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► **To cite this version:**

Emmanuel Mignot, T. Moyne, Delphine Doppler, Nicolas Rivière. Clear-water scouring process in a flow in supercritical regime. *Journal of Hydraulic Engineering*, 2016, 142, pp.04015063. 10.1061/(ASCE)HY.1943-7900.0001100 . hal-01516087

HAL Id: hal-01516087

<https://hal.science/hal-01516087v1>

Submitted on 21 Nov 2018

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1 Clear-water scouring process in a flow in supercritical regime

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12 Abstract

13 The aim of this research is to measure the clear-water scouring produced by supercritical flow
14 around a rectangular shaped obstacle. The initial uniform flow condition without the obstacle is
15 such that the Shields parameter remains slightly lower than critical, so that the sediment
16 constituting the mobile bed is not transported. After the obstacle is suddenly inserted, the
17 sediment begins to move. At specific times after this the 2D water surface and the 2D bed
18 topography fields around the obstacle are then measured. The initial flow pattern exhibits a
19 typical bow-wave like hydraulic jump, detached upstream from the obstacle, occurring over the
20 rough plane bed. Then, as for the more widely studied subcritical regime configuration, the scour
21 initiates on the sides of the obstacle and migrates towards its upstream face, where the scour
22 depth continues to increase with time. This causes the hydraulic jump to migrate downstream,
23 approaching the obstacle with negligible effect on the bed topography. Downstream from the
24 obstacle, the sediment deposits and forms a specific deposition zone whose maximum elevation
25 also increases with time before reaching a plateau. The flow pattern downstream of the obstacle
26 is strongly influenced by this deposition and exhibits two consecutive bow-waves aligned in the
27 streamwise direction with the hydraulic jump located upstream. The experiment runs for two
28 hours and even though all evolution rates decrease with time, this duration is not sufficient to
29 obtain a stable situation of the flow pattern and bed topography. The paper ends with a
30 similarity analysis of the typical field conditions for which this clear-water scouring process
31 could occur.

32

33 **Introduction**

34 Open-channel flows around obstacles and subsequent scour formation at the toe of the obstacle
35 has been widely studied, mostly due to its importance for bridge pier or abutment stability. The
36 experiments available in the literature and cited in the papers below were mostly focused on
37 steady subcritical flows over fixed or mobile beds and for mobile bed experiments, under live-
38 bed or clear-water configurations. Much less research has been devoted to such flows in
39 supercritical regimes, but the published results are then summarized in the following section.

40 *Subcritical flow over a fixed or mobile bed*

41 The most studied configuration is that of subcritical flow over a (usually smooth) fixed-bed. As
42 the incoming flow approaches the obstacle, the adverse pressure gradient between the flow
43 upstream and the obstacle leads to a boundary layer separation in the near-bottom region and
44 the creation of a horseshoe vortex at the toe of the obstacle on its upstream side. Graf and
45 Yulistiyanto (1998), Ahmed and Rajaratnam (1998), and Roulund *et al.* (2005) described the
46 flow patterns upstream of the obstacle and within the horseshoe vortex. The experiments of
47 Roulund *et al.* (2005) and Sadeque *et al.* (2008) showed that the bed shear stress is negative far
48 upstream from the obstacle, goes to zero, and finally becomes positive as the obstacle is
49 approached. The location at which the bed shear stress reaches zero corresponds to the
50 separation point of the boundary layer and thus the upstream limit of the horseshoe vortex.
51 Dargahi (1989), Sahin *et al.* (2007) and Escauriaza and Sotiropoulos (2011) showed that,
52 depending on the inflow Reynolds number, the horseshoe vortex can consist of a single or
53 multiple vortices.

54 In experiments with a mobile bed without sediment recirculation, usually referred to as ‘clear-
55 water’, the flow condition is selected so that the Shields parameter remains lower than critical
56 and thus no sediment transport takes place in the absence of the obstacle (and, therefore, in the
57 far field). Authors such as Muzzammil and Gangadhariah (2003), Unger and Hager (2007), Dey
58 and Raikar (2007), Kirkil *et al.* (2008), Gober *et al.* (2010), Diab *et al.* (2010) or Link *et al.* (2012)
59 describe the scouring process taking place around the obstacle. The horseshoe vortex appears in
60 front of the obstacle at the very beginning of the experiment, and the scour initiates at an angle
61 of about 75° to the channel axis due to the accelerating flow along the sides of the obstacle. Then
62 the scour extends towards the upstream face of the obstacle that is towards the horseshoe
63 vortex which is replaced by a downflow within the developing scour with complex vortex
64 dynamics (see Kirkil *et al.* 2008 or Link *et al.* 2012). The depth and upstream extension of the
65 scour then increase and a larger scale vertical recirculating flow occurs within the scour hole,
66 composed of one or more coherent vortices. According to Hager and Unger, (2010), “it is
67 currently accepted that pier scour advances logarithmically with time and that an equilibrium
68 scour depth is hardly attained, except for weak approach flow conditions or a non-uniform

69 sediment". It is important to note that Dey and Raikar (2007) and Diab *et al.* (2010) showed that
70 the scour depth is increased and that the scour progresses more slowly, and with steeper slopes
71 if the cylindrical obstacle is replaced by a square of sides equal to the circular pier diameter.
72 Downstream from the pier, the flow initially separates and a wake with recirculating flow forms
73 a zone of deposition immediately downstream from the scour zone (Kirkil *et al.* 2008). As time
74 progresses, the separation point moves downstream (see Oliveto and Hager, 2014) and this
75 recirculation zone becomes negligible. The maximum deposition height in the downstream zone
76 remains limited.

