Three-dimensional numerical simulation of tsunami-borne debris-loads on bridges

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ABSTRACT

Tsunamis are natural disasters that sometimes follow large-magnitude offshore earthquakes and cause significant damage to coastal bridges. In addition to the destructive power of the tsunami bore, shipping containers and other debris carried by the bore, increase the potential for catastrophic damage. To better understand and mitigate the effects of tsunami-borne debris, it is important to have insight into the hydrodynamic and structural processes involved when a bore carrying debris impacts a bridge. This insight may be gained from experimental modelling in a laboratory flume, but few flumes world-wide are adequately equipped and those experiments that have been conducted have not been related to bridges. Alternatively, it may be achieved by numerical modelling. This paper describes the application of a numerical technique based on smoothed-particle hydrodynamics coupled with finite element structural models (SPH-FEM) to investigate fluid-debris-bridge interaction during a tsunami. The technique is first validated against data from those experiments that have been conducted, and then used to undertake a three-dimensional parameter study to determine impact forces with and without debris in the water. Parameters studied include strength of bore, initial water level, bridge elevation, and debris mass. In some cases, the debris moves over the bridge, in other cases below the bridge, while occasionally it becomes trapped under the offshore overhang. It was found that the presence of the debris significantly increases the total applied loading on a bridge, with the mean horizontal and vertical impact forces being 4.2 and 2.6 times larger, respectively, than during a tsunami without debris.

1 INTRODUCTION

Urbanization of coastal areas has increased the number of structures susceptible to damage from tsunamis, including critical infrastructure such as highway and railroad bridges. Previous tsunamis have damaged many bridges and caused significant financial loss (Unjoh & Endoh, 2006, Aglipay et al., 2011; Kajitani et al., 2013). Tsunamis bores can also carry debris such as shipping containers and other floating objects which increase the likelihood damage to these structures. Since bridges play a vital role in transportation networks and recovery efforts following a disaster, it is important to understand the debris-flow-bridge interaction, quantify the loads exerted on bridges, and develop design and retrofitting guidelines to improve the resilience of coastal bridges. In recent years, while progress has been made in designing resilient infrastructure to withstand natural disasters, limited studies have focused on the debris impact loadings on coastal bridges. Yang (2016) used the material point method and found that debris impact forces in water can be 35% higher than in-air cases. Istrati et al., (2020) conducted three-dimensional numerical simulation and reported that the debris damming loads have a major effect on the overturning moment and the location of the trapped debris is critical for structural design. Hasanpour et al., (2021) used the novel coupled SPH-FEM modelling technique and found it to accurately capture debris transport and impact, observing high levels of debris pitching which reduced contact area and impact force. Majtan et al., (2021) studied debris impact forces on a masonry arch bridge during flooding using the SPH method. Hasanpour et al., (2022) carried out numerical simulation and reported that debris can have both horizontal and vertical velocities at the instant of impact, and in some cases as the debris moves below the bridge, it accelerates and applies secondary impacts with magnitude larger than the ones of the initial impact. Istrati and Hasanpour et al. (2022) reported that the debris impulsive loads on piers can be 6 to 10 times larger than the fluid forces. The objective of this study is to examine the effects of various parameters on debris impact loadings on a bridge superstructure, using a three-dimensional coupled finite element and smoothed particle hydrodynamics modelling technique.

2 METHODOLOGY

In this study, we employed the coupled SPH-FEM numerical technique utilizing the LS-DYNA software package. To validate our approach, we used the results from two sets of experiments conducted by others as described below. Once validated, the numerical technique was used to conduct the parameter study described in this paper.

The first of these experiments was conducted by Ko (2013) in the Large Wave Flume of the O.H. Hinsdale Wave Research Laboratory at Oregon State University. The flume, which is 104.24 m long, 3.66 m wide and 4.57 m deep, is equipped with a piston-type wavemaker. In these experiments, Ko measured the free-surface and fluid velocity using wave gages and acoustic doppler velocimeters along the flume. A single column was used as a coastal structure. The debris was a 1:5 scale aluminum model of a standard intermodal container, and was 1.22 m long, 0.49 m wide, and 0.58 m high, with a draft of 9.1 cm. Although the debris was free to move in both horizontal and vertical directions, it was constrained from translating across the flume width. The experiments were therefore 2-dimensional in nature.

