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Numerical simulations of dam-break waves impacting a rigid wall

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ABSTRACT: Tsunamis, landslides and the failure of artificial dams can be modelled as dam–break waves, unsteady flows sometimes characterized by shock–wave fronts. During their propagation these waves may interact with obstacles, eventually causing destruction and losses on nearby areas. The evaluation of the front propagation and of the impact force is of utmost interest for risk mitigation. We performed a series of both 3–D, non–hydrostatic, Reynolds–Averaged Navier–Stokes (RANS) and Large Eddies numerical Simulations (LES) of laboratory dam–break experiments using the Volume of Fluid (VOF) approach. We carried out experimental tests in a prismatic, rectangular channel locked downstream by a vertical wall; we measured the free surface configuration and the force by the wave on the downstream wall to validate the numerical results. Numerical predictions show strong 3–D effects developing nearby the wall characterized by air entrainment and free surface deformation. The VOF approach for tracking the free surface successfully allows to catch these flow features and the free surface evolution shows a good agreement with both RANS and LES simulations. Results are compared with 3–D, hydrostatic, depth–averaged numerical simulations. Although the latter cannot capture the 3–D features of the flow, they are able to predict both the impact time and the magnitude of the impact force peak.

1 INTRODUCTION

Dam–break waves arise from the sudden release of water stored in a reservoir and may cause huge damages to the surrounding landscape such as: human fatalities, ecological and environmental problems, economic losses. Numerical modeling is nowadays a powerful tool to predict the dam–break wave propagation and its interaction with structures located along its path in order to evaluate flood–related hazards. Therefore, the comparison of numerical results with experimental data is paramount to assess the performance of the mathematical models. To accurately reproduce the interaction between dam–break waves and obstacles advanced numerical models are required. On the other hand, to implement field–scale

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simulations there is the need to reduce the simulation costs, employing less sophisticated models. To compare the different modeling possibilities further aspects should be considered, e.g., the interaction with the channel sidewalls, turbulence effects and the assumption of hydrostatic pressure distribution. In terms of their complexity, the depth–integrated model based on solving the one–dimensional (1–D) De Saint–Venant equations (Lauber & Hager 1998) (SVE) is the simplest one. Compared with the SVE approach, the Reynolds–Averaged Navier–Stokes (RANS) and the Large Eddy Simulation approaches allow to relax the aforementioned assumptions.

In the present paper, we aim to develop clear guidelines on the engineering applications for which SVE can provide sufficiently accurate predictions, and those that require more complex modeling capabilities (3D RANS or LES models). Laboratory experiments have been performed in a rectangular channel, by reproducing a dam–break wave impacting against a rigid downstream vertical wall. By measuring the temporal evolution of the pressure on the wall we derived the total impact force acting on it. Experimental results are compared with numerical predictions obtained from three different models of increasing complexity and computational cost. The simplest numerical model is based on the 1–D SVE approach, assuming an infinitely-wide channel. We also performed non-hydrostatic numerical simulations: the 3–D LES and 3–D RANS with the Volume of Fluid (VOF) technique (Hirt & Nichols 1981) to track the interface. Numerical predictions are compared with the experimental data in terms of flow evolution and wave-induced pressure distribution and impact force on the vertical wall.

2 NUMERICAL MODELS

The main features of the numerical models considered in the present study are summarized in Table 1.

Table 1. Main features of the considered numerical models. Hardware configuration and average computational time are reported for each simulation.

	De Saint–Venant model	*Reynolds–Averaged Navier–Stokes*	*Large Eddy Simulation*
Pressure distribution	hydrostatic	non-hydrostatic	non–hydrostatic
Phase	water	air and water	air and water
Dimension	1D	3D	3D
Turbulence modeling	– –	$K-\varepsilon$	Dynamic Smagorinsky
Notation	SVE	3D RANS	3D LES
Processor	INTEL i7-7700 3.60 GHz	Argon HPC	Argon HPC
RAM	48 GB	28 nodes of 4 GB per core	28 nodes of 4 GB per core
Simulation time	0.1 hr	120 hrs	360 hrs

2.1 *Navier–Stokes solver*

The numerical model is the same as the one used by Del Gaudio et al. 2024 and Munoz & Constantinescu 2020 to study dam–break waves with 3–D RANS model. Further details about the discretization of the Navier–Stokes equations term can be found there. The eddy viscosity model for the RANS can be found in Munoz & Constantinescu 2020, whereas the latter is calculated using the dynamic Smagorinsky model for the LES, eq. Rodi et al. 2013. The free–surface is implemented through the Volume of Fluid (VOF) method (Hirt & Nichols 1981). In VOF, a pure–advection equation is solved for the volume fraction of water in a cell, V_f. The mean mesh size in non–dimensional wall units is 300 in all the three dimensions: near

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the walls we performed a refinement by means of prism layers reaching the value of one for both 3D RANS and LES simulations, thus total number of grid points is of about 2.69×10^6. At the top boundary, where only air is present, a pressure outlet boundary condition was imposed, which is standard treatment for this type of two–phase flows. The velocity was set equal to zero on all the solid surfaces and the surfaces were assumed to be smooth. A constant time step was used corresponding to a maximum CFL number of 0.2.

