Experimental study of resonant shallow flows past a lateral cavity: a benchmark test for high-resolution numerical models

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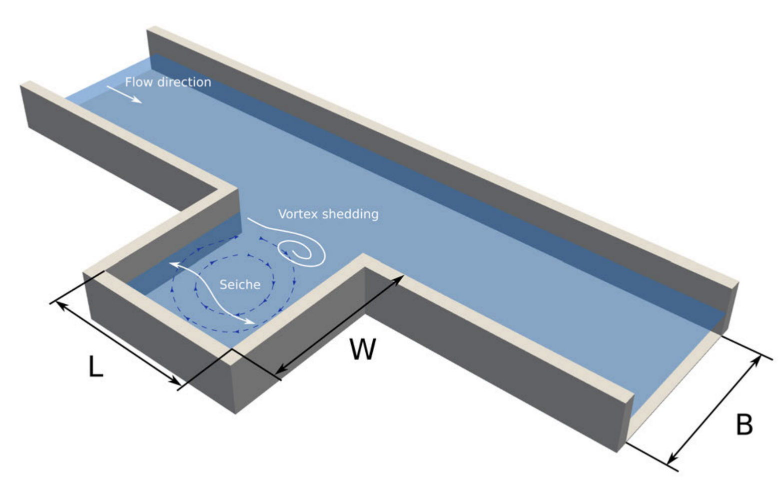
1. Resonant shallow-flows in lateral cavities

The study of resonant shallow flows past a lateral cavity is of great relevance due to their interest in civil and environmental engineering [1]. Such flows exhibit the presence of a standing gravity wave, called seiche, which is coupled with the shedding of vortices at the opening of the cavity. A complete understanding of such phenomenon is necessary as it may determine the mass exchange between the main channel and the cavity [2]. A better insight into this phenomenon helps to improve the design and implementation of innovative river bank restoration techniques.

An experimental study of the resonant flow in a laboratory flume with a single lateral cavity is herein presented. Five different flow configurations at a fixed Froude number (Fr=0.8) are considered. The main novelty of the present work is the use of a pioneering non-intrusive experimental technique [3] to measure the water surface at the channel-cavity region. This optical technique offers high resolution 2D data in time and space of the water surface evolution, allowing to determine the relevant features of the seiche oscillation, i.e. spatial distribution of oscillation nodes and anti-nodes, oscillation modes and amplitude of the oscillation. Such data are supplemented with Particle Image Velocimetry measurements to perform a more detailed study of the resonance phenomenon. High-resolution two-dimensional amplitude oscillation maps of the seiche phenomenon are presented for the experimental water depth. Experimental velocity fields inside the cavity are presented and confirm the inherent coupling between the unstable shear layer at the opening of the cavity and the gravity standing wave. The high quality of the experimental data reported in this work makes this data set a suitable benchmark for numerical simulation models in order to evaluate their performance in the resolution of turbulent resonant shallow flows.



