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Paper:

Inter-Model Comparison for Tsunami Debris Simulation

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Assessing the risk of tsunami-driven debris has increasingly been recognized as an important design consideration. The recent ASCE/SEI7-16 standard Chapter 6 requires all the areas included within a 22.5° spreading angle from the debris source to consider the debris impact. However, it would be more reasonable to estimate the risks using numerical simulation models. Although a number of simulation models to predict tsunami debris transport have been proposed individually, comparative studies for these simulation models have rarely been conducted. Thus, in the present study, an inter-model comparison for tsunami debris simulation model was performed as a part of the virtual Tsunami Hackathon held in Japan from September 1 to 3 in 2020. The blind benchmarking experiment, which recorded the transport of three container models under a tsunami-like bore, was conducted to generate a unique dataset. Then, four different numerical models were applied to reproduce the experiments. Simulated results demonstrated considerable differences among the simulation models. Essentially, the importance of accurate modelling of a flow field, especially a tsunami front, was confirmed to be important in simulating debris motion. Parametric studies performed in each model and comparisons between different models also confirmed that a drag coefficient and inertia coefficient would influence the simulated debris trajectory and velocity. It was also shown that two-way coupled modelling to express the interaction between debris and a tsunami is important to accurately model the debris motion.

Keywords: tsunami, debris, numerical modelling, inter-model comparison, Hackathon

1. Introduction

Numerical modeling can play an important role in assessing the risks and effects of a tsunami on coastal communities. Tsunami propagation and inundation simulation models, which mostly rely on two-dimensional (2D) Nonlinear Shallow Water (NSW) equations or Boussinesq-type equations, have been extensively validated and applied to assess the potential damage due to tsunami hydrodynamic loads in many coastal areas (e.g., [1–4]). However, the cause of damage in coastal areas is not limited to hydrodynamic loads but also debris loads. In fact, many forensic engineering field surveys on tsunami-affected regions have shown the significant effects of debris on structural failures in coastal areas (e.g., [5–9]).

In 2016, the American Society of Civil Engineers (ASCE) published design standard guidelines (ASCE/SEI7-16) to address the design of structures in tsunami-prone areas [10]. ASCE7-16 adopts an empirical method, proposed by Naito et al. [11], to determine the maximum spreading area of debris transported by a tsunami. In this method, the debris is assumed to propagate in the direction of flow from its origin (debris source), with ±22.5° lateral spreading. The limit of the debris displacement is determined by either the estimated inundation depth (less than 0.91 m) or the size of the area enclosed in the ±22.5° cone (50 times the plan area of the debris). However, since the method is based on a limited dataset, the estimated spreading area of debris is conservative as demonstrated through physical experiments [12–14]. Thus, it would be meaningful for tsunami-prone coastal communities to numerically predict the area where debris could cause a substantial impact. To date, many simulation models have been proposed to predict the debris transport in a tsunami (as introduced in the following section). However, compared to tsunami propagation and inundation simulation models, comprehensive investigations and discussions on numerical modelling of tsunami debris are limited. In addition, to the authors' knowledge, no published studies exist, which have compared different tsunami debris simulation models. A recent state-of-the-art review [15] also indicated that, while progress on research related to debris motion and impact has been made in recent years, there are still aspects which have yet to be understood when it comes to debris motion and associated impact during extreme hydrodynamic events.

A three-day virtual Tsunami Hackathon, which is a benchmarking workshop for various tsunami simulation models, took place in Japan from September 1 to 3, 2020 (see https://tsnmhack.github.io/index.html for further information on this event). Among a total of 7 benchmarking problems, one of them focused on the transport of multiple shipping containers under a tsunami bore. This paper summarizes the results of this benchmarking problem and the discussion carried out during the three-day event. This study also aims to present the accuracy and limitations of cutting-edge tsunami debris simulation models and provide useful information and guidance to practitioners and researchers involved with numerical modelling.

2. Literature Review: Progress in Development of Tsunami Debris Simulation Model

There are mainly two approaches to simulate a floating object exposed to a tsunami, which include either a three-dimensional (3D) model or a 2D model. The 3D model is based on the Navier–Stokes (N–S) equations. The N–S equations can simulate complex 3D flow features around debris and directly evaluate the forces exerted on it by integrating the local pressure [16]. The development and application of 3D models for a floating object exposed to a tsunami-like flow have been actively studied in recent times (e.g., [16–19]). However, large computational costs are associated drawbacks when applied to a relatively large coastal area. On the other hand, a 2D simulation model solves the NSW or Bousinessq equations for a flow field, and Newton's motion of equation for debris movement. Thus, less computational costs are required and can be more practical than 3D models. The authors summarized below the progress made in the development of 2D tsunami debris simulation models.