77 Live-bed scouring experiments are performed with a Shields parameter exceeding the critical
78 value, so that sediment transport takes place over the bed even without (and far from) the
79 obstacle, and an additional flow loop to recirculate the suspended sediment. The methodology
80 followed by Jain and Fischer (1980), Chiew (1984), Melville and Chiew (1999) or Sheppard and
81 Miller (2006) is to gradually increase the inflow velocity and measure the corresponding
82 equilibrium scour depth. As this velocity increases, "a peak in the equilibrium scour depth [is
83 observed] at the transition from clear-water to live-bed conditions, a decrease in equilibrium
84 scour depth [is observed] just beyond this peak, and a second peak in the live-bed scour range
85 (believed to occur where the bed 'planes out')" (Sheppard and Miller 2006). According to Jain
86 and Fischer (1980), this process is the result of a competition between: i) the increasing
87 sediment transport from upstream region where erosion takes place as the critical Shields
88 parameter is exceeded and ii) the increasing strength of the scour mechanism to dislodge
89 particles from the bottom of the scour hole. Visualization or velocity data acquisition in such
90 suspended sediment flow is delicate and most authors restrict their data to the scour depth
91 evolution and magnitude in the 'equilibrium' state.

92 Additionally, effects of unsteadiness have been investigated in laboratory, clear water conditions
93 by authors such as Lai *et al.* (2009) or Hager and Unger (2010) or in field, flood conditions by Lu
94 *et al.* (2008).

95 *Supercritical flows over a fixed or mobile bed*

96 All previously cited papers (and the extensive accompanying literature) deal with flows in the
97 subcritical regime, obviously related to the fact that most bridge piers are constructed in rivers
98 where the flow regime remains subcritical even during floods. However, in mountainous areas
99 the flow can become nearly critical or even supercritical. For instance, in areas like the French
100 island, La Reunion in the Indian Ocean or Chile, the river flow can be supercritical even during
101 normal hydrological conditions, and reach high Froude numbers after heavy rains, resulting in a
102 significant increase in sediment transport.

103 Much less research has been reported on the interaction between a supercritical open channel
104 inflow and a bridge pier. Jiang and Smith (2000) reported that a stationary shock wave forms in

105 front of the obstacle, shaped as a bow wave near the centerline and a V-wave further away. Near
106 the centerline (the symmetry axis), the shock is perpendicular to the flow axis, with a subcritical
107 flow on the downstream side of the jump deflected away from the centerline, passing on either
108 side of the obstacle. Further from the centerline, the supercritical inflow experiences an oblique
109 jump at the trailing edge of the V-wave and the flow downstream from the jump remains
110 supercritical with a deflected flow direction, as predicted by Ippen (1951). This flow pattern is
111 highly similar to that observed in aerodynamic studies of detached shock waves upstream of
112 bluff bodies (see, for example, Shapiro, 1953). More recently, Mignot and Riviere (2010) and
113 Mignot *et al.* (2011) have investigated the interaction between a supercritical open channel
114 inflow over a smooth bed and a rectangular shaped obstacle, focusing on both flow structures
115 which occur in front of the obstacle: the detached hydraulic jump and the horseshoe vortex. This
116 research shows that if the inflow is turbulent, then the detachment length of the hydraulic jump
117 exceeds the detachment length of the horseshoe vortex. Along the centerline, the flow first
118 reaches the detached, bow-like, hydraulic jump, undergoes transition to the subcritical regime
119 and then reaches the horseshoe vortex which acts as a positive step, leading to a sudden
120 increase of the water depth (see Fig. 1). Finally the flow is deflected around the obstacle. The
121 authors also adapted the analytical model developed by Mockel (1949) for the shape and
122 location of the detached shock wave in a supersonic flow around a bluff body to the present
123 supercritical, open-channel, flow in order to predict the evolution of the dimensionless
124 detachment length of the hydraulic jump as the Froude number of the inflow increases. Finally,
125 in a further study, Riviere *et al.* (2012) observed a complete modification of the previously
126 reported flow pattern as the turbulent intensity of the incident flow is increased by an additional
127 flow disturbance (a von Karmann vortex street from a narrow obstacle introduced upstream
128 along the centerline and by removing the upstream stilling device). The detachment length of the
129 hydraulic jump is not affected but the length of the horseshoe vortex increases so that both
130 detached structures occur at the same distance from the obstacle.

131 A few studies dealt with scour resulting from supercritical flow around an obstacle such as
132 studies from Jain and Fischer (1980) or Chiew (1984). At the highest values of the inflow
133 velocity, the upstream Froude number exceeds 1 (with values up to 1.5), but the authors did not
134 report specific modifications in the flow pattern or the scour depth tendency. In this study, the
135 determining factor seems to be the Froude number at which the critical Shields parameter is
136 reached (lower than 1) and for which the configuration passes from clear-water to live-bed,
137 rather than Froude equal to 1. It is important to note that for the supercritical flow
138 configurations tested by the authors, the Shields parameter exceeds the critical value so that the
139 flow around the pier is considered as 'live-bed' and antidune fields were observed. The authors

140 provide an empirical relation between the maximum scour depth and the difference between the
141 inflow Froude number and the critical Froude number.

