Use of fluid structure interaction technique for flash flood impact assessment of structural components

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Abstract
Prediction of the initial impact force is a major task associated with flood damage assessment of structures subjected to flash flooding especially due to dam break and levee breach. Investigation of failure modes such as overturning and sliding due to soil scouring or erosion is not relevant if the structure first fails by the massive initial dynamic impact. Therefore, a careful assessment of the initial flood impact is critical for the design of structures and during the flood damage assessment process. In most of the past flood damage studies, total flood load acting on the structures was estimated by maximum velocities and water depths obtained from the two-dimensional hydrodynamic models or the field data. The outcome of these results has shown potential uncertainty in current methods. We present a new approach to calculate the load on structural components impacted by a dam break wave, by modelling the three-dimensional free surface fluid–structure interaction (FSI) using the incompressible computational fluid dynamics (ICFD) techniques. Two experimental datasets available in the literature are used to validate the results. Finally, we conclude that FSI/ICFD method can be used to accurately determine the initial impact force on structural components subjected to flash floods for flood damage assessment.

KEYWORDS
dam break, flash flood, flood damages, fluid–structure interaction (FSI), incompressible computational fluid dynamics (ICFD)

1 | INTRODUCTION

The assessment of structural capability to withstand flash flooding is useful in emergency planning especially in the case of a dam break or high-velocity floods. Methods used to estimate the impact force acting on the structure due to flash floods are still questionable (Gallegos, 2011; Gallegos, Schubert, & Sanders, 2012; Lobovský, Botia-Vera, Castellana, Mas-Soler, & Souto-Iglesias, 2014). In a real situation, the pressure acting on the structure at the time of initial impact is very high (Aureli, Dazzi, Maranzoni, Mignosa, & Vacondio, 2015; Cummins, Silvester, & Cleary, 2012; Kleefsman, Fekken, Veldman, Iwanowski, & Buchner, 2005). Further analysis of other effects like foundation damage due to inundation time and soil scouring is not relevant if the structure first fails from the initial impact. Two-dimensional models are not capable of accurately predicting the high-velocity dam break impact (Aureli et al., 2015) but low-velocity flow impacts (Aureli et al., 2015). Recent research studies have shown an

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increasing trend of using incompressible computational fluid dynamics (ICFD) techniques for wave impact problems. Common methods used in these three dimensional (3D) numerical models are based on Reynolds averaged Navier–Stokes equations integrated by smoothed particle hydrodynamics (SPH) Lagrangian methods (Barreiro, Crespo, Domínguez, & Gómez-Gesteira, 2013; Colagrossi & Landrini, 2003; Colagrossi, Lugni, & Broccini, 2010; Cummins et al., 2012; Cuomo, Allsop, Bruce, & Pearson, 2010; Ferrari, Dumbser, Toro, & Armanini, 2009), Eulerian methods (Abdolmaleki, Thigarajan, & Morris-Thomas, 2004; Kleebsman et al., 2005; Yang, Lin, Jiang, & Liu, 2010) or hybrid Eulerian–Lagrangian methods (Raad & Bidoae, 2005). Most of these models have been validated from experimental datasets related to coastal applications (Chan, Cheong, & Tan, 1995; Cuomo et al., 2010; Kirkgöz, 1995; Lugni, Broccini, & Faltinsen, 2006; Ramsden, 1996; Ramsden & Raichlen, 1990; Thusyanthan & Madabhushi, 2008). In all of these studies, structural components are analysed as rigid structures and material properties of the structure are not taken into consideration. No studies have been conducted to estimate the reaction force and structural damage/deflections due to dam break or high-velocity flood impact by introducing material properties to the structure using fluid structure interaction FSI/ICFD method. Therefore, this study provides a more comprehensive approach to close this gap.

In this study, we assess the fluid structure interaction by (a) estimating the force/pressure applied on the structure by free-flowing fluid movement due to a water column collapsed by gravity and (b) observing the impact of the above force on the structure by considering the material properties. The “impact” mentioned above may or may not result in a visible deformation depending on the magnitude of the applied force. As the material properties are considered, the method is capable of generating a simulation that indicates a deformation in the structure whenever a higher force is applied. Hence, the structure is not considered to be rigid and may fail at any moment given the applied force is large enough.