2.1. Transport of Timbers

One of the first 2D simulation models, which simulated floating objects under tsunami-like flow conditions, is the one proposed by Goto [20]. Goto [20] performed hydraulic experiments to investigate the motion of timbers drifting in various uniform flow conditions. The same author then numerically simulated their movement based on the equation of motion, which considered the drag and inertial forces as external forces [21].

2.2. Transport of Boulders

Noji et al. [22] focused on the transport of boulders by a tsunami and developed a numerical model, which was later improved by Imamura et al. [23, 24]. The improved model by [24] can consider the various transport modes of boulders (sliding, rolling, and saltation) by introducing a variable friction factor, which changes based on ground contact time. An important aspect of the model is that the effects of resistance forces from the boulder on the tsunami flow was also taken into account.

2.3. Transport of Ships and Vessels

Many drifted ships, including large vessels, caused serious damage to several coastal areas during the *2004 Indian Ocean Tsunami* (e.g., [5, 25]). This has led to further studies on the numerical modelling of drifted objects under tsunami conditions. Fujii et al. [26, 27] physically generated a long-period wave in their wave basin and tracked the motion of a modelled vessel. These authors also developed a simulation model, which coupled the NSW equations and discrete element method (DEM) [27]. Using the same experimental facility, Ikeya et al. [28] measured the forces exerted on the drifted vessel and evaluated them by extending Morison equation. The evaluation method proposed by [28] was later incorporated in a simulation model, developed by Honda et al. [29] and Tomita and Honda [30]. The developed model was later applied to simulate vessels drifted during the *2011 Tohoku Earthquake and Tsunami* [31, 32]. These authors demonstrated that despite the model being able to simulate the transport of vessels relatively well, their initial position and direction significantly influenced their trajectories and final positions. Currently, the model, initially developed by [29], is freely available as a part of solvers (STOC-DM) in T-STOC (Tomita et al. [33]).

Kobayashi et al. [34] also developed a simulation model for a drifted ship. The model is based on the equation of motion with three-degrees of freedom (3DOF) (surge, sway and yaw). Hashimoto et al. [35, 36] improved the model of [34] to consider the spatial velocity distribution along the ship's hull to calculate the exerted forces, and the effects of a collision with other structures. Using the improved model, Suga et al. [37] ran 6,776 simulations and calculated the drifting and stranding prediction probability for Kesennuma City, Japan, during the *2011 Tohoku Earthquake and Tsunami*.

Kihara et al. [38] proposed a probabilistic approach to evaluate the risks of drifted ship impact using their developed tsunami debris simulation model. Using the Monte Carlo simulation, in which drag and inertia coefficients, and the intensity of flow turbulence were randomly varied, the exceedance probability of a vessel impacting a seawall was estimated in [38]. Recently, Kihara and Kaida [39] confirmed that their simulation model [38] could reproduce the experimental results of Kaida and Kihara [40] relatively well.

Considering that many of the previous studies had focused on a single ship as a drifting object, Heo et al. [41]