The second of these experiments was conducted by Shafiei-Amraei (2016) and Shafiei et al. (2016) in the hydraulics laboratory of the Department of Civil Engineering at University of Auckland. They conducted these experiments in a wave flume that was 14 m long, 1.2 m wide, and 0.8 m deep, equipped with an automatic gate that could release water from a reservoir 11 m long, 7.3 m wide, and 0.6 m deep. A square prism measuring 300 mm × 300 mm × 600 mm, was used as the coastal structure. Experiments with two types of debris were conducted, namely a rigid acrylic disk and a box-shaped device with an embedded impact accelerometer. The disk had an outer diameter of 200 mm, thickness of 50 mm, mass of 500 g, and density of 318 kg/m^3, while the box had a cross-section of 100 mm × 100 mm × 300 mm, mass of 510 g, and density of 170 kg/m^3. Of particular note, these were 3-dimensional experiments.

Excellent agreement was obtained between the numerical simulations using SPH-FEM and the results from the above experiments, but the details are not given here due to space limitations. Further information on methodology, validation results, numerical models, and assumptions can be found in Hasanpour et al. (2021) and Hasanpour et al. (2023).

For the parameter study described in this paper, we modified the previously validated numerical model. Of note, we replaced the coastal structure with a scaled bridge deck and used a standard shipping container to represent the debris. Additionally, we increased the reservoir length, moved the outlet to avoid boundary effects, added an artificial beach for energy dissipation, and placed an empty reservoir at the end to collect released water. In this way we could study effect of bore height, bridge elevation, and still-water depth. Figure 1 shows a cross-section (top), and three-dimensional and plan views (bottom) of the numerical model.

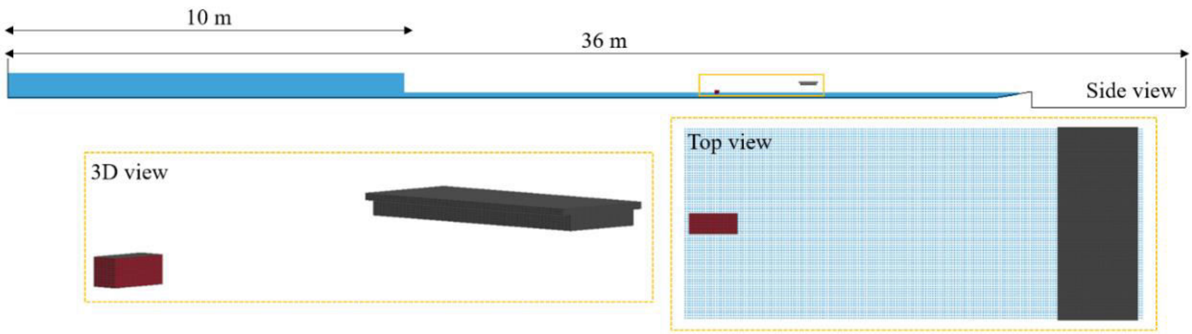

Figure 1: Cross section of the computational domain (top), three-dimensional and plan views of numerical models with the debris and the bridge (bottom)

3 RESULTS AND DISCUSSION

3.1 Tsunami-debris-deck interaction and flow patterns

3.1.1 Tsunami flow characteristics

We examined a broad range of hydrodynamic conditions, including two different reservoir depths (H_r=0.40 and 0.60 m) and four initial water depths (d=0.10, 0.15, 0.20, and 0.25 m). Figure 2 illustrates the variation of the free-surface and fluid velocity at a location close to the offshore side of the debris, in the case where H_r=0.6 m and d=0.25 m. The figure demonstrates that the tsunami bore has a relatively long duration, which enables the transportation of debris until it impacts the bridge. Furthermore, the figure shows that the velocity of the tsunami bore is suitable for simulating tsunami-like conditions.