There are studies reported in the literature on building damage due to floods (Gallegos et al., 2012; Jongman et al., 2012; Kelman & Spence, 2003; Kreibich & Dimitrova, 2010; Maiwald & Schwarz, 2012; Martins, Leandro, & Djordjević, 2018; Nadal, Zapata, Pagan, Lopez, & Agudelo, 2010). Different types of damage functions have been developed for flood damage assessment of buildings, using relationships between flood characteristics and extent of the economic damage (Gallegos et al., 2012; Kelman & Spence, 2004; Nadal et al., 2010; Roos, 2003).

Physical damage to the building has been estimated from field data or by carrying out the structural analysis. Flood forces required for the structural analysis have been calculated from the flood parameters obtained from two-dimensional hydrodynamic models or site-specific data.

Depth-damage curves (stage-damage curves) and the velocity-depth curves are the commonly used methods in flood damage assessment to estimate the building damage. Stage-damage curves were first introduced in the 1960s (Kates, 1965; White, 1964). Since then several methods for flood damage assessment have been developed (Dutta & Tingsanchali, 2003; Greenaway & Smith, 1983; McBean, Fortin, & Gorrie, 1986; Parker, Green, & Thompson, 1987; Penning Rowsell, 1977), however, stage-damage curves are the widely used method in current flood damage models. In this case, inundation depth is treated as the major determining parameter. Nevertheless, these depth based damage estimates are highly uncertain as the aggregated damage is caused by variations of various flood parameters, and not only the depth (Gallegos et al., 2012). As mentioned in “Effects of long and short duration flooding on building materials (FEMA, 2005),” the use of depth-damage curves is not recommended: “whenever high velocity flows, ice or debris induced damage, erosion and soil/foundation failure, or unusually long-duration flooding is likely.”

With this uncertainty existing in the stage-damage functions, velocity-stage damage curves have been developed incorporating force, discharge, and velocity functions as damage criteria (Black, 1975; CH2M Hill, 1974; Claussen, 1989; Claussen & Clark, 1990; Dale, Edward, Middelmann, & Zoppou, 2004; Gallegos et al., 2012; Kreibich et al., 2009; McBean, Fortin, & Gorrie, 1986; McBean, Gorrie, Fortin, Ding, & Moulton, 1988). Influence of other factors like flood duration, contamination and preparedness are also being considered for the assessment of flood damage based on post-survey data from the 2002 flood in Germany (Kreibich, Thieken, Petrow, Muller, & Merz, 2005; Thieken, Muller, Kreibich, & Merz, 2005). Velocity-stage damage curves only represent the overall instability of the building. If the water depth and the flow velocity at a specific building fall on the curve, the building is considered to have become unstable and in the ultimate limit state. Buildings are considered stable or having a partial damage if the combination of flow velocity and water depth at the building falls to the left of the curve. Gallegos et al. (2012) graphically compared the structural damage criteria described above to the Baldwin Hills flood damage case study and have shown the potential uncertainty of these methods, especially in high-velocity floods.

Few studies using either complementary or alternative methods with respect to the techniques discussed above have been proposed to assess the flood damage. Kelman and Spence (2004) evaluated the effects of
hydrostatic forces due to flood water depth differentials inside and outside of the building and flood water velocity to assess the risks from coastal flooding. Roos (2003) evaluated the vulnerability of concrete and masonry buildings due to several loading cases by considering various flood parameters and compared the total floodwater load to the strength of the walls. However, these results were of qualitative nature, thus limiting their applicability as a generic technique.

A new method has been developed to estimate the direct physical impact of flood actions on reinforced concrete frame buildings with infill concrete-block walls by Nadal et al., 2010. The Vulnerability of a building has been modelled based on the failure mechanisms of individual building components. The total flood load (hydrostatic and hydrodynamic forces) generated during a flooding event has been assessed with respect to the resistance of each building component. Finally, expected flood damage of individual building components has been represented as a three-dimensional function of depth and velocity as dependent variables (Nadal et al. (2010)).

Nevertheless, all of the above-mentioned studies have basically used the velocities and water depths obtained from either two-dimensional models or field data. In addition, these methods are either case specific or applicable to slow rise floods.

Under the aforementioned circumstances, three-dimensional hydrodynamic analysis using reliable software with the capability to correctly model the fluid dynamics of free surface flow is important to assess the flash flood impact. Having FSI capability is important as that helps to analyse the structural deformation within a single model by automatically applying the fluid impact.

