Building flood resilience: insights from dam-break scenario analysis.

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ABSTRACT: The devastating floods that struck Belgium in July 2021, claiming 39 lives and causing an estimated 2 billion euros in damages, prompted the launch of the FLOOD project, led by Buildwise (www.buildwise.be). This initiative has a critical mission: to develop construction standards that comprehensively address flood-related risks and loading. As part of the FLOOD project, the present study focuses on the assessment of forces in dam-break flow scenarios interacting with obstacles featuring buildings. Experimental measurements are compared to results obtained from two numerical models: a 2D model solving the shallow-water equations and a 3D turbulent model using OpenFOAM. This research provides essential insights into dam-break flow dynamics, offers guidance for optimizing protective infrastructure design, and significantly contributes to the development of flood-resilient construction standards tailored to the specific needs of Belgium, advancing the field of flood risk management.

1 INTRODUCTION

Recent floods have significantly impacted Belgium: July 2021, but also West Flanders in November 2023 and East Flanders in January 2024. These events were not limited to Belgium; similar incidents were observed in the same year in other countries, including, for example, Germany, the Netherlands, and Italy. Notably, the 2023 floods in the Emilia-Romagna region of Italy were particularly devastating, resulting in 14 fatalities and causing material damages estimated at 10 billion euros (France Télévisions, 2023) These tragic events underscore the severe and wide-reaching impacts of such natural disasters.

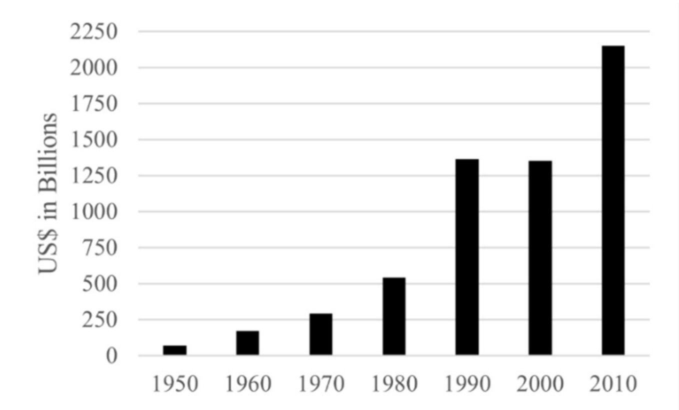

Figure 1. Total damage caused in the world by flood disaster (*Public EM-DAT Platform*, n.d.).

Regrettably, there is a noticeable increase in the frequency of extreme flood events worldwide, a trend intimately linked with climate change (IPCC, 2012). As illustrated in Figure 1, the damages caused by floods have shown a global increase since the 1950s. In Belgium, there is a lack in building design and renovation standards regarding flood risks, unlike the well-established norms for other natural disasters like earthquakes and wind. This absence of flood-specific regulations in a world increasingly prone to severe flooding due to climate change underscores the urgent need for developing comprehensive guidelines and regulations to effectively mitigate the impacts of such events.

Following the catastrophic events of July 2021, Buildwise launched the Flood project, dedicated to developing the necessary knowledge for establishing practical directives and strategies for construction and renovation in flood-prone areas. To achieve this, the project is adapting international standards to fit the Belgian context, utilizing a combination of laboratory and field measurements. These efforts are focused on identifying structural vulnerabilities and implementing targeted enhancements, while considering the distinct characteristics and environments of buildings. A key aspect of the Flood project involves thoroughly investigating building resilience in flood conditions. UCLouvain significantly contributes to this by developing a scientific framework for assessing the forces during floods and accurately determining the load buildings can withstand under such conditions.

To effectively manage flood risks, understanding the nature of the flood and associated hazards is of paramount importance. Belgium predominantly experiences two types of floods: coastal and riverine, although other forms like runoff, failure of infrastructure assets, drainage and sewer system flooding, and groundwater issues also occur. Each type of flooding presents unique challenges and potential forces on structure. The primary forces exerted on buildings during riverine floods include hydrostatic and hydrodynamic pressures, along with debris impact. Factors such as erosion and scouring exacerbate these forces, potentially destabilizing structures. Coastal floods require similar considerations, with the added complexity of wave-induced forces.

Table 1. Categorization of flood actions (adapted from Kelly et al., 2020).

Relevance	Predictability	Flood action types
High	Relative	Lateral hydrostatic pressure, hydrodynamic pressure and water contact.
Variable	Relative	Buoyancy issues.
Variable	Low	Debris impacts, erosion, capillary rise, velocity actions and non-physical issues.