2. Experimental setup

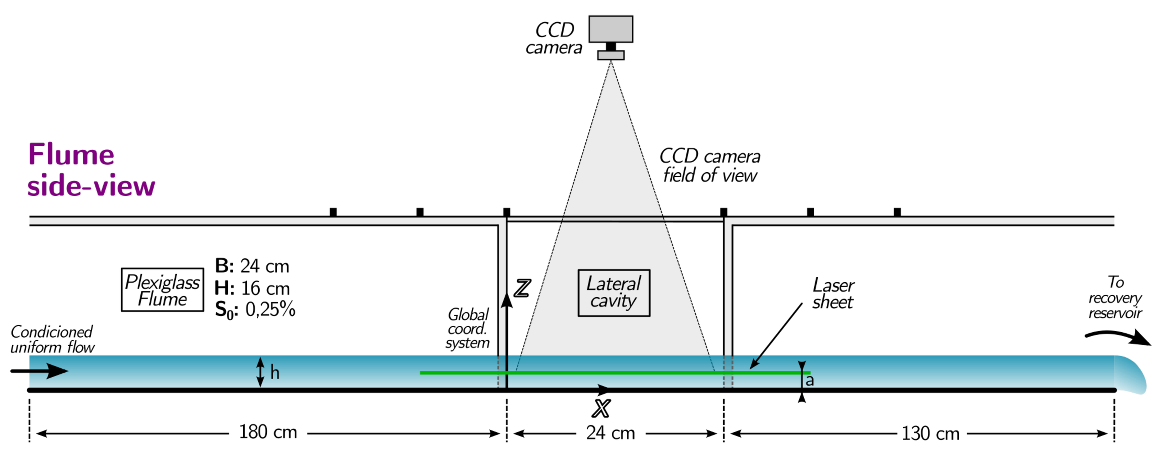
Experimental facility

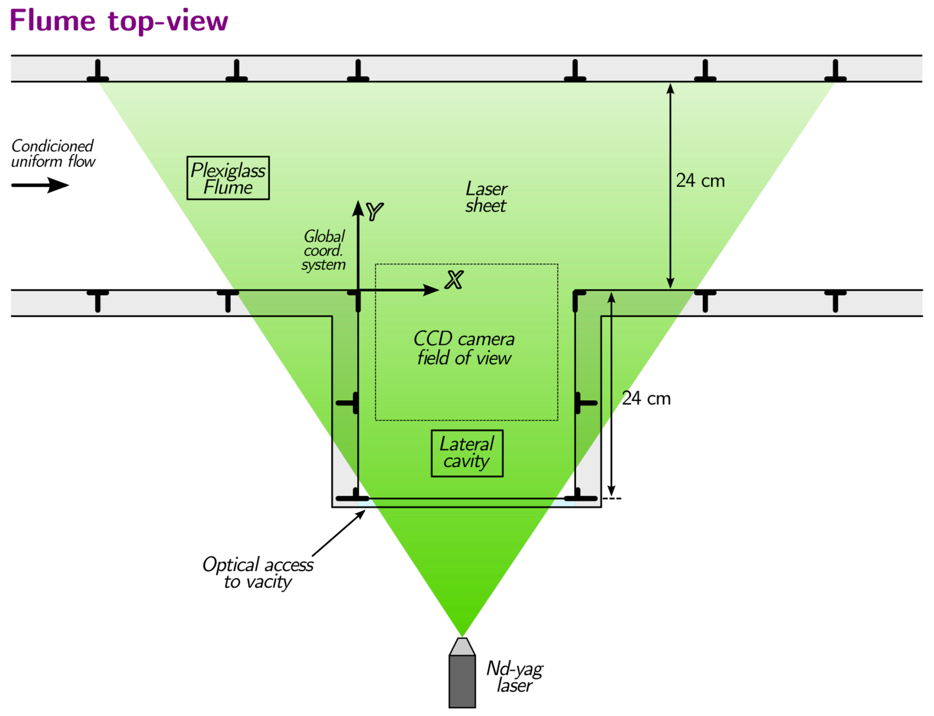
The experimental facility consists of a recirculating, free-surface open channel made of methacrylate. The channel is 6 m long with a constant B = 24 cm width rectangular cross-section. The measurement reach started 2.66 m downstream the channel inlet and ws 3.34 m long with 0.25% longitudinal slope. A square lateral cavity 24 × 24 cm (width to length ratio W/L = 1) also made of methacrylate was placed on one side of the channel, separated 1.80 m meters from the measurement reach beginning, ensuring fully developed flow. The inflow to the channel was from an upstream reservoir, which was fed using a recirculation system from a recovery tank placed at the end of the channel. The inflow discharge was controlled using a flowmeter inserted in the recirculation conduit.

