Structure of inland flows impacting buildings: wall-jet vs. hydraulic jump

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## Supercritical flows and obstacles

- **Supercritical rivers (Piedmont plains)**

- **Urban floods (streets with steep slopes)**

- **Tsunami: inland flow often supercritical**
  
  \[ Fr = 1.1 - 1.4, \text{Sendai (Nandasena et al., 2012)} \]
  
  \[ Fr = 0.5 - 0.9, \text{Samoa, (Jaffe et al., 2009)} \]
  
  \[ Fr = 0.9 - 2, \text{Irian Jaia (Matsutomi et al., 2001)} \]

<table>
<thead>
<tr>
<th>Bridge piers</th>
<th>Street furniture</th>
<th>Buildings, houses:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Damage</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Water depth</td>
</tr>
</tbody>
</table>
Part 1

Scientific Issues
Wide-spread knowledge concerning 2D compressible flows

**Subsonic flows:**
- flow velocity $U < a$ (speed of sound)
- disturbances can travel upstream
- flow « anticipates » the presence of an obstacle
- deviation by streamlines curvature

**Supersonic flow:**
- flow velocity $U > a$ (speed of sound)
- disturbances cannot travel upstream
- no anticipation, no streamlines curvature
- adaptation : shock wave
Slender bodies, bluff bodies and shocks

**Slender body:**
- imposes a small deviation ($\theta = O(10^\circ)$)
- promoted by an oblique shock wave
- flow remains supercritical (most of the time)
- $\theta_{\text{max}} = 0$-$34^\circ$ for $M=1$-$3$

**Bluff body:**
- imposes a strong deviation ($\theta = 90^\circ > \theta_{\text{max}}$)
- appearance of a detached shock wave
- a subsonic zone forms
- deviation through streamlines curvature within this subsonic zone
- well described by an analytical model (Moeckel, 1949)
Free-surface flows

Analogy with compressible flows:

- speed of sound  $\rightarrow$ surface waves celerity $a = \sqrt{gh}$
- subsonic  $\rightarrow$ subcritical
- supersonic  $\rightarrow$ supercritical
- Mach number  $\rightarrow$ Froude number $Fr = U/a$

Noticeable differences:

- confined between the bed and the free-surface
- influence of the bed friction
- compressible: 2D  /  free-surface: backwater effects, vertical cross velocities
The detached hydraulic jump

- previous works in water (Defina and Susin 2006, Mignot and Rivière, 2010)
- 1st symposium in Tohoku (2012) : influence of a gap below the obstacle
- Granular flows (Irstea Grenoble, e.g. Faug et al., 2015)
- Main characteristics correspond to detached shockwaves

- upstream supercritical flow ($Fr > 1$)
- detached hydraulic jump
- subcritical zone with $Fr < 1$
- streamline deviation within this zone
- bow-wave at the stagnation point
The «wall-jet-like bow-wave»

- Knowledge available on the detached hydraulic jump
- Observed experimentally
- Analogous to the detached shock wave in 2D compressible flows
- Problem: both field cases and experiments with «thin» obstacles lead to another flow structure: the so-called «wall-jet-like bow-wave»

Photograph of the wall-jet-like bow-wave around a bridge pier in the "Rivière des Galets" river, La Réunion Island, France, in March 2006:

No hydraulic jump forms …

Courtesy of Paul Bonnet, DEAL 974 (ex DDE 974)
Scientific issue

Apparent paradox :

• Flow manages to skirt the obstacle
• Without formation of a subcritical zone
In other words
• the flow skirts the obstacle although the flow remains in supercritical regime and should not be able to « anticipate » the presence of the obstacle

Objectives :

• Understand this new form of workaround
• Condition of appearance of one form or the other (wall-jet or jump)
• By means of experiments and conceptual model
Part 2

Experimental facilities and measuring devices
Experimental facilities

Water table

• Adjustable slope
• No side wall effects: $B=0.75 \text{ m} > h=O(5 \text{ mm})$
• Turbulent flows though limited Reynolds number
• $Fr = 0.56 - 6.35$

$\begin{array}{|l|c|}
\hline
\text{Width } B (\text{ m}) & 0.75 \\
\text{Length } L (\text{ m}) & 1.2 \\
Q_v (\text{ L/s}) & 0.25 - 3.2 \\
h (\text{ mm}) & 1.28 - 12.33 \\
R (\text{ mm}) & 13 - 100 \\
L_u/h & 40.6 - 391 \\
h/R & 0.012 - 2.57 \\
Fr & 0.56 - 6.35 \\
Re & 1300 - 16000 \\
We & 1 - 50 \\
\hline
\end{array}$
**Experimental facilities**

**Conventional open-channel**

- Adjustable slope
- $B = 0.25\text{m}$: limits depth $h$ and $Fr$
- $Fr = 0.5 - 2.5$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width $B$ (m)</td>
<td>0.25</td>
</tr>
<tr>
<td>Length $L$ (m)</td>
<td>9.24</td>
</tr>
<tr>
<td>$Qv$ (L/s)</td>
<td>0.51 - 21.89</td>
</tr>
<tr>
<td>$h$ (mm)</td>
<td>10 - 50</td>
</tr>
<tr>
<td>$R$ (mm)</td>
<td>10 - 50</td>
</tr>
<tr>
<td>$Lu/h$</td>
<td>100 - 500</td>
</tr>
<tr>
<td>$h/R$</td>
<td>0.3 - 4</td>
</tr>
<tr>
<td>$Fr$</td>
<td>0.5 - 2.5</td>
</tr>
<tr>
<td>$Re$</td>
<td>$1e4$-$2e5$</td>
</tr>
<tr>
<td>$We$</td>
<td>5-800</td>
</tr>
</tbody>
</table>