Kelly et al. categorizes flood actions into three groups based on their predictability and relevance, as detailed in Table 1. In the “high relevance” category, hydrostatic and hydrodynamic pressures are featured. Hydrostatic pressure is readily calculable and depends solely on the water depth on either side of a structure. In contrast, hydrodynamic pressure is primarily influenced by the flow velocity and is more challenging to ascertain. As explained by Kreibich et al. (2009), flow velocity is a significant parameter in modeling flood-induced damages. Therefore, accurately assessing these pressures, particularly hydrodynamic, is crucial for an effective flood risk management strategy.

This study seeks to improve methods for evaluating hydrodynamic loads by finding a balance between ease of application and accuracy. For this purpose, laboratory experiments were conducted; a dam-break flow scenario was recreated, and an obstacle was positioned within the flow. The exerted forces on the obstacle were quantified using pressure sensors. The outcomes of our experiments will serve to confirm or revise the existing formulas found in the literature. The validity of these formulas will be discussed, particularly in the context of highly transient flow conditions.

2 REVIEW OF EXISTING FORMULATIONS

In our experiments, the obstacle placed within the dam break flow was subjected to water pressure on its surfaces, resulting in a total force F. This force comprises two components: the hydrostatic force F_{stat}, which is the resultant of the water depth pressure along the obstacle's surface, and the hydrodynamic force F_{dyn}, arising from the water's velocity as it impacts and flows around the obstacle.

Figure 2. Laboratory experimental setup.

The hydrostatic force can be calculated using Equation 1, which integrates the hydrostatic pressure p_{stat} over the surface A of the obstacle in contact with water:

$$F_{stat} = \int_A p_{stat}\, dA = \int_A \gamma h\, dA \quad (1)$$

where h indicates the water depth along the obstacle's surface and γ is the density of water.

The hydrodynamic force is inherently complex due to its sensitivity to the varying conditions of flow and is composed of two fundamental contributions: drag and inertia. The drag component F_D correlates with the velocity of the water flow, embodying the resistance faced by the structure as water moves past it. Conversely, the inertial component F_I is tied to the acceleration of the water, reflecting the mass of water that the structure must displace during its interaction with the flow.

The experimental tests we have conducted offer the advantage of enabling a detailed study of both components. In these dam break flow tests, the inertia forces play a crucial role during the initial impact phase, while the drag forces become the predominant factor as the flow transitions into a quasi-static state.

Drawing from the work of Naudascher (1991), when the structure is stationary, an effective approximation of the total hydrodynamic force acting on a structure is given by:

$$F_{dyn} = F_D + F_I = \frac{\rho}{2} A\, C_D \left| V \right| V + \rho A C_m \dot{V} \quad (2)$$

where ρ represents the water density, A denotes the cross-sectional area of the structure, V is the approach velocity of the flow, C_D is the drag coefficient, and C_m is the inertia coefficient.

The drag and inertia coefficients serve as comprehensive parameters that encapsulate the complexities of the flow. These coefficients are influenced by a myriad of factors, including the obstacle's shape, its surface roughness, the Reynolds number, the separation distance between neighboring obstacles, and the Keulegan-Carpenter number (The Overseas Coastal Area Development Institute of Japan, 2020). While existing tables provide values for a range of basic scenarios, it is crucial to apply these coefficients with considerable caution. Hamel-Derouich (1993) warns against the extrapolation from existing data, emphasizing the limitations of applying these coefficients beyond their tested conditions. Therefore, any unique shape or configuration for which coefficients are not readily available must undergo experimental testing to accurately determine their values.

Despite these complexities, the drag force component is widely accepted and integrated into the majority of building standards, reflecting a consensus on its reliability. The standards and guidelines referenced in this study, which have informed our methodologies and analyses, are detailed as follows:

- ASCE: *Minimum design loads and associated criteria for buildings and other structures* (USA, 2016).
- FEMA: *Engineering principles and practices for retrofitting flood-prone residential structures* (USA, 2012).
- Coulbourne Consulting: *Guide for design of flood-resistant buildings* (Canada, 2021).
- OCDI: *Technical standards and commentaries for port and harbour facilities in Japan* (Japan, 2020).
- MBIE: *Tsunami loads and effects on vertical evacuation structures* (New Zealand, 2020).
- ABCB Standard : *Construction of buildings in flood hazard areas* (Australia, 2012).

On the other hand, the evaluation of the inertial force component presents a broader spectrum of methodologies. To address this, our study not only relies on the established standards but also delves into the comprehensive set of formulas provided by Wüthrich et al. (2018) for estimating wave-induced forces on structures. This extensive set of formulas is applied in our experimental dam break flow tests, allowing for a comprehensive comparison between the formulas themselves and with the experimental results. This approach aims to verify the applicability and reliability of these formulas in such scenarios, providing a critical assessment of their performance in predicting the initial impact forces.

