been carried out for a better understanding of hydraulic, morphological, and ecological phenomena occurring in the local widening [3,4]. The studies conclude that sediment transit must be guaranteed in long term in order to avoid the filling of the widened part and assure the project success.

The bed shear stress must be thus high enough to keep grains in motion. A widely used method for determining local bed shear stress is to fit a logarithmic curve to velocity profile data [5]. Indeed, for subcritical flow, the shear velocity is related logarithmically to the variation of velocity with depth as shown in Eq.1 [6]. Then the shear stress is computed based on the shear velocity (Eq.2). By comparing the computed shear stress for a certain grain size with the critical one according to Shields diagram [7] (Eq.3), its chance of being transported can be assessed.

The Ultrasound Doppler Velocity Profile method (UVP) has been applied in the present project. Since 1995, this method has recurrently been used at the Platform of Hydraulic Construction (PL-LCH) in several hydraulic research projects [8].

$$u = \frac{u_*}{\kappa} * ln\left(\frac{z}{z_0}\right) \tag{1}$$

$$\tau = \rho * u_* \tag{2}$$

$$\tau_{cr} = \theta_{cr} * \rho * g * (s-1) * d \tag{3}$$

where z is height above the bed, z_0 is the characteristic roughness length, u is velocity, $u*$ is shear velocity, s is the ratio between the sand and the water densities, and θ_{cr} is dimensionless critical shear stress.

2. Methodology

2.1 Study area

The 3rd Rhône River correction is divided in various priority levels based on the potential flood risk. The Martigny bend section is set as a priority measure due to potential damages of over 600 million Swiss francs for a 100-year flood event. Upstream of the bend, a local widening (bed widening factor: > 2, length: > 500 m, width: ~180 m) is planned at the Verney section (Figures 1-2).

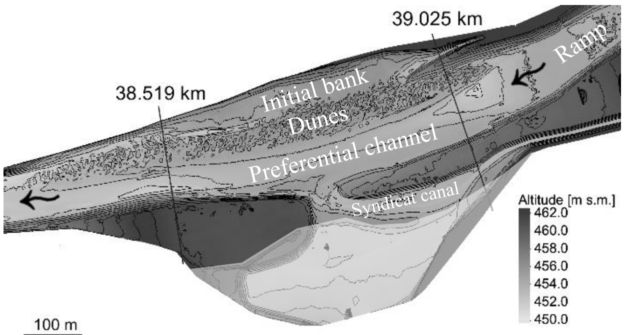

Figure 1: Bathymetry of the Verney widening at the end of the 100-year flood test (Lidar survey) and its configuration.

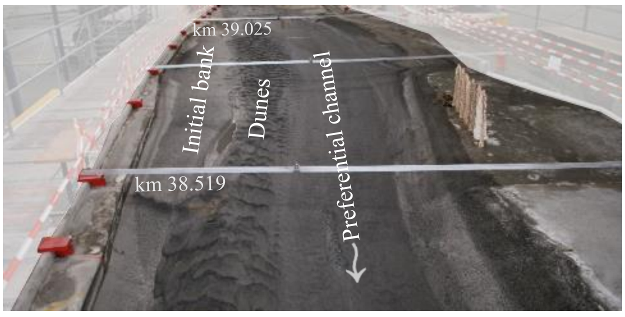

Figure 2: Verney widening at the end of 100-year flood test run (upstream view).

2.2 Models

The PL-LCH team exploited two models: a physical and a 2D numerical one. The latter computes only the depth averaged streamwise velocities. Therefore, the current paper focus only on the physical model results. The model respects the similarities of Froude (conservation of the ratio between inertia and gravity forces) and bed load transport. The scales factors are shown in Table 1 for the geometrical scale λ.

Table 1: Scale factors of the physical model

Parameter	Scale factor
Length	$\lambda = 52$
Velocity	$\lambda^{1/2} = 7.21$
Discharge	$\lambda^{5/2} = 19'499$

As a preliminary step, morphodynamic tests (bed erosion and sediment transport) have been performed to obtain the initial bathymetry (Figures 1-2). A steady-state flood scenario with a return period of 100 years (Table 2) has been run in order to measure velocity profiles.

