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Scale effects in a Vertical Double Slot Fishway

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Abstract

This paper presents results on the scaling effects between a full-scale a Vertical Double Slot Fishway (VDSF) in Malaucène, on the Garonne River (France) and its 1:6 model reproduction in the Pprime Institute of the University of Poitiers (France), which assured the Froude similitude. Acoustic Doppler Velocimetry (ADV) measurements were performed to access the three components of the velocity on two profiles in each fishway. Full-scale measurements are exposed. Flow topology, mean flow and unsteady velocity components features as well as turbulence kinetic energy are evaluated for both scales and compared to one another. Results show a good agreement between the dynamics of the turbulent flow in both scales, which endorse the use of laboratory scale models for designing full-scale fishways in the future and in particular VDSFs. The flow and turbulence features could be estimated from laboratory experiments and extrapolated for an ecohydraulics point of view.

Keywords: Vertical double slot fishway; Ecohydraulics; Scale effects; In-site and laboratory experiments; Turbulent flow;

1. INTRODUCTION

Adopted in 2000, the Water Framework Directive dictates that all European countries must achieve a good ecological status or potential of their water bodies. This involves, among other things, to insure longitudinal connectivity, especially in classified rivers. The removal of obstacles may be a solution, but many of them are useful for human activities and cannot be withdrawn. As an alternative, fishways are often installed to allow fish passage upstream of obstacles.

Although the general design of the Vertical double slot fishways (VDSFs) is relatively old (Clay, 1995), their flow characteristics have been the subject of very few studies (Fujihara et al., 2003; Zhang et al., 2023). To our knowledge, no publications focus on the hydraulics of only VDSFs. The existing VDSFs were designed on the basis of criteria used for the Vertical single Slot Fishways (VSFs) that were widely used and studied (Rajaratnam et al., 1986; Marriner et al., 2014; Klein & Oertel, 2016; Ballu et al., 2016, 2017; Zhao et al., 2022).

A study of the turbulent flows occurring inside a VDSF is underway at the Pprime Institute in Poitiers (France) (Lejeune et al., 2022). It aims at identifying the impact of different parameters (slope, discharge...) on the flow patterns and at optimising the design criteria for future VDSFs. Experiments are carried out on a scale-model of an existing French VDSF. However, all the quantities measured on the scale-model cannot be transposed to full-scale due to scaling effects, specifically concerning the fluctuating quantities. Indeed, scale effects occur when the force ratios are different between the natural phenomenon and the laboratory controlled-one. The bigger the scale factor, the further the observations will be from one another. In this work, an estimation of the scale effects between a full-scale VDSF and its reproduction (six times smaller, using the Froude similitude) is presented.

2. DATA ACQUISITIONS

2.1. Description of experiments and positions of profiles measured

Two sets of similar experiments were conducted: one in a full-scale VDSF, located in Malause on the Garonne River (France) in July 2022, the other on a 1:6 scale-model of this VDSF in the Pprime Institute, University of Poitiers (France). Acoustic Doppler Velocimetry (ADV) measurements were carried out during both campaigns with a SonTek MicroADV 16 MHz. The three-components of the velocity on several profiles with a 50 Hz frequency over a 300 s acquisition time were collected. Raw data were then filtered with a phase-space filter to remove aberrant values, as recommended for this type of data (Goring & Nikora, 2002). Post-treated data were used to determine information about turbulence (mean velocity, turbulence kinetic energy, ...) and temporal and spatial flow patterns in VDSFs. For the full-scale experiment, the ADV was immersed inside a pool and moved into the desired positions using a metal transverse structure that can be seen below (**Figure 1**).



Figure 1. Experimental set-up for (a) the full-scale ADV measurements (Vertical Double Slot Fishway of Malause, Garonne River, France) (b) the 1:6 scale model ADV measurements (Pprime Institute, University of Poitiers, France)

The measurements were conducted in the fifth pool from upstream (over seven) in the on-field full-scale VDSF and in the third pool (over five) in the 1:6 laboratory experiments. The main dimensions of the pools of the full-scale VDSF are presented below (**Figure 2**). The slot width is of $b = 450$ mm, the width and length of the pools are $B = 4$ m and $L = 5$ m, respectively. The fishway is equipped with bottom macro-roughnesses (truncated cones, density of 10%, using the methodology implemented before (Ballu et al., 2017)). The diameters of each cone at its base is $D_{MR-b} = 200$ mm and at its top $D_{MR-h} = 150$ mm. The fishway slope is of $s = 4\%$. The water level drop between two successive pools was measured all along the VDSF and the average value is $\Delta h = 174$ mm, and the water depth in the middle of the fifth pool is of $h = 2$ m. The flow discharge during the 1:1 experiments has been measured using an Acoustic Doppler Current Profiler (ADCP). For the laboratory experiments, the flowrate was controlled and measured using a flowmeter. The flowrate was normalised using a previously introduced expression [1] (Puertas et al., 2004).