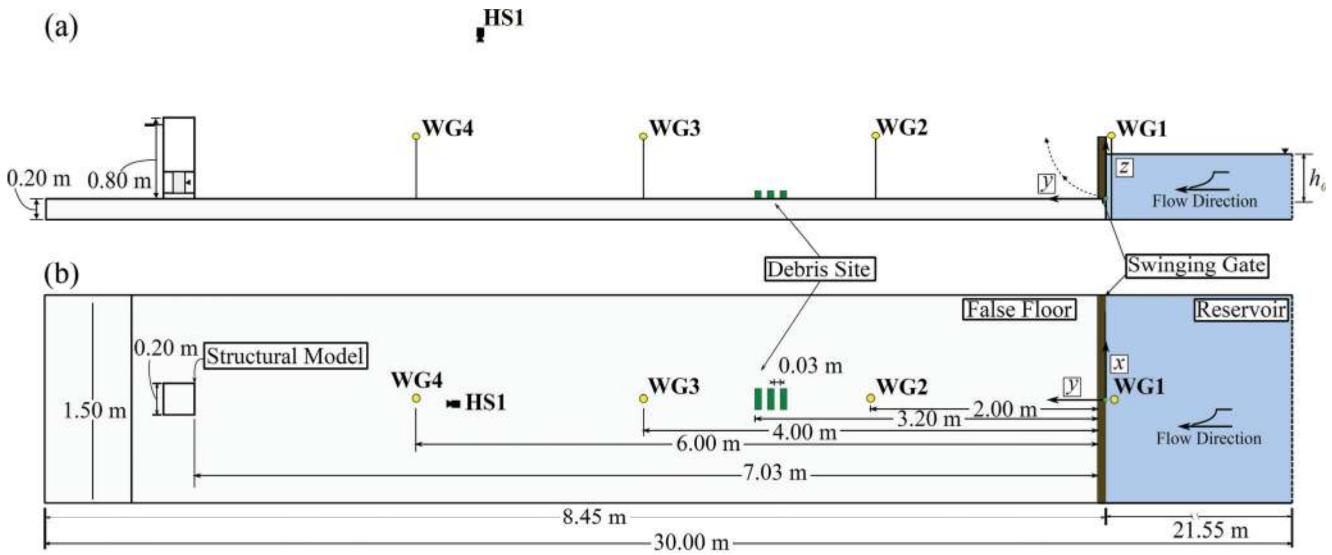

Fig. 1. Experimental setup (not to scale): (a) side view, (b) top view.

performed hydraulic experiments, in which a tsunami-like wave drifted multiple ships. [41] then attempted to reproduce their experimental results with their developed tsunami debris simulation model. The same model was later applied to Kesennuma City by Shigihara et al. [42]. As the initial position of ships and collisions among ships was found to have significant impacts on their trajectories and grounding positions, [42] pointed out the necessity of considering a variety of conditions to investigate the risk of tsunami debris in a coastal area. Yamashita et al. [43] also developed an integrated numerical model to predict and evaluate the complex phenomena caused by tsunami inundation, sediment transport and drifting debris and applied the model to Kesennuma City during the *2011 Tohoku Earthquake and Tsunami*. The simulation results revealed a complex tsunami damage scenario in a narrow bay. These results concluded that the erosion of the bay increased the drifting distance of the ships to the onshore side.

2.4. Transport of Containers

While the aforementioned models were originally developed to simulate the motion of ships exposed to a tsunami, the simulation models by Kumagai et al. [44] and Anno et al. [45], were developed aiming to track the transport of a shipping container, which is generally located on the ground before the arrival of a tsunami. Gotoh et al. [46] also developed a simulation model, which can simulate the motion of a group of shipping containers.

2.5. Transport of Other Debris

As a variety of debris was generated during the *2011 Tohoku Earthquake and Tsunami*, tsunami debris simulation models have been more required to consider the various types of debris since then. A simulation model, proposed by Nojima et al. [47, 48], considered a variety of debris such as shipping vessels, containers, cars, timbers, and tanks. Using the developed simulation model, Nojima et al. [49] numerically investigated the impacts of the variation of draft, drag and inertia coefficients on debris trajectories. Their model was later improved to consider the effects of friction forces, debris–debris interactions, and resistance forces on tsunami flow [50] and was validated with their experiments [51].

During the *2011 Tohoku Earthquake and Tsunami*, it was also observed that collapsed buildings became floating objects and were drifted by the tsunami. Thus, a tsunami debris simulation model that can predict and evaluate the generation of debris caused by building collapse and their movement, has also been actively studied since then. One example is the model developed by Kozono et al. [52], which was later improved to consider the debris–debris interactions in Kozono et al. [53]. Chida and Takagawa [54] also focused on the phenomena and investigated the differences in assumptions used to model a floating building using STOC-DM [33].

3. Benchmark Experiment

3.1. Experimental Setup

To investigate the performance of tsunami debris simulation models, the hydraulic experiment was recently performed in the Hydraulic Laboratory of the University of Ottawa (Ottawa, Canada) (**Fig. 1**) [55]. According to the authors' literature review on the numerical simulations for tsunami debris, most of the existing models were validated with the drifted ships, initially placed in a sea area. However, the applicability of such models to debris has not yet been clarified. Thus, the authors physically modelled shipping containers drifted by a tsunami-like bore and decided to use the results as benchmark for the simulation models.