142 *Present work*

143 The present research differs from the studies cited above as it is performed in clear water
144 conditions, as it is dedicated only to the supercritical regime and as its objectives differ. The first
145 objective of the present work is to verify whether the flow pattern observed by Mignot and
146 Riviere (2010) over a fixed smooth bed also occurs with a rough bed and how this flow pattern
147 evolves with time as the scour evolves. The second objective is to measure and analyze the
148 dynamics of the scouring and deposition processes around the obstacle in the presence of a
149 detached hydraulic jump and compare them with the subcritical configurations reported in the
150 literature. In the present clear water experiments, the absence of bed forms such as the ones
151 reported in the cited live bed experiments allows to focus on this hydraulic jump/scour hole
152 interaction. The experimental set-up is first presented along with all measurement devices. Then
153 the time-evolution of both bottom topography and flow pattern are presented and discussed.
154 Finally, the similarity of the present flow with natural flows is discussed.

155 **Experimental approach**

156 *Experimental set-up*

157 The experiments have been conducted in an open-channel flume located in the Laboratory of
158 Fluids Mechanics and Acoustics (LMFA) at the University of Lyon (INSA Lyon, France). The flume
159 sketched in Fig. 2a is 1.4m long, straight, with a rectangular cross-section of width $b=0.49\text{m}$ and
160 a constant streamwise slope of $i=6.7\%$. The discharge $Q=2.87\text{ L/s}$ is measured in the pumping
161 loop using an electromagnetic flowmeter (Endress-Hausser) with an uncertainty $\pm 0.05\text{L/s}$. The
162 upstream boundary condition consists of a grid buffer and a honeycomb with a small mesh in
163 order to stabilize the inflow. The downstream boundary condition is a critical depth. The
164 uniform water depth in the channel then equals $h_n=9.35\text{mm}$ (precision of 0.05mm). The inflow
165 velocity equals $U=Q/bh_n=0.63\text{ m/s}$, the Froude number equals $Fr=2.07$ and the Reynolds number
166 $Re=2.3\times 10^4$.

167 The selected sediment is composed of blasting shot - steel - balls, (approximately spherical) of
168 diameter $d=1.5\text{ mm}$ and dispersion $\sigma=(d_{84}/d_{16})^{1/2}=1.06$, and density $\rho_s=7400\text{ kg/m}^3$, shown in
169 Fig. 2d, leading to a vertical aspect ratio of $h_n/d=6.2$. It is important to note that within the
170 sediment there are some clusters formed by two or three balls that have fused together. Along
171 the first 50cm of the channel, the bed level is increased by a step of 19mm and is covered by one
172 layer of glued sediment (Fig. 2). The length over water depth ratio for this upstream channel
173 reach is equal to 53, ensuring the establishment of the supercritical uniform flow at inlet. The

174 downstream reach is 40 cm long, and is similar to the upstream reach. The mobile bed section
175 thus occupies the central reach, 50cm long (over the $b=49\text{cm}$ channel width). The rectangular
176 chamber is filled with sediments over a layer of about 20.5mm (Fig. 2b), initially flattened by a
177 moving plate. The mean sediment elevation is used as vertical elevation reference $z=0$.

178 The bed shear stress estimated in the uniform flow conditions (without the obstacle) equals:
179 $\tau = \rho_w g h_n i = 6.15 \text{ N/m}^2$ and the Shields parameter - corrected by factor η for high slopes
180 following the recommendations from Cheng and Chen (2013) - equals $\theta = \frac{\tau}{(\rho_s - \rho_w) g d} / \eta =$

181 0.048 with a dimensionless particle diameter of $d_* = d \left[\frac{(g\rho_s - g\rho_w)}{\rho_w \nu^2} \right]^{1/3} = 60$. The corresponding
182 critical Shields parameter on Shields diagram equals $\theta_{cr} \sim 0.045$ with ρ_w and ν the water density
183 and kinematic viscosity respectively. The uniform flow is thus very close to the incipient motion;
184 this was verified by two observations:

185 i) after the few over-exposed sediment grains have been removed the bed remains stable
186 for long times

187 ii) a slight increase in the discharge or the slope results in significant sediment motion.

188 The obstacle is an impervious rectangular-shaped empty box with splayed corners, open along
189 its bottom face of length (along the flow axis) $L=65\text{mm}$ and width (along the transversal axis)
190 $R=98\text{mm}$. The borders are sharp so that the obstacle can be inserted rapidly into the water and
191 through the sediment bed, all the way down to the rigid bed of the flume, with very little
192 disturbance of the sediment bed. It was verified (by eye) that inserting the obstacle did not cause
193 any sediment motion and this is corroborated by the fact that negligible change of topography is
194 measured in the 10 first seconds following the obstacle insertion. A specific device attached to
195 the flume ensured that the obstacle location was the same in each experiment. The $x=y=0$ origin
196 is located at the center of the obstacle with x aligned with the principal flow direction and y with
197 the transverse direction.

198 *Measurement devices*

199 The bed topography and water level are defined along the z axis (referred to as “vertical axis”)
200 which is perpendicular to the bed (differing from the terrestrial vertical due to the bottom slope
201 $i=6.7\%$). The same laser grid technique is employed for measuring both the bed topography and
202 the free surface elevation, using slightly different procedures. For measuring the bed
203 topography, the flow is stopped by switching off the pump and blocking the inflow, the water
204 evacuates through a reverse flow in the pump towards the downstream tank and the topography
205 is measured once the bed is dry. The free surface elevation is measured at constant discharge, by
206 mixing a small amount of white dye in the water to render the water opaque.