$$Q^A = \frac{Q}{\sqrt{g \times b^5}} \quad [1]$$

with Q the flow discharge ($\text{m}^3 \cdot \text{s}^{-1}$), g the standard gravity ($9.81 \text{ m} \cdot \text{s}^{-2}$) and b the width of the slot (m). The measured Q^A is then equal to 7.0.

The profiles studied for this work are the profile C, which is transversal at $X = 1065 \text{ mm}$ ($= 2.37 \cdot b$) and the profile E', which is longitudinal and located at $Y = 1950 \text{ mm}$ ($= 4.33 \cdot b$). A specific point of the profile C (C5), located at $X = 1065 \text{ mm}$ ($= 2.37 \cdot b$) and $Y = 1295 \text{ mm}$ ($= 2.88 \cdot b$) where the velocity from the slot jet is maximum was also investigated in order to study the temporal fluctuation of the velocity in this zone. All the elements of interest are located at half the water depth, hence $Z = 1000 \text{ mm}$ ($= 2.22 \cdot b$). The elements of interest are also drawn on the figure below (Figure 2).

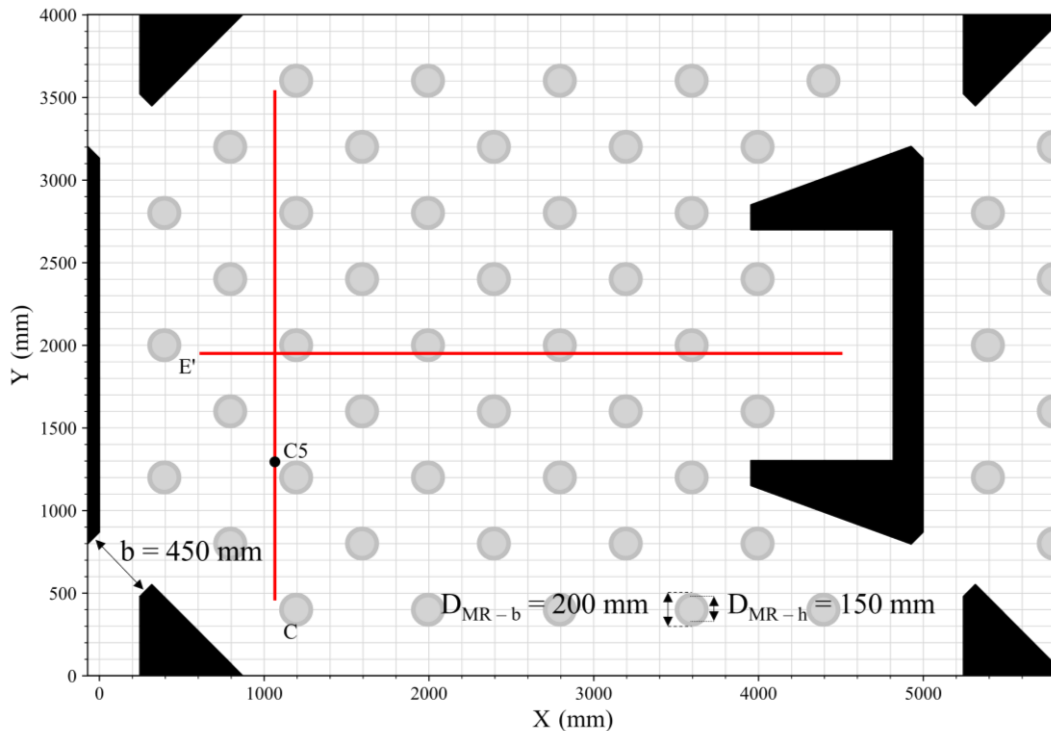


Figure 2. Dimensions of the full-scale VDSF pools and profiles positions

2.2. Scaling laws

The 1:6 scale laboratory model was established from the dimensions of the VDSF in Malause using the Froude similitude. This criterion is often used to study flow characteristics in fishways, since it jointly considers inertia and gravity forces, both important in this type of free-surface flow. In order to maintain the same Froude number [2] in the 1:1 (full-scale) VDSF and in the 1:6 scale model, the following equations for time (t) [3], mean or fluctuating velocity (U) [4] and turbulent kinetic energy (k) [5] can be deduced, using n as the geometrical scale (here $n = 6$).

$$Fr = \frac{U}{\sqrt{g \times h}} \quad [2]$$

$$t_{full-scale} = \sqrt{n} \times t_{scale-model} \quad [3]$$

$$U_{full-scale} = \sqrt{n} \times U_{scale-model} \quad [4]$$

$$k_{full-scale} = n \times k_{scale-model} \quad [5]$$

with U the velocity ($\text{m} \cdot \text{s}^{-1}$), g the standard gravity ($9.81 \text{ m} \cdot \text{s}^{-2}$), h the water depth (m).

