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1 **EMERGING OBSTACLES IN SUPERCRITICAL OPEN-CHANNEL FLOWS:**

2 **DETACHED HYDRAULIC JUMP VS. WALL-JET-LIKE BOW-WAVE**

3 N. Riviere¹

4 Professor, Université de Lyon, LMFA, INSA de Lyon, 20 av. A. Einstein, 69100 Villeurbanne, France

5 G. Vouaillat

6 Graduate Student, Université de Lyon, LMFA, INSA de Lyon, 20 av. A. Einstein, 69100 Villeurbanne, France

7 G. Launay

8 Graduate Student, Université de Lyon, LMFA, INSA de Lyon, 20 av. A. Einstein, 69100 Villeurbanne, France

9 E. Mignot

10 Associate Professor, Université de Lyon, LMFA, INSA de Lyon, 20 av. A. Einstein, 69100 Villeurbanne, France

11
12 **Keywords: supercritical flow, open-channel, obstacle, hydraulic jump, wall jet, bridge**
13 **pier, tsunami**

14 **Abstract**

15 A supercritical open-channel flow can skirt an emerged obstacle by using two distinct forms
16 of workaround: a detached hydraulic jump or a so-called "wall-jet-like bow-wave". These two
17 forms stem from the properties of supercritical flow and are described with details.
18 Experiments assess the conditions of appearance of one form or the other, depending on both
19 the upstream Froude number and flow depth to obstacle width ratio. A conceptual model,
20 based on mass conservation, reproduces and explains the corresponding transition. For the
21 wall-jet-like bow-wave, additional information is given regarding the water depth oscillations;
22 the associated Strouhal number show they are caused by the reverse spillage on the obstacle
23 face. Implications of the present results on scouring and on forces exerted by the flow on
24 structures justify future works on the subject.

¹ Corresponding author : nicolas.riviere@insa-lyon.fr

25 **Introduction**

26

27 Emerging boulders in mountainous watercourses, buildings within the inland flow
28 following a tsunami event, bridge abutments in a flooded floodplain, bridge piers in
29 supercritical rivers in piedmont plains, vehicles in sloping streets during urban floods,
30 avalanche protection devices, *etc.*, are examples of impervious, emerged obstacles embedded
31 in supercritical, open-channel flows. It is observed that the supercritical flow can use two
32 distinct ways of workaround to skirt such obstacles: a detached hydraulic jump or a so-called
33 "wall-jet-like bow-wave". The scientific questions of the present work are the conditions of
34 appearance and the mechanisms associated with each of these two workarounds. First, widely
35 spread results concerning the deflection of a supersonic gas flow are worth reminding, as they
36 present strong analogies with our open-channel supercritical flow problem.

37 *Compressible flows and detached shock waves*

38 An impervious obstacle forces a compressible flow to deviate in order to skirt it. The
39 corresponding workaround adopts different forms, depending on the flow regime and on the
40 obstacle shape. When the flow is subsonic, its velocity is smaller than the speed of sound:
41 disturbances created by the presence of the obstacle can travel upstream. They cause the
42 curvature of the streamlines that ensures the flow deflection. Figuratively speaking, subsonic
43 flows anticipate the presence of the obstacle and the deflection is gradual, through a
44 streamlines curvature. When the flow is supersonic, its velocity is higher than the speed of
45 sound and disturbances created by the presence of the obstacle cannot go back up the flow.
46 Figuratively speaking again, a supersonic flow does not anticipate the presence of the obstacle
47 and the deflection is sudden, through a shock wave that adopts two forms. When the
48 deflection required to skirt the obstacle is small enough (case of slender bodies), an oblique
49 shock wave performs the deflection. The streamlines remain straight lines but experience an

50 abrupt change of direction through the shock. The limit between such a small deflection and a
51 strong deflection described hereafter (or between a slender and a blunt body) is not purely
52 geometrical. It corresponds to the maximum deflection angle θ_{\max} allowed by an oblique
53 shock which depends on the upstream Mach number M (Shapiro, 1953) and can be derived
54 using mass and momentum balances (Jaumotte, 1971): θ_{\max} is in the range $0-34^\circ$ for $M=1-3$. If
55 the deflection exceeds this threshold value (case of blunt bodies), a detached shock wave
56 forms upstream from the obstacle. Within the zone delimited by the obstacle and the shock,
57 the flow becomes subsonic and anticipates the presence of the obstacle: the curvature of the
58 streamline is possible and performs the deflection of the flow. Mass and energy
59 considerations allow estimating the detachment length of the shock (Moeckel, 1949) for
60 axisymmetrical bodies, and for 2D obstacles that are more similar to the present problem.

61 ***Supercritical open-channel flows and detached hydraulic jumps***

62 Similar phenomena characterize the deflection of an open channel flow by an emerged
63 obstacle. If the flow is subcritical, it deviates progressively through a streamlines curvature,
64 which is additionally combined with backwater effects. If the flow is supercritical, such
65 gradual phenomena are not possible as the flow velocity is higher than the celerity of the
66 gravity waves. In such case, if the deflection is small enough (case of an emerged, sharp
67 obstacle), it is carried out by an oblique hydraulic jump. The maximum deflection angle θ_{\max}
68 through such an oblique jump depends on the upstream Froude number Fr . From mass and
69 momentum considerations, Ippen (1951) provides a graphical representation of θ_{\max} which is
70 in the range $0-33^\circ$ for $Fr=1-3$. This range is comparable to the one encountered with
71 compressible flows (see preceding section), and was corroborated by experiments on two
72 supercritical flows deflecting each other (Mignot *et al.*, 2008). Considering the analogy with
73 compressible flows, the case of deflection angles exceeding θ_{\max} (case of blunt emerged

74 obstacles) corresponds to the formation of a detached hydraulic jump upstream from the
75 obstacle. Indeed, authors such as Defina and Susin (2006), Mignot and Riviere (2010) or
76 Mignot *et al.* (2016) observed such a detached hydraulic jump around rectangular, wide
77 obstacles. Detached hydraulic jumps also form in supercritical granular flows (Cui and Gray,
78 2013), as observed in the field around avalanche protection devices (Faug *et al.*, 2015).

79 ***The so-called “wall-jet-like bow-wave” and the present scientific issues***

80 However, in the field, the flow observed around blunt obstacles such as bridge piers or
81 boulders in supercritical rivers can take a quite different form, which contradicts apparently
82 the preceding classification of supercritical flow deflections. This form is named herein "wall-
83 jet-like bow-wave", *i.e.* a bow-wave formed by an upward wall-jet on the obstacle upstream
84 face. Photograph of Figure 1 depicts such a flow, around a bridge pier, in the "Rivière des
85 Galets", La Réunion Island, France. The flow manages to skirt the obstacle without forming a
86 detached hydraulic jump. Yet, the curvature of the streamlines in the horizontal plane is
87 theoretically impossible as neither a detached hydraulic jump, nor the associated subcritical
88 zone downstream, form. The present paper focuses on this apparent paradox and the
89 competition between the two flow forms: the detached hydraulic jump and the wall-jet-like
90 bow-wave. It is organised as follows. As the work is mainly experimental, section 2 is
91 devoted to describe the two different facilities used. Section 3 provides a detailed description
92 of the two flow forms. Section 4 establishes the conditions of transition from one form to
93 another, which is explained using a conceptual model. Section 5 provides additional
94 characteristics of the wall-jet-like bow-wave: water depth and associated fluctuations in the
95 vicinity of the stagnation point. Section 6 sums-up the main findings of this work, completed
96 by some discussions and prospects.