The flume used in the present experiment is 30 m long, 1.5 m wide, and 0.8 m deep, though a large part of the flume (21.55 m) was used as an impoundment reservoir with a water depth of $h_0 = 0.40$ m (**Fig. 1**). A tsunami-like bore (dam-break wave) was generated by instantaneously opening a swing gate of an upstream reservoir. The gate was initially placed on top of the 0.20-m-high horizontal false bed. The false bed had a length of 8.45 m and was covered by sand particles glued to a hard surface, resulting in a Darcy–Weisbach friction factor (f) of its surface of 0.0293. The center of the flume at the edge of the swing gate was defined as the origin of x- and y-axes, and the origin of z-axis was defined at the top of the false bed.

Froude similitude with the geometric scale of $1:40$ was used in the experiment. Thus, a 20-foot shipping container (ISO668/688) was downscaled to have the dimensions of $0.06 \times 0.06 \times 0.15$ m. The container model was made of pine, resulting in a mass of 0.286 kg and a draft of around 0.031 m. The coefficient of static friction between the container model and false bed surface was roughly estimated to be 0.3. Three container models (debris models) were placed in the flume and aligned in the flow direction, with the centroid of the furthest one located at $y = 3.20$ m. They were placed with their long axis perpendicular to the flow direction, and the spacing between the edges of the debris was set to be 0.03 m. According to the distance from the gate, they were named Debris 1 (the one furthest from the gate), Debris 2 (middle one), and Debris 3 (the one closest to the gate), respectively.

A building model was placed at the distance of 7.03 m downstream from the swing gate to investigate the debris loading. It should be noted that the present study did not consider the debris loading, and only focused on the transport of shipping containers until they reached around 0.30 m away from the front of the building. The reason mainly lies in the difficulties in accurately tracking the behavior of debris near the building model: the splash of water, generated by touching the building model, significantly obstructed the view of the video, mounted on top of the flume.

3.2. Instrumentation

The location of the instruments used in the experiment are shown in **Fig. 1**. Four capacitance-type wave gauges (WGs) were used to record the time history of the generated tsunami bore without debris model. WG1 was placed at the reservoir ($y = -0.01$ m), and the time when the water level recorded by WG1 dropped was defined to be the time origin ($t = 0.000$ s). WG2, WG3, and WG4 were placed at $y = 2.00$, 3.20, and 4.00 m, respectively. Each of the WGs was calibrated before installation to satisfy a calibration coefficient greater than 0.99, and a sampling rate was set to be 1,200 Hz. The raw data were recorded using two data acquisition (DAQ) systems (HBM MX840B and HBM MX1601B; HBM, Darmstadt, Germany), which were synchronized with FireWire (IEEE 1394 [56]; Apple, Cupertino, CA) connection.

The motion of the containers was tracked using a high high-resolution camera (HS1), placed above the flume. An external trigger was used to start HS1 and it was synchronized with the DAQ systems. The motion of the debris was captured using a camera-based objecting tracking algorithm outlined in [57].

The experiments without debris and with debris were repeated 20 and 17 times, respectively, and the obtained results were averaged (with standard deviation for debris trajectories).

4. Simulation Models

A four simulation models were used to reproduce the benchmark experiment. Three weeks before the Tsunami Hackathon, information regarding the experimental setup and hydrodynamic results (i.e., time histories of water surface elevation, recorded at WG1–4 without debris) was provided to the operator of each model. Operators were requested to reproduce the tsunami-like bore in the experiment by either reproducing the impoundment reservoir or directly inputting the time history at the position of WG2. Then, with the hydrodynamic results, they were requested to submit their simulated motions of the three drifted containers. The results of the present experiment were not available before the Tsunami Hackathon, meaning that the tests were completely blind.

Table 1 represents a summary of the governing equations, numerical treatments and numerical conditions adopted by each model to reproduce the experiment. Here, each of the models and relevant references are briefly introduced:

1. Model of Kihara and Kaida [39]: The model was originally developed by Kihara et al. [38]. The model solves the equation of motion by considering drag, inertia forces, and Froude–Krylov force as lateral hydrodynamic forces on debris using the modified Morison equation. The collisions with the other debris and structures are expressed by adopting the spring-dashpot system. The most characteristic point is that the model has been developed toward application to the probabilistic assessment on debris impact and can consider debris diffusion due to disturbance.

