The isolated building test case : results from the IMPACT benchmark

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SUMMARY
Within the IMPACT project, one aim of the Flood Propagation work package is to investigate floods in urban areas following a dam break. As a first step, and in order to limit the number of parameters involved in this complex flow, an idealised test case was designed. This consists in a dam-break flow in a channel with a single building downstream from the dam, not aligned with the flow direction. Experimental measurements have been performed by means of different techniques (point and field measurements) and the results provided a complete data set. Blind simulations of the flow were run in a benchmark session – the so-called isolated building test case – in order to assess the abilities of numerical models. Eight modellers from six different institutions (members and non-members of the project) participated to this benchmark. The results are presented in this paper, under the form of a comparison between experiments and numerical simulations.

1 INTRODUCTION
Flows may be considerably affected by the presence of natural or artificial obstacles. In the case of severe floods, for example due to dam- or dike-break, the influence of such obstacles is even amplified. Neglecting this influence in numerical simulations of such flows could lead to heavy misinterpretation.

At the large scale of a real flood event, it is not always possible to distinguish between the different features of the flow. Therefore, it was decided to design an idealised experiment that limits the parameters involved in the flow. A single obstacle representing a building is placed
in a channel, immediately downstream from the dam. Through appropriate measurements of
the flow, it is possible to identify its specific features.

This test is part of the broader study of flood propagation in urban areas undertaken within the
frame of the IMPACT project. It was used as a benchmark to validate numerical models and
strategies aimed at simulating flows in urban areas. The benchmark was run as a blind test by
eight modellers from six different institutions. Results from this blind test are presented in this
paper.

2 TEST CASE DESCRIPTION

The experiments were carried out in the laboratory of the Civil and Environmental
Engineering Department of the Université catholique de Louvain (UCL) in Belgium. The
channel is sketched in Figures 1-3.

It has a total length of 35.80 m and is 3.60 m wide. The upstream reservoir is 6.90 m long.
The cross section is trapezoidal near the bed (Figure 3a). The dam is represented by a gate
located between two solid blocks; its cross-section is rectangular and it is 1.00 m wide (Figure
3b). To simulate a dam break, the gate is pulled up rapidly. The building, located 3.40 m
downstream from the dam, consists in a rectangular block with dimensions 0.80 x 0.40 m. It
makes an angle of 64° with the channel axis (Figure 2). After measurement in uniform
conditions, the Manning bed friction coefficient was found to be $n = 0.01 \text{ s m}^{-1/3}$.

![Figure 1: Experimental set-up (dimensions in meters)](image1)

![Figure 2: Location and dimensions of the building (in meters)](image2)
The channel is closed by a wall at the upstream end. The downstream boundary condition consists in a weir and a chute, but has no influence on the flow during the test duration, which is 30 s. At the initial time, the water level is 0.40 m in the upstream reservoir and there is a thin layer of 0.01 m of water in the downstream part of the channel.

3 FLOW DESCRIPTION

A few seconds after the rapid opening of the gate, the strong dam-break wave reflects against the building, almost submerging it, and the flow separates, forming a series of shock waves crossing each other. A wake zone can be identified just downstream from the building, bounded by cross waves. The flow rapidly reaches an almost steady state with a decreasing discharge due to the emptying of the reservoir. Also, re-circulation zones can be identified between the building and the walls.
This description of the flow is illustrated by means of figures obtained from computed results (Noël et al., 2003). Figure 4 shows the free-surface elevation at $t = 1$ s, with the two-dimensional spreading of the flood wave.

At $t = 3$ s, the reflection of the wave against the building has occurred and results in the formation of an oblique hydraulic jump (Figure 5). The circular front wave also reflects against the side walls of the channel and lateral jumps are formed. Figure 6 shows the flow after 10 s: the upstream reservoir empties and the hydraulic jump formed by the reflection against the building migrates in the upstream direction. The separation of the flow around the building and the wake zone can also be identified.
4 EXPERIMENTAL MEASUREMENTS AND RESULTS

The water level is measured by means of 6 water-level gauges located in the channel as indicated in Figure 7: one gauge in the reservoir to monitor its emptying and thus the inflow discharge, and the others around the building. Their exact position is summarised in Table 1.