3 EVALUATION OF IMPACT FORCES

To replicate the flow dynamics observed in dam break experiments, we initiated a series of numerical simulations. Our initial step involved the utilization of the Watlab computational code , developed and made available as open source by UCLouvain (https://sites.uclouvain.be/hydraulics-group/watlab/index.html). Watlab efficiently solves the Saint-Venant equations using a finite volume scheme on an unstructured mesh, accurately representing the flow characteristics.

However, as the flow evolved into a distinctly three-dimensional form during the impact between the wave and the obstacle, the limitations of the 2D model assumptions became evident, questioning the accuracy of the results. To address this, we transitioned to a more robust solution, employing a 3D turbulent model using OpenFOAM. This method enabled a more precise representation of the complex, three-dimensional flow dynamics.

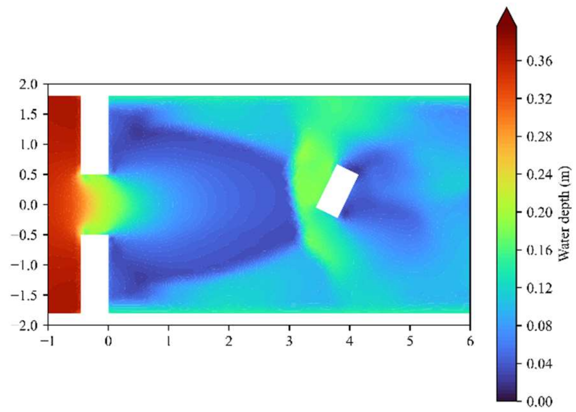

Figure 3. 2D simulation of the dam break flow using Watlab.

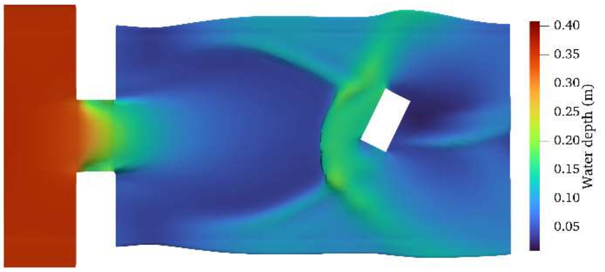

Figure 4. 3D simulation of the dam break flow using OpenFOAM.

Figure 5 provides a comprehensive representation of the study's findings, integrating various data sets. It displays the force exerted on the obstacle as estimated from experimental pressure measurements, alongside the force progression calculated by the Watlab and OpenFOAM numerical models. The force calculated with OpenFOAM is derived from the provided pressure data, whereas, since pressure is not a variable in Watlab, the forces are computed using water heights and velocities with Equation 1 for hydrostatic force F_{stat} and Equation 2 for drag force F_D, by adopting a drag coefficient of 1.25 as recommended by ASCE 7-16. Additionally, the figure shows force estimates calculated using the ASCE's impact and drag force formulas.

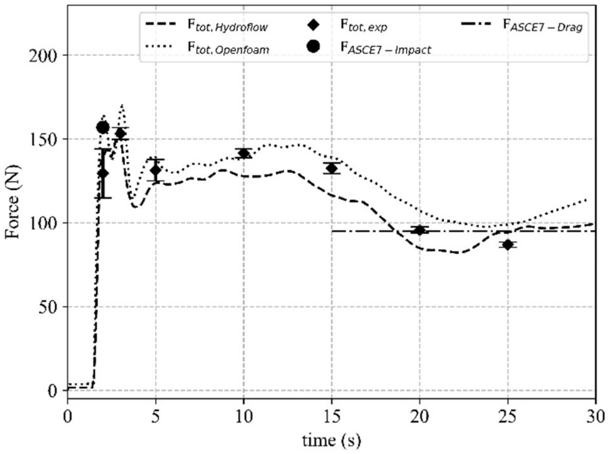

Figure 5. Evolution of the force of a dam break flow against an isolated obstacle.

Figure 5 effectively demonstrates the proficiency of both computational codes in accurately simulating the force, with the results aligning closely with the experimental data. Despite the three-dimensional nature of the flow at the point of impact, the 2D model successfully captures the force dynamics, underscoring its applicability in such scenarios. Generally, the figure also reveals that the American buildings standards provide highly satisfactory estimates for the impact and drag forces, affirming their relevance and accuracy in the context of this study.

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