Flow Limitation and Riverbank Protection Design Using Asymmetrical Flow Mapping on a Physical Hydraulic Model

Vecsernyes Zsolt[1], Andreini Nicolas[1]

[1] Laboratory for Applied Hydraulics, University of Applied Sciences Western Switzerland, HES-SO, HEPIA Geneva 1202, Switzerland

The experimental monitoring of an asymmetrical flow pattern, realised on a physical model at the Laboratory for Applied Hydraulics of HEPIA, yielded accurate dimensioning of a flow limitation device and appropriate riverbank protection design. The studied structures were then implemented on the Aire River in Geneva. The main goals of the Aire River revitalization program in Geneva are: hazard and risk mitigation. Inundation risk is mitigated for the Q300y=120 m³/s design discharge by an orifice-weir structure yielding a 400'000 m³ flood retention. A free transit flow is achieved for all hydrological conditions by an innovative two-stage driftwood retention device [1] preserving the orifice of driftwood clogging. Since upstream from the orifice flow conditions are strongly asymmetrical, velocity field needed to be monitored on a physical hydraulic model [2]. Velocity measurement was carried out by means of Met-Flow UVP probes and the shear stress calculated. The experimental analysis results yielded an appropriate orifice geometry and riverbank protection design.

Keywords: Asymmetrical flow, Velocity field mapping, Orifice geometry design, Rive bank protection

1. Introduction

In the frame of the third stage of the Aire River revitalisation project, inundation risk of Geneva is mitigated by an orifice-weir structure yielding flood retention (Figure 1). Upstream from this discharge limitation structure the revitalised reach of the Aire River is implemented over its former right bank and connected to the orifice through a gravel pit. The flood retention field extends over the gravel pit and the revitalised river reach. The former rectilinear river reach axially connected to the orifice is only supplied by drainage. A convergent flow is therefore encountered at the orifice.

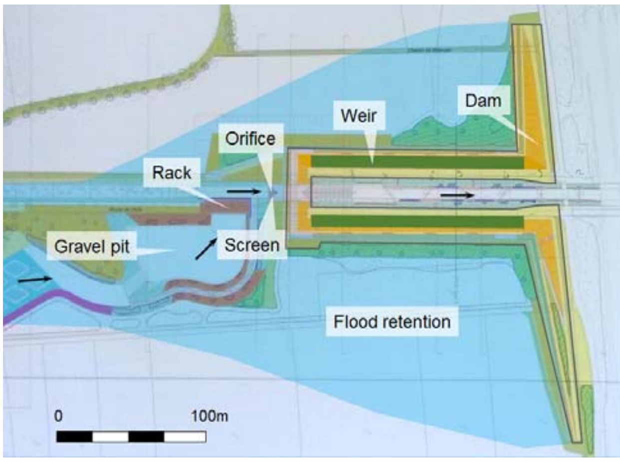

Figure 1: Synoptic view of the Aire River inundation risk mitigation structures. The orifice implemented in the dam yields discharge limitation by flood retention.

Due to the predominant contribution of the revitalised stream, the flow takes an S shape in the vicinity of the discharge limitation device in order to pass the bottom opening of the dam. The resulting asymmetrical flow expands into abutment of the left river bank and induces uncommon axial forces and shear stress on the latter which must be fought in order to avoid bank erosion. The asymmetrical flow pattern may also alter the hydraulic comportment of the orifice responsible of the discharge limitation. For these raisons flow pattern needed to be monitored on a physical hydraulic model.

2. Experimental set-up

The experimental investigations were conducted at the Laboratory for Applied Hydraulics (LHA) of HEPIA Geneva, CH. The physical model of the Aire River was constructed with a 1:40 (model : prototype) length scale (Figure 2). Flow analyses obeyed Froude similarity. Velocity scale in these conditions became 1:6.325.

The velocity field monitoring required permanent flow conditions achieved by means of the closed circuit facilities of the laboratory. Hence a constant hydraulic head corresponding to 100 m³/s (prototype) was guaranteed upstream from de orifice opening with a free supercritical downstream outflow.