97 **Physical modelling and experiments**

98 *Dimensional analysis*

99 The problem involves parallelepipedal obstacles, within a uniform supercritical flow in a
100 prismatic, rectangular channel. The seven dimensional variables that characterize the flow are
101 thus: the uniform upstream water depth h , the upstream mean velocity U , the obstacle width
102 R , the water properties (density ρ , dynamic viscosity μ and surface tension with air σ) and the
103 gravity acceleration g . Indeed, as the flow is supercritical, the obstacle length (in the
104 streamwise direction) is not considered: it was checked experimentally that it only modifies
105 the wake. Moreover, only parallelepipedal obstacles, emerged with a flat face in front of the
106 flow, are considered herein and R is enough to characterize the whole obstacle shape. Finally,
107 the channel width B is always large enough compared to the obstacle width R so that
108 disturbances induced by the presence of the obstacle reach the walls downstream from the
109 obstacle (see Defina and Susin, 2006), again with no influence on the flow around the
110 obstacle in a supercritical flow. Hereafter, the paper focuses on three flow features which are
111 the flow form (wall-jet-like bow-wave or detached hydraulic jump), the water depth h_{jet} at the
112 stagnation point on the obstacle face and the peak frequency f_p associated with the
113 fluctuations of this water depth. These three features depend on the seven parameters cited
114 above, and this reads:

$$115 \quad (\text{flow form}, h_{jet}, f_p) = \Phi(h, R, U, \rho, \mu, g, \sigma) \quad (1)$$

116 Vaschy-Buckingham's Π -theorem, with h as length scale, h/U as time scale and ρh^3 as mass
117 scale, reduces Eq.(1) to a dependency of the three dimensionless flow features on four
118 dimensionless parameters:

$$119 \quad \left(\text{flow form}, \frac{h_{jet}}{h}, \frac{f_p h}{U} \right) = \Phi \left(\frac{h}{R}, \text{Fr} = \frac{U}{\sqrt{gh}}, \text{Re} = \frac{4\rho U h}{\mu}, \text{We} = \frac{\rho U^2 h}{\sigma} \right) \quad (2)$$

120 where h/R is the depth to obstacle width ratio, Fr the upstream Froude number, and Re the
 121 upstream Reynolds number based on the upstream water depth (justified notably when
 122 considering $h \ll B$). We is the Weber number that accounts for capillary effects due both to
 123 surface tension and local water/air interface curvature. These dimensionless parameters can be
 124 rearranged. We can be combined with Fr and Re to form the Morton number Mo (*e.g.* Kobus,
 125 1984 ; Chanson, 2009 ; Mignot and Riviere, 2010) as:

$$126 \quad Mo = \frac{g\mu^4}{\rho\sigma^3} = \frac{We^3}{Fr^2(Re/4)^4} \quad (3)$$

127 Mo depends only on the physical properties of the fluid and on the gravity acceleration. It is
 128 constant when considering that both present experiments and typical field engineering
 129 situations involve water and air, on earth. Replacing We by Mo suppresses one dimensionless
 130 parameter (as Mo is constant): this is beneficial when seeking for an empirical correlation. It
 131 should be noted, however, that such a correlation will be invalidated when using other fluids,
 132 characterized by another Mo value. Similarly, surface tension effects accounted for by We
 133 will not be quantified, as it is addressed in the "Discussion on scale effects" section. Finally,
 134 some of the dimensionless parameters are recombined to enhance their physical meaning. It is
 135 indeed more meaningful to compare h_{jet} with the kinetic height of the incoming flow (as
 136 detailed in section "Properties of the wall-jet-like bow-wave"). In the same way, it is more
 137 meaningful to form a Strouhal number St comparing the peak frequency f_p with the time scale
 138 $2U/g$ associated with the reverse spillage (as detailed in section "Discussion on scale
 139 effects"). Hence, at last, the three flow features of interest depend on the flow characteristics
 140 as follows:

$$141 \quad \left(\text{flow form, } h_{jet}^* = \frac{h_{jet}}{U^2/2g}, S_t = \frac{2f_p U}{g} \right) = \Phi\left(\frac{h}{R}, Fr, Re, Mo\right) = \Phi\left(\frac{h}{R}, Fr, Re\right) \quad (4)$$

142 where Mo is finally discarded as it is a constant. As a brief, all the flow features will depend
143 on three dimensionless parameters: h/R , Fr , Re . Next section describes the experiments used
144 to characterize this dependency.

145 ***Experimental Facilities***

146 Two different facilities are used: one water table and one open-channel (Figure 2). Facility 1
147 is a water table previously used for the study of detached hydraulic jump (Mignot and Riviere,
148 2010). It is characterized by a very high width to depth ratio B/h allowing thus to avoid any
149 lateral confinement effect (Mignot *et al.*, 2016). The walls are made of glass. The slope can be
150 continuously adjusted up to several percent. The water is provided from a 400L tank through
151 different screens that straighten and smooth the flow. Facility 2 is an open-channel, with
152 adjustable slope, vertical glass walls and a steel bottom (Lelouvetel *et al.*, 2009). Compared to
153 the water table, it is characterized on the one hand by higher discharges and water depths, but
154 on the other hand by a smaller width $B=0.25\text{m}$ which imposes experiments with narrow
155 obstacles (namely $R<40\text{ mm}$) to avoid any lateral confinement effect. The water is provided
156 by a constant level tank, fed from an underground sump. Table 1 sums-up the characteristics
157 of these two facilities: width B , useful length L , distance from the entrance to the obstacle L_u ,
158 range of discharge Q_v , range of water depth h upstream from the obstacle, range of mean
159 velocities $U=Q_v/Bh$, range of obstacle width R . h is the normal depth, upstream from – and
160 undisturbed by – the obstacle. Indeed, the ratio L_u/h is always higher than 40 in facility 1,
161 higher than 100 in facility 2 so that the flow can be considered as fully developed when
162 reaching the obstacle for most of the experiments. Changing simultaneously the discharge, the
163 channel slope and the obstacle width allows modifying h/R , Fr and Re independently. The
164 corresponding ranges of these dimensionless parameters are given in table 1 for the two
165 facilities.

167 ***Instrumentation***

168 In both facilities, an electromagnetic flowmeter measures the discharge and a limnimeter
169 measures the water depth upstream from the obstacle. Associated uncertainties ΔQ_v
170 (discharge) and Δh (upstream water depth) are different for the two facilities and given in
171 table 1. Additionally, water depth elevation and its fluctuations on the obstacle front are
172 measured using conductive wave probes (Wave Monitor, from Churchill Control) with an
173 acquisition frequency of 10 Hz, during 300 seconds. The gap between the two tips is
174 shortened to 2 mm in order to increase the probe sensitivity. The probe is fixed directly on the
175 obstacle upstream face, in the symmetry plane, and its calibration is performed with the same
176 geometry. The uncertainty was estimated to 0.5 mm (Mignot *et al.*, 2008). The signal
177 associated with free-surface oscillations at the stagnation point is then processed to obtain the
178 time-averaged, the standard deviation (not shown here) and the corresponding peak
179 frequencies in the energy spectra provided by FFT with an averaging over short periodograms
180 (Welch, 1967). These experiments are performed only in the open-channel (facility 2)
181 associated to higher velocities; indeed, in the water table (facility 1), the oscillations are of so
182 limited amplitude that no peak frequency can be sorted out from the physical noise created by
183 the free-surface disturbances unavoidable in supercritical flows. Finally, a camera (Manta G-
184 223b, 400Hz at 150x150 pixels, by Allied Vision, associated to an AF Nikkor 20-35mm
185 f/2.8D lens by Nikon) mounted below the transparent bottom and a horizontal laser sheet
186 introduced through the right wall 1mm above the bottom allow to characterize horizontal
187 pathlines in the vicinity of the obstacle by injecting home-made fluorescent particles (as
188 proposed by Pedocchi *et al.*, 2008) with an average diameter 25 μm .