*Image of a diagram with labels: Obstacle, $Qv$, $R$, $B$, and $L_u$. Diagram shows a Rectangular Channel with labels for $Lu$, $R$, and $B$.*
Part 3

Two-flow forms: details and condition of appearance
1st form: Detached hydraulic jump

- Confirms and reproduces previous experiments
2nd form: Wall-jet-like bow-wave

- Very different features
- Deviation is vertical, in the close vicinity of the obstacle
Conditions of appearance

Dimensional analysis

• Look for the dimensionless parameters that rule the flow
• Vaschy-Buckingam’s Π-theorem leads to 4 parameters:

\[ \Phi \left( \frac{h}{R}, \text{Fr} = \frac{U}{\sqrt{gh}}, \text{Re} = \frac{4 \rho U h}{\mu}, \text{We} = \frac{\rho U^2}{\sigma} \min(h, R) \right) = 0 \]

- **Water depth to obstacle width ratio**
- **Fr : Froude Number (velocity/celerity)**
- **Re : Reynolds number (inertia/viscosity)**
- **We : Weber number (inertia/capillary effects)**
Conditions of appearance

Experimental results

- clear dependency on $h/R$ and $Fr$; no noticeable influence of $Re$ and $We$
- fixed $Fr$: jump forms when $h/R$ decrease, i.e. when obstacle width increases

Explain this segregation with a limit $h/R = f(Fr) \rightarrow \text{conceptual model}$
Conditions of appearance

Conceptual model:

- based on mass conservation
- jump forms if the wall jet is not able to evacuate the water blocked by the obstacle

\[ Q_{in} = R \cdot h \cdot U \]

- Inlet discharge (blocked by the obstacle)
  \[ Q_{in} = A_{blocked} U = RhU \]

- Maximum outlet discharge
  \[ Q_{out_{\text{max}}} = e \cdot h_{jet_{\text{max}}} \cdot u_{out} = Ch \frac{U^2}{2g} \]

- Jump forms if:
  \[ Q_{out_{\text{max}}} < Q_{in} \iff \frac{h}{R} < \frac{2}{C \cdot Fr^2} \]

Accounts for head-losses, mass leaving the jet, etc.
Conditions of appearance

Comparison with experiments
• agreement satisfactory with $C=1.1$
• transition explained by mass conservation

$\frac{h}{R} = \frac{2}{C \cdot Fr^2}$

- Wall-jet if the lateral jets can evacuate the flow blocked by the obstacle
- Hydraulic jump otherwise
Part 4

Properties of the wall-jet-like bow-wave
Properties of the wall jet: water depth

**Stagnation point**: conversion from kinetic energy to potential energy

\[ \Delta h = \frac{u_{surf}^2}{2g} \]

**Measurements:**
- conduction wave-probe
- time-averaged water depth on the front face
- oscillations and associated frequencies
Time averaged jet height

Results

• \( h_{\text{jet}} \) higher for hydraulic jumps
• with a wall-jet:
  - \( h_{\text{jet}} \) decreases with \( h/R \)
  - \( h_{\text{jet}} \) decreases with \( Fr \)

Jet behaviour

\[
\frac{Q_{\text{in}}}{Q_{\text{out-max}}} = \frac{2/C}{Fr^2 \frac{h}{R}}
\]

\( >1 \) : jump

\( =1 \) : wall-jet with \( h_{\text{jet}} = u_{\text{surf}}^2/2g \)

\( <1 \) : wall-jet with \( h_{\text{jet}} < u_{\text{surf}}^2/2g \)
Water depth oscillations at the stagnation point

- Acquisition of water depths during 300 s
- FFT with an averaging over short periodograms (Welch, 1967)
- corresponding peak frequencies

For a given $h/R$, peak frequency $= f(Fr)$
Water depth oscillations at the stagnation point

Strouhal number:

\[ St = \frac{2U}{g} f_p \]

- Distribution around \( St \approx 0.85 \)
- Frequency proportional to \( U/g \)
- Oscillations due to the (periodic) reverse spillage

\( U/g \) : Time scale both of free-fall and climb-up
\( 1/f_p \) : Time scale of the oscillations

\( h/R = 0.6 \)
\( h/R = 1 \)
\( h/R = 2 \)
\( h/R = 3 \)
Conclusions
Conclusions

• Two flow forms clearly identified of workaround
  The known « detached hydraulic jump »
  The new so-called « wall-jet-like bow-wave »

• Wall-jet-like bow-wave
  - Apparent paradox : no transition to a subcritical flow to skirt the obstacle
  - Different from 2D compressible flows: water exits vertically
    it « disappears » from the flow
    this suppresses the need of a streamline curvature
In terms of mitigation ...

- For a given inland flow: $Fr$ and $h$ are fixed
- $R$ depends on the obstacle:
  - Its size: car vs house vs hospital
  - Its orientation: longer dimension parallel or perpendicular
  - Considering $h/R$ values: buildings will often create hydraulic jumps
  - Conclusions modified for more streamlined obstacles
Prospects

• Extend the study to more streamlined obstacles

• Behaviour of the flow with multiple obstacles, as used for avalanche protection devices, corresponding to urbanized zones

• In terms of risk: keep velocity of convert it in depth?