Navier–Stokes equations accurately describe the motion of an incompressible viscous fluid flow with a free liquid surface. There are several methods described in the literature for the treatment of the free surface in numerical modelling. Among these, volume of fluid method, level set method and smooth particle hydrodynamics method are popular. A synopsis of the different methods available can be found in (Osher & Sethian, 1988; Scardovelli & Zaleski, 1999).

Out of these methods, volume-of-fluid method and smooth-particle hydrodynamics method have already been validated by Kleefsman et al. (2005) and Cummins et al. (2012) respectively using two experimental datasets (Issa and Violeau (2006) and Yeh and Petrof as published by (Raad & Bidoae, 2005). In contrast, we use the Level set method with a Eulerian formulation to calculate the reaction forces and pressures in a flash flood event. The calculations are performed using ICFD techniques available in LS-DYNA free surface module (Çaldichoury & Del Pin, 2012) and we use the above two datasets to validate the results. In addition, we take the material properties of the structure into consideration. To our knowledge, this is the first instance that the structure is not assumed to be rigid in flash flood impact analysis based on FSI. Moreover, the former simulation studies by Kleefsman et al. (2005) and Cummins et al. (2012) are more focused on water profiles, and in our study, we give our attention to impact pressures and forces with the flash flood structural damage scenario in mind.

Section 2 provides a brief description of the main features of the free surface module in LS-DYNA that is used to reproduce the results of the two experimental datasets. Section 3 details the experimental setup and numerical model development. Results and discussion are presented in Section 4. Section 5 concludes the study.

2 | FINITE ELEMENT MODELLING

Incompressible computational fluid dynamics (ICFD) focuses on the solution of CFD problems, where the incompressibility constraint may be applied. We use the free surface module available in ICFD LS-DYNA to model the fluid flow. The solver of the free surface module in LS-DYNA uses a level set method to solve the Navier–Stokes equations that represent the moving interfaces of fluids (Osher & Sethian, 1988). It is a fast and reliable technique and depends on an implicit representation of the interface whose equation of motion is numerically approximated using Euler scheme. Large Eddy simulation (LES) model is used along with the Smagorinsky model to model the turbulence (Çaldichoury & Del Pin, 2012; Del Pin & Çaldichoury, 2013).

In order to accurately represent fluid structure interactions, it is necessary to let the fluid part and structural part to evolve in a coupled system. Here, fluid forces applied on the structure and the impact resulting on the structure interact at each time step. The solver may run as a stand-alone CFD solver, where only fluid dynamics effects are studied, or it can be coupled to the solid mechanics solver to study loosely or strongly coupled fluid–structure interaction (FSI) problems. Loosely coupled schemes require only one solution of either field (fluid or solid) per timestep in a sequential manner whereas strongly coupled schemes require the convergence of the fluid and solid variables at the interface. We used the strong coupling method for the analysis because it is the most consistent and accurate method for transferring both loads and displacements across the FSI interface by solving the full nonlinear problem. LS-DYNA solid mechanics solver uses the implicit solver when
strong coupling is activated (Çaldichoury & Del Pin, 2012). The forces applied on the solid domain will be transmitted on the structure and identified as pressure boundary conditions at the time of fluid–structure interaction.

Due to the availability of massively parallel processing (MPP) which is a type of efficient computing methods available in LS-DYNA, computing time can be saved by providing a good CPU scalability. In this method, many separate CPUs are running in parallel each with their own memory rather than a shared memory to execute a single analysis (Del Pin & Çaldichoury, 2013). The special LS-DYNA R8 MPP Linux solver is used in this study to perform numerical modelling to make use of this computational advantage.

3 | EXPERIMENTAL SETUP AND NUMERICAL MODEL DEVELOPMENT

A comprehensive, three-dimensional numerical analysis was conducted to investigate the dam break impact on structures, using free surface ICFD module in LS-DYNA (Çaldichoury & Del Pin, 2012). The two experimental datasets available in the literature were used to validate the numerical model results.

3.1 | Case study 1

3.1.1 | Experimental setup

Maritime Research Institute Netherlands (MARIN) has performed experiments on breaking dam flows (Issa & Violeau, 2006) and, we use this dataset for the FSI analysis based on level set method.