Description of the experiments

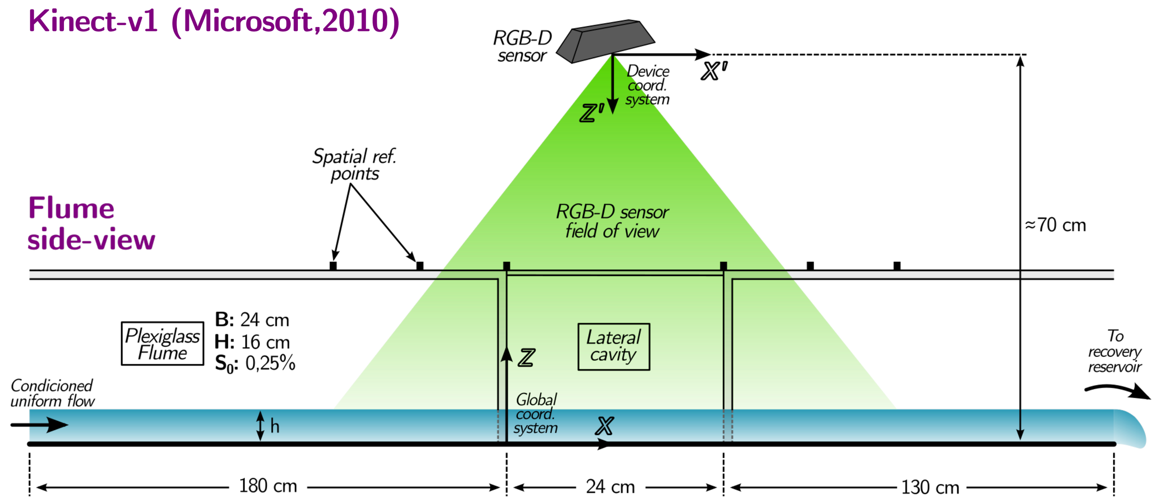
The uniform flow conditions at the measurement reach were varied by adjusting the discharge at the channel inlet. Five different steady experiments were carried out S6, S8, S10, S12 and S14 with constant inflow discharges 6, 8, 10, 12, and 14 m3/h respectively. The Froude number at the main channel was 0.8 for all the cases, whereas the Reynolds number varied from around 5000 (S14) to 2400 (S6).