190 **Description of the two flow forms**

191 The detached hydraulic jump in a supercritical, open-channel, water flow was already
192 described by Defina and Susin (2006), Mignot and Riviere (2010) and Mignot *et al.* (2016). In
193 a top view (Figure 3), the jump toe forms a hyperbola, which asymptotes form an angle β_∞
194 with the upstream flow direction, such as $\sin(\beta_\infty)=1/Fr$. The corresponding detachment length
195 λ_{jump} equals several times the water depth. As the supercritical flow crosses the jump (side
196 view, Fig. 3), it experiences an abrupt water depth increase and experiences locally a
197 subcritical regime. The backwater curve is pronounced, due to the presence of a stagnation
198 point which causes the formation of a small bow-wave, as observed around bridge piers in
199 subcritical rivers (Richardson and Panchang, 1998). This backwater curve causes a strong
200 adverse pressure gradient which promotes the boundary layer separation and the appearance
201 of a horseshoe vortex (Ballio *et al.*, 1998). This vortex strongly interacts with the hydraulic
202 jump both on fixed beds (Mignot and Riviere, 2010; Riviere *et al.*, 2012) and in presence of
203 scouring (Mignot *et al.*, 2016). The pathlines on Figure 4 clearly show that (i) the flow
204 deviates through a streamlines curvature downstream from the toe of the jump and that (ii) the
205 horseshoe vortex detachment length λ_{hsv} is of the order of h .

206 The so-called wall-jet-like bow-wave, described by Figure 5, is significantly different from
207 the detached jump. The flow deviates abruptly upward, very close to the obstacle, at a
208 distance of about one water depth h upstream from the obstacle, which is also the scale of the
209 radius of curvature at the jet basis (side view, Figure 5). A vertical wall-jet forms on the
210 upstream face of the obstacle, quite similar to impinging liquid jets in air (*e.g.* Wilson *et al.*,
211 2012) but with two distinct features. First, the bottom wall forms a 90° angle with the obstacle
212 front face, which acts as a bucket on the flow, causing a deviation from a horizontal to a
213 vertical direction. Second, the lateral confinement exerted by the surrounding, non deflected,
214 supercritical flow prevents the jet from spreading laterally. This is shown by the horizontal

215 pathlines near the bottom (Figure 6) where, conversely to the detached jump case, no
216 upstream streamline curvature is visible till the very vicinity of the obstacle, *i.e.* a distance of
217 the order of $0.1h$. The adverse pressure gradient starts at the same location as the jet
218 deflection, so that the streamwise extent of the horseshoe vortex considerably reduces with a
219 detachment length λ_{hsv} of the order of $0.1h$. As a consequence, the flow is not disturbed by the
220 obstacle until reaching its close surrounding. On the obstacle face, the upward jet separates
221 towards both sides of the stagnation point and forms two lateral jets outing in a top-side
222 diagonal direction from the obstacle corners (top view, Figure 5). The jet, in its upper part, in
223 front of the obstacle, has the form of a breaking bow-wave with a reverse spillage, which
224 causes periodic oscillations of the jet. Indeed, as water from this spillage falls into the
225 supercritical flow, upstream from the obstacle, it suddenly reduces the kinetic energy of the
226 flow, and so the water elevation at the stagnation point. This suppresses the spillage: the
227 upstream flow recovers its initial kinetic energy and this is the beginning of a new cycle. With
228 these wall-jet-like bow-waves, the deflection of the jet is directed in the upward direction. In
229 other words, the discharge blocked by the obstacle is deviated outside from the flow, where it
230 is reintroduced downstream from the obstacle, disregarding of the possible reverse spillage.
231 This is completely different from the hydraulic jump case, where the blocked discharge is
232 deviated laterally and always remains within the main flow.

233

234 **Condition of appearance of the flow forms**

235 *Condition of occurrence of the wall-jet-like bow-wave in experiments*

236 The condition of appearance of one form or the other is correlated to the dimensionless flow
237 parameters by observing the form obtained under a large number of experimental conditions,
238 including both supercritical and subcritical flows. A first set of experiments was performed

239 using the water table facility 1 and a second one using the open-channel facility 2.
240 Corresponding ranges of parameters are listed in table 1. These two sets are plotted on Figure
241 7, in a $(Fr, h/R)$ plane. The open symbols correspond to the upward deflection of the flow by a
242 wall-jet-like bow-wave and are all located in the upper part of the graph and for $Fr > 1$. The
243 closed symbols correspond to a crosswise deflection of the flow by a streamline curvature and
244 backwater effects downstream a hydraulic jump (case of a supercritical upstream flows, $Fr > 1$)
245 or throughout the whole flow (case of a subcritical regime, $Fr < 1$).

246 Among the three parameters provided by Eq.(4), the couple of parameters $(Fr, h/R)$ is clearly
247 a selective criterion to characterize the flow typology. It is not the case for the Reynolds
248 number, as shown by the overlap of the two datasets obtained in the two facilities (triangles
249 for facility 1, squares for facility 2) with quite different ranges of Re (see table 1). In the
250 subcritical regime, no wall-jet-like bow-wave exists as the flow deflection starts upstream
251 from the obstacle: this is illustrated on Figure 7 by the sudden transition at $Fr=1$ from a wall-
252 jet-like bow-wave to a crosswise deflection, for $h/R > 2$. Now, in the supercritical regime, for a
253 given Froude number, the wall-jet-like bow-wave occurs for high h/R ratios and the detached
254 jump for smaller ones. For a given h/R ratio, the wall-jet-like bow-wave occurs for high
255 Froude numbers. As a brief, the increase of both h/R and Fr favours the appearance of the
256 wall-jet-like bow-wave. The conceptual model developed in next sections explains this
257 behaviour.