In this experiment, a $3.22 \times 1.0 \times 1.0$ m$^3$ rectangular tank with an open roof was divided into two compartments: an upstream reservoir and a downstream floodplain as shown in Figure 1. A gate of 1.0 m width was used to separate these two units. A depth of 0.55 m of water is ready to flow into the floodplain when the gate is opened by means of a releasing weight that pulls the door up instantly. A box with dimensions $0.403 \times 0.161 \times 0.161$ m$^3$ was firmly oriented in the floodplain area in order to obtain the frontal impact measurements. The pressure at points $P_1$, $P_2$, and $P_3$ as shown in Figure 2 were measured using pressure sensors and we use the readings at these points to validate our analysis.

3.1.2 | Numerical model

Our numerical model consists of a fluid domain space with water and air, and a rectangular concrete cube is fixed to the bottom as shown in Figure 1. We modelled the surrounding atmospheric air and water column using shell elements. The keyword MESH_SURFACE_NODE is used to define a node and its coordinates and the
keyword MESH_SURFACE_ELEMENT to specify a set of surface elements. Together, they are used to generate the automatic volume mesh for the fluid domain. The water column is initially at rest and at time = 0 s, made to collapse under the influence of gravity by activating the LOAD_BODY_Z keyword. The concrete box was modelled using the solid brick elements. A solid brick element is the general term used in LS-DYNA to represent the basic numerical particle of the solid structure. They can have displacements and are not rigid since we have introduced the material properties as detailed in Section 3.3.

For the initial numerical model, 15 mm size quad shell elements (a grid of 215 × 67 × 67) were used to construct the fluid mesh and 5 mm solid brick elements were used to model the concrete box. The simulation was carried out up to 1.2 s with a 0.001 s time step and the Courant–Friedrichs–Lewy (CFL) number of 1.0. Smagorinsky sub-grid scale model was created with Smagorinsky coefficient \( C_s = 0.24 \).

Quad shell elements of 12 mm (a grid of 268 × 83 × 83) and 10 mm (a grid of 322 × 100 × 100) were also used to construct the fluid mesh for subsequent models to achieve consistent results and to perform mesh refinement studies. Due to the system constraints of the computer, the smallest fluid mesh size that can be used was 10 mm.

3.2 | Case study 2

3.2.1 | Experimental setup

The experiment performed by Yeh and Petrof as published by (Raad & Bidoae, 2005) utilised a rectangular tank 0.61 × 1.6 × 0.75 m³ with a 0.12 m square column located 0.9 m from one end of the tank. A volume of water 0.61 × 0.4 × 0.3 m³ was initially enclosed behind a gate as shown in Figure 3 and then collapses under the influence of gravity, with the sudden release of the gate at time 0 s. This initiates water flow towards the column and net force acting on the column was measured. A thin layer of water of 10 mm depth was initially placed at the bottom of the tank downstream of the gate to facilitate a smooth flow.

3.2.2 | Numerical model

For the initial model, 10 mm quad shell elements (a grid of 160 × 61 × 75) were used to construct the fluid mesh and the box was modelled as a concrete structure with 5 mm size solid brick elements. The simulation was carried up to 1.0 s with a time step of 0.001 s and the CFL number of 1.0. Smagorinsky sub-grid scale model was created with \( C_s = 0.24 \). A fluid mesh with 8 mm (a grid
of 200 × 76 × 94) and 6 mm (a grid of 267 × 102 × 125) quad shell elements were used to construct the subsequent models until accurate results were obtained. The deflection of the column was not noticeable since the water load was not enough to develop significant deflections in the column.

### 3.3 Material parameters

In both case studies, material properties for the fluid domain were input by using the ICFD_MAT card with a density of 1,000 kg/m$^3$ and dynamic viscosity of 0.001 N s/m$^2$ for water. A rectangular concrete cube was used for the numerical model to represent the box used in the Case study 1 and a rectangular concrete column was used in the Case study 2. There are several concrete models available in LS-DYNA (Hallquist, 2007). However, *MAT_CONCRETE_DAMAGE (MAT_72 R3 and MAT_72), *MAT_WINFRITH_CONCRETE (MAT _84/85), and *MAT_CSCM_CONCRETE (MAT_159) were the most frequently used models in impact analysis in the literature. In this study, we used *MAT_WINFRITH_CONCRETE (MAT_84/85) to model the concrete elements. Additional material parameters used are listed in Table 1.