207 The measurement method is detailed in the Appendix. Bed topography and free surface
208 elevation were measured at two locations – one upstream of the obstacle and one downstream;
209 the measurement zones overlapped slightly to provide some verification of the reproducibility
210 of the results. Taking advantage of the symmetry of the flow, only the left side of the domain was
211 measured, with a spatial resolution of about 15mm.

212 *Procedure*

213 The procedure used is as follows:

214 1- the plane sediment bed reference level ($z=0$) is established, with the bed flattened as
215 described above.

216 2- the pump is switched on and steady uniform flow is established, without the obstacle.
217 Prominent, exposed grains are rapidly washed away by the flow.

218 3- the obstacle is inserted rapidly, time is set to $t=0$ and measurements start. Two different
219 procedures were used for the free surface and the topography measurements:

220 3a- for the free-surface measurement, photos of the laser grid intersection on the opaque
221 water surface are taken at fixed times and the free-surface is later reconstructed for all times.
222 This procedure involving steps 1, 2 and 3a is performed twice, once for each zone.

223 3b- for the topography measurement, the flow is suddenly stopped after the desired
224 running time by blocking the flow through the upstream honeycomb; once the bed is sufficiently
225 dry, a photo of the laser grid on the sediment bed is taken. The whole procedure involving steps
226 1, 2 and 3b is then repeated for a different running time.

227 Reproducibility of the scouring process was verified by repeating the procedure several times
228 and comparing the results. The impact of stopping the flow in step 3b was verified by comparing
229 the bed topography i) measured after 40 minutes of continuous flow and ii) measured after 4
230 consecutive series of 10 minutes of flow (with thus four consecutive stops). The differences in
231 bed topography after 40 minutes were limited and negligible relative to the total evolution as
232 highlighted in Fig.3. This method appears to underestimate slightly the water depth because the
233 water is not fully opaque (unlike the sediment); when the laser grid is projected onto the free-
234 surface, the light penetrates the water slightly before being reflected, so that the image spots are
235 actually located somewhere within the upper layer of the water (see, for example, Lipeme Kouyi
236 *et al.*, 2003).

237 **Results**

238 *Flow pattern at initial time.*

239 As the obstacle is introduced at $t=0$ s, the bed is flat and the flow pattern (not shown here) is very
240 similar to the one at $t=0.5$ min in Fig.3: a detached hydraulic jump of hyperbolic shape forms

241 upstream of the obstacle as described by Mignot and Riviere (2010). The detachment length λ of
242 the toe of the jump along the centerline ($y=0$) equals about 80mm, that is $\lambda/R \sim 0.8$ which is of
243 same order of magnitude as the detachment length measured for a Froude number of 2 by
244 Mignot and Riviere (2010) (see their figure 12a). As shown by Riviere *et al.* (2012, figure 4) the
245 water depth and water level increase with downstream distance, reaching a maximum elevation
246 of about $z_w=h=30\text{mm}$ at the upstream face of the obstacle. The free surface on either side of the
247 centerline evolves in a similar fashion but with a more limited maximum elevation ($z_w=15\text{mm}$
248 for $y=-180\text{mm}$). The hydraulic jump reflects at the left bank (located at $y=-245\text{mm}$) and a cross-
249 wave is observed for $x>100\text{mm}$. Behind the obstacle, the water depth and water level are very
250 low, so that the bed is almost dry just downstream from the obstacle along the centerline.

251 *Evolution of the bed topography*

252 As in the subcritical regime, the scour starts along each side of the obstacle with a maximum
253 scour depth of 4 mm at $t=30\text{s}$ extending over the whole side of the obstacle (along x axis) and a
254 width of 30mm. At the location of the detached hydraulic jump, no erosion is observed, as
255 revealed by line L1 for $x \sim -50\text{ mm}$ at $t=30\text{s}$ in Fig.4.

256 As time progresses, the scour extension increases towards upstream, downstream and in the
257 transverse directions, as revealed by L2 and L3 lines in Fig.4, but the scour always remains more
258 extended towards downstream, than upstream. After $t=1.5$ minutes, the scour reaches the
259 upstream corner of the obstacle and starts to extend along its front face; the scour reaches the
260 centerline $y=0$ at $t \sim 3\text{min}$. Nevertheless, the maximum scour depth remains located on the side
261 of the obstacle ($x=0$ and $y=-R/2$) and reaches about -10mm after 3 minutes and -15mm after 30
262 minutes (see line L3). After $t=30\text{min}$, the maximum scour depth does not increase much further
263 but the area of the deep scour region keeps on increasing: the $z_b < -10\text{mm}$ region reaches the
264 centerline at $t \sim 60\text{min}$ and a thin layer of $z_b < -14\text{mm}$ is observed along a semicircle around the
265 upstream half of the obstacle at $t=120\text{min}$ on Fig.5.