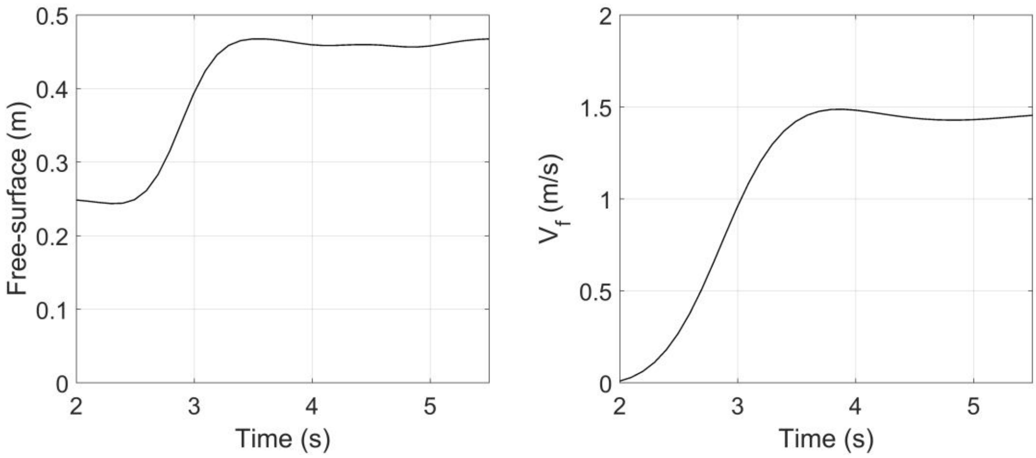

Figure 2: Time history of free-surface (left) and fluid velocity (right) for the case where H_r=0.60 m, and d=0.25 m

3.1.2 Snapshots of debris-flow-bridge interaction

In this study, we considered the transverse orientation of the debris, with the major axis of the debris being perpendicular to the wave propagation. Figure 3 presents a selection of snapshots that show the debris-flow-bridge interaction. Our observations revealed three distinct movements of the debris that are a function of flow characteristics, bridge elevation, and debris mass, including (a) debris impacting the bridge and moving below it, (b) debris impacting the deck and moving above it, (c) and debris remaining below the offshore overhang.