3 RESULTS

The experimental set–up instrumentation and accuracy and the experimental procedure can be found in Del Gaudio et al. (2024).

For presenting the results, the following dimensionless variables are introduced:

$$t = \frac{\tilde{t}}{t_c},\ z = \frac{\tilde{z}}{h_0},\ x = \frac{\tilde{x}}{h_0},\ v = \frac{\tilde{v}}{(gh_0)^{0.5}},\ P = \frac{\tilde{P}}{P_c},\ F = \frac{\tilde{F}}{F_c}, \tag{1}$$

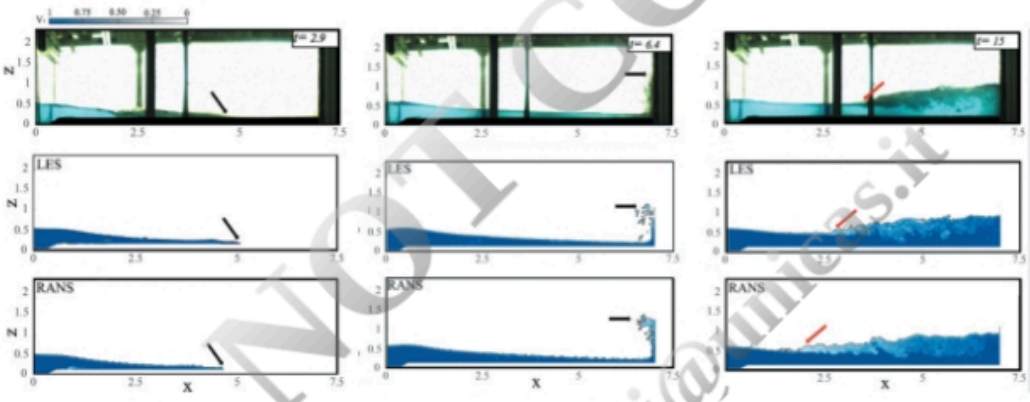


Figure 1. Flow evolution of the dam–break wave. Methylene blue is dissolved into the water to improve image readability. Contour plots represent volume fractions V_f predicted by the corresponding 3–D RANS and 3–D LES simulations. The black arrow shows the front position, while the red arrow shows the front of the backward–propagating bore.

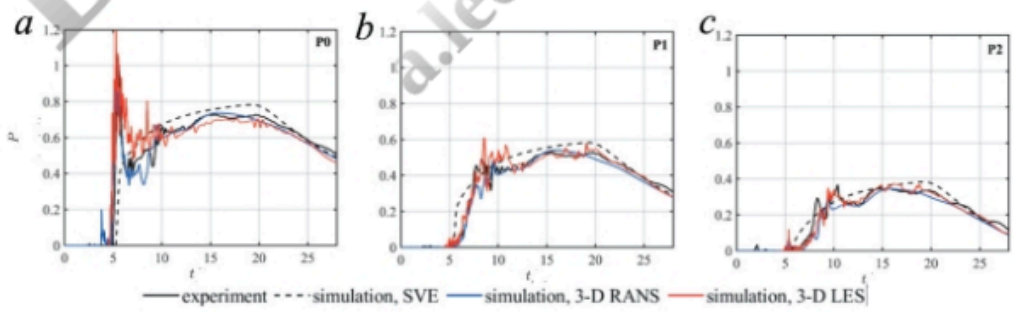


Figure 2. Time histories of the non–dimensional pressure at points (a) P_0 (1 cm above the bed), (b) P_1 (5 cm above the bed) and (c) P_2 (9 cm above the bed), derived from laboratory experiments (black lines), and predicted by SVE (dotted black lines), 3–D RANS (blue lines) and 3–D LES (red lines) numerical simulations.