Table 2: Scenario characteristics

Return period [yr]	Q [m^3/s]	Qsed [m^3/s]
100	1'174	156

The granulometry data are scaled down using the Shields diagram (Table 3). The critical shear stress has been computed for d_m and d_{90}.

Table 3: Grain size and critical shear stress

	Prototype scale [mm]	Model scale [mm]	Critical shear stress (prototype scale) [Pa]
d_m	42.7	0.8	32.2
d_{90}	85.5	1.6	72.5

2.3 Instrumentation

Two UVP (Ultrasonic Velocity Profiler) transducers of 2 MHz were fixed on a manual mobile support moving along pre-existing rails (Figures 2-3). The 1st transducer was oriented in the main flow direction while the 2nd one was set perpendicular to it. Measurements were done along the profiles km 39.025 and 38.519 (Figure 1).

Table 4: UVP transducer configuration

Parameter	Value	Unit
Start point	4.07	mm
Channel distance	2.96	mm
End point	149.11	mm
Maximum depth	456.58	mm
Maximum velocity	+/- 297.5	mm/s
Velocity resolution	2.342	mm/s
Frequency	2188	Hz

In general, the distance between two velocity profile measurements was set to 10 cm. Each measurement station consisted in 100 profiles per transducer and was manually activated. Table 4 shows the used parameters.

A P20 ScanStation from Leica Company was used for Lidar surveys before and after each test in order to interpolate velocities along the whole profile. The P20 theoretical precision is announced to be less than 1 mm. However, only a 3 mm precision (15.6 cm in prototype scale) could be reached. Moreover, thanks to the laser wavelength (808 nm), it is possible to scan the bathymetry while the model is still filled with clear water. However, because of too high turbidity in the water, the Lidar surveys were done without water. In consequence, it is assumed that the bathymetry at the time of the UVP measurements corresponds to the one during Lidar scanning.

The Water Surface Elevation (WSE) was measured using ultrasonic probes at different points. Its value has then been extrapolated for the entire cross section (theoretically flat-water surface).

Table 5 shows the different instruments used and their precision while Figure 3 presents the experimental set-up.

Table 5: Details and precision in situ of the instruments

Instruments	Company	Precision
Doppler effect Ultrasonic Velocity Profiler (UVP)	Met-flow SA	1 mm/s
ScanStation P20	Leica Geosystems	3 mm
Ultrasonic probes		1 mm

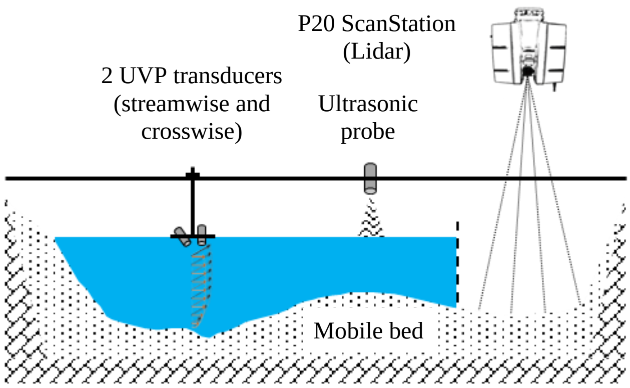

Figure 3: Experimental set-up

2.5 Data processing

For UVP measurements, the whole processing has been done with a MATLAB script fully developed by PL-LCH team [9]. After detecting the river bed using the echo signal, only the measuring channels recorded above the ground were kept. Moreover, the first measuring channels were removed because of their proximity to the transducer. Velocities from the top measuring channel were extended to WSE (given by US probe) in order to estimate the discharge passing through the section, and thus, verify the

UVP measurements. At the same time, velocities were scaled and adjusted regarding the ultrasonic wave incidence angle to normal (θ ≈ 15.5° ±3°). The two transducers had the same incidence angle.

Lidar data have been georeferenced and meshed (reducing points). Then the elevation of the riverbed measuring channel detected with the echo signal is matched with the bathymetry at the end of the test.

Velocity magnitude and standard deviations are then interpolated (linear interpolation method) and extrapolated (nearest neighbor extrapolation) on a grid of 10 cm x 12 cm. The grid delimitations are WSE and the river bed. For standard deviation, the results were not extended to WSE.