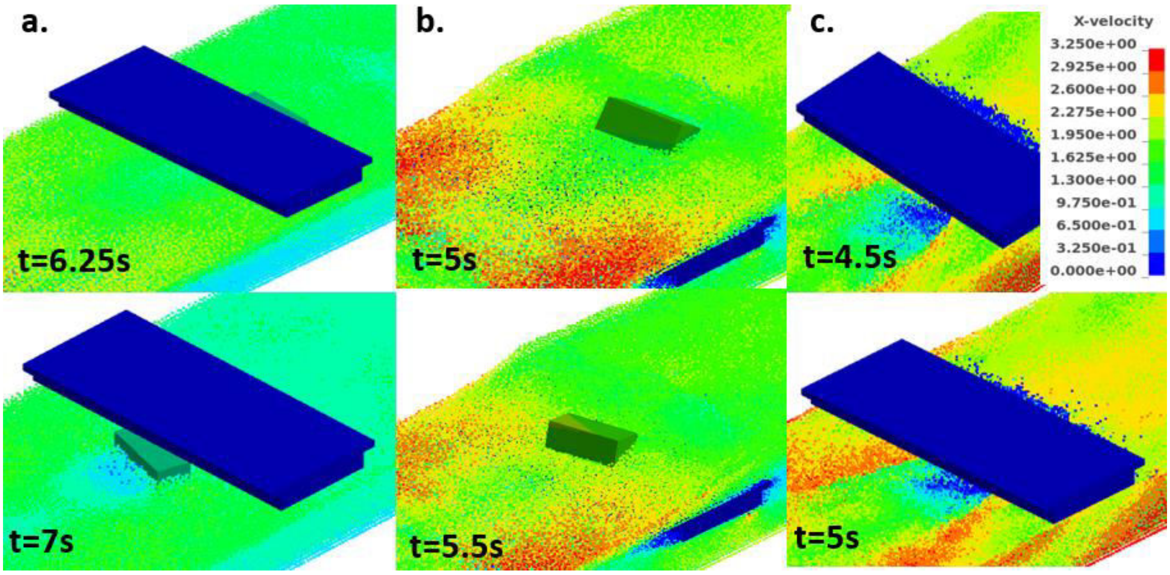

Figure 3: Debris-flow-bridge interaction

3.1.3 Debris velocities

Figure 4 shows the time-histories of the debris horizontal (Vx_d) and vertical (Vz_d) velocities for different cases with similar bore strength (H_r=0.60 m) and bridge elevation (Z_b=0.30 m), but varying initial water levels including d=0.10, 0.15, and 0.20 m. Our results demonstrate that the initial standing water depth plays a significant role in determining the debris velocities and subsequently affects the debris-flow-bridge interaction. For instance, in the case of the shallowest water depth (d=0.10 m), as the container moves inland, we observed that it impacts the offshore side of the bridge and becomes trapped below the offshore overhang until the end of the inundation process (debris velocities drop significantly and become almost zero). In contrast, in the cases of d=0.15 and 0.20 m, where the debris impacts the offshore side of the bridge and moves below it, we observed an increase of about 70% in the horizontal velocity as the initial water level increases. After the primary impact on the bridge, the debris accelerates, and the horizontal velocity increases, reaching approximately 87% and 120% of the horizontal impact velocities for cases with d=0.15 and 0.20 m, respectively.

In this investigation, our observations show that as the debris moves below the soffit, the vertical velocity increases significantly and can even surpass the velocity of the initial impact. For instance, we found an increase of approximately 163% and 80% in the debris vertical velocity relative to the impact velocity for cases with d=0.15 and 0.20 m. These results agree with the findings of Hasanpour et al., (2021), which highlight the significance of considering both the debris horizontal and vertical velocities at the moment of primary impact and follow-up impact for future predictive force equations and risk assessment frameworks.

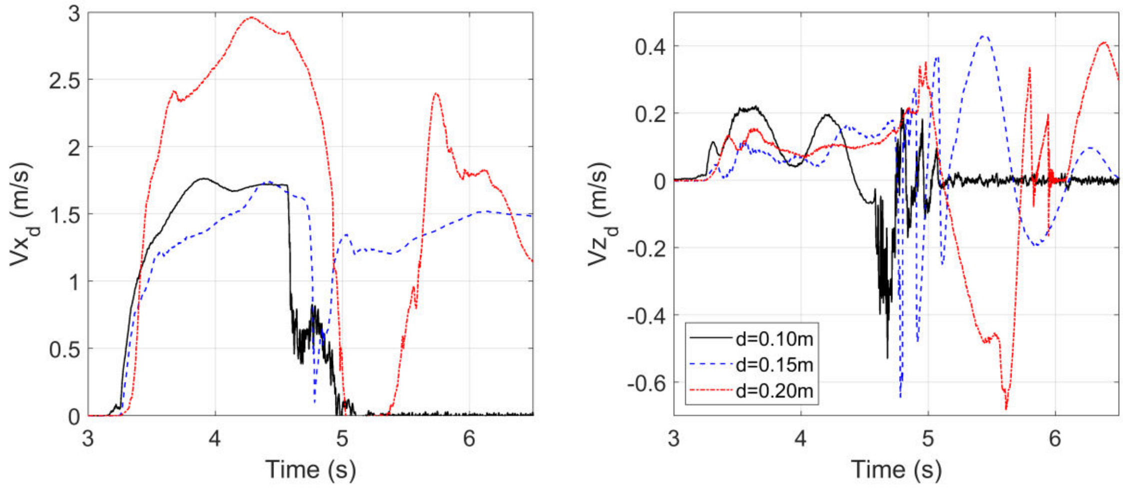

Figure 4: Time-series of horizontal (left) and vertical (right) debris velocities for the cases with the same bore strength and bridge elevation, but different initial water depths

