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Experimental and numerical evaluation of the force due to the impact of a dam-break wave on a structure

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ABSTRACT

Flood events caused by the collapse of dams or river levees can have damaging consequences on buildings and infrastructure located in prone areas. Accordingly, a careful prediction of the hydrodynamic load acting on structures is important for flood hazard assessment and potential damage evaluation. However, this represents a challenging task and requires the use of suitable mathematical models. This paper investigates the capability of three different models, i.e. a 2D depth-averaged model, a 3D Eulerian two-phase model, and a 3D Smoothed Particle Hydrodynamics (SPH) model, to estimate the impact load exerted by a dam-break wave on an obstacle. To this purpose, idealised dam-break experiments were carried out by generating a flip-through impact against a rigid squat structure, and measurements of the impact force were obtained directly by using a load cell. The dynamics of the impact event was analyzed and related to the measured load time history. A repeatability analysis was performed due to the great variability typically shown by impact phenomena, and a confidence range was estimated. The comparison between numerical results and experimental data shows the capability of 3D models to reproduce the key features of the flip-through impact. The 2D modelling based on the shallow water approach is not entirely suitable to accurately reproduce the load hydrograph and predict the load peak values; this difficulty increases with the strength of the wave impact. Nevertheless, the error in the peak load estimation is in the order of 10% only, thus the 2D approach may be considered appropriate for practical applications. Moreover, when the shallow water approximation is expected to work well, 2D results are comparable with the experimental data, as well as with the numerical predictions of far more sophisticated and computationally demanding 3D solvers. All the numerical models overestimate the falling limb of the load hydrograph after the impact. The SPH model ensures good evaluation of the long-time load impulse. The 2D shallow water solver and the 3D Eulerian model are less accurate in predicting the load impulse but provide similar results. A sensitivity analysis with respect to the model parameters allows to assess model uncertainty. Finally, the experimental data collected have been made available online as supplementary material for validation purposes.

1. Introduction

Buildings and infrastructure located near dams or river levees can be hit by severe flood events with potentially damaging consequences in the case of collapse of these retaining structures. On the one hand, the presence of construction in the flooding area, along with topographic irregularity, can strongly affect the dynamics of the inundation and the flood characteristics; on the other hand, violent loads acting on structures can cause serious damages and even compromise their stability.

A reliable characterization of the fluid–structure interaction is a key task not so much for accurately predicting flood evolution, as for evaluating potential direct damages to structures, defining appropriate failure and damage criteria as well as effective design methods, and planning corrective and preventative measures of damage reduction [24]. Furthermore, the assessment of the capability of structures to withstand flood actions is useful in emergency planning, especially in the case of rapid inundations due to dam-break events, because flood-resistant buildings can guarantee the occupants' safety without the need of evacuation. Hence, in flood risk analysis [61] impact force should be considered as an important parameter, appreciably affecting the hydraulic hazard level. However, the careful prediction of flood actions on structures is a challenging task, especially in the case of violent impact

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processes, because of the large number of geometric and hydraulic parameters involved [35,49].

Actually, some of these hydraulic quantities (for example, maximum water depth, maximum velocity, flood arrival time, rapidity of the rise, and duration of the flood [4]) are naturally involved, through appropriate combinations, in the formulation of several damage and failure criteria proposed in literature (e.g. [53]). Erpicum et al. [23] employed one of these failure criteria to interactively modify the topography during dam-break simulations. Aureli et al. [6] suggested including maximum total force (thereby accounting for contemporary hydrostatic and dynamic loads) in the set of hydraulic quantities useful for flood inundation modelling and hydraulic hazard assessment. Moreover, on the basis of a dataset concerning a real dam-break event, Gallegos et al. [27] performed structural damage predictions by coupling a hydrodynamic model with a damage model and analyzed the sources of uncertainty associated with the parameters involved.

Mathematical models are indispensable tools for evaluating hydraulic quantities involved in flood hazard analysis and should not only effectively deal with irregular topography, wetting and drying, and transcritical flows, but also accurately predict force actions on structures located in the flow domain. Two-dimensional (2D) shallow water modelling is a widely accepted mathematical tool to simulate rapidly varying open channel flows, even in the presence of obstacles, buildings (either isolated or multiple), and topographical singularities (e.g. [5,55,57,58,66]) or real bathymetry (e.g. [6,9,23,32,67]). In this context, if the interest lies in the detailed reconstruction of the near-field flow, a building is usually schematized as a rigid block with impervious walls or, equivalently, as a hole in the computational domain [56]. Otherwise, if a far-field simulation of the flow is sufficient for the purpose of the study, the approaches based on the fictitious strong increment of the friction coefficient [23] or on the concept of porosity of a built-up area [10,54,59] are used to obtain an overall prediction of the actual effects of these obstacles on flood propagation. Schubert and Sanders [56] compared different methods to model flood propagation in urban areas on the basis of a real-field dam-break application in order to highlight advantages and drawbacks of the different approaches.