Using those expressions, it was possible to transform the measures obtained in the 1:6 scale model back to full-scale for further comparisons. The following results will be presented in 1:1 scale (whether native 1:1 scale or corrected to 1:1 scale for scale-model results).

3. SCALE EFFECTS ESTIMATION

The topology, mean flow and fluctuations occurring inside the 1:6 scale VDSF were presented previously (Lejeune et al., 2022). Here, the velocity magnitude and the turbulent kinetic energy along the two profiles studied are presented below (**Figure 3** and **Figure 4**). The same topology was observed in both scales, and the results are really close to one another. This is a really promising result, since it includes data from field experiments, where hydraulic conditions were less controlled than in laboratory experiments. In profile C, the two jets coming from the slots created a rise of the mean velocity on the velocity profile. Outside of the area of the jets, the velocity was much lower in both configurations. The two jets mixed together in the middle of the pool in both scales, as can be seen in profile E', as the mean velocity increased significantly before decreasing downstream of the middle of the pool. The same patterns of turbulent kinetic energy could be observed in both scales. The fluctuations were highest in the middle of profile C, with two smaller pikes due to the wavering of the jets. In profile E', the highest values of turbulent kinetic energy were located in the area close to the central baffle of the previous pool and they then decreased along the upstream-downstream direction, except near the middle of the central baffle in both scales.

The 1:6 scale-model overestimated the velocity slightly, in high-velocity areas (such as the two jets on profile C). The scale effects seemed rather limited on mean velocities. Also, the scale-model underestimated slightly the turbulent kinetic energy along the profile E', while it gave similar results to full-scale along the profile C. The fluctuations seemed more dependent to scale effects than the mean velocity, although the results are still quite close. Several reasons can explain those small differences. The choice was made to design the scale model based on the Froude similitude; however, the Reynolds number was different, since both criteria cannot be maintained in the scaling. The Reynolds number -using the slot width for the reference dimension and the theoretical velocity occurring inside a slot based on water level drop between pools- of the full-scale is equal to $Re_{full-scale} = 831000$ whereas the Reynolds number of scale-model is equal to $Re_{scale-model} = 61000$ (more than thirteen times lower than $Re_{full-scale}$). Furthermore, the ADV-probe used to collect the velocities was the same in the two measurement campaigns and in proportion to the pool volumes, both the volume intrusion by the probe and the volume of measurements had a bigger impact on the 1:6 scale-model than on the full-scale VDSF. The velocity fluctuations occurring inside the full-scale VDSF had larger amplitudes as can be seen below on the specific point, C5 (**Figure 5**). The fluctuating velocity on the streamwise-direction was slightly more contained in the 1:6 scale-model than in full-scale. Nevertheless, the frequency of the two were rather similar, meaning that the unsteady flow is not affected by scale in this configuration.