| Parameter                  | Value       |
|----------------------------|-------------|
| Density                    | 2,400 kg/m$^3$ |
| Uniaxial compressive strength | 32 MPa     |
| Uniaxial tensile strength  | 2.04 MPa    |
| Tangent modulus            | 3.010e+01 MPa |
| Poisson’s ratio            | 0.15        |
| Fracture energy            | 74 N/m      |

### 4 RESULTS AND DISCUSSION

We used LS-DYNA R8 LINUX executable to run the simulations. Due to high-performance MPP scalability, this model was able to run in a normal desktop computer with 32 GB RAM and Intel® Core™ i7-4770 CPU at 3.40 GHz processor by allocating a high number of CPUs. However, running time depended on mesh resolution and the time step. As expected, finer mesh and smaller time steps gave significantly higher computer times.

#### 4.1 Case study 1

In the experiment, the water approached the box at time 0.4 s and water wave started to break at time 0.56 s. The corresponding snapshot is shown in Figure 4b. The simulation run was paused exactly at these two events (as per the snapshot shown in Figure 4a), and the corresponding time readings (0.4 and 0.56 s) agree well with the experimental results.

![Case study 1: dam break simulation compared with the experiment (a) water is approaching the box at 0.4 s and (b) water wave is starting to break at 0.56 s](image-url)
A grid refinement study using three different mesh sizes: 15, 12, and 10 mm, was carried out to show the consistency of the pressure results at points $P_1$, $P_2$, and $P_3$. Figures 5, 6, and 7 show the comparison between impact pressures obtained from different mesh resolutions and the experimental data at points $P_1$, $P_2$, and $P_3$, respectively. The readings at each of the points are summarised in Table 2. Results of the finest mesh model show a better agreement with the experimental data whereas coarser grids of 15 and 12 mm over-predict the impact pressure.

A mesh convergence analysis was carried out by using the procedure in (Celik, Ghia, & Roache, 2008) and the results are shown in Table 3. Accordingly, it is shown that the fine-grid convergence index of the grid is small with an acceptable maximum error below 8.3% for all cases except for the $P_1$ value. Although this calls for a further mesh refinement, the limitations of the computer hardware did not permit us to do that and obtain mesh convergence. Thus, hereafter, we analyse the results from the finest mesh (10 mm) only.

The root mean square error (RMSE), coefficient of determination ($R^2$), and coefficient of correlation (CC) values of the finest mesh model are given in Table 4. RMSE values are reasonably low and $R^2$ is close to 1, which indicate that the modelled results have a good fit with the experimental values. As CC of the experimental and modelled pressures for the finest mesh is close to 1 at all $P_1$, $P_2$, and $P_3$ locations (see Table 4), time lag is not considerably high.

The $R^2$ value is relatively smaller at $P_1$ than at other pressure points. This observation aligns with the large grid convergence index in this particular instance that demonstrated model fit can be improved for $P_1$ by refining the grid size.

An observation was made that for $P_1$, the experimental is lower whereas in $P_3$, the experimental is higher. However, RMSE for $P_1$ and $P_3$ (at 1476.59 and 747.52 N/m$^2$, respectively) seem to be proportional to their absolute values (i.e., 12,337 and 5,261 N/m$^2$, respectively). This suggests that the above observation is not a systematic behaviour and may be due to some random variation.

The effect of time step size, $\delta t$ was also considered. When $\delta t$ is greater than 0.001 s, impact pressures and forces were under-estimated compared to the experimental data while $\delta t = 0.001$ s gives more accurate and consistent results. Therefore, the results in the former case are not discussed in the subsequent sections.