266 In the meantime, a deposition region forms and grows with time in the wake of the obstacle at
267 $x \sim 100$ to 150mm and $y \sim 20-30\text{mm}$, as revealed by line L5. This deposition region grows
268 upstream and reaches the back face of the obstacle at $t \sim 3\text{min}$ but the increasing extension of the
269 scour in this region limits the extension of the deposition zone for $t > 10\text{min}$. This deposition
270 takes place on both sides of the centerline but Figs.3 and 4 reveal that along the centerline itself
271 (along L1 at $y \sim 0$), the bed elevation remains almost unchanged. The deposition pattern strongly
272 differs from the deposition patterns observed for subcritical flow configurations for which a
273 dune aligned with the centerline is observed downstream from the obstacle (see Kirkil et al.,
274 2008 or Oliveto and Hager 2014). As a consequence, after $t \sim 120\text{min}$, a complex pattern of flow
275 deposition and scour takes place with both regions of about the same extension but the scour
276 depth is about twice the deposition elevation (see Fig.6).

277 Fig.6 shows the time evolution of the maximum measured erosion depth and deposition height
278 around the obstacle. Both maxima appear to increase following a somewhat logarithmic curve
279 during the first 10 minutes with a higher slope for the scour depth than for the deposition
280 elevation. Afterwards, the maximum erosion depth and deposition elevation reach a plateau.

281 *Evolution of the flow pattern*

282 In this section, the time evolution of the flow pattern is described separating the domain into
283 four regions.

284 i) Upstream from the obstacle, the detached hydraulic jump approaches the obstacle. As
285 revealed by line L1 (Fig.4) for negative x values, the $z_w=20\text{mm}$ elevation moves from $x=-80\text{mm}$ at
286 $t=30\text{s}$ to $x=-50\text{mm}$ at $t=3\text{min}$. Upstream from the jump, the water depth then becomes equal to
287 the upstream uniform depth, as at $t=5\text{min}$ at $x\sim-100\text{mm}$. Since, as shown above, the jump does
288 not affect the bed elevation as it moves downstream, the extension of the region impacted by the
289 hydraulic jump decreases and is replaced by a flat bed with uniform flow. It can also be seen
290 that, as time progresses, the scour depth increases in front of the obstacle and thus, whilst the
291 water level does not change, the water depth strongly increases in this region and exceeds
292 40mm at $t\sim 60\text{min}$.

293 ii) along the sides of the obstacle, the crest of the hydraulic jump also moves downstream and
294 towards the obstacle (along the transverse axis). At $t=30\text{s}$, the crest is located at $x\sim 55\text{mm}$ along
295 $y=-180\text{mm}$ and at $x\sim 25\text{mm}$ along $y=-100\text{mm}$ (along L2) and at $t=3\text{min}$, it moves to $x\sim 100\text{mm}$
296 ($y=-180\text{mm}$) and $x\sim 0\text{mm}$ ($y=-100\text{mm}$) respectively. Meanwhile, the crest elevation decreases
297 (see L2). This behavior is confirmed by the displacement of the maximum elevation along line L3
298 towards the obstacle. As the jump moves downstream and towards the obstacle, the location
299 previously occupied by the hydraulic jump remains at its initial elevation ($z_b\sim 0$, as can be seen
300 along L2 and L3) and the flow there becomes uniform (the water depth equals the normal depth
301 as prior to the introduction of the obstacle). Again, the extent of the region affected by the
302 obstacle diminishes towards the obstacle.

303 iii) still along the sides of the obstacle, in the region just downstream from the hydraulic jump,
304 the bed remains quite flat at its initial elevation for $t<10\text{min}$ and the water depth equals the
305 water level except along the lateral face of the obstacle where the scour develops and where the
306 water level decreases (see L3) but not enough to ensure a constant water depth which in turn
307 increases. Later on ($t>10\text{min}$), the flow pattern becomes more complex and is detailed in the
308 following paragraph.

309 iv) downstream from the obstacle, for $t\sim 30\text{s}$, the deposition elevation is negligible and the water
310 depth and water level decrease significantly. Later, for $t<5\text{min}$, the deposition elevation
311 increases and the water level and water depth slightly increase. Then, as the deposition
312 elevation exceeds 6mm locally, the water level remains high but the water depth strongly

313 decreases; the region far downstream from the obstacle becomes almost dry. For $t \geq 30$ min, the
314 deposition zone covers a considerable area, with significantly increased elevation, so that this
315 deposition zone acts as a 'second obstacle' located downstream of the main one. As a
316 consequence, a second bow wave (similar in shape to a hydraulic jump) forms parallel to the
317 first one, located about 100 mm downstream, but with a maximum crest elevation displaced to
318 the side at $y \sim -60$ mm. It can also be observed, Fig.3 (for $t=60$ min), Fig.4 (along L2), Fig.5
319 ($t=120$ min) and the photo in Fig.7 ($t \sim 90$ min) that a third elevated depth zone forms at about
320 100mm downstream from this second one. The present measurements do not allow us to
321 determine whether these two bow-waves (located at $x=100$ mm and $x=200$ mm along L2 in Fig.4)
322 are hydraulic jumps (with a local Froude number passing from higher to lower than 1) or just
323 gravity waves.

324 *Evaluation and measurement of the sediment volume leaving the flume*

325 The bed volume (eroded within the 50cm long and 49cm wide mobile bed region) is evaluated
326 using two approaches i) directly from a 2D integral of the bed topography at different times (see
327 Fig.3) and ii) by measuring the weight of sediment caught in a sediment trap located at the outlet
328 of the flume. This second technique requires relating the weight of the dried sediment with the
329 equivalent bed volume. This relation is obtained by setting up a 20.5mm high bed as for all
330 experiments and running the flow without obstacle to let the over-exposed sediment elements
331 leave the flume (see the experimental set-up section) then collecting all the sediments from this
332 mobile bed region, drying and weighing them.