![Figure 7: Position of the gauging points where the water level and the velocity are measured](image)

<table>
<thead>
<tr>
<th>Gauge</th>
<th>x (m)</th>
<th>y (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G1</td>
<td>2.65</td>
<td>1.15</td>
</tr>
<tr>
<td>G2</td>
<td>2.65</td>
<td>-0.60</td>
</tr>
<tr>
<td>G3</td>
<td>4.00</td>
<td>1.15</td>
</tr>
<tr>
<td>G4</td>
<td>4.00</td>
<td>-0.80</td>
</tr>
<tr>
<td>G5</td>
<td>5.20</td>
<td>0.30</td>
</tr>
<tr>
<td>G6</td>
<td>-1.87</td>
<td>1.10</td>
</tr>
</tbody>
</table>

Table 1: Position of the gauges

The experiment was run several times and showed a very good reproducibility. The velocity was measured by two different means: (i) at the same locations as the water level measurements by means of an Acoustic Doppler Velocimeter (ADV), and (ii) by means of a Voronoï imaging technique (Capart et al., 2002) yielding the surface-velocity field. With the ADV probes, no complete vertical velocity profiles were measured. Only one velocity data was measured at each gauging point, at a height of 3.6 cm above the channel bed to ensure that the probes were submerged during the whole experiment. As the flow is a rapid transient with hydraulic jumps and re-circulation zones, it is not fully developed i.e. the velocity profile is not yet logarithmic. The velocity distribution is closer to a uniform distribution and this kind of “mid-depth” measurement yields a good evaluation of the depth-averaged velocity. Figure 8 shows a comparison between mean velocity (ADV measurements) and surface velocity (Voronoï imaging technique) at gauge G4: the good agreement validates both techniques and is also another indicator of the reproducibility of the experiment.

The experimental results are described in details in Soares Frazão et al. (2004).
5 BENCHMARK RESULTS

The benchmark description is given in Soares Frazão and Zech (2002). Participants were requested to run the test for 30 s and to provide the computed values of $h, u, v$ at each gauging point as well as field-results over the whole channel at times $t = 1$ s, $t = 5$ s, $t = 10$ s, $t = 20$ s.

5.1 Summary description of the computations by the participants

The blind test was run by eight different modellers from six different institutions, members and non-members of the IMPACT project. All modellers use a finite-volume method. Details concerning each particular model can be found in the individual modellers papers listed in the references. A summary is given in Table 2.

For this test case, UCL uses a Roe-type finite volume scheme (Soares Frazão and Zech, 2002) and a quadrangular mesh discretisation (Noël et al., 2003). The edges of the building are represented as solid walls.

CEMAGREF (Mignot and Paquier, 2003) presented three sets of results corresponding to different mesh sizes and types. The edges of the building are represented as solid walls.

Two authors from the University of Zaragoza computed the test case. Mulet used three different representations of the building (Mulet, 2003): (i) as a local bed elevation, i.e. the building walls consist in very steep slopes; (ii) with the edges represented as solid walls; and (iii) as a zone with a higher friction coefficient. Results by Murillo computed on a triangular mesh and with solid walls for the building edges are detailed in Murillo et al. (2003).

Capart (2003), from the National Taiwan University, represented the building embedded within the grid as a zone of higher elevation. But, as he used a square mesh that cannot fit exactly the oblique walls of the building, he spread the abrupt bed slope over several cells using a binomial smoothing of the elevation surface, to smoothen the sharp angles created by the mesh. This results in a hill-like representation of the building which could have some influence on the numerical results.
The University of Parma presented two sets of results computed by two different methods described in Aureli et al. (2003): the SLIC model by Toro (1997) and the WAF scheme by Toro (1997). They used square and quadrangular meshes.

Finally, the University of Pavia computed the test case on a quadrangular mesh with triangular cells around the building to match its shape exactly. They used two different treatments of the source terms detailed in Petaccia and Savi (2003): (i) a pointwise discretisation, denoted by PET-P in Table 2; and (ii) an upwind treatment denoted by PET-U.

<table>
<thead>
<tr>
<th>Organisation</th>
<th>Author</th>
<th>Order</th>
<th>Building</th>
<th>Mesh</th>
<th>Size (m)</th>
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<tbody>
<tr>
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<td>Noël &amp; Soares Frazão</td>
<td>UCL</td>
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<td></td>
<td>Mignot &amp; Paquier</td>
<td>CEM3</td>
<td>W</td>
<td>Q / T</td>
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<tr>
<td>UDZ</td>
<td>Mulet</td>
<td>Z-MA-E</td>
<td>BE</td>
<td>Q</td>
<td>0.050</td>
</tr>
<tr>
<td></td>
<td>Mulet</td>
<td>Z-MA-F</td>
<td>F</td>
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<td>CAP</td>
<td>BE</td>
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<td>W</td>
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<tr>
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<tr>
<td>Pavia</td>
<td>Petaccia</td>
<td>PET-P</td>
<td>Q / T</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

W : wall; BE : bed elevation increase; F : friction; Q : quadrangles; T : triangles; S : squares

Table 2: Participants to the benchmark

5.2 Comparison of numerical and experimental results

As summarised in Table 2, 15 sets of results were obtained from the participants. For the clarity of the comparison plots, only one set of results is represented for each participant. It was chosen to compare results computed on a 0.05 m mesh with the solid-wall representation of the building. The authors refer to the individual papers for a more detailed sensitivity analysis of the results.