4.2 | Case study 2

In the experiment, when the water column initially impacts the concrete column at 0.252 s, the force applied on the column is suddenly increased within few milliseconds and reached a maximum of 32.15 N at 0.312 s. In
TABLE 2  Case study 1: simulated versus experimental pressure comparison

| Location | Simulation with 15 mm mesh | Simulation with 12 mm mesh | Simulation with 10 mm mesh | Experiment |
|----------|---------------------------|---------------------------|---------------------------|------------|
|          | Time (s)  | Max impact pressure (N/m²) | Time (s)  | Max impact pressure (N/m²) | Time (s)  | Max impact pressure (N/m²) |
| P_1      | 0.435     | 16,370                    | 0.430     | 14,356                    | 0.429     | 11,239                     |
| P_2      | 0.438     | 13,140                    | 0.442     | 9,433                     | 0.446     | 8,127                      |
| P_3      | 0.483     | 6,036                     | 0.478     | 5,457                     | 0.476     | 6,564                      |

TABLE 3  Case study 1: results of the mesh convergence analysis

| Maximum impact pressure (with monotonic convergence) | P_1 | P_2 | P_3 |
|------------------------------------------------------|-----|-----|-----|
| ϕ_{ext}^{P_1}                                       | 4,588.44 | 9,009.00 | 5,095.47 |
| e_{a}^{P_1}                                         | 16.37  | 3.94  | 3.73  |
| e_{ext}^{P_1}                                       | 168.87 | 0.73  | 3.25  |
| ϕ_{ext}^{P_2}                                       | 8,209.09 | 9,009.00 | 5,095.47 |
| e_{a}^{P_2}                                         | 14.03  | 39.30 | 10.61 |
| e_{ext}^{P_2}                                       | 74.88  | 4.71  | 7.10  |
| GCI_{medium}                                        | 53.5  | 5.6  | 8.3  |
| GCI_{fine}                                          | 78.5  | 0.9  | 3.9  |

Abbreviations: e_{a}, approximate relative error; e_{ext}, extrapolated relative error; GCI, grid convergence index; ϕ_{ext}, extrapolated value.

TABLE 4  Case study 1: root mean square error (RMSE), coefficient of determination (R²), and coefficient of correlation (CC) values for simulated versus experimental data

| Location | Simulation with 10 mm mesh |          |          |
|----------|---------------------------|----------|----------|
|          | RMSE (N/m²)  | R²      | CC       |
| P_1      | 1,476.59     | 0.648   | 0.938    |
| P_2      | 863.49       | 0.838   | 0.973    |
| P_3      | 747.52       | 0.854   | 0.979    |

FIGURE 8  Case study 2: dam break simulation compared with the experiment (a) collapsed water column reaching concrete column at 0.258 s and (b) subsequent impact at time 0.281 s

FIGURE 9  Case study 2: force time history using different mesh sizes in the simulation compared to experimental data

FIGURE 10  Case study 2: impulse time history using different mesh sizes in the simulation compared to experimental data
the 6 mm mesh model simulation, the fluid initially impacts the column at 0.258 s and reached a maximum of 30.22 N force at 0.281 s. These results are graphically represented in Figure 8 and give a good agreement with the experimental data.

Figures 9 and 10 show the net force acting on the column and the impulse for experiment and simulation results respectively. We used three different mesh sizes 10, 8, and 6 mm. The maximum force for 8 mm mesh is not between those for 10 and 6 mm mesh sizes.

Finest mesh gives a good match to the experimental force an initial time to reach the column. In contrast, coarse mesh gives a more accurate maximum impact time. This fact needs further study in a future sensitivity analysis and is beyond the scope of the present study. However, in general, the simulations agree very well with the experimental values. The results of Case study 2 is summarised in Table 5.

A mesh convergence analysis was carried out and the results are shown in Table 6. Accordingly, it is shown that the fine-grid convergence index of the grid is small with an acceptable maximum error below 0.6%. Since this reflects that mesh convergence has been achieved for the selected mesh sizes and also with the limitations with the computer hardware, we did not carry out further mesh refinements. Thus, hereafter, we analyse the results from the finest mesh (6 mm) only.

The root mean square error (RMSE), coefficient of determination ($R^2$), and coefficient of correlation (CC) values for the finest mesh are given in Table 7. RMSE values are reasonably low and $R^2$ is close to 1, which show that the modelled results have a good fit with the experimental values. The correlation coefficient of the experimental and modelled data for the finest mesh is 0.951. This indicates that the time lag is not considerably high.