333 Fig.8 reveals that the results from the two methods agree and that at initial time, the erosion
334 process is very intense and this intensity rapidly decreases with time. The erosion rate appears
335 to follow a power law reasonably closely for the 5 first minutes, followed by a more gentle
336 constant rate until the end of the experiment ($t=120$ min).

337 **Discussions**

338 *Analysis of the hydraulic jump displacement*

339 The aim of this section is to discuss the reason why the hydraulic jump moves downstream
340 towards the obstacle.

341 The jump displacement can be analyzed based on the mass conservation balance proposed by
342 Moeckel (1949) and adapted to open-channel flow by Mignot and Riviere (2010). In Fig.9a, the
343 blue line represents the jump, whose detachment length along the symmetry axis is noted λ ; the
344 section of length L_o corresponds to the minimum flow section, where the Froude number thus
345 equals 1 (L_o thus corresponds to the critical section). Flow in the region enclosed by i) the jump,
346 ii) the vertical symmetry plane, iii) the obstacle and iv) the section of length L_o is subcritical

347 ($Fr < 1$) whilst elsewhere the flow is supercritical ($Fr > 1$). The flow rate entering the subcritical
348 region is noted Q_i with $Q_i = L_i h_i U_i$ with h_i and U_i the normal water depth and corresponding
349 velocity of the uniform flow upstream. The discharge leaving this region through L_o is noted Q_o
350 with $Q_o = L_o h_o U_o = L_o h_o^3 g^{1/2}$ (as $Fr_o = 1$) and h_o the mean water depth along L_o . Thus the continuity
351 equation can be written:

$$352 \quad L_i h_i U_i = L_o h_o^3 g^{1/2} \quad (1)$$

353 As time progresses, we consider that h_i and U_i remain unchanged as the bed is not affected by the
354 hydraulic jump (as discussed above, see for instance line L1 in Fig. 4). Consequently, from Eq (1)
355 $h_o^3 L_o / L_i$ must remain constant. Fig.3 reveals that h_o increases with time as the scour develops
356 near the upstream side corner of the obstacle; consequently the ratio L_o / L_i has to decrease. The
357 sketch in Fig.9b reveals that, from geometrical considerations, if λ increases from λ_1 to λ_2 the
358 increase of L_o (from L_{o1} to L_{o2}) greatly exceeds that of L_i (from L_{i1} to L_{i2}) so that the ratio L_o / L_i
359 increases; conversely if λ decreases from λ_2 to λ_1 , L_o / L_i must decrease as required by continuity.
360 Based on this analysis, the scour process developing in the vicinity of the side corners of the
361 obstacle is responsible for the hydraulic jump approaching the obstacle.

362 The preceding explanation needs to be qualified. Mignot et al. (2011) showed that the horseshoe
363 vortex also influences the position of the hydraulic jump: the horseshoe vortex modifies the
364 'effective' channel bottom, which incidentally makes it impossible to close Eq (1). In the present
365 configuration, as time increases, the scour in front of the obstacle increases and so the horseshoe
366 vortex may become confined within the scour, as previously described by Kirkil *et al.* (2008),
367 and the corresponding discussion by Gobert *et al.* (2010), or more recently by Link *et al.* (2012).
368 The main flow should then take place « above » the horseshoe vortex whose impact on the
369 hydraulic jump becomes negligible. This also affects the jump detachment length.

370 *Comparison of scour geometry with subcritical cases*

371 The subcritical scour configuration closest to the present configuration seems to be the one from
372 Diab et al. (2010) who considered a square pier (in their figures 3 and 4b), in the clear-water
373 regime with gravel as sediment, instead of the finer sediment usually used in other studies. One
374 important difference is that in the present case the obstacle is rectangular and not square. Figure
375 4b from Diab et al. (2010) shows that, in subcritical conditions, the maximum scour depth
376 initially occurs at an angle of about 45° to the mean flow axis and then moves towards the
377 symmetry plane in the upstream region after about $T=5340$, with T the dimensionless scour
378 time, as defined by Oliveto and Hager (2002). Oppositely, in the present case, Fig.10 reveals that
379 the maximum scour depth starts on the side of the obstacle (angle equal to 90°) and remains at
380 this location for long times, until at least $t=120$ minutes ($T=36500$, with $T \sim 5.07t$ in the present
381 study, with t expressed in seconds) where the maximum scour depth becomes about equal along
382 the upstream and side faces of the obstacle (angles of 0° , 45° and 90°). Another major difference

383 is that, in this study, at intermediate times ($t=5$ to 10 min, that is $T=1520$ to 3040), the scour
384 along the upstream face (angle of 0°) is negligible whilst it is already deep on the side of the
385 obstacle ($z_b=-12\text{mm}$ at an angle of 90°); in comparison, Diab et al. (2010) found that at such time
386 ($T=1920$ to 3240), the scour depth along the upstream face is about equal to that along the side
387 face. A third major difference lies in the downstream region where, in subcritical conditions,
388 Diab et al. (2010) found that the maximum scour depth is about half that of the upstream region
389 (for $T\sim 11760-72540$), whilst in the present supercritical configuration, the scour remains
390 negligible at least during the first 120 minutes ($T=36500$), as shown in Fig. 4. The final major
391 difference between scouring in subcritical and supercritical inflows concerns the influence of the
392 channel to obstacle width ratio b/R . In this study, the obstacle and the jump are separated from
393 the side walls by a region where the flow is both fully-developed and in the supercritical regime.
394 The characteristics of this flow depend only on the upstream conditions and bottom slope and
395 are thus completely independent of the position of the side walls. As long as the hydraulic jump
396 intersects with the side walls downstream from the rear of the obstacle (as in the present case,
397 see Fig. 3), the side walls will not influence the scouring process in the near-obstacle region, and
398 there is no need to consider the blockage ratio.

