# Velocity Measurements in Transient Flow Downstream of a Submerged Vertical Drop

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ABSTRACT

## 1. Introduction

Hydraulic jumps occur when supercritical flow becomes subcritical under momentum conservation conditions and is used as energy dissipation mechanism in the design of stilling basins. In some cases a vertical negative step is constructed at the entrance of a stilling basin in order to stabilize the hydraulic jump under all operating conditions. In laboratory experiments the flow is controlled by a sluice gate upstream, and a sharp crested overflow downstream of the step. Five different rapidly varying types of flow have been observed around a step under supercritical flow conditions upstream (Moore and Morgan, 1957, Ohtsu and Yasuda, 1991, Mossa et al. 2003) The minimum B-jump is the hydraulic jump at the toe of the step, the B-jump is a submerged jump downstream of the step, the wave-train is a transient, surface jet-type flow without formation of a hydraulic jump, the wave-jump is the flow of an ascending jet forming a standing wave downstream of the step, before it dives and results in a submerged hydraulic jump, and the A-jump is the flow where the hydraulic jump is formed upstream of the step. These flow profiles appear with this sequence by increasing the tailwater depth downstream continuously. The transition from supercritical to subcritical flow over a fully submerged negative step has been studied by experiments regarding the measurement of flow depths upstream and downstream of the jump as well as the pressure at the face of the step, but not the internal turbulent flow properties in terms of velocity measurements. Aim of the present work is the measurement of the two-dimensional velocity field in the region of a wave-train using Particle Image Velocimetry (PIV) for three upstream Froude numbers 1.99, 2.55 and 2.99.

## 2. Experimental

The measurements were made at the Laboratory of Applied Hydraulics of the School of Civil Engineering at the National Technical University of Athens, Greece, in a horizontal channel 10.50 m long with rectangular cross section 0.255 wide and 0.50 high. The section of the channel where measurements were taken has been modified to accommodate the experiments by replacement of the steel, nontransparent bottom with Lucite, and the vertical side glass walls with new ones with improved optical properties. The water supply was obtained via a recirculation system that consists of a 3 kW pump with variable speed motor and maximum discharge capacity of 40 L/s connected to a 2.65 $m^3$ water tank at the downstream end of the channel, and PVC pipe of nominal diameter 0.2 m through which water was pumped to the upstream end of the channel. A downstream facing vertical step 10.3 cm high and 1 m long made of Lucite was placed 4.85 m upstream of the channel end. A vertical sluice gate was positioned 0.35 m upstream of the step face, in order to control the supercritical flow. The flowrate was measured with an ultrasonic flow meter of 2-5% accuracy, attached in the horizontal PVC pipe and the flow depths were measured with point gauges.

The two-dimensional velocity field in the vertical mid-plane of the channel downstream the step was measured with PIV technique under a wave-train. To implement PIV silver coated hollow glass seeding spheres of diameter 10 μm and density 1.04 g/$cm^3$ were illuminated with a dual cavity double pulsed $Nd^{+3}$-YAG laser with maximum energy output 135 mJ, and maximum flashing frequency of 15 Hz at visible green light (532 nm). The images of the particles were captured with a CCD camera with spatial resolution 2048 x 2048 pixels and maximum frequency of 15 Hz. After dividing the images into a dense grid of smaller interrogation windows, cross-correlation was utilized to compute the local average two-dimensional displacement vector in each interrogation window, and hence the instantaneous two-dimensional velocity field. Three different experiments were implemented for the measurement of the velocity field of the transient wave-train flow type, the hydraulic conditions of which (height of the step d, discharge Q, upstream and downstream depths $y_1$ and $y_2$, the upstream and downstream velocities $V_1$ and $V_2$ and the upstream Froude number) are summarized in Table 1.

**Table 1.** Initial hydraulic conditions of the experiments measured with the PIV technique.

| Experiment | d (cm) | Type of jump | Q (L/s) | $y_1$ (cm) | $y_2$ (cm) | $V_1$ (m/sec) | $V_2$ (m/sec) | $Fr_1$ |
|---|---|---|---|---|---|---|---|---|
| 1 | 10.3 | Wave-train | 14.21 | 4.30 | 21.50 | 1.30 | 0.26 | 1.99 |
| 2 | 10.3 | Wave-train | 18.17 | 4.30 | 22.96 | 1.66 | 0.31 | 2.55 |
| 3 | 10.3 | Wave-train | 21.26 | 4.30 | 24.23 | 1.94 | 0.34 | 2.99 |