### Table 5: Case study 2: simulated versus experimental result comparison

|                      | Simulation with 10 mm mesh | Simulation with 8 mm mesh | Simulation with 6 mm mesh | Experiment |
|----------------------|---------------------------|---------------------------|---------------------------|------------|
| Max. force (N)       | 29.312                    | 29.229                    | 30.223                    | 32.150     |
| Time of max. force (s)| 0.307                     | 0.298                     | 0.281                     | 0.312      |
| Initial time to reach the column (s) | 0.266                     | 0.263                     | 0.258                     | 0.252      |

### Table 6: Case study 2: results of the mesh convergence analysis

|                      | Maximum impact force (with oscillatory convergence) $F$ |
|----------------------|--------------------------------------------------------|
| $d_{21}^{21}$ ext    | 30.36                                                  |
| $e_{a}^{21}$         | 3.29                                                   |
| $e_{21}^{21}$ ext    | 0.47                                                   |
| $v_{ext}^{22}$       | 29.21                                                  |
| $e_{a}^{32}$         | 0.28                                                   |
| $e_{ext}^{32}$       | 0.07                                                   |
| GCI$_{medium}$       | 0.1                                                    |
| GCI$_{fine}$         | 0.6                                                    |

### Table 7: Case study 2: root mean square error (RMSE), coefficient of determination ($R^2$), and coefficient of correlation (CC) values for simulated versus experimental data

|                      | RMSE (N) | $R^2$ | CC       |
|----------------------|----------|-------|----------|
| Simulation with 6 mm mesh | 2.425    | 0.951 | 0.989    |

4.3 | Discussion

Work by Kleefsman et al. (2005) using the volume-of-fluid method and Cummins et al. (2012) using smooth-particle hydrodynamics method give results similar to our study (see Table 8). Although most of the readings of the former studies are difficult to read due to poor resolution, all three methods, in general, are capable of simulating the experimental data. However, it is noticeable how our results better simulate the experiment in the majority of the instances.

Furthermore, the former two methods do not use the material properties and assume the structures as rigid. Therefore, as opposed to the ICFD FSI method used by us, these methods cannot analyse the deflection.

This capability of deformation analysis is very important in flood damage assessment, where the structural failures occur due to a sudden impact. In order to observe these structural deformations, a dataset with a higher water depth (to apply a higher force to the column) is required. Forces applied to the structure in both of the experiments are not enough to give a sufficient level of deformation/deflection to the structure. In future studies, we expect to investigate the failure mechanism of different structural components using ICFD–FSI technique, by applying the relevant material models, comprehensive parametric methods and a suitable experimental dataset that satisfies the above condition.
5 | CONCLUSION

In this study, we used FSI/ICFD method based on the level set method to calculate the initial impact force on structural components by a dam break wave. This is done by considering fluid structure interaction through analysis of free surface forces of fluid and the material properties of the structure. To our knowledge, this work departs from previous works that assume structures as rigid components. We validated the efficacy of using FSI/ICFD method, by using the pressure and force data from two major experimental studies, which were well replicated in the simulation. Therefore, this study shows that the ICFD free surface method provides a useful approach to model the fluid structure interactions.

As forces applied to the structures in the experimental data available were not adequate to give a sufficient level of deflection/deformation, an exact structural failure scenario could not be replicated in this study. However, our simulation accurately depicts the development of the forces due to waves. These forces would inevitably lead to a structural failure, given the relevant level of vulnerability exists in the material properties. A future study will carry out the simulations with different structural components and perform a comprehensive sensitivity analysis. This would eventually lead to simulating flash flood impact on a structure more realistically, well in advance.

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TABLE 8  Case study 1 & 2: result comparison with other methods

| Measurement | Volume-of-fluid method (Kleefsman et al., 2005) | Smooth-particle hydrodynamics method (Cummins et al., 2012) | Level set method | Experiment |
|-------------|-----------------------------------------------|----------------------------------------------------------|-----------------|------------|
| Case study 1 | $P_1$ ~11,100 N/m²                           | Not available                                             | 12,337 N/m²     | 11,239 N/m²|
|             | $P_2$ Not available                           | Not available                                             | 9,075 N/m²      | 8,127 N/m² |
|             | $P_3$ ~5,000 N/m²                             | Not available                                             | 5,261 N/m²      | 6,564 N/m² |
| Case study 2 | $F$ Not available ~34 N                      | 30.22 N                                                   | 9,075 N/m²      | 8,127 N/m² |

Abbreviations: $P$, pressure; $F$, force.
KANKANAMGE ET AL.

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