NUMERICAL MODELLING OF FLUID-STRUCTURE INTERACTION INVOLVING TSUNAMI BORE AND DEBRIS IMPACT

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INTRODUCTION

The 2011 Tohoku earthquake and tsunami event resulted in the well-known nuclear power plant disaster at Fukushima. In this context, Ishiki et al. (2023) critically reviewed tsunami-resistant design approaches to nuclear power stations and identified shortcomings with current design codes in Japan and the U.S for the quantification of tsunami loads.

One of the key aspects with no general consensus is the role and significance of floating debris in tsunamis. There are multiple uncertainties including whether to combine debris impact force with any other tsunami-related loads while not including loads from damming and multiple debris impacts, which might compromise the structural reliability designed in conformity with these codes.

Towards improved quantification of tsunami loads, the present work employs a numerical coupling strategy using smoothed particle hydrodynamics (SPH) and the finite element method (FEM) as shown in Figure 1. The present study highlights the capabilities of SPH to reproduce complex interaction between a tsunami-like bore carrying debris and a structure through validation studies, aiming to demonstrate the effectiveness of the one-way coupling technique combined with FEM. A versatile open-source code, DualSPHysics v5.2, is used solving the Navier-Stokes equations based on a weakly-compressible SPH formulation (Domínguez et al. 2022).

VALIDATION TEST CASES

Shafiei et al. (2016a) carried out an experimental investigation into impact force and pressure of a tsunami bore on a square prism structure. Figure 2 displays a schematic diagram of the experimental wave flume. The reservoir was filled with water to a depth of 600mm, and then the water was released by lifting the automatic gate at a rising speed of 0.65m/s. The gate was lifted until reaching an opening height of 300mm. The gate opening was not fast enough to cause a sudden dam break, and therefore the sliding gate was explicitly modelled as a moving boundary in the simulation. The sliding gate remained open for 4s before it was closed automatically. The structure, represented by a 600mm high and 300mm square prism, was positioned 10m away from the automatic gate. Every test case was repeated five times in the experiment where all the data was logged at a sampling rate of 1kHz, so the mean values were compared to the corresponding SPH predictions with different initial inter-particle distance (*dp*) and an output interval set to 1ms.

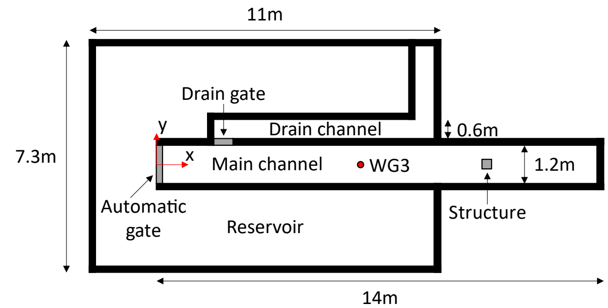

Figure 2 - Plan view of experimental setup (adapted from Shafiei et al. (2016a))

Next, Shafiei et al. (2016b) experimentally investigated impact force of tsunami-borne debris on the same structure as seen in Figure 3. A disc-shaped floating object 200mm in outer diameter, 50mm in thickness, and 550g in mass was placed 2m upstream from the target structure. A wireless tri-axial impact accelerometer was attached to the disc as a smart debris device. Another load cell with a sampling frequency of 5kHz was installed underneath the square prism. The number of repetitions was ten times for each test case.

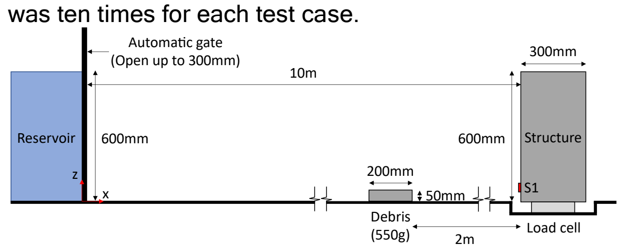

Figure 3 - Experimental setup including debris (adapted from Shafiei et al. (2016b))

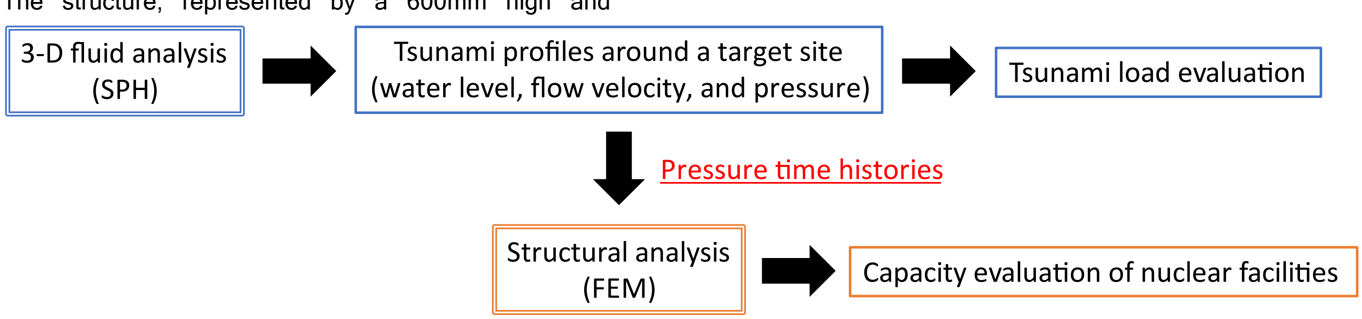

Figure 1 - Tsunami-resilient design framework coupling SPH and FEM

SIMULATION RESULTS

Figure 4 presents time histories of bore height at *x*=6.2m (see WG3 in Figure 2). The SPH model agreed well with the measured data and showed clear spatial convergence. However, the water surface elevation was overestimated to a small degree near the automatic gate and conversely underestimated as the incident bore got closer to the structure. This could well be due to the cumulative effect of the simplistic no-slip condition imposing zero velocity on boundary particles. Spatial resolution enhancement yielded an increase in bore velocity which was faster than the measurement. The early arrival time may also be influenced by the boundary conditions employed in the SPH simulations.