399 Another comparison of the scouring process between the present supercritical configuration
400 and the more widely-studied subcritical configurations is presented here. The increase of the
401 maximum scour depth with time, plotted in Fig. 6, is compared with the semi-empirical formula
402 proposed by Oliveto and Hager (2002) and validated against data for subcritical conditions from
403 a range of other studies. Using the parameters proposed by the authors for an abutment and a
404 uniform sediment of high density and taking as subcritical approach conditions the conjugate
405 water depth ($h_0=2.3\text{cm}$) and velocity ($V_0=0.25\text{m/s}$) downstream from the hydraulic jump along
406 the symmetry plane of the inflow, this prediction results in the continuous line shown in Fig. 6.
407 The agreement between the predicted and measured maximum scour depth evolution with time
408 is reasonable, at least after a few minutes, which suggests that the processes driving the scour
409 might be similar in the two flow regimes. It would also have been interesting to compare the
410 maximum deposition elevation plotted in Fig. 6 with the empirical formula from Oliveto and
411 Hager (2014) fitted on subcritical configuration data from the literature. This formula involves
412 both a water depth, which could be read directly on Fig.3, and a typical velocity, controlling the
413 deposition, which was not measured, so it is unfortunately not possible to present this
414 comparison. To conclude, some aspects of the scouring processes occurring in supercritical and
415 subcritical inflow differ markedly, whilst others appear to be rather similar.

416 *Correspondence with field conditions*

417 The experiments were conducting using rather heavy sediments (blasting shot) to ensure a
418 Shields parameter slightly below the critical one; nevertheless, this does not prevent from
419 respecting similarities with field flows. In order to determine the field conditions which are
420 dynamically similar to those of the experiments, we consider: i) a Froude similarity with
421 $Fr'=2.07$, ii) an arbitrary laboratory/field scale of 1/10, iii) a field sediment density $\rho'_s=2650$
422 kg/m^3 , iv) the Manning equation for the uniform incoming flow (with a Manning coefficient
423 $n'=d'^{1/6}/21.1$ as proposed by A. Strickler in 1923), v) and a critical Shields parameter θ_{cr}' ,
424 corresponding to the incipient motion as in the experiment, with the prime sign referring to the
425 field scale. The resulting field variables are then: for the inflow, a velocity $U'=2\text{m/s}$, a slope
426 $i'=8.4\%$ and a water depth $h'=9.35\text{cm}$ (leading to a Reynolds number $Re'=7.4\times 10^5$; for the
427 sediment: a mean diameter $d'=6.5\text{cm}$ and a Shields parameter $\theta'=0.055$; and for the obstacle:
428 $R'L'=98\text{cm} \times 65\text{cm}$. Finally, the time equivalent to the present 120 min of experiments equals 6.3
429 hours with a maximum scour depth of about 16cm and a maximum deposition elevation of 9cm.
430 In such a full scale flow the ratio of depth to sediment diameter would be very low ($h'/d'=1.4$),
431 but might be characteristic of a very shallow flow over a gravel bed interacting with a large
432 obstacle ($R'/h'=10.5$), and would be most likely to occur in torrential flow on a steep slope. So
433 the field conditions could correspond, for example, to bridge pier in a torrential stream or river.
434 The width of such watercourses varies quite widely, from, for example, the 520m wide Rivière
435 des Galets at Saint Etienne de la Reunion to the 10m wide (50m during a flood) Mapocho river in
436 Santiago (Chile). Now, correspondence with field conditions remains limited due mainly to the
437 shallow depth ($h'\sim 10\text{cm}$) of the incoming supercritical flow. This limited depth was imposed by
438 the need to produce a flow in the supercritical regime but without transporting sediments from
439 upstream, in order to focus on the role of the hydraulic jump. This approach slightly differs from
440 the works by Jain and Fischer (1980) or Chiew (1984) who also considered an inflow in
441 supercritical regime but under live-bed conditions. The clear-water conditions considered
442 herein could be representative of different flow configurations in the field such as scour in a
443 river with large sediments for which the Shields stress far from the obstacle would not exceed its
444 critical value. Future work should be devoted to investigating scouring in more realistic
445 supercritical flow conditions, such as live-bed conditions.