258 ***Conceptual model explaining the transition***

259 The deflection of the flow, either upward (wall jet) or crosswise (jump) is ruled by the mass
260 conservation: the impervious obstacle blocks a part Q_{in} of the incoming flow, which must be
261 evacuated elsewhere. As the flow is supercritical, Q_{in} simply reads:

$$262 \quad Q_{in} = RUh \quad (5)$$

263 Considering a wall-jet-like bow-wave, the discharge evacuated by the jet is estimated
 264 considering Figure 5. Assuming energy conservation from the flow to the jet initial horizontal
 265 section, the kinetic energy is also conserved as the sum of potential energy and pressure is
 266 constant. The velocity at the jet base is thus U . Considering mass conservation, with a
 267 velocity U , the jet section is still $(R.h)$. As its width is R , its thickness (in the streamwise
 268 direction) is h . This thickness decreases as and when the jet goes up, due to mass losses
 269 caused by lateral evacuation, and its average value is $e=C_1.h/2$. The jet can reach, at the
 270 stagnation point, a maximum height $h_{jet-max}=(C_2.C_3)U^2/2g$ above the upstream flow, where C_2
 271 and C_3 are constants that account respectively for head-losses ($C_2<1$) and for the kinetic
 272 energy coefficient upstream in the flow ($C_3>1$). The mean transverse outlet velocity is noted
 273 u_{out} , assumed such as $u_{out} = C_4U$ where C_4 ($C_4<1$) is a constant that accounts for both head
 274 losses and kinetic to potential energy transfers in the wall-jet. By considering $C=C_1C_2C_3C_4$,
 275 the maximum discharge $Q_{out-max}$ that can be evacuated through the two-sides of the wall-jet
 276 reads:

$$277 \quad Q_{out-max} = 2e h_{jet-max} u_{out} = CU \frac{U^2}{2g} h \quad (6)$$

278 The wall-jet-like bow-wave exists if and only if the jet is able to evacuate all the discharge
 279 blocked by the obstacle, in other words if $Q_{out-max} \geq Q_{in}$. Considering eqs. (5&6), this leads to:

$$280 \quad \frac{h}{R} > \frac{2}{C \cdot Fr^2} \quad (7)$$

281 This limit is plotted on Fig. 7, using $C=1.1$, and restricted, of course, to $Fr>1$. It corresponds
 282 fairly well to the transition observed experimentally. Most of the points corresponding to a
 283 wall-jet-like bow-wave are located above this limit, while most of those corresponding to a
 284 detached-hydraulic jump are located below. Hence, the mechanism, leading to one form or
 285 another, appears to be well understood, it simply relies on the mass conservation. For high h/R

286 ratios, corresponding to thin blunt (parallelepipedal) obstacles, the wall-jet is able to evacuate
287 the flow blocked by the obstacle. For small h/R ratios, corresponding to obstacles that are
288 wide with regards to the water depth, the wall-jet is not able to evacuate the whole blocked
289 discharge ($Q_{out-max} < Q_{in}$). Water must skirt the obstacle laterally, within the flow, and this
290 requires a streamlines curvature. The latter can be obtained only within a subcritical regime.
291 Thus, a hydraulic jump forms and replaces the wall-jet.

292 ***Transition and asymptotic behaviours***

293 Devoted experiments are undergone to characterize the transition from one form to another,
294 across the limit plotted in Figure 7. To do so, for a few given slopes, the discharge is
295 decreased little by little to pass from a wall-jet-like bow-wave to a jump and then increased
296 little by little to recover a wall-jet. These experiments show no hysteresis effect: the transition
297 occurs for the same discharge, *i.e.* for the same $(Fr, h/R)$ value in both cases. More, these
298 experiments reveal that the transition is not a brutal phenomenon: starting from a wall-jet-like
299 bow-wave, when decreasing little by little h/R and in a lesser extent Fr (by decreasing little by
300 little the discharge for a fixed slope), the reverse spillage is at first very rare, and then occurs
301 more often, creating each time, temporarily, a subcritical zone (and thus a detached jump)
302 upstream from the obstacle. When the reverse spillage occurs most of the time, the subcritical
303 zone remains almost all the time and this leads to the occurrence of the permanent detached
304 hydraulic jump. This indicates that the limit between the two forms in the $(Fr, h/R)$ plane
305 (Figure 7) is somehow subjective. To obtain the points of Figure 7, the following strategy is
306 used in the channel (facility 2): for a fixed h/R value, starting with a detached jump, the
307 Froude number is increased until an oscillation of the water depth on the obstacle front face is
308 observable. This indicates a spillage and is considered as the transition to the wall-jet-like
309 bow-wave. In the water table (facility 1), this transition is obtained as follows: the discharge is

310 increased little by little for a given slope, thus increasing h/R and increasing Fr at the same
311 time.

312 Note moreover that for high h/R values, the wall-jet-like bow-wave becomes similar to the
313 bow-wave around a ship-stem (e.g. Delhommeau *et al.*, 2009). In this case, the blocked
314 discharge Q_{in} is rapidly evacuated by the jet: the height on the obstacle face is clearly smaller
315 than the kinetic height, *i.e.* $h_{jet} < h_{jet-max}$, and the thickness e of the jet rapidly decreases and
316 becomes significantly smaller than h .

317

318 **Properties of the wall-jet-like bow-wave**

319

320 The detached hydraulic jump configuration was deeply investigated by Mignot and Riviere
321 (2010) and the present section is devoted to describe the other flow form considered herein:
322 the wall-jet-like bow-wave. With this flow form, the stagnation point is associated to water
323 depth elevation and oscillations.

324 ***Time-averaged water depth at the stagnation point***

325 The time-averaged jet height above the flow is h_{jet} (Figure 5). Its measured values, once made
326 dimensionless relative to the kinetic height, so that $h_{jet}^* = h_{jet}/(U^2/2g)$, are sketched on Figure
327 8-a, as a function of the Froude number, for different values of the depth to obstacle width
328 ratio h/R . The closed symbols correspond to hydraulic jumps. Watching the open symbols,
329 corresponding to wall-jet-like bow-waves, h_{jet}^* decreases as both Fr or h/R increase. This can
330 be explained again by the mass conservation. Indeed, with $Q_{out-max} > Q_{in}$, all the discharge Q_{in}
331 is evacuated before the wall-jet reaches the kinetic height and $h_{jet} < h_{jet-max}$. In other words,
332 $h_{jet}/h_{jet-max}$ decreases if $Q_{in}/Q_{out-max}$ decreases. Yet, from Eq. (7), the ratio $Q_{in}/Q_{out-max}$ reads:

333
$$\frac{Q_{in}}{Q_{out-max}} = \frac{2/C}{Fr^2 \frac{h}{R}} \quad (8)$$

334 This confirms that both $h_{jet}/h_{jet-max}$ and $h_{jet}^* = C_2.C_3.(h_{jet}/h_{jet-max})$, following the behaviour of
 335 $Q_{in}/Q_{out-max}$, decrease when increasing h/R (due to a decrease of Q_{in}) or when increasing Fr
 336 (due to an increase of both $h_{jet-max}$ and $Q_{out-max}$). Incidentally, h_{jet}^* is correctly fitted by the
 337 following correlation:

338
$$h_{jet}^* = 1.7 \left(\frac{h}{R} \right)^{-0.24} Fr^{\left(-0.24 \frac{h}{R} - 0.17 \right)} \quad (9)$$

339 which coefficients were determined using a least squares method. The agreement is shown by
 340 Figure 8-b, where the correlation provides results in the (-5%; +10%) range from
 341 experimental ones. Finally, it is worth noting that values $h_{jet}^* > 1$ are encountered. This is
 342 possible considering that the surface velocity U_{surf} is higher than the mean velocity U . A
 343 classical estimate of this velocity is $U_{surf} = U/0.8$ (e.g. Graf and Altinakar, 2000) and
 344 corresponds indeed to an upper bound of $h_{jet}/(U^2/2g)$ which is $1.6 \approx (1/0.8)^2$, depicted by the
 345 dashed line in Figure 8-a.