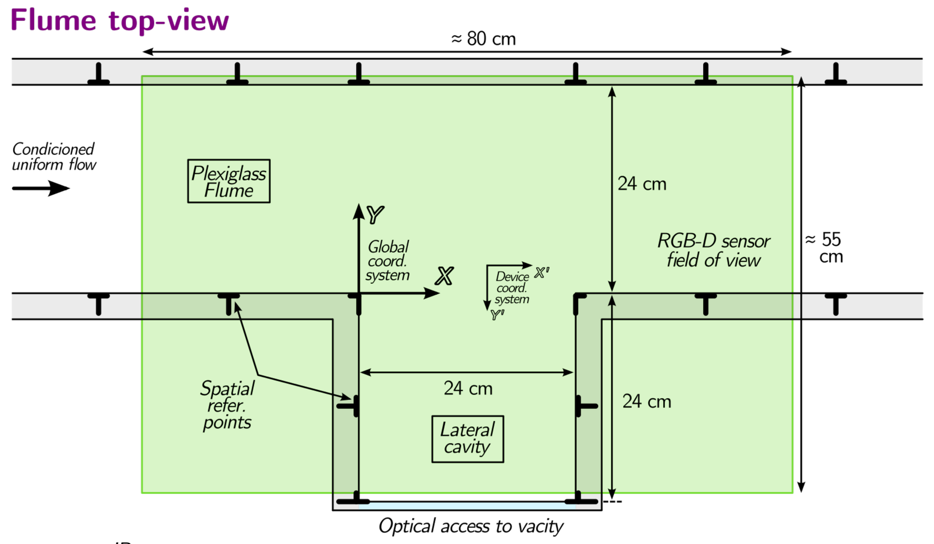
PIV velocity measurement

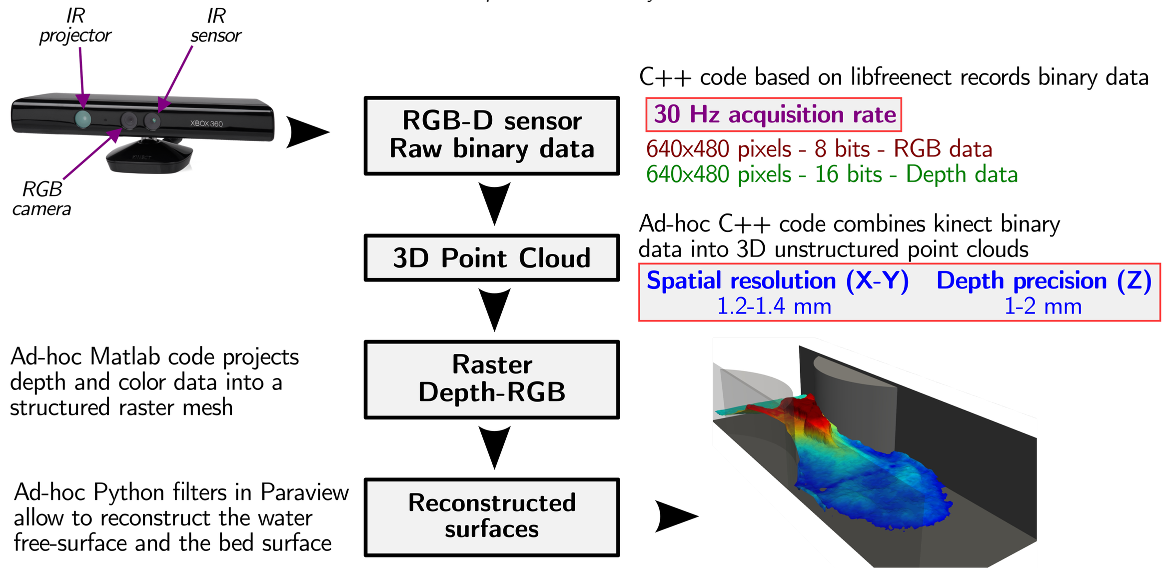




Water surface measurement with RGB-D sensor

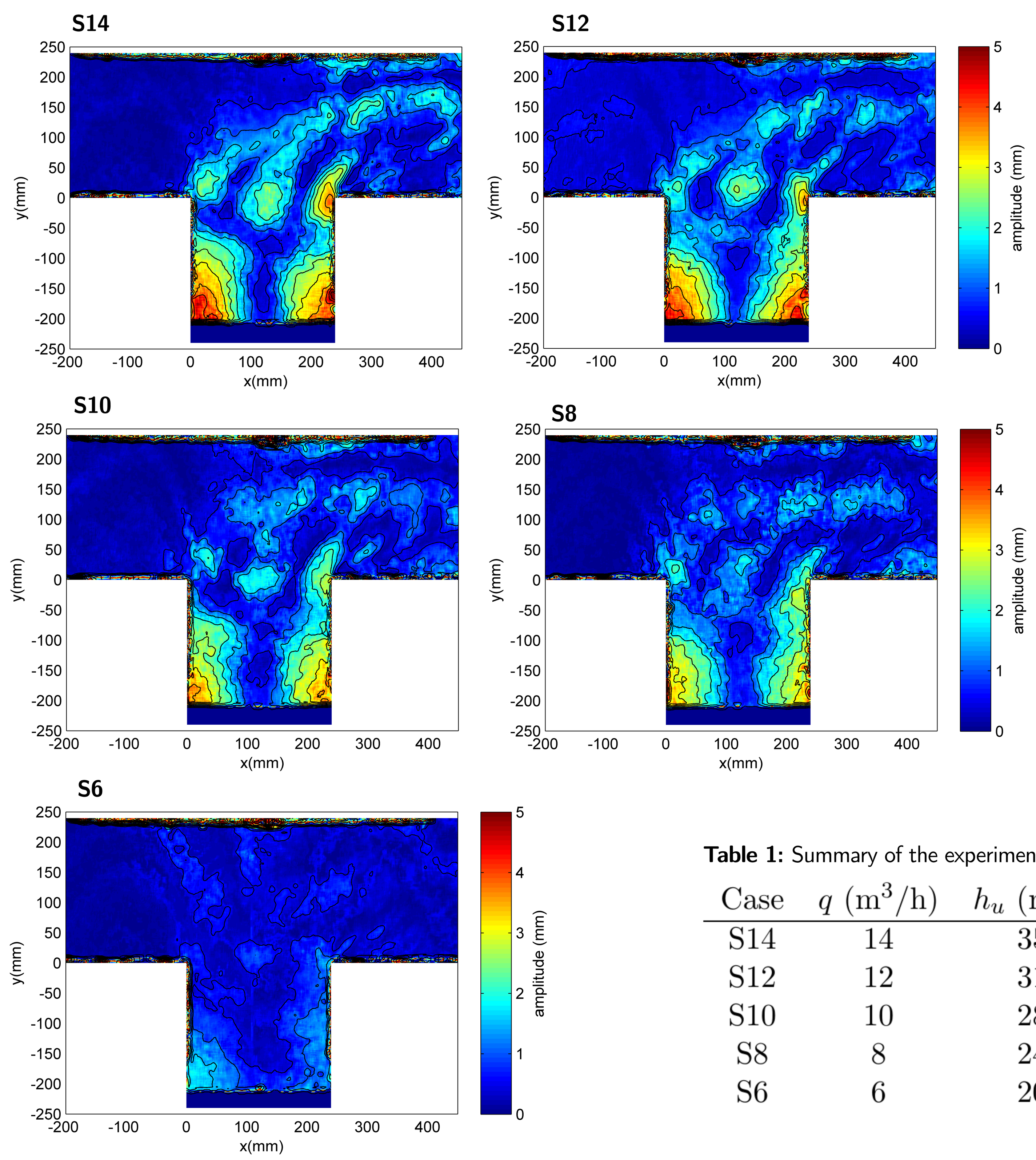






3. Experimental results

Free surface oscillation at the channel-cavity region: 2D map of the seiche patterns



The longitudinal seiche inside the lateral cavity was observed in all the experiments, being stronger for the cases with higher discharge. The spatial distribution of the amplitude of the first oscillation mode (i.e. associated to the fundamental seiche frequency, k = 1) was computed from the 2D water surface elevation time series. This representation allows to visually analyze the oscillation patterns in the channel-cavity region.