3.2 Debris impact loads on bridge deck

Figure 5 shows the time-histories of the applied horizontal and vertical forces to the bridge superstructure by debris (F_d) and fluid (F_f) for the cases with the same bore strength and bridge elevation, but different initial water depths (d=0.10, 0.15, 0.20, and 0.25 m). In the shallowest water depth case (d=0.10 m), the hydrodynamic forces are negligible and the floating container exerts much greater horizontal and vertical forces; up to 2 and 1.2 times larger horizontal and vertical forces, respectively. As the water depth increases to 0.15 and 0.20 m, the bridge is subjected to both debris and fluid impact forces, with the horizontal debris impact force being 1.5 and 2 times greater than the maximum fluid forces, respectively. In terms of the vertical force, both debris and fluid apply similar maximum loads to the bridge. These cases also exhibit a magnitude of the primary horizontal debris impact force that is about 1.75 times the uplift force. Additionally, the figure illustrates the soffit experiences several uplift forces after the primary impact as the debris moves below the bridge, which is consistent with the observations of Hasanpour et al., (2021). The magnitude of the secondary uplift force is about 76% and 82% of the initial impact for cases with d=0.15 and 0.20 m, respectively. In the scenario where the initial water depth is at its maximum (d=0.25 m), the debris impacts the deck and subsequently travels above it, the magnitude of the horizontal impact force exerted by the debris is approximately 1.6 times that of the fluid force. Additionally, as the debris moves over the deck, it exerts a downward force that is roughly 40% of the respective horizontal force.

In summary, we observed that as the initial water depth increases, the impact forces exerted by debris in both the horizontal and vertical directions also increase. By comparing the debris horizontal impact force at an initial water depth of 0.10 m to that at 0.25 m, we can see that the force increases by approximately 100%. Similarly, when comparing the debris-induced uplift force at an initial water depth of 0.20m to that at the shallowest water depth of 0.10 m, we see that the force is approximately 75% greater. These observations reveal the complexity of the phenomena and necessitate the development of more comprehensive predictive equations that consider both horizontal and uplift forces in future risk assessment frameworks.