346 ***Water depth fluctuations***

347 In case of a wall-jet-like bow-wave, the water depth fluctuations at the stagnation point
 348 exhibit a clear peak frequency f_p that increases when Fr (Figure 9-a) or h/R (not shown here)
 349 increases. A Strouhal number St is defined to check the dependency of these depth
 350 fluctuations on the flow parameters and reads:

351
$$St = \frac{2U}{g} f_p \quad (10)$$

352 This number is the ratio of a characteristic time of advection in the flow, $2U/g$, and of the
 353 characteristic time of the water depth fluctuations, namely $1/f_p$. $2U/g$ is twice U/g which is a

354 characteristic time both for water to climb up to the stagnation point located at a height $U^2/2g$
355 above the free-surface, and for water to fall from this stagnation point down to the free-
356 surface (free-fall under gravity in the spillage). The St values are sketched on Figure 9-b: they
357 are distributed around an average value $St=0.84$, for all the experiments with $R \geq 20\text{mm}$. This
358 fixed value indicates that the time scale $2U/g$ is relevant and that the oscillating phenomenon
359 is linked to climbing and then falling down water associated with the reverse spillage.
360 However, Strouhal numbers differ for very small obstacle widths R ($R=10\text{mm}$ in Fig. 9-b),
361 while no oscillations are observed for very small water depths h , and this is discussed in the
362 next section, devoted to scale effects

363

364 **Discussion on scale effects**

365 The wall-jet-like bow-waves produced in the laboratory appear to be very similar to the ones
366 occurring in the field and depicted by Figure 1. However, as h or R strongly reduces, scale
367 effects occur as capillary effects become noticeable.

368 Obtaining small h/R values (namely $h/R < 0.5$) requires – at least with the present experimental
369 facilities – producing flows with small water depths. In this case, the jet presents an
370 alternative form named here “clinging bow-wave”. The water depth is almost constant at the
371 stagnation point, forms an upper roll edge with no reverse spillage and with the jet clinging on
372 the lateral walls of the obstacle. To check if this phenomenon is due to pressure effects, as it is
373 for a clinging nappe on a sharp crest weir, a rectangular plate replaces the obstacle. This plate
374 is an obstacle with negligible longitudinal length, and thus with no lateral walls, but same
375 width R as the obstacle. The jet on the plate face is not modified compared to the one obtained
376 with the standard obstacle. This shows that pressure effects on the lateral walls are not
377 responsible for the formation of the clinging bow-wave. The latter is rather attributed to

378 capillary effects. Dimensional analysis in Eq.4 showed that all flow physical phenomena are
379 accounted for by the quartet (h/R , Fr , Re , Mo). It is nevertheless useful to go back to the
380 Weber number as in Eq.2, as We gives relevant indications on the importance of these
381 capillary effects. Yet, a relevant length scale to compute this number is available: it is the
382 minimum radius of curvature at the air/water interface. We thus reads:

$$383 \quad We = \frac{\rho U^2}{\sigma} \min(h, R) \quad (11)$$

384 Clinging bow-waves correspond actually to the smallest values of the Weber number of the
385 present experimental dataset (table 1), and present the same features as surface tension driven
386 wall jets, notably the upper roll edge referred as "film jump" by Wang *et al.* (2013).
387 Unfortunately, models from these authors cannot be used herein as the present jet (i) with
388 bigger scales, remains mainly driven by gravity rather than by capillary effects, and (ii) does
389 not have a round section.

390 Oppositely, flows with high h/R values (higher than 3) are produced in the channel using
391 small width obstacles ($R=10\text{mm}$) to avoid any lateral confinement effect. With such narrow
392 obstacles, some-millimetres long elongated drops form at the jet tip and this is attributed to
393 capillary effects. This jet modification does not infer with the time averaged water depth on
394 the obstacle frontal face (plotted on Figure 8). Conversely, the new jet form modifies the
395 unsteady behaviour of the wall jet. A second frequency peak appears in the energy spectra
396 associated with the water depth variations, which is not a harmonic of the first one. It is
397 attributed to the free-fall of the elongated drops. The corresponding Strouhal numbers are
398 included on Figure 9-b (open symbols, with two St values for each (Fr , h/R) value) where they
399 form two populations: smaller values of about $St \approx 0.6$ and higher values of about $St \approx 1.7$. This
400 is different from the single average values of about $St \approx 0.84$ obtained for the wider obstacles,
401 ($R > 20\text{mm}$).

402 Such capillary effects are negligible at the field-scale relevant to hydraulic engineers. At the
403 laboratory scale, they do not influence the transition from a wall jet to a hydraulic jump. They
404 can modify the wall jet features and this may be experienced in other small-scale experiments.

405

406 **Concluding remarks and discussion**

407 This paper dealt with the two flow forms that can be encountered around a rectangular,
408 emerged obstacle embedded in a supercritical, open-channel flow. A first one is the "detached
409 hydraulic jump", for which the workaround of the obstacle is promoted by a streamlines
410 curvature, in a horizontal plane, allowed by the subcritical region between the jump and the
411 obstacle. A second one is the so-called "wall-jet-like bow-wave", for which the flow remains
412 supercritical until it reaches the obstacle, preventing from any streamline curvature in the
413 horizontal plane to skirt the obstacle. This apparent paradox – with a reasoning based on the
414 knowledge on 2D compressible flows – is explained by one property of the open-channel
415 flow: its vertical confinement between the bottom and the free-surface. Through the wall-jet,
416 the water can leave this confined region between the bed and the free-surface and the
417 workaround is performed outside from the main flow, without requiring a horizontal
418 streamline curvature. However, such a jet is not always able to evacuate all the water blocked
419 by the obstacle, especially when the obstacle width R becomes noticeably higher than the
420 water depth h . In this case, a detached hydraulic jump forms and replaces the wall-jet-like
421 bow-wave. The threshold ratio h/R , corresponding to this transition, decreases with the Froude
422 number, in agreement with a conceptual model that shows that the transition is driven by mass
423 conservation. Focusing on the wall-jet-like bow-wave, the wall-jet height above the flow is
424 also driven by mass conservation. It depends both on Fr and h/R , as summed-up by an
425 empirical correlation. Finally, the wall-jet is subject to height oscillations: the associated

426 Strouhal number was found to be constant, confirming that these oscillations correspond to a
427 cycle of climbing-falling down water associated to the reverse spillage on the upstream face.

428 *Discussion*

429 Nevertheless, still considering emerged obstacles, the present results may be quantitatively
430 modified by changing the obstacle shape. In presence of a wall-jet-like bow-wave, more
431 streamlined obstacles – such as obstacles with circular or ovoid horizontal sections that are
432 more representative of bridge piers – may facilitate the flow evacuation by the side jets. The
433 two flow forms will exist but the threshold curve $h/R=f(\text{Fr})$ marking the transition from one to
434 the other is expected to be lowered: the wall-jet-like bow-wave should form for smaller h/R
435 for a given Fr. The present results will also be modified when considering weakly emerged
436 obstacles. Part of the wall jet discharge will be evacuated above the obstacle, facilitating the
437 appearance of a wall-jet-like bow-wave *i.e.* again shifting the transition to smaller h/R values.
438 This corresponds typically to almost emerging boulders in supercritical rivers.