2. NDA-FD: NDA-FD was originally developed by Heo et al. [41]. The model solves the equation of motion by considering drag and inertia forces as lateral hydrodynamic forces on debris. The collisions with the other debris and structures are expressed by solving momentum conservation equations. The model has been applied to simulate the drift of ships in Kesennuma during the *2011 Tohoku Tsunami* [42, 43].

3. STOC-DM: STOC-DM was originally developed by Honda et al. [29] and is currently an open-source model as a part of T-STOC [33]. The model solves the equation of motion by considering drag and inertia forces as lateral hydrodynamic forces on debris.

Table 1. Summary of the simulation model and numerical conditions used. Alphabet inside the parenthesis shows a numerical condition changed in each run of simulations. For instance, Model 1 ran a total of 4 simulations and each of the numerical condition is shown as (a), (b), (c), and (d).

	Model ID, Name			
	1. Model of Kihara and Kaida [39]	2. NDA-FD [41]	3. STOC-DM [33]	4. Model of Nojima et al. [50]
Equation solved for a flow field	Nonlinear shallow water equations	Nonlinear shallow water equations	Nonlinear shallow water equations	Nonlinear shallow water equations
Numerical scheme for spatial discretization	Staggered grid method	Staggered grid method	Staggered grid method	Staggered grid method
Numerical scheme for time discretization	Leap-frog method	Leap-frog method	Leap-frog method	Leap-frog method
Numerical treatment of tsunami front	Kotani et al. [58]	Kotani et al. [58]	Kotani et al. [58]	Kotani et al. [58]
Approach used to generate the tsunami-like bore in the experiment	Reproduce the reservoir	Input the time history of water level at WG2	Reproduce the reservoir	Reproduce the reservoir
Manning's roughness coefficient (s/m$^{1/3}$)	0.007	0.01	(a) 0.0293, (b) 0.007, (c) 0.007	0.01
Equation solved for motion of debris	Equation of motion	Equation of motion	Equation of motion	Equation of motion
Considered external forces	Drag force, Inertia force (the effects of added mass), Friction force, Collision force, Froude–Krylov force	Drag force, Inertia force, Friction force, Collision force	Drag force, Inertia force, Friction force, Collision force	Drag force, Friction force, Collision force, Difference in hydrostatic forces
Drag coefficient	(a)(c)(d) 3.0 at the beginning and later 1.5, (b) 1.5	1.5	Different value is used for front and rear of the debris (Tomita et al. [30])	1.5
Inertia coefficient	(a)(b)(c) Ikesue et al. [59], (d) 0.0	1.75	(a) 2.0, (b) 3.0, c) 2.0	N/A
Friction coefficient between debris and ground	0.3	0.3	0.3	0.2 for static, 0.4 for dynamic
Numerical treatment of collision force	(a) N/A (b)(c)(d) Spring-dashpot system	(a) N/A (b) Solve momentum conservation equations	Solve momentum conservation equations	Spring-dashpot system
1 Way or 2 Way	1 Way (does not consider the interaction between debris behavior and the flow field)	1 Way (does not consider the interaction between debris behavior and the flow field)	1 Way (does not consider the interaction between debris behavior and the flow field)	2 Way (considers the interaction between debris behavior and the flow field)
Effects of random diffusion of debris	Considered by intensifying turbulent diffusion (Manning coefficient of 0.05 was used to determine the intensity)	N/A	N/A (though it is possible to include the effects)	N/A
Spatial grid size [m]	0.05	0.02	0.01	0.04
Time step [s]	0.00002	0.001	0.001	0.00005

The collisions with the other debris and structures are expressed by solving momentum conservation equations. The model has been improved and applied to debris related problems in the works of [31, 32, 54, 60].

4. Model of Nippon Koei: The model was originally developed by Nojima et al. [50]. This model solves the equation of motion by considering the force caused by hydrostatic pressure and the drag force as the lateral fluid forces, and the force due to the bottom friction force and the terrain gradient as the forces received from the ground for debris. The collisions with the other debris and structures are expressed by adopting the spring-dashpot system. The model has been applied to simulate the debris impact forces exerted on a building [51].