The shear stresses are only computed based on the UVP velocity profiles and for the velocity magnitude. As mentioned before and shown in Figure 4, a linear regression is done in a semi-logarithmic graph. The coefficient of determination (R^2) is computed for validating the log profile. Its value must be over 0.9 otherwise the shear stress is not calculated.

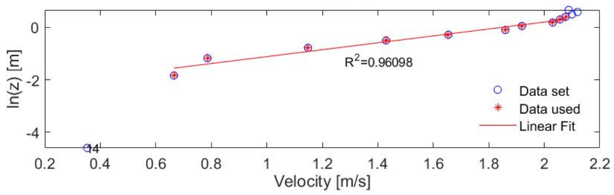

Figure 4: Example of a linear fitting on the velocity magnitude profile on a semi-log graph (profile km 38.519)

4. Results

The velocity magnitudes on both extracted sections show similar structures, despite their different locations (Figures 5-6). High velocities can be observed in a specific area. Velocities are higher at the Verney end (< 4 m/s against < 3.5 m/s) but the area is narrower (~40 m against ~60 m). This area where bed load is in majority transported is labelled as preferential channel or "Super Channel" On its right, the velocities are progressively lowering.

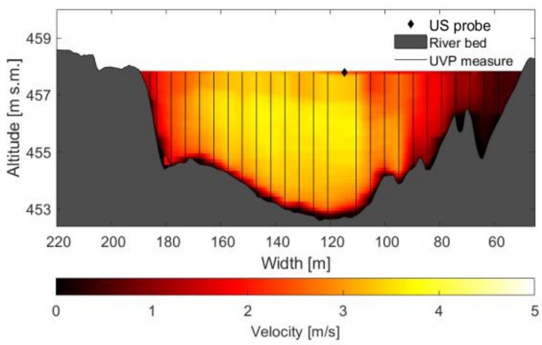

Figure 5: Velocity magnitude for the section km 39.025

The crosswise velocity component is negligible for both sections. Figure 7 illustrates the variation rate for section km 38.519. The variation rate between the magnitude and the flow direction component is less than 5 %. This confirms the initial assumption of a non-complex flow occurring in the widened area. However, some UVP measures show a variation rate higher than 10 %. These points are located where the streamwise velocities are low, i.e. on top of the dunes where bed form roughness is highest. As such, the river flow deviates from logarithmic velocity profiles [10].

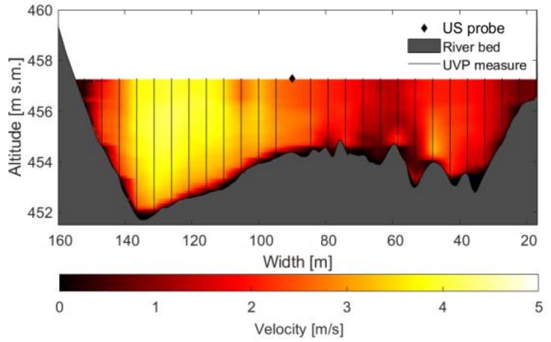

Figure 6: Velocity magnitude for the section km 38.519

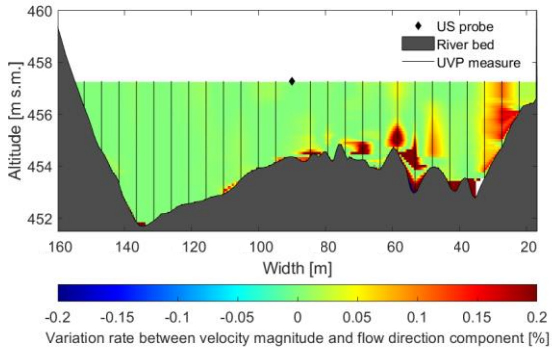

Figure 7: Variation rate between velocity magnitude and flow direction component

Standard deviation results show a similar pattern as the crosswise velocities (Figure 8). The values are low (< 0.4 m/s) for the preferential channel but are high above the dunes (> 0.6 m/s). The flow is more disturbed because of theses macro shapes. The disturbance is even more significant for the standard deviation of the crosswise velocities (Figure 9).