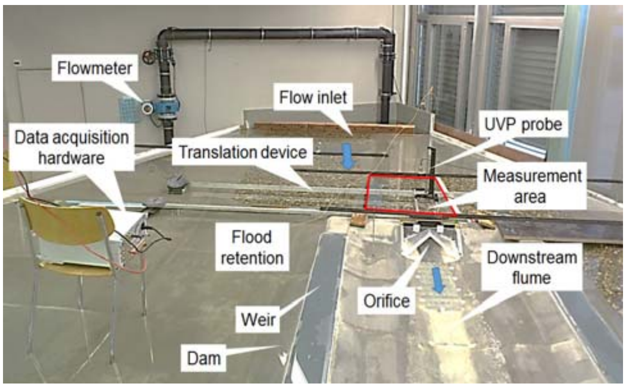

Figure 2: Partial view of the Aire River physical model at the LHA of HEPIA, with the flow monitoring facilities installed upstream from the discharge limiting orifice.

A single Met-Flow, 1 MHz, UVP ultrasound probe was implemented upstream from the orifice (Figure 3). The flow mapping was obtained by moving the probe step-by-step over the measurement area, in 16 points and 3 rows. Rows were positioned at respectively y = 15 m; y = 30 m; y = 45 m; upstream from the orifice.

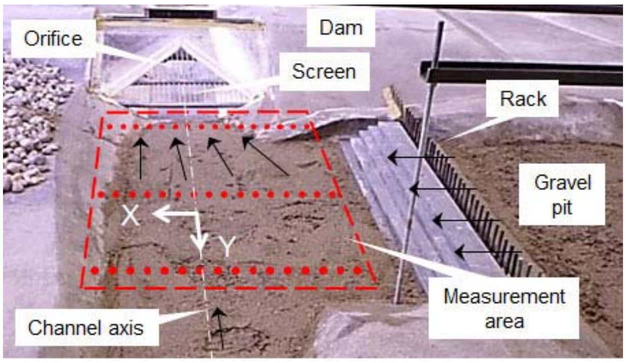

Figure 3: Upstream view of the dam showing the UVP measurement scheme composed of 16 points set in 3 rows.

The probe was installed with an angle of 30° from the vertical (Figure 4). Two measurement series were carried out: **a.** the horizontal projection of the ultrasonic beam pointed upstream and parallel to the channel axis, and then **b.** towards the gravel pit and perpendicular to the channel axis. A complete velocity mapping could be achieved upstream from the orifice, in two perpendicular orientations.

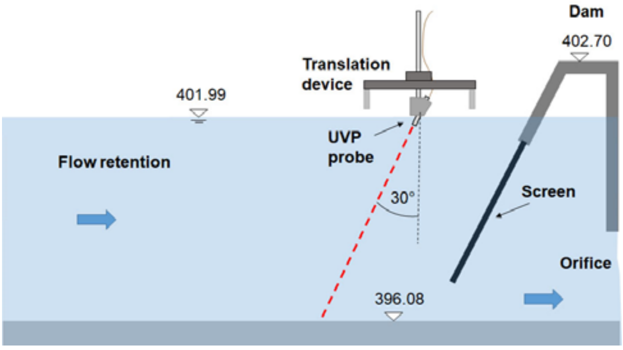

Figure 4: UVP probe implemented upstream from the discharge limiting orifice of the dam.

3. Results

3.1 Flow velocity mapping

The recorded velocity data was post processed with the help of a MATLAB subroutine yielding the graphical representations of the flow field. All values are hence considered as according to prototype.

Under permanent flow conditions (Q100y = 100 m³/s, prototype), the flow patterns were analysed in 13 different levels above the channel bed, between 396.00 AMSL and 302.00 AMSL. Thus, the velocity vectors were plotted in horizontal plans, every 0.50 meter.

Over the channel bed (Figure 5) flow is inhibited by the encountered boundary effect yielding a weak velocity field. In the vicinity of the bottom opening flow is strong due to continuity reaching 1.2 m/s. Flow pattern is clearly directed in the axis of the orifice.