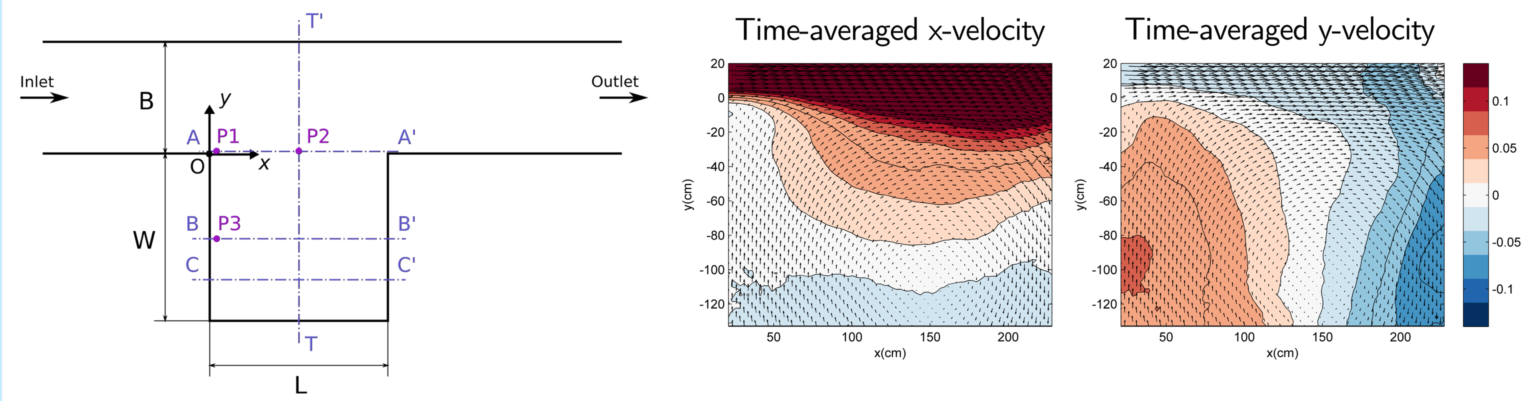
It was observed that the strongest water surface elevation variations appears inside the cavity and corresponds to the seiche oscillation. Seiche amplitudes ranged from almost 4.5 mm, for the case S14 to less than 2 mm, for the case S6. The seiche direction was observed to be streamwise, as the oscillation node is located at the crosswise section T-T' of the channel-cavity region. This means that the oscillation wavelength is twice the width of the cavity. Both experimental and numerical results show that the strength of the seiche is reduced as moving from the innermost region of the cavity to the positive region of the y axis.

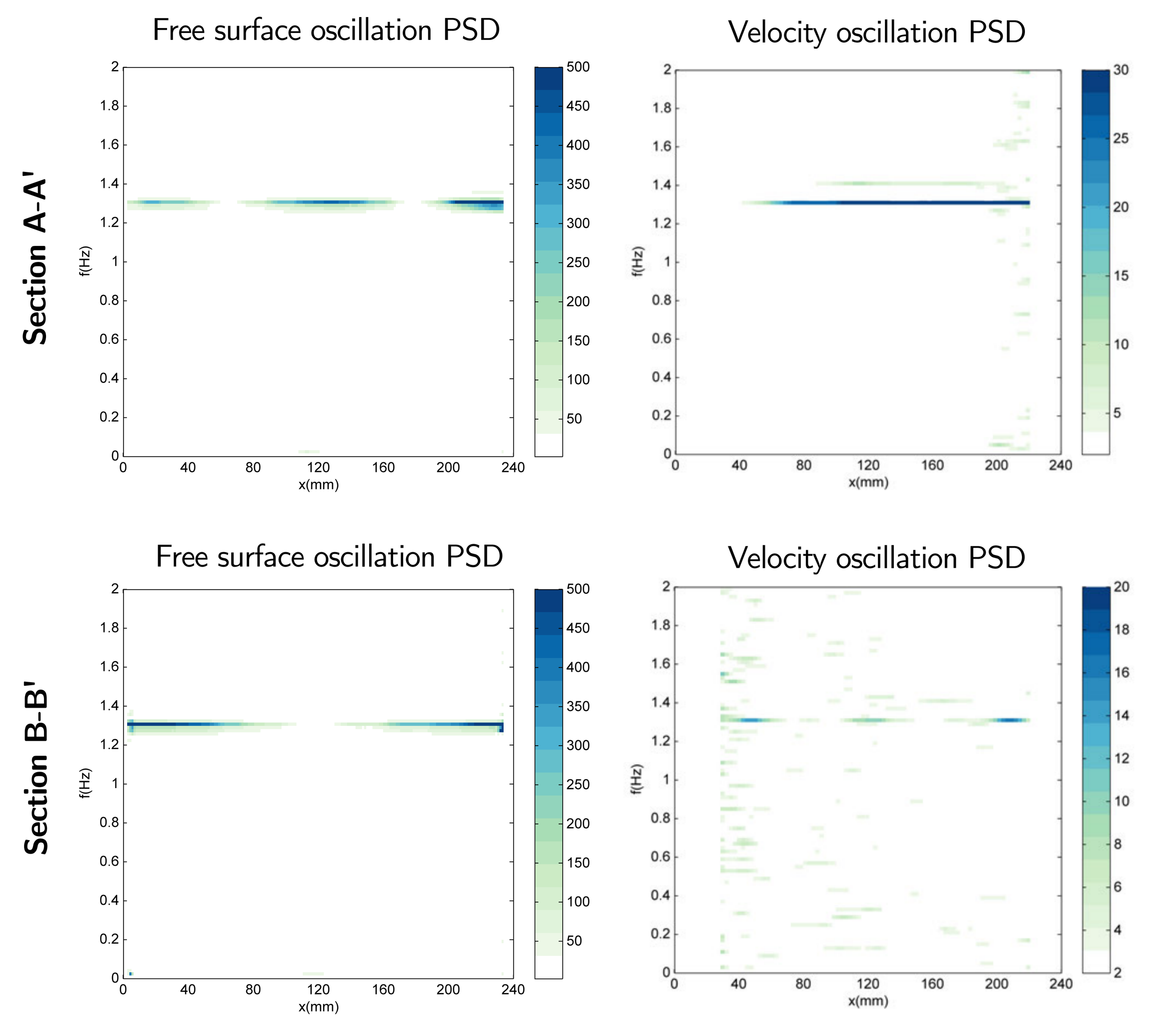
The maximum seiche amplitude, denoted as Δh, it is one order of magnitude lower than the water depth and it is observed to decrease as the discharge is reduced. If calculating the dimensionless seiche amplitude as the ratio $\Delta h/h_u$, with h_u the water depth upstreamthe cavity, it is observed that this quantity is around 0.13 for cases S8, S10, S12 and S14. Contrarily, for S6 the strength of the seiche is much lower. The measured seiche period T_{exp} showed a good agreement with the corresponding theoretical value T_{theo}, estimated as T_{theo}=$2L/nc$ where L = 0.24 m, n = 1 (i.e. first harmonic) and c=$(gh_u)^{0.5}$, using h_u as an estimation of the water depth in the cavity.