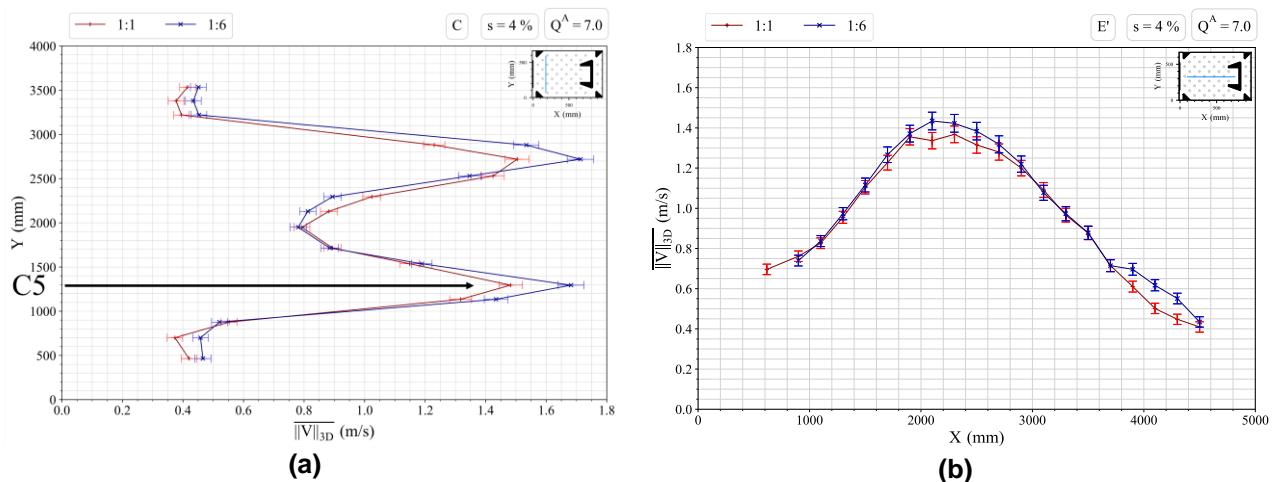


Figure 3. Velocity magnitude for the full-scale VDSF (in red) and the 1:6 scale-model (in blue) for (a) profile C and (b) profile E'. The discharge Q^A [1] was equal to 7.0 and the slope s was equal to 4%.

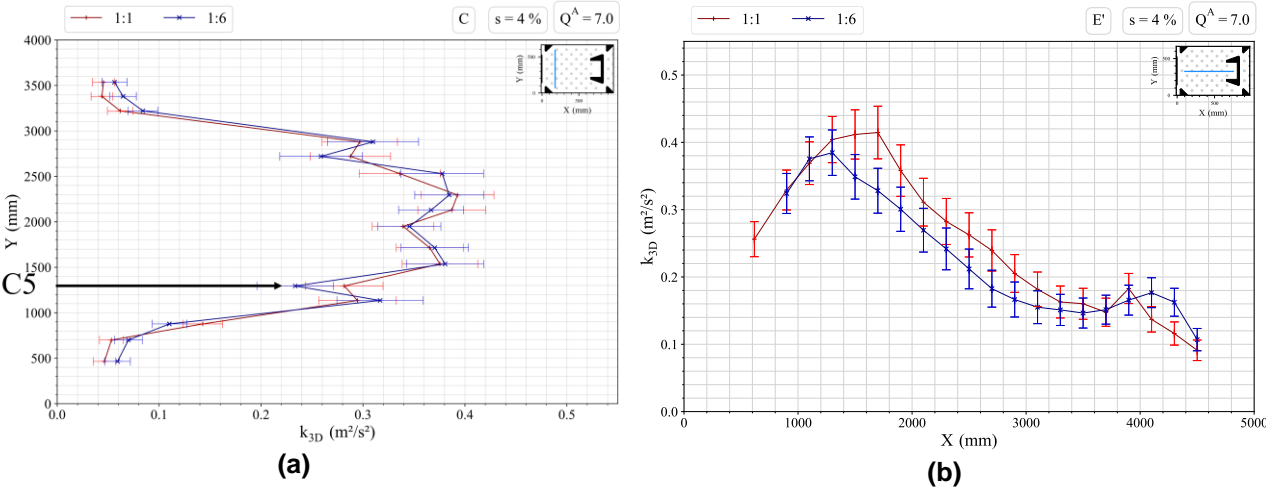


Figure 4. Turbulent kinetic energy for the full-scale VDSF (in red) and the 1:6 scale-model (in blue) for (a) profile C and (b) profile E'. The discharge Q^A [1] was equal to 7.0 and the slope s was equal to 4%