439 Present results may be used in different hydraulic engineer's applications. A first one is risk
440 mitigation. The supercritical flow encountered in sloppy streets during urban floods (Mignot
441 *et al.*, 2006) or within the inland flow following immediately a tsunami event (Matsutomi *et*
442 *al.*, 2001 ; Nandasena *et al.*, 2012) will interact differently with different kind of obstacles.
443 For a given Froude number, a wall-jet-like bow-wave will form around bridge piers with
444 $h/R>1$, as corroborated by the observations of Motley *et al.* (2015) but conversely, a detached
445 hydraulic jump will form around a building with $h/R<1$, as corroborated by Testa *et al.* (2007)
446 where the jumps formed around different buildings interact, causing a global increase of the
447 water depth in a model city. More generally, the results foreshadow huge variations of the
448 force exerted by supercritical flows on obstacles (building, piers, vehicles ...) as the water
449 depth elevation h_{jet} on the obstacle face can be significantly smaller than the kinetic height

450 $U^2/2g$. For the hydraulic jump, this is due to energy dissipation which depends on the Froude
451 number. For the wall-jet-like bow-wave, it was shown that $h_{jet}/(U^2/2g)$ depends both on Fr and
452 h/R . Future work should be devoted to characterize these forces. A second hydraulic
453 engineer's application related to the present results is scouring in supercritical flows. Boyer
454 and Roy (1991) show that, in supercritical regime, the scour depth upstream a boulder-like
455 obstacle is proportional to the water depth in front of the obstacle. This is consistent with
456 Mignot *et al.* (2016) who, in presence of a detached hydraulic jump, observed no fundamental
457 changes in the inception of scouring compared to subcritical flow cases. Indeed, upstream
458 from the obstacle, the flow reaches a subcritical regime through the jump; skirting the
459 obstacle, it accelerates at the upstream corners, increasing there the bed shear and causing the
460 scour inception, as observed in fully subcritical flow regimes (*e.g.* Diab *et al.*, 2010). In
461 presence of a wall-jet-like bow-wave, the lateral jets evacuate the discharge "outside" from
462 the flow and suppress the acceleration at the obstacle corners. Moreover, the water depth at
463 the obstacle stagnation point differs with a hydraulic jump and a wall-jet, and depends on the
464 two dimensionless parameters (Fr, Re). Hence, by modifying both velocities and water depth,
465 wall-jet-like bow-waves are expected to influence the scouring at the toe of piers, and this
466 should be addressed in future works.

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540

541

542 Table 1. Characteristics of the two experimental facilities

	Facility 1 (water table)	Facility 2 (channel)
Width B (m)	0.75	0.25
Length L (m)	1.2	9.24
L_u (m)	0.5	5
Q_v (L/s)	0.25 - 3.2	0.51 - 21.89
ΔQ_v	± 0.05 L/s	± 1 %
h (mm)	1.28 - 12.33	10 - 50
Δh (mm)	± 0.25	± 0.5
R (mm)	13 - 100	10 - 50
L_u/h	40.6 - 391	100 - 500
h/R	0.012 - 2.57	0.3 - 4
Fr	0.56 - 6.35	0.5 - 2.7
Re	1300 - 16000	10000 - 208000
We	1 - 50	5 - 800

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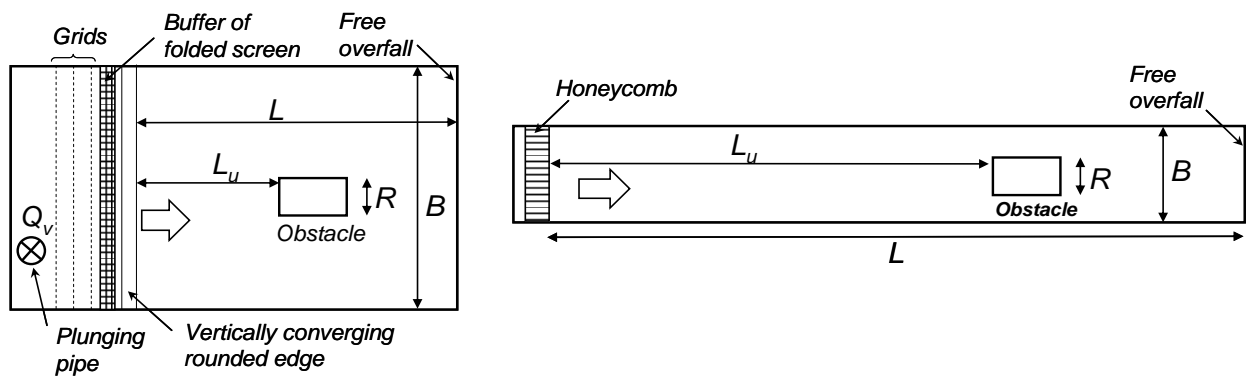
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547 *Figure 1. Photograph of the wall-jet-like bow-wave around a bridge pier in the "Rivière des*
548 *Galets", La Réunion Island, France, in March 2006. Courtesy of Paul Bonnet, DEAL 974 (ex*
549 *DDE 974)*

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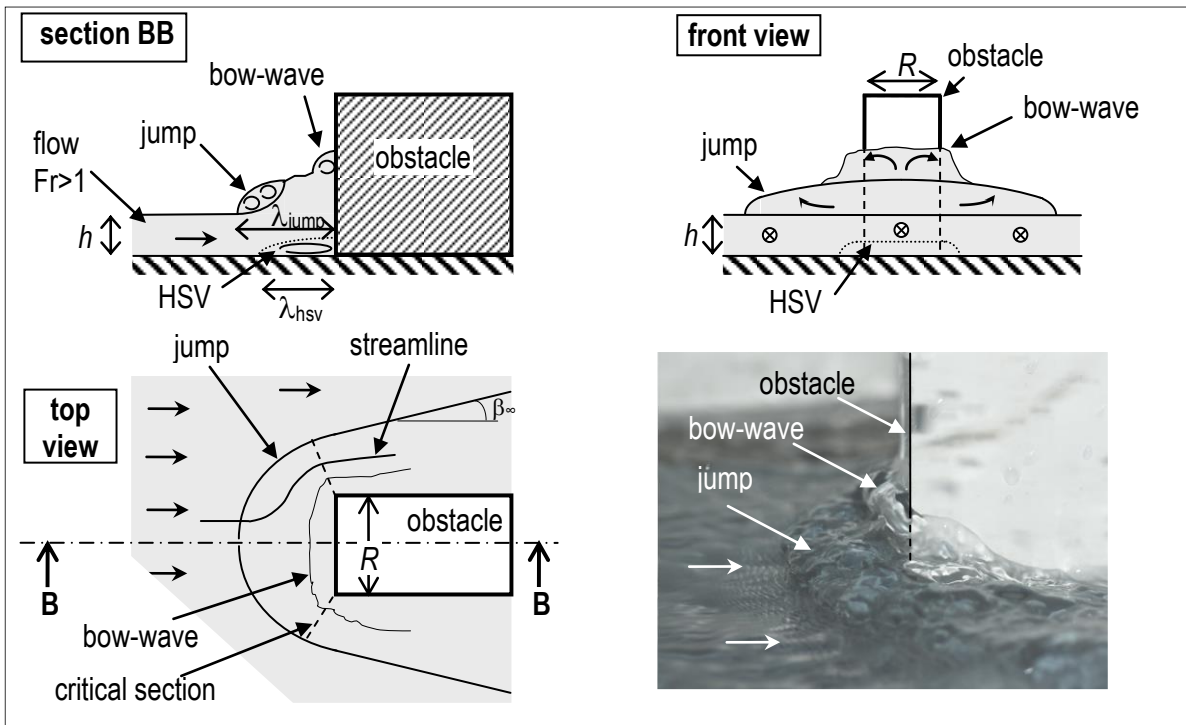