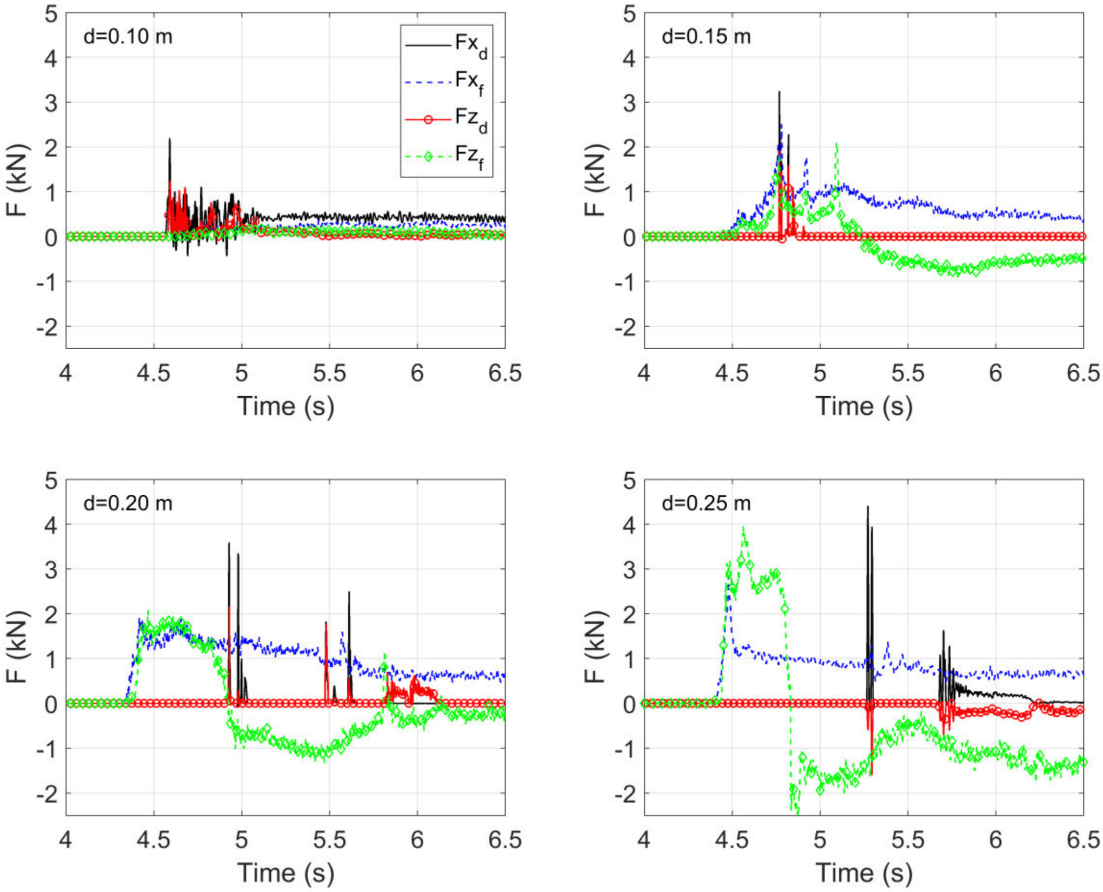

Figure 5: Applied horizontal and vertical fluid and debris impact forces for the cases with the same bore strength and bridge elevation, but different initial water levels

3.3 Role of debris

In order to determine the effect of debris on the total applied loads (hydrodynamic and debris forces) on the bridge superstructure, the researchers re-analyzed the studied cases under clear-water conditions (absence of debris) and compared the results to those obtained with the presence of debris. Figure 6 shows the time-series of the total applied horizontal (Fx_t) and vertical (Fz_t) loads on the bridge superstructure for three selected cases including (H_r=0.40 m, d=0.15 m, Z_b=0.20 m), (H_r=0.60 m, d=0.20 m, Z_b=0.30 m), and (H_r=0.60 m, d=0.25 m, Z_b=0.30 m). It is noteworthy that in the case of H_r=0.60 m and d=0.20 m, we found that there is no significant difference in total applied forces on the deck for both configurations (with and without debris) as the debris moves over the deck without any interaction with the deck. The data in this figure and for the representative cases show that the presence of debris significantly increases the total horizontal and vertical uplift forces, particularly for higher bridge elevations. This is due to the fact that in these cases, the tsunami bore barely reached the deck, and therefore, the debris-induced forces are more likely to govern the failure mechanism of the bridge superstructure. For instance, in the case of the highest deck elevation (0.35 m), debris causes an increase of up to 6.5 and 4.7 times in the total horizontal and vertical forces, respectively. Overall, the data demonstrate that debris plays a more significant role in the horizontal impact force than in the vertical force.