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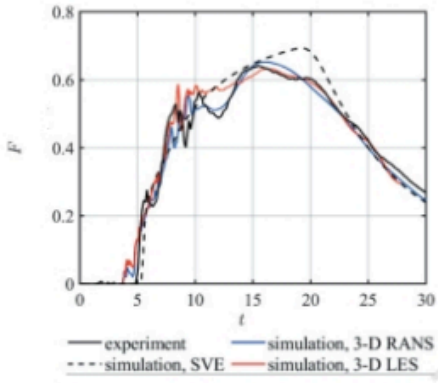


Figure 3. Time histories of the non–dimensional force, derived from laboratory experiments (black lines), and predicted by SVE (dotted black lines), 3–D RANS (blue lines) and 3D LES (red lines) numerical simulations.

where $t_C = \sqrt{\frac{2h_0}{g}}$ (Lauber & Hager 1998), $P_c = \gamma h_0$ with $\gamma = 9810\text{Nm}^{-3}$ the specific weight of water, $F_c = 0.5\gamma h_0^2$.

In terms of free–surface evolution, the Navier–Stokes (NS) numerical simulations show a very good agreement with experimental data. Both models provide a good prediction of the wave celerity and the impact time with the endwall (see Figure 1, $t = 2.9$). During the interaction with the wall, a thin, vertical jet–like flow forms and reaches the maximum run–up at approximately $t = 6.4$ in both simulation and experiment (Figure 1). The VOF technique implemented for tracking the free surface allowed reproducing all the main flow features observed experimentally: the flow overturning, the air entrainment and the formation of air bubbles. After the impact, the jet falling backward into the incoming water generates a counterclockwise vortex characterized by three–dimensional flow features and a backward–propagating bore. Both NS models well reproduce the backward propagating bore and the generation of a thick layer of fluid inside the bore with entrained air. Compared to the experimental evidences and the 3–D LES results, the 3D RANS simulation predicts slightly larger celerity for the backward propagating bore (Figure 1, $t = 15$).

A further crucial point for assessing the accuracy of the numerical model is its capacity to predict the temporal evolution of the pressure on the endwall and, ultimately, the magnitude of the impact force on it. Figure 2a shows that both NS models correctly capture (i) the pressure peak at the bottom of the endwall occurring when the thin front of the wave reaches the wall at around $t/t_0 = 5$, and (ii) the subsequent pressure oscillations induced by the backward–propagating bore for $t/t_0 > 10$. Due to the hydrostatic distribution assumption, the SVE simulation can not reproduce the Dirac–delta like behavior observed during the impact (Figure 2a). However, it efficiently predicts (i) the wave front celerity during the propagation, as confirmed by the comparison with the experimental impact time, and (ii) the second pressure peak during the nearly hydrostatic phase occurring during the backward propagation of the bore. All the numerical models provide a good prediction of the pressure temporal evolution at points $P1$ and $P2$, located at a higher elevation. Comparison of the numerical simulations and experimental data of the impact force show a similar level of agreement to that observed for the pressure time histories. The NS models can reproduce the oscillations due to the presence of the rotating vortex during the impact phase. Then, in terms of the maximum peak force the differences with the experimental value is less than 3%. The SVE simulation, on the other hand, does not reproduce the oscillations during the impacting phase (Figure 3, $5 \leq t \leq 10$) but the error of the maximum peak is still less then 10%.

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4 CONCLUSION

The hydrostatic models are able to fairly accurately reproduce the wave front celerity during the propagation phase and the maximum peak of both pressures and force on the endwall with an error less than 10%. More advanced and time–consuming models as 3–D RANS and 3–D LES can both reproduce the main flow features observed experimentally during the wave–structure interaction such as: flow overturning, air entrainment and formation of air bubbles by means of VOF surface tracking technique, non–hydrostatic pressure distribution and turbulence model. Thus, we can conclude that for main flow features and global parameter as forces, the 3–D RANS can be very accurate, and it is not necessary to use the more time–consuming 3–D LES with the Dynamic Smagorisky model; moreover, for engineering application a standard SVE may predict the wave impact time and maximum peak force with an error of less than 10%.

REFERENCES

A. Del Gaudio, G. La Forgia, G. Constantinescu, F. De Paola, C. Di Cristo, M. Iervolino, A. Leopardi, A. Vacca. Modeling the impact of a dam–break wave on a vertical wall, accepted for publication on the Journal: Earth Surface Processes and Landforms, 2024.

Hirt C W and Nichols B D. Volume of fluid (VOF) method for the dynamics of free boundaries. Journal of Computational Physics, 39(1):201–225, 1981.

Lauber J G and Hager W. "Experiments to dambreak wave: Sloping channel," Journal of Hydraulic Research 36, 761–773 (1998)

Munoz D H and Constantinescu G. 3–D dam break flow simulations in simplified and complex domains. Advances in Water Resources, 137:103510, 2020

Rodi W, Constantinescu G, and Stoesser T. Large–eddy simulation in hydraulics. Crc Press, 2013.

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