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553 *Figure 2. Schematic, top views of facilities 1(left) and 2(right)*

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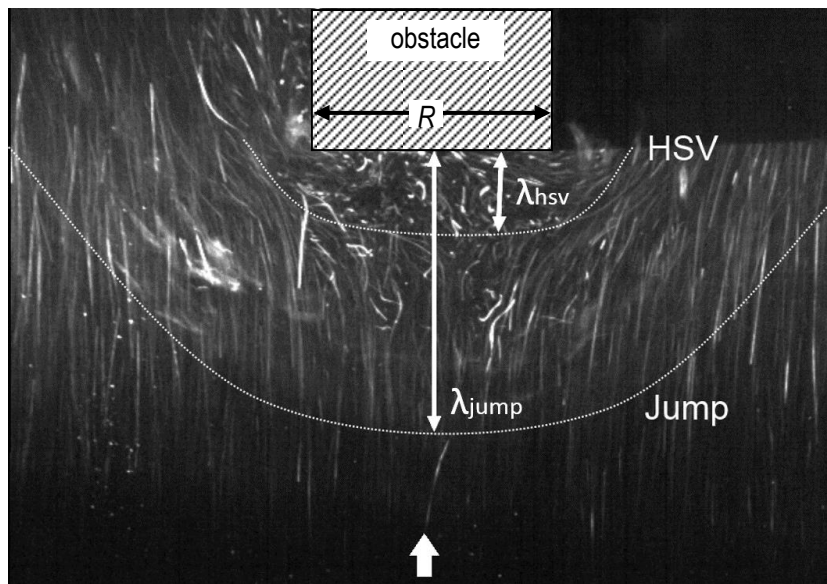
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Figure 3. Detached hydraulic jump around a rectangular obstacle: schematics and photograph.



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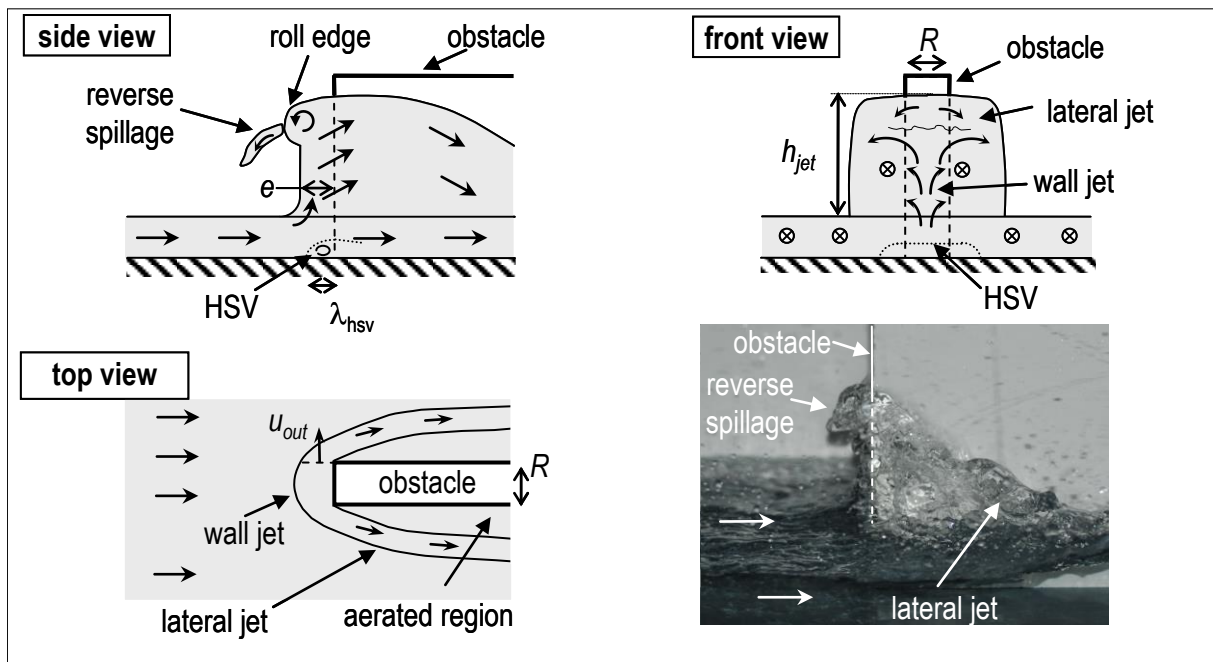
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Figure 4. Pathlines below a detached hydraulic jump using a time-exposure photograph (Facility 1; $R = 20 \text{ mm}$; $U = 0.652 \text{ m/s}$; $h = 5.14 \text{ mm}$; $\lambda_{\text{jump}} \approx 20 \text{ mm}$ and $\lambda_{\text{HSV}} \approx 6 \text{ mm}$). Note that the top-right region of the photograph is dark due to the obstacle shadow.

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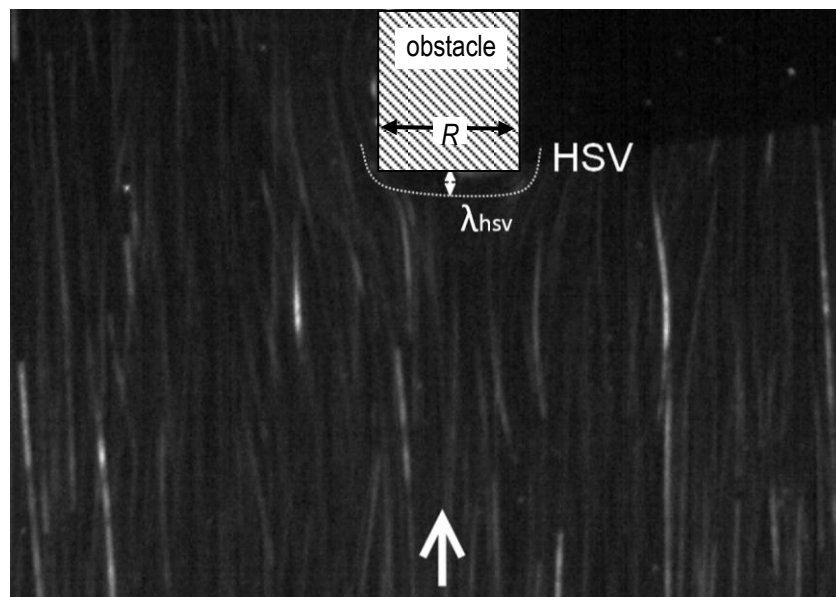


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568 *Figure 5. Wall-jet-like bow-wave around a rectangular obstacle: schematics and photograph*

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572 *Figure 6. Pathlines below a wall-jet-like bow-wave using a time-exposure photograph*

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(Facility 1; $R = 6 \text{ mm}$; $U = 0.652 \text{ m/s}$; $h = 5.14 \text{ mm}$; $\lambda_{hsv} \approx 0.8 \text{ mm}$.)