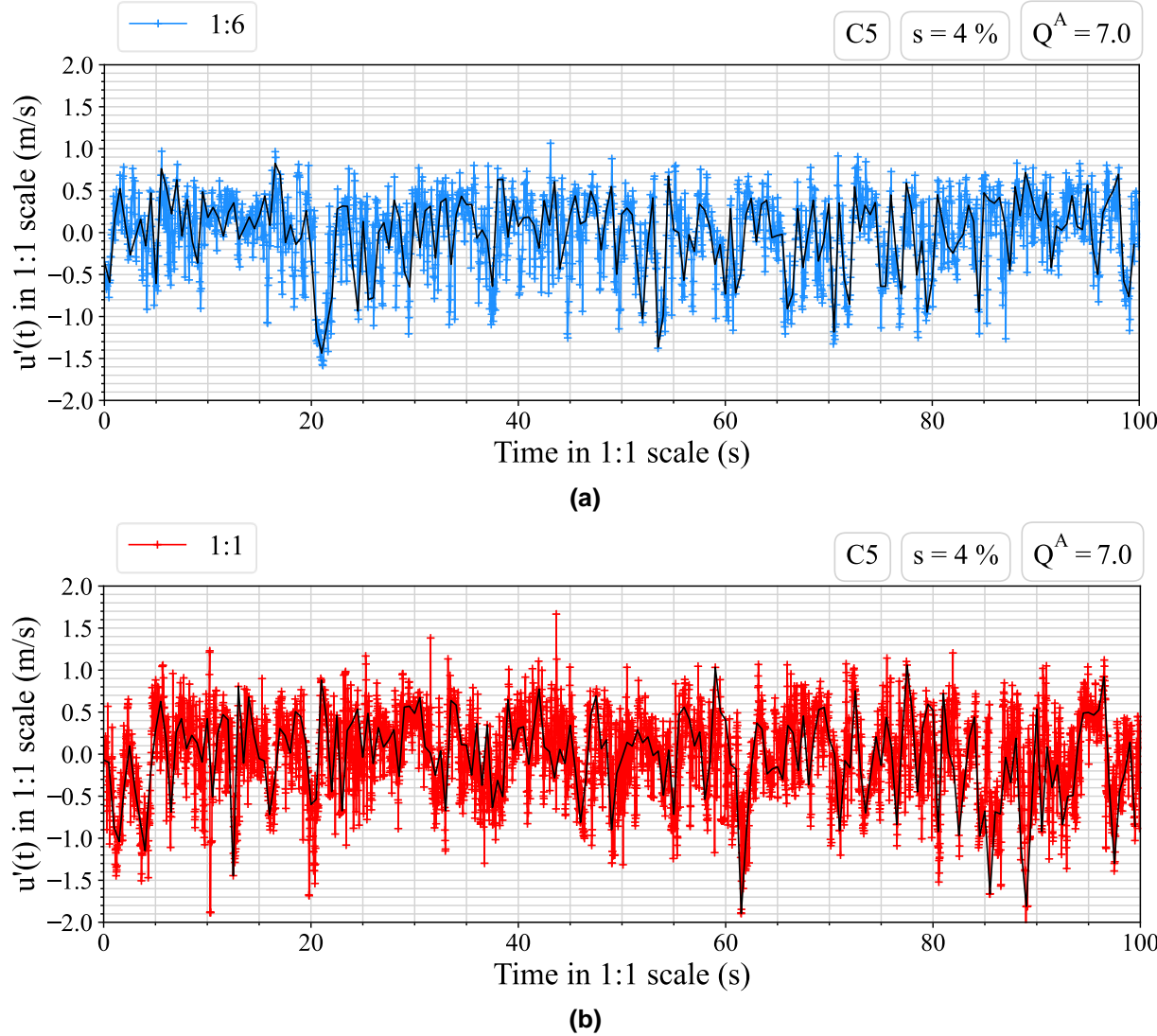


Figure 5. Time evolution of the u' fluctuating velocity in 1:1 scale at point C5 for (a) the 1:6 scale-model and (b) the full-scale VDSF.

4. CONCLUSIONS

In order to understand hydraulics inside fishways and draw conclusions on the impact of different parameters on flow patterns, the use of scaled models in laboratories is widely applied. However, the impacts of scaling are less known and are often a source of uncertainties when designing full-scale fishways. This study compared results from a full-scale Vertical Double Slot Fishway (VDSF) in Malause on the Garonne River (France) and its 1:6 scale-model reproduction (Pprime Institute, University of Poitiers, France). It appeared that the flow topologies of both scales were really similar, that the 1:6 scale-model is an appropriate way to understand and estimate the flow occurring inside a VDSF. There are some differences between the quantitative values, but they are truly minor considering the experiments undertaken. Those differences could come from several well-known sources, like the difference in Reynolds number due to Froude similitude or the inflow conditions that were difficult to adjust and control to reproduce exactly in both VDSFs. The difference could be also come from measurement artefact. Indeed, both experiment campaigns were conducted with the same probe, meaning that the ratio of the intrusion and integration volumes to the volume of the pool were different in the two scales. Despite these uncertainties, the results show good agreement and allow us to rely on the 1:6 measurements to provide valuable information and criteria for the design of VDSFs, from an ecohydraulic perspective.

To extrapolate criteria design for future fishways, the search of corrective factors will be pursued to improve slightly the laboratory findings when switched back to 1:1 scale. It will focus on minimising the difference between full-scale and laboratory turbulence and unsteady measurements, using least square approach.

5. ACKNOWLEDGEMENTS

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