In the upstream part of the analysed channel velocity increases with measurement level. This transition can be followed over Figures 5-6-7.

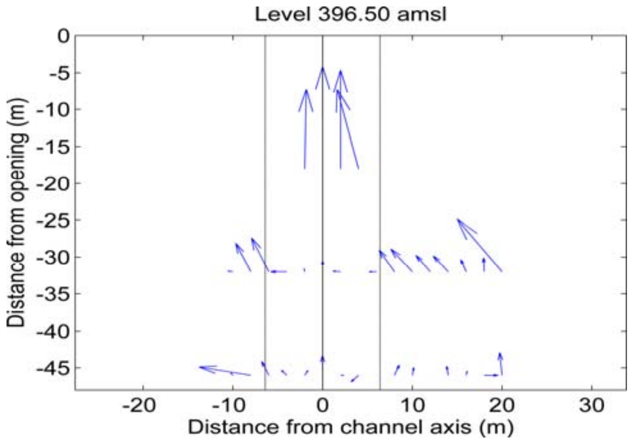

Figure 5: Flow velocity pattern shown near the channel bed, at level 396.50 AMSL. Bed boundary effect reduces the velocity in the upstream analysed channel portion. Near the opening flow takes an axial path towards the orifice.

In Figure 6, the velocity field at level 397.50 AMSL is shown. The asymmetrical flow pattern takes progressively place with the rise of measurement level. Flow pattern at the orifice is mainly axial, yet with a growing lateral component due to flow arriving from the gravel pit.

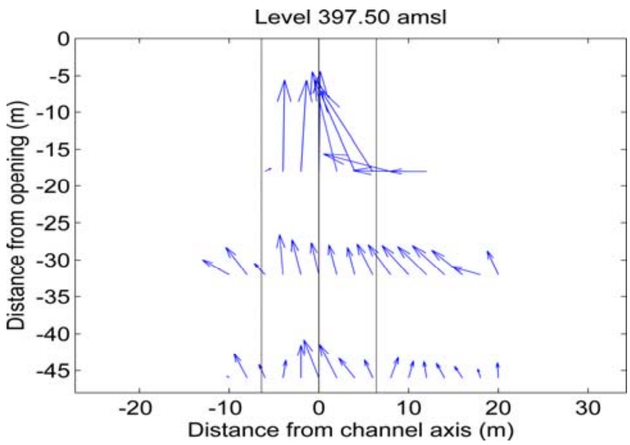

Figure 6: Flow velocities shown at level 397.50 AMSL, revealing the increase flow in the upstream part of the examined channel. Close to the opening flow takes a lateral component.

In Figure 7, the velocity field at level 399.50 AMSL is shown. The expected asymmetrical flow pattern is clearly developed and thus pointed out. Flow remains relatively strong close to the orifice, with a main axial component.

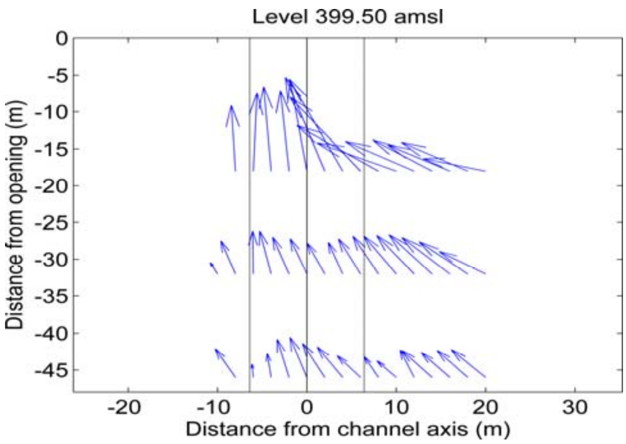

Figure 7: Flow velocities shown at level 395.50 AMSL, revealing the expected asymmetrical pattern.

The velocity field integrated over the whole water column is plotted as two orthogonal 2D flow intensity maps in Figure 8 and Figure 9. These presented results were obtained for the probe positioned at y = 15 m upstream from the orifice, and respectively for Y and X axes (c.f. Figure 3).