## 3. Results

The length scale $y_c$+d contains information regarding the potential energy of the flow in terms of the step height d and the minimum energy (or flow rate) in terms of critical depth $y_c$, and will be used to normalize vertical distance from bottom. The mean velocity flow field and vorticity field are depicted in Figs. 1(i) and (ii) respectively for Experiment 1 of Table 1. The vertical distribution of dimensionless horizontal velocity component $u/V_1$ and turbulence intensity $u_{rms}/V_1$ are shown in Figs. 2(i) and (ii) respectively versus the dimensionless vertical distance from the bottom $y/(y_c+d)$ for Froude numbers 1.99, 2.55 and 2.99 at dimensionless horizontal distance from the step $x/(y_c+d)=0.95$. From Figs. 1 and 2 (left) it is evident that there exists a significant recirculation area below the top of the step. The mean velocity field exhibited its highest value at a level higher than that of the step, while the greatest value of vorticity was observed at the location downstream of the step face, where the supercritical water jet met the subcritical flow. From Fig. 2(ii), it can be noted that the turbulence intensity in the horizontal direction can be as high as 24% at $y/(y_c+d)=0.6$ for Froude number $Fr_1$=2.99.

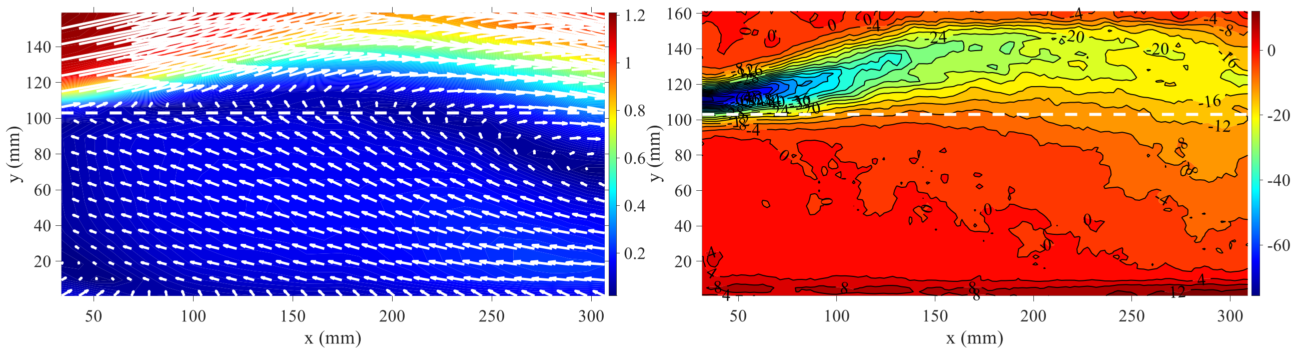


**Fig. 1.** Mean velocity field (m/s) left, and vorticity field ($s^1$) right, of a wave-train with Froude number 1.99 (dotted line shows schematically the elevation of the step).

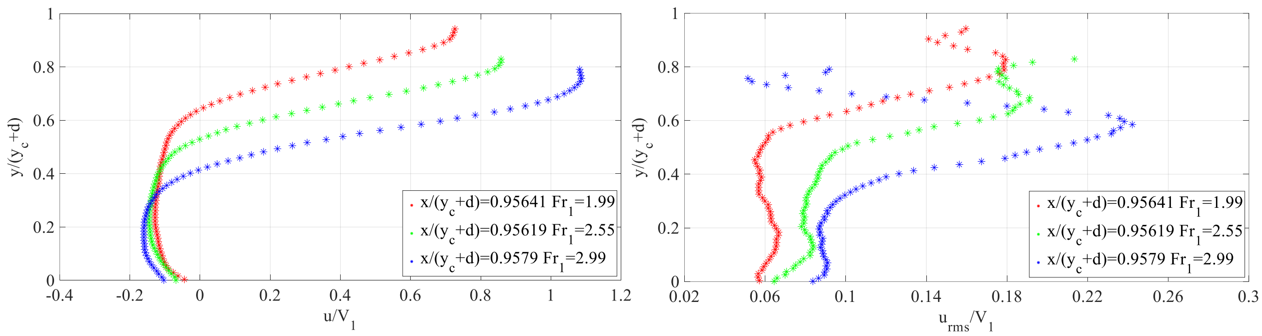


**Fig. 2.** Normalized horizontal velocity $u/V_1$ left, and turbulent intensity of the horizontal velocity $u_{rms}/V_1$ right, versus the dimensionless distance from the bottom $y/(y_c+d)$ for wave-train with Froude numbers 1.99, 2.55 and 2.99, at distance $x/(y_c+d)=0.95$ from the step.

**References**

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