Table 1: Summary of the experimental results for the water surface oscillation

Case	q (m^3/h)	h_u (mm)	Fr	Re	T_{exp} (s)	T_{theo} (s)	$\Delta h_{k=1}$ (mm)	$\Delta h/h_u$
S14	14	35	0.79	5018	0.77	0.82	4.29	0.123
S12	12	31	0.81	4415	0.80	0.87	4.04	0.130
S10	10	28	0.79	3754	0.84	0.92	3.53	0.126
S8	8	24	0.80	3086	0.91	0.99	3.19	0.132
S6	6	20	0.78	2381	1.00	1.08	1.72	0.086

Flow velocity in the cavity: Coupling between free surface oscillation, seiche and vortex shedding





The velocity measurements evidence a clear vortical flow circulation inside the cavity for all the cases. The location of the center of the main vortex is closed to the center of the cavity. Here only case **S14** is showed, where the seiche was strongest. There exists a coupling mechanism between the vortex shedding at the opening of the cavity (Section A-A') and the seiche (Section B-B').

In order to analyze the spatial variation of the oscillation modes, both in the water surface elevation and the velocity module, the normalized power density spectrum (PSD) along the sections A-A' and B-B' were computed for all the experiments.. The PSD distribution of the experimental water surface elevation and velocity module evidences that the fundamental oscillation mode is associated to the seiche in the cavity (Section B-B'), with a measured frequency that matches the theoretical estimation (see Table 1). It is worth noting that the velocity oscillation also occurs according to the seiche frequency at the oppenig of the cavity (Section A-A'). In general, no significant secondary oscillation modes are observed in the experimental water surface and velocity oscillations. Particularly, the presence of the transverse seiche (oscillating at half the longitudinal seiche frequency) is not detected in the frequency analysis.

Acknowledgements

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