Since the discharge limitation device is built as a bottom opening of the dam, the main flow takes a tube shape close to the orifice as shown in Figure 8. This vein characterised by values larger than 1.0 m/s sinks from the gravel pit (Figure 9) and bends right towards the orifice.

Flow velocity reduction observed in Figure 8 (at 398.60 ASML; on channel axis) is induced by the horizontal bar of the drift wood protection screen.

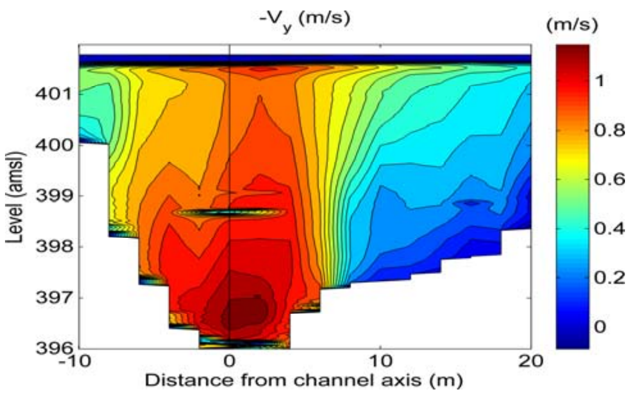

Figure 8: Flow map achieved on the physical model (c.f. Figure 3). Velocity vector field, -Vy, parallel to the channel axis. Core velocity takes place near the channel axis.

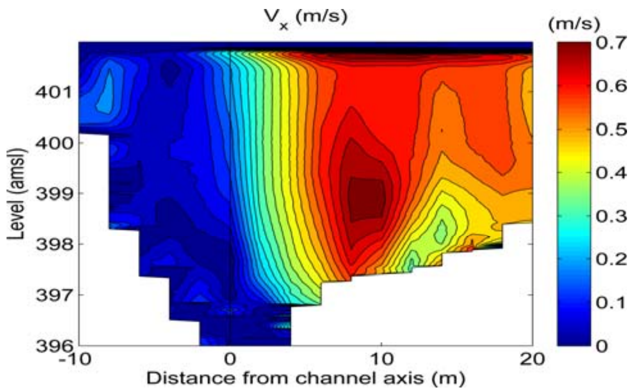

Figure 9: Flow map achieved on the physical model. Velocity vector field, Vx, perpendicular to the channel axis. Core velocity found close to rack of the gravel pit.

3.2 Impact on the orifice's rating curve

In order to respect the inundation risk mitigation goals of the Aire River project, the hydraulic comportment of the orifice needed to be analysed on the physical model. As shown in Figure 10, a hexagonal geometry was proposed respecting architectural aspects.

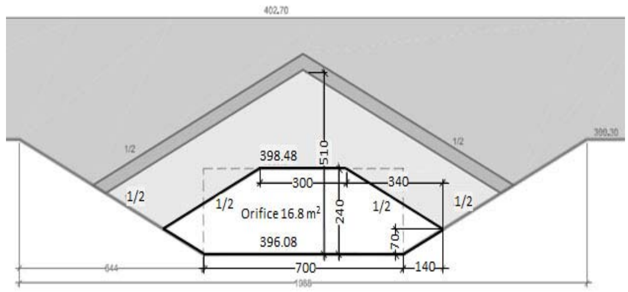

Figure 10: Discharge limiting orifice, with a 9.8 m large, 2.4 m high hexagonal bottom opening of the dam.

Even though the asymmetrical upstream flow pattern may impact the rating curve of the bottom opening, the analyses could yield an appropriate orifice geometry. The rating curves shown in Figure 11 point out that a hexagonal geometry could be correctly fitted to the defined hydraulic constraints. Therefore a 9.8 m large and 2.4 m high bottom opening could be adopted for construction on the Aire River.