All of the above-mentioned models employ 2D NSW equations to simulate the flow field and solve them using the staggered leap-frog method. When including the effects of resistance force acting from the debris onto the fluid, the 2D NSW equations are expressed as follows (only x direction for the momentum conservation equation):

$$\frac{\partial \eta}{\partial t}+\frac{\partial M}{\partial x}+\frac{\partial N}{\partial y}=0, \qquad (1)$$

$$\frac{\partial M}{\partial t}+\frac{\partial}{\partial x}\left(\frac{M^2}{D}\right)+\frac{\partial}{\partial y}\left(\frac{MN}{D}\right) = -gD\frac{\partial \eta}{\partial x}-\frac{gn^2}{D^{\frac{7}{3}}}M\sqrt{M^2+N^2}-F_x, \qquad (2)$$

where η, M, N, D, n, and g are the water level, discharge flux in the x and y direction, total water depth, Manning roughness coefficient, and the gravity acceleration, respectively. F_x, F_y represent the sum of the external forces acting on the debris, which work as resistance forces acting on fluid. In the present simulations, only Model 4 considered resistance forces, meaning that Model 4 performed a two-way coupled fluid-solid interaction simulation. Although Models 1 and 3 can technically consider these effects, the module was not used in the present study. It should be noted that Models 1, 3, and 4 numerically generated the tsunami-like bore by reproducing the impoundment reservoir, while Model 2 directly inputted the time history of the water surface elevation at WG2.

To simulate the transport of debris exposed to a tsunami, all models considered the motion with 4DOF (surge, sway, heave, and yaw). However, since a 2D model does not simulate vertical velocity, their movement in the vertical direction (heave) was estimated using the draft of debris instead of solving the motion equation. As a result, the following equations of motion in 3DOF (surge, sway, and yaw) were solved in all the models.

$$M\boldsymbol{a} = \boldsymbol{F}, \quad \ldots\ldots\ldots\ldots \quad (3)$$

$$I\omega_z = T, \quad \ldots\ldots\ldots\ldots \quad (4)$$

where M, $\boldsymbol{a}$, $\boldsymbol{F}$, I, ω_z, T are mass, acceleration vector, external force vector, inertia moment, angular velocity around the vertical axis of debris, and torques around the vertical axis, respectively. As external forces, most of the models consider drag, inertia, friction, collision forces. However, when looking at the external forces considered in each model in detail, there are some differences between them, especially in the numerical treatment of the drag, inertia, and collision forces.

For instance, the drag force $\boldsymbol{F}_{drag}$ is expressed by Eq. (5) in Models 1, 2, and 4.

$$\boldsymbol{F}_{drag} = \frac{1}{2}\rho_w C_D \int (\boldsymbol{U} - \boldsymbol{u_d})\,|\boldsymbol{U} - \boldsymbol{u_d}|\,dA, \quad \ldots \quad (5)$$

where ρ_w, C_D, A, $\boldsymbol{U}$, $\boldsymbol{u_d}$ are the density of water, drag coefficient, projected area of the submerged part, flow velocity, and debris velocity, respectively. However, while constant drag coefficient was used in Models 2 and 4, Model 1 considered a larger coefficient at the beginning of the interaction between tsunami and debris. Instead of using Eq. (5), Model 3 expressed the drag force considering the weighting function and relative velocity in front and rear of the debris. In addition, the different value is used for the drag coefficient between front and rear of the debris (see [33] for further information).

While the inertia forces were not considered in Model 4, the following inertia forces (the effects of added mass) were considered in the other three models.

$$\boldsymbol{F}_{inertia} = \rho_w V C_M \left(\frac{\partial \boldsymbol{U}}{\partial t} - \frac{\partial \boldsymbol{u_d}}{\partial t}\right), \quad \ldots\ldots \quad (6)$$

where V, C_M are the volume of the submerged debris fraction and inertia coefficient (or added mass coefficient). However, values used for C_M are different among the models (see **Table 1**).

To calculate the effects of collision with other debris and structures, Models 1 and 4 adopted the spring-dashpot system, based on the DEM method. In contrast, Models 2 and 4 calculated the debris velocity after the collision by solving the momentum conservation equation for translational motion and the angular momentum conservation equation for rotational motion. It should also be mentioned that although the effects should be minor in the present simulations, other forces (e.g., Froude–Krylov force, difference in hydrostatic forces) are also considered in some of the models (see **Table 1**).

Finally, one of the important aspects regarding debris transport is in their random nature. In fact, many of the previous experiments (e.g., [13, 14]) demonstrated that the trajectory of drifted debris slightly differs