This selection reduced the number of results to 8, indicated as follows (see also Table 2): UCL, CEM3, Z-MA-W, CAP, Z-MUR, P-AUR2, P-MAR2, PET-P.
5.2.1 Gauge G6

This gauge is located in the upstream reservoir and constitutes thus an indication of the inflow discharge. Figure 9 shows the comparison between experimental and numerical results. It can be observed that all modellers reproduce accurately the water-level evolution.

Figure 9: Experimental vs. numerical results (water level) at gauge G6

Figure 10: Experimental vs. numerical results (water level) at gauge G1
5.2.2  **Gauge G1**

Gauge G1 is located between two reflected waves: the lateral reflection against the side walls of the channel and the main reflection against the building. The location of these waves varies in time and this results in an irregular water surface as can be seen on the experimental curve in Figure 10. Numerical models generally reproduce well the waves, but not their exact location, which results in important variations in the results.

The difference between numerical results obtained with first- and second-order accuracy can be clearly observed: first-order results yield a much smoother profile, while second-order results tend to generate small waves on the water surface, which seems closer to the reality. However, neither the period nor the phase are accurately reproduced.

5.2.3  **Gauge G2**

This gauges clearly shows the reflection of the wave against the building, around $t = 15$ s (Figure 11).

![Figure 11: Experimental vs. numerical results (water level) at gauge G2](image)

![Figure 12: Computed water surface at $t = 20$ s by Mulet and Alcrudo](image)
Some numerical models seem to be completely missing the formation of the hydraulic jump. In fact, there is just an error in the position of the hydraulic jump, as can be seen from the computed water surface by Mulet and Alcrudo at $t = 20$ s in Figure 12. The location of the gauges is indicated by red points and it clearly appears that the hydraulic jump is located downstream from the gauge. For this gauges, it appears that only first-order accurate schemes were able to predict with a reasonable accuracy the arrival time of the hydraulic jump.

5.2.4 Gauge G3

Gauge G3 is located downstream from the lateral hydraulic jump formed by the reflection of the front wave against the side walls of the channel. The agreement with the experimental results is good and all models give a similar evolution of the water level (Figure 13). When looking at Figure 14 showing the velocities $u$ and $v$, the conclusion is even better as the agreement between experimental and computed results is very good. The flow there is mainly one-dimensional ($v$-velocity close to zero) and is in a quasi steady state as the velocities do not vary very much.
Figures 14 (continued): Experimental vs. numerical results (velocity) at gauge G3

5.2.5 Gauge G4

The results for this gauge are presented in figure 15. The gauge records a first peak in the water level corresponding to the “splash” when the water reflects against the building. Then, a hydraulic jump is formed that reaches the gauge around $t = 5$ s. A second wave reaches the gauge around $t = 14$ s, coming from the reflection against the side walls of the channel.

Figures 15: Experimental vs. numerical results (water level) at gauge G3

5.2.6 Gauge G5

The results for the water level at gauge G5 are presented in figure 16, and for the velocities in figure 17. This gauge is located downstream from the building, in the wake zone. Wake eddies can be particularly well identified in the $v$-component of the velocity in figure 17. In figure 16, it appears that the water surface is quite irregular. The mean water level is well reproduced by the numerical models, but not the details of the flow. Especially the first-order models yield a much smoother water surface. Second-order models represent some oscillations and irregularities of the water surface.
Concerning the velocity measurements, the conclusions are similar. First-order models completely miss the oscillations of the \( u \)- and \( v \)-components of the velocity induced by the wake eddies. They give a good estimate of the average velocity at the gauging point. Second-order models capture more details of the flow, they present oscillations which indicates that they reproduce the wake eddies. However, the phase, amplitude and period of the oscillations is not exact.

Figure 16: Experimental vs. numerical results (water level) at gauge G5

Figure 17: Experimental vs. numerical results (velocity) at gauge G5
6 CONCLUSION

Results from a benchmark session devoted to floods in urban areas were presented. The test case consisted in a dam-break flow in a valley with a single building. Although the numerical models used by the participants are all of the same type (finite-volumes), the results present a significant variability in some cases. Among the factors of this variability, the most important seem to be the mesh (refinement, mesh aligned or not with the building), the treatment of the source terms, the order of accuracy of the numerical model and the way the building is represented (as solid walls, in the topography or as a region of higher friction).

All numerical models were able to simulate the flow, and to reproduce its main features. The main errors are in the exact timing of arrival of the reflected waves, i.e. general phase errors. An overall agreement is generally observed for the water level, even if not all the details of this complex flow are reproduced.

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- CEMAGREF (France)
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- University of Zaragoza (Spain)
- CESI (Italy)
- Stakraft Grøner AS (Norway)
- Instituto Superior Technico (Portugal)

REFERENCES