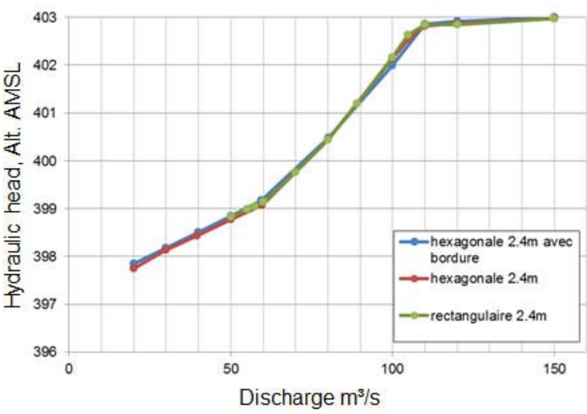

Figure 11: Rating curves for three different orifice geometries, proving the appropriate choice of the hexagonal one.

3.3 Shear stress applied on the left channel bank

As demonstrated above (Figure 5 to Figure 9), flow expands into abutment of the left river bank over the whole water column, inducing shear stress. It is therefore appropriate to determine shear stress as a function of velocity, as followed

$$\tau = \rho \left(\frac{U \cdot \kappa}{ln\left(\frac{l_m}{l_0}\right)} \right)^2 \quad (1)$$

According to [3], in Eq. 1, ρ is the specific mass of water, U is the velocity near the wall, κ is the von Karman's constant which equals 0.408, l_m is a distance measured as 8% of the total curvilinear ray from river bank taken into account for shear stress (Figure 12), and l_0 is the roughness height.

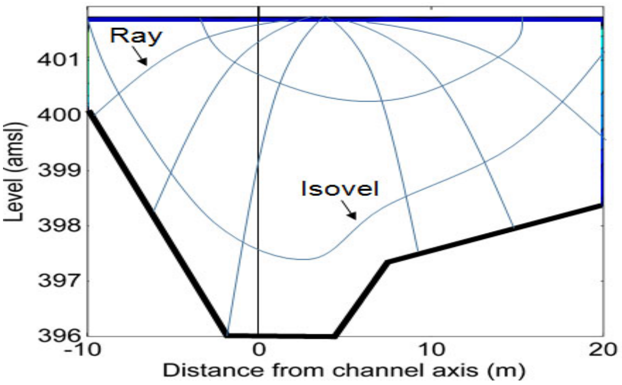

Figure 12: Orthogonal Ray-Isovel network taken into account for shear stress analysis in the upstream vicinity of the orifice.

Typical shear stress values reach $\tau \leq 200$ N/m² near the left channel bank upstream from the orifice. This value has to be scaled up by a 1.35 multiplication factor due to the velocity component normal to the left river bank, yielding values larger $\tau \geq 270$ N/m². These constraint require a rip-rap bank protection [4].

3.4 Constructed structures on the Aire River

As demonstrated on Figure 13, the analyses carried out at the Laboratory for Applied Hydraulics of HEPIA yielded the construction of a hexagonal discharge limiting orifice on the Aire River as defined on the physical hydraulic model. Upstream from the orifice a rip-rap channel bank lining was adopted.

Figure 13: Structures constructed on the Aire River as defined on the physical hydraulic model. A hexagonal orifice and a rip-rap channel bank lining were adopted upstream from the latter.

6. Summary

The achievements of the present study underline that the appropriate choice of structural measures in river restoration may be assisted by physical model tests in particular when uncommon flow pattern conditions are encountered.

In the Aire River revitalisation programme in Geneva the velocity field mapping of an asymmetrical flow pattern revealed pertinent on physical hydraulic model.

The experimental study carried out by means of a Met-Flow UVP probe at the Laboratory for Applied Hydraulics of HEPIA – Geneva, pointed out that despite the encountered asymmetrical flow pattern the hydraulic low of the orifice opening is weakly affected. Yet, in order to respect the inundation risk mitigation goals of the Aire River revitalisation project the dimensions of the proposed hexadecimal opening had to be tested on physical model and adjusted.

The study results also pointed out that in the upstream vicinity of the discharge limiting orifice, notable shear stress is applied on the left rived bank due the encountered asymmetrical transverse flow. These results yielded the re-evaluation of the bank protection technique initially planned by plant engineering. Therefore, a rip-rap structure was erected over the entire height of the left bank as channel lining.

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