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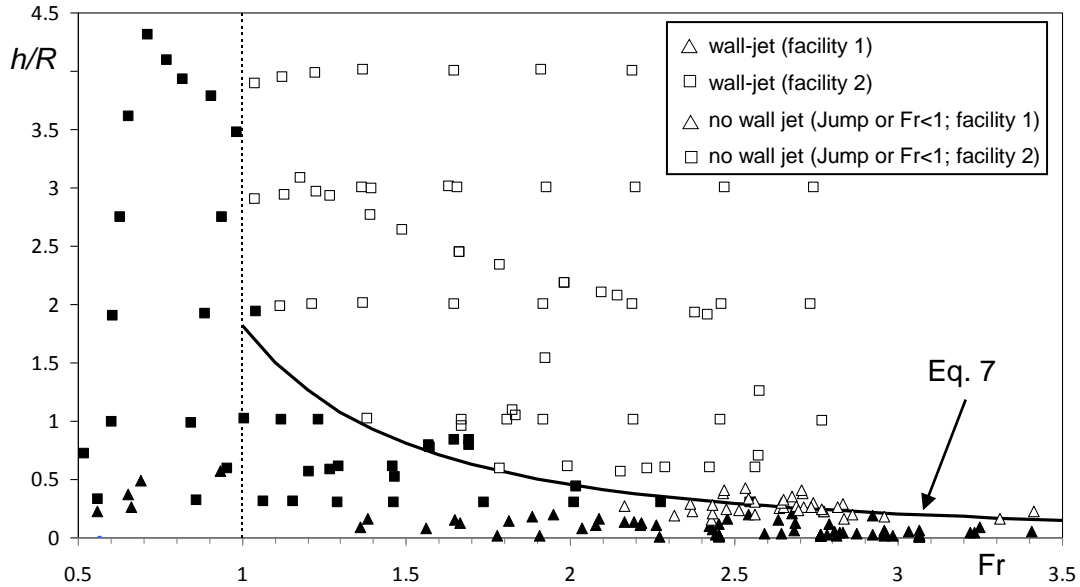


Figure 7. Flow forms plotted in the $(Fr, h/R)$ plane, reported from present experiments.

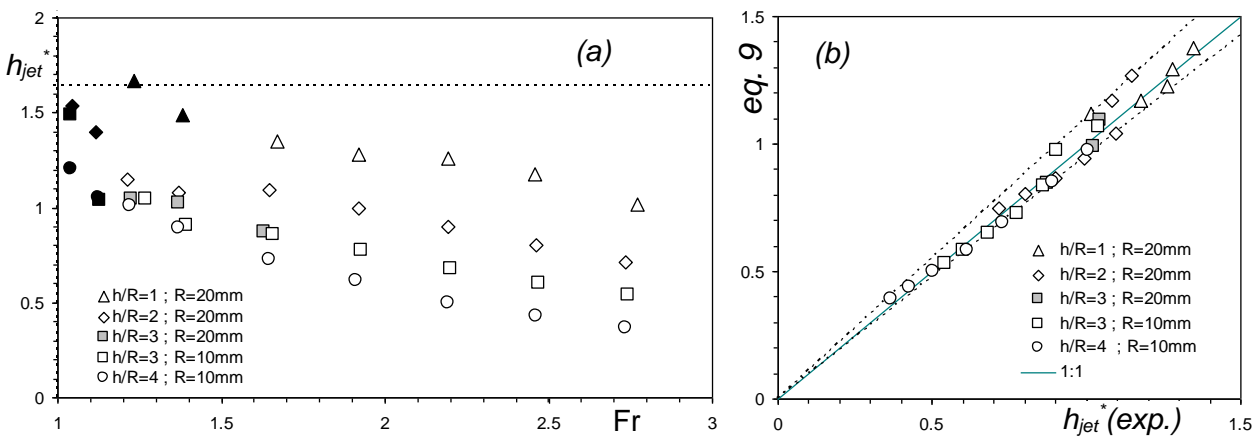
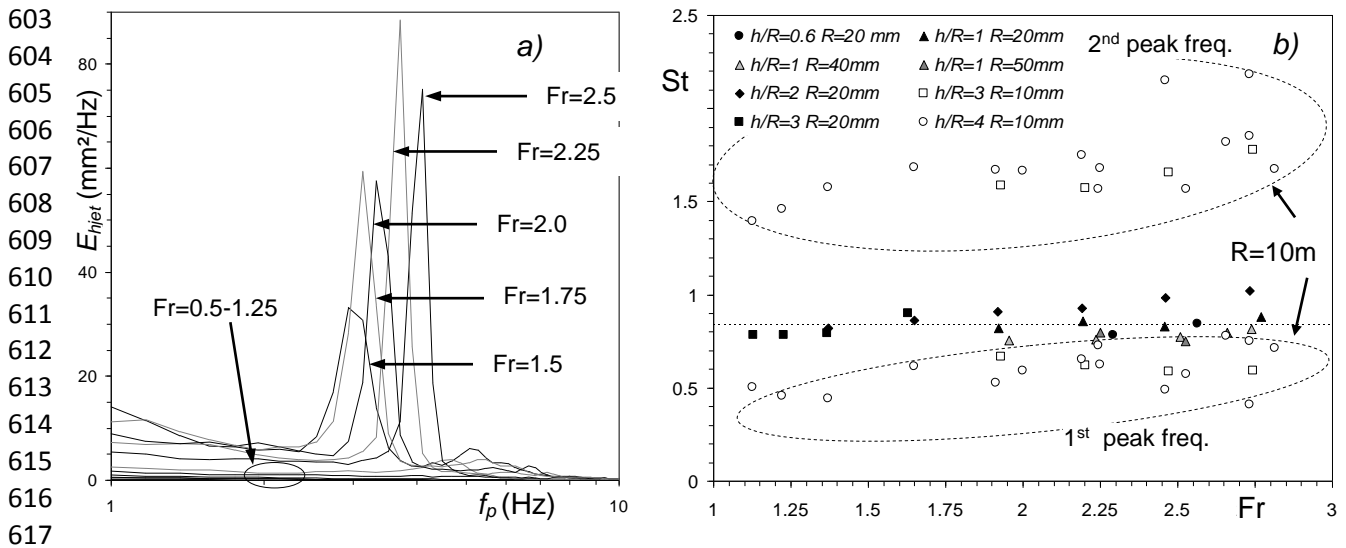


Figure 8. (a) Time-averaged relative jet height $h_{jet}^* = h_{jet} / (U^2/2g)$ measured in the channel (facility 2) as a function of the upstream Froude number, for different h/R values; open symbols correspond to a wall-jet-like bow-wave while closed symbols correspond to a hydraulic jump. (b) Comparison of the empirical correlation (Eq. 9) with the experimental data.



618 *Figure 9. a) Example of frequency spectra associated with water depth fluctuations on the*
 619 *obstacle upstream face for $h/R=2$ and increasing Froude numbers, obtained in facility 2 and*
 620 *b) Strouhal numbers corresponding to water depth fluctuations on the obstacle upstream face*
 621 *as a function of the upstream Froude number, for different h/R values.*
 622