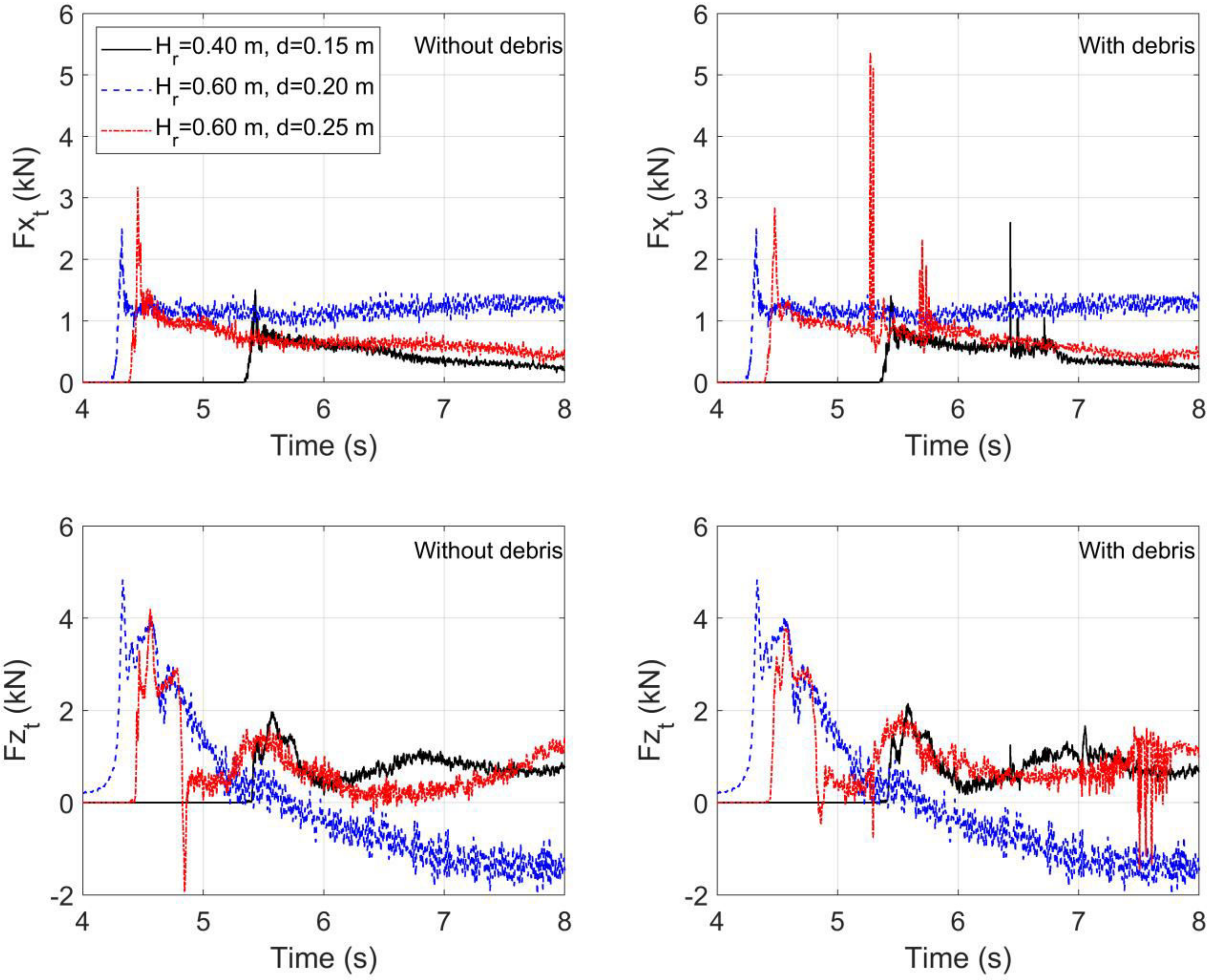

Figure 6: Applied horizontal and vertical total impact forces for the three selected cases for two scenarios; with and without debris

4 CONCLUSIONS

In this study, we employed the coupled SPH-FEM technique to perform three-dimensional numerical simulations to investigate the effects of bore strength, initial water level, bridge elevation, and debris mass on the debris-flow-bridge interaction during tsunamis. However, due to space limitations, we did not include the results for debris mass in this paper. Our investigation led to the following conclusions:

- We discovered three distinct movements of debris resulting from the interplay of flow characteristics, bridge elevation, and debris mass. These movements are (i) debris colliding with the bridge and flowing underneath, (ii) debris colliding with the bridge and flowing over it, and (iii) debris remaining below the offshore overhang.
- Our study found that when the debris moves below the bridge following the primary impact, there is a significant increase in the horizontal velocity. Specifically, horizontal velocity reaches approximately 87% and 120% of the respective velocities of the primary impact for cases with d=0.15 and 0.20 m, respectively. Additionally, as the debris moves below the soffit, the vertical velocity increases significantly, surpassing the velocity of the initial impact in some cases, with an increase of approximately 163% and 80% in the debris vertical velocity relative to the impact velocity for cases with d=0.15 and 0.20 m, respectively.

- Our research discovered that as the initial water depth increases, there is a corresponding increase in the impact forces exerted by debris in both the horizontal and vertical directions. Specifically, we observed an increase of approximately 100% and 75% in the horizontal and vertical directions, respectively, when comparing the initial water depth of 0.10 m to 0.25 m.
- Our study revealed that debris significantly increases the total horizontal and vertical forces, particularly for higher bridge elevations. This is because in these cases, the tsunami bore barely reaches the deck, making debris-induced forces the primary factor in the imposed loads on the bridge superstructure.

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