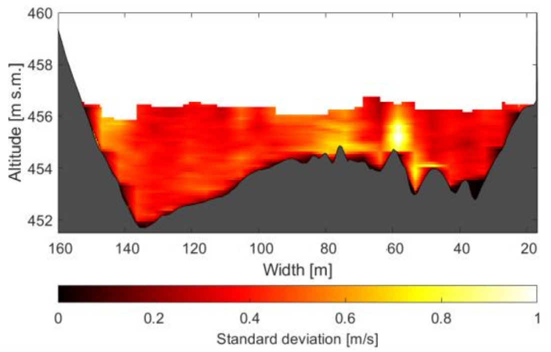

Figure 8: Standard deviation of the flow direction velocities for the profile km 38.519

Standard deviations at section km 38.519 are lower than the ones at the section km 39.025. The velocities are less dispersed at the downstream section part of Verney than upstream. This is due to the proximity of the ramp and the flow adaptation to the widened bed (Figure 1).

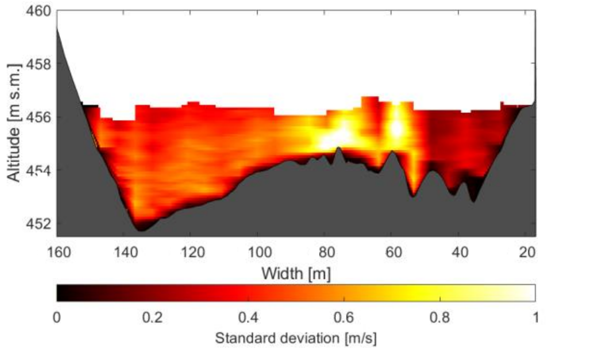

Figure 9: Standard deviation of the crosswise velocities for the profile km 38.519

Regarding the shear stress distribution (Figures 10-11), the results show the same trend. Indeed, shear stresses higher than the critical shear stress for d_m and even d_{90} have been computed in the "Super Channel". It is not the case for the riverbanks except locally for the dunes located at a distance of 40 m to 90 m on the section km 38.519. These points perfectly match the ones with high crosswise velocities and standard deviation. For reminder, the shear stress is only computed for velocity profiles with R^2 higher than 0.9.

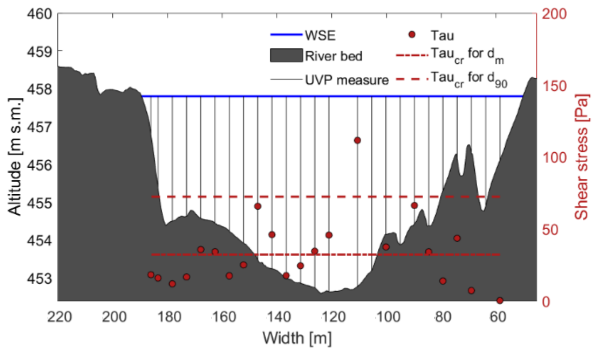

Figure 10: Shear stresses computed for the profile km 39.025

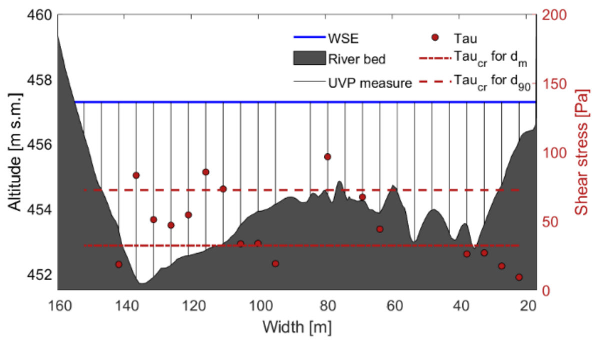

Figure 11: Shear stresses for the profile km 38.519

5. Conlusions

In conclusion, this paper brings up the existence of a preferential channel or "Super Channel" where velocities are high and shear stresses are greater than the critical values for d_{90}. This guarantees bed load transit along the Verney Widening and prevents its filling with sediment over time.

Moreover, there is a clear distinction between the flow structure in this preferential channel and the banks. Flow over initiated sediment deposits and dunes show different velocity profiles. In classical steady state uniform open channel flow, a logarithmic velocity profile establishes naturally [11], whereas outside the main channel flow velocity distributions tend to be less structured. The cross flow component is more significant. Therefore, computed shear stress based on the log profile is less accurate. Nevertheless, grain motion could be identified along the dunes even for large grain sizes.

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