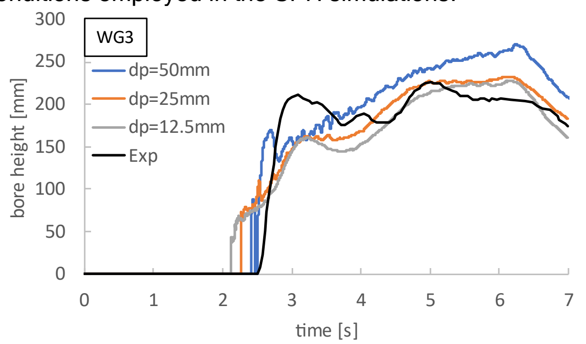

Figure 4 - Time histories of bore height

Figure 5 plots time histories of bore pressure on the front face of the structure at *z*=32mm (see S1 in Figure 3). The first peak was more prominent with finer resolution, which may not have been captured in the experiment, so the numerical result may be nearer reality. Higher resolution also eliminated noise-like spikes during the impulsive stage. It is noted that the pressure distribution on the front surface was not perfectly symmetrical, and similarly non-symmetric behaviour would be observed in the experiment where the pressure sensors are likely to miss the peak impact locations. During the quasi-steady state, the SPH prediction was generally satisfactory but greater than the experimental measurement, probably owing to the overestimation of bore velocity.

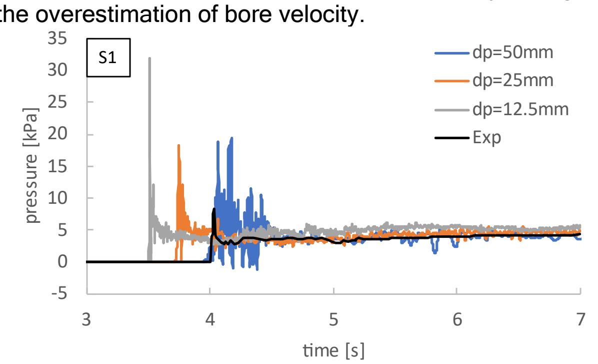

Figure 5 - Time histories of bore pressure

Figure 6 shows the velocity field when the floating body collided against the square prism. Figure 7 shows time histories of horizontal acceleration of the debris derived from the SPH model with *dp*=10mm and the experiment. While the predicted debris acceleration is of similar magnitude to the experiment arriving slightly earlier (~0.05s), the numerical debris acceleration shows a clear high frequency component. The structure attached to a load cell and debris were made of 5mm acrylic sheets in the physical model but assumed to be rigid in SPH. The high-frequency oscillations observed numerically therefore stem from the assumption of the perfect rigidity of the structure and the collision of the rigid bodies. This will be eliminated by using the more sophisticated rigid-contact-deflection algorithm of the multi-physics engine Project Chrono coupled with DualSPHysics. The validation work of debris impact is currently in progress, which will be included in the in-depth simulation results for the full ICCE paper.

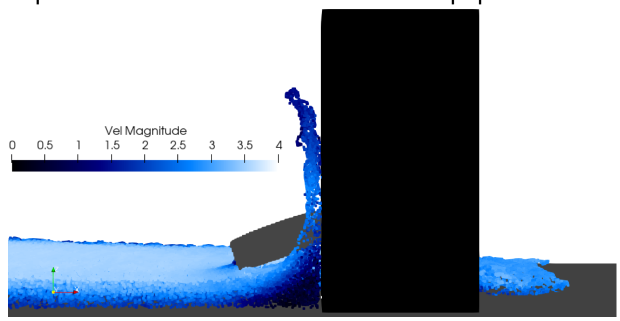

Figure 6 - Flow velocity at the time of debris impact

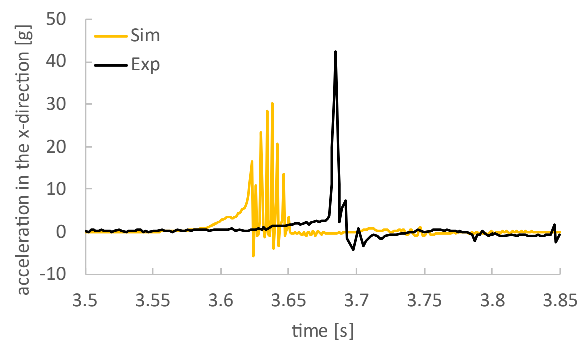

Figure 7 - Time histories of horizontal acceleration of debris

CONCLUSION

The ongoing validation of SPH modelling has demonstrated the reliability for tsunami hazard assessment, exploring scenarios complicated by floating debris. A coupled SPH-FEM piece of work will be showcased, looking at the response of a reinforced concrete structure to tsunamis with floating debris.

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