However, it seems obvious to expect that a vertically-averaged approach would show limitations in reconstructing the impact of a dam-break wave against an obstacle, since this phenomenon is locally markedly three-dimensional (3D) and presents strong curvatures of the free surface with non-hydrostatic distribution of pressure along the vertical direction. For this reason, impact processes are usually analyzed in literature by means of 3D numerical models based on Reynolds averaged Navier–Stokes equations integrated by using Eulerian methods (e.g. [1,37,70]), SPH (Smoothed Particle Hydrodynamics) Lagrangian methods (e.g. [8,17,18,20,25]), or hybrid Eulerian–Lagrangian methods [50]. Furthermore, air entrainment effects can also be important in this kind of phenomena, thereby the adoption of a two-phase model is advisable.

This paper aims to compare the capability of 2D shallow water, 3D Eulerian, and 3D Lagrangian models to predict the impact forces caused by a dam-break wave on a structure. The 2D model adopted is a finite volume MUSCL-Hancock scheme based on the weighted surface-depth gradient method (WSDGM) recently proposed by Aureli et al. [7]. The Eulerian 3D model is the FLUENT commercial package, which can handle two-phase flows using the VOF (Volume of Fluid) technique [33]. Meshless Lagrangian 3D modelling is carried out using Dual-SPHysics, a free open-source SPH code specifically developed for free-surface hydrodynamics which solves the Navier–Stokes equations [30]. This software is accelerated by means of the Compute Unified Device Architecture (CUDA), which enables the simulation of violent flows with very high spatial resolution [2,68]. Numerical results are compared with data from new physical experiments in order to assess the accuracy of these mathematical models in reproducing an impact process and predicting the associated peak force. A sensitivity analysis on the model parameters is accomplished in order to evaluate the uncertainty associated with the numerical predictions. The main advantages and shortcomings of the three models in this kind of engineering applications are highlighted.

The literature review confirms that experimental studies on this subject have so far mainly dealt with marine and coastal applications (see, for example, [15,21,36,42,51,52,62]), and have been frequently directed towards the design of coastal and off-shore structures. In particular, Lugni et al. [42] investigated the flip-through generated by a sloshing wave by means of a particle image velocimetry technique and highlighted three different modes of the flip-through event according to the breakup features of the approaching wave. The kinematic field and dynamic behaviour were analyzed in detail for each flip-through mode. Later, Lugni et al. [43,44] focused their attention on the flip-through mode characterised by the entrapment of an air cavity in front of the wall. Moreover, several experimental studies reported in literature concerned debris flow (e.g. [3,64,71]), with the aim of both giving insight into the physics of the process and providing recommendations for the design of defence structures. On the other hand, fewer laboratory investigations have been devoted to studying the impact of a dam-break wave against a structure (e.g. [12,13,37,65]), although this topic has recently gained more attention [16,41]. The laboratory test case proposed by Yeh and Petroff concerning the impact of a dam-break wave (propagating on wet bed) against a tall structure has been widely employed in literature and is considered a reference for validation purposes [28,50].

A new laboratory investigation was therefore carried out in order to obtain further experimental data for the validation of numerical codes. Since flood waves originated by a total dam failure and propagating in a prismatic channel have mainly been considered in literature, a partial dam-break was induced on dry bed to investigate the frontal collision of the resulting flooding wave against a prismatic obstacle simulating an isolated building. It can certainly be expected that the impact load time series, and in particular the peak load value (which in general is of greater interest for real applications), depends on the shape of the obstacle, on its position and orientation within the flooding area, and on the shape of the impacting wave. However, only the dependence of the peak force on the dam-break initial condition (with reference to the headwater depth) is analyzed in this work.

The net hydrodynamic load exerted by the wave on the structure was measured by means of a load cell able to compensate errors due to off-centre forces. In this way an integral measurement of the dynamic interaction between fluid and structure is directly provided (see, for example, [12,13,52]). Since the designers' practical interest is often focused on the evaluation of the total force (possibly associated with its probability of occurrence), this measuring technique is preferable to the one based on the integration of multiple simultaneous pressure measurements obtained from several transducers mounted on a wall (as in [14,16,42,60], for example). Moreover, several experimental studies in literature have shown that pressure measurements obtained during very strong impacts are typically highly scattered, thus impact force appears more suitable than impact pressure to assess the effectiveness of numerical models in the framework of impact wave problems.

The paper is structured as follows. The experimental set-up is detailed in Section 2, whereas the three numerical models are presented in Section 3. In Section 4 a typical observed load time history is linked to the phases of the impact physics, and a repeatability analysis is carried out in order to assess the reliability of the experimental data. The consistency of the load impulse in