446 **Conclusions**

447 The aim of this research was to investigate the scouring process occurring in a steady uniform
448 flow in the supercritical regime interacting with an emergent, impervious obstacle of
449 rectangular shape, in a clear-water configuration. For the sake of simplicity, the selected flow
450 configuration was at incipient motion, that is with the Shields parameter slightly below critical

451 before inserting the obstacle, which required the use of heavy particles, made of steel. A specific
452 measuring device was set up in order to measure the 2D bed topography and water surface
453 elevation at different times through the experiment. The main results of the paper are that:
454 - initially, the flow pattern above a flat rough bed, is similar to that observed in previous studies
455 of flow over a smooth fixed bed with a bow-wave like detached hydraulic jump upstream from
456 the obstacle and a very shallow –almost dry – flow region downstream.
457 - as time progresses, the scour begins on the sides of the obstacle and grows upstream and
458 downstream, whilst the depth of the scour hole increases. This pattern is similar to that reported
459 for subcritical flow configurations. Downstream of the obstacle, the deposition pattern consists
460 of two elevated regions separated along the centerline by a much less elevated ‘streamwise
461 channel’.
462 - the sediment transport and topographical changes affect the hydraulic jump which, as time
463 passes, moves towards downstream with a decreasing crest water level. Two reasons to explain
464 the hydraulic jump displacement towards the obstacle are proposed. Downstream from the
465 obstacle, the flow pattern is strongly affected by the deposited sediments and after one to two
466 hours, two additional bow-waves parallel to the hydraulic jump are observed, with a constant
467 streamwise distance of 100mm between each, and with a crest elevation that decreases with
468 downstream distance.
469 - finally, the hydraulic jump seems not to affect the sediment erosion. This is quite an unexpected
470 result as, favoring the boundary layer separation, the jump was expected to participate in the
471 scouring process, either through its action on the horseshoe vortex (see Riviere et al., 2012), or
472 through direct turbulent structures impacting the bed (as for Bellal et al., 2003). This might be
473 because of the rather low inlet Froude number ($Fr=2.07$), resulting in an ‘oscillating jump’
474 (Chow, 1959); at higher Froude numbers, the impact of the jump on the scour might become
475 stronger. Conversely, the present data reveal that it is the scouring process that seems to
476 determine the behavior of the hydraulic jump (location, shape and crest elevation).

477 **Acknowledgments**

478 The authors would like to thank prof. Oscar Link from the University of Concepcion (Chile) for
479 his advice during the writing of the manuscript.

480 **Appendix**

481 The measurement method is first detailed for the free-surface elevation measurement and then
482 adaptations performed for the bed topography measurement are indicated. A laser (Z-LASER
483 Z30M18S-F-640-11X11P) is equipped with special lenses that split the beam into 11x11 narrow
484 beams tilted up to 28° relatively to the incident laser axis. The laser is placed perpendicular to

485 the flume, above the flow, and projects the grid of $N = 11 \times 11$ regularly spaced points on a
486 selected zone. A camera is positioned to one side of the flume, with its axis inclined by about 45°
487 relative to the horizontal (see Fig.11a). The image taken by the camera in the measurement zone
488 with no water ($z=0$) is called the *reference image* (labeled '0') and contains N points M_j^0 ($j=1\dots N$)
489 with coordinates in the camera image frame (labeled 'i') noted $(x_i(j,0), y_i(j,0))$. Once water is
490 flowing in the flume, each laser beam j will intersect the free surface at a point P_j^h at coordinates
491 (x,y,h) with local elevation $z_w(x,y)$ in the frame of the flume. Each luminous point P_j^h is viewed on
492 the camera image as a spot, a few pixels wide, with center M_j^h and coordinates $(x_i(j,h), y_i(j,h))$ in
493 the image frame (sensor plane on Fig 11b).

494 The principle of the method relies on two basic optical effects. Firstly, on the camera image any
495 image point M_j^h exhibits a deviation $[x_i(j,h)-x_i(j,0)]$ (and $[y_i(j,h)-y_i(j,0)]$) which is proportional to
496 the local water elevation $z_w(x,y)$ (Fig. 11b) with a coefficient denoted α_j that depends on the
497 laser beam j . Using this property, the N coefficients α_j are inferred from a calibration procedure
498 performed by projecting the laser onto calibration plates of known thickness. Secondly, due to
499 the camera angle and the large depth of field, length distortion has to be considered: for a
500 regular laser grid, the further two points are from the camera focal point, the closer to each
501 other they appear on the photo. This effect depends on the surface elevation. A second
502 calibration procedure is thus needed (without the laser) to establish the relationship between
503 the (x,y) coordinates of the real intersection point of the laser beam with the free-surface and the
504 image in-plane coordinates. We use a target drawn on several calibration plates, consisting of
505 regularly spaced points of known actual coordinates (x,y,z_w) . Image processing and linear
506 interpolation are applied to determine a projection mapping $(x_i(z_w), y_i(z_w), z_w) \rightarrow (x,y,z_w)$. After
507 calibration (determination of the α_j and of the projection mapping), for any image of the grid
508 projected on the free surface, the measurement procedure is as follows. First, the image
509 coordinates (x_i, y_i) of the centers of the N spots M_j^h are determined by image processing. Second,
510 the water depth at each N point is calculated using $h(x_i(j), y_i(j)) = [x_i(j)-x_i(j,0)] / \alpha_j$. Third, knowing
511 h for each M_j^h , the real in-plane coordinates (x,y) of the water surface/laser intersections P_j^h are
512 inferred from the projection mapping $(x_i(h), y_i(h), h) \rightarrow (x,y,h)$. Fourth, the water depth map (as
513 presented in the results section) is deduced from linear interpolation of the actual coordinates
514 (x,y,h) of the N measured points.

515 The principle used to obtain the sediment elevation maps is similar to that described for the
516 free-surface except that the calibration plates are located at elevations ranging from the fixed
517 bottom ($z=-20\text{mm}$) to the maximum sediment deposition elevation: $z\sim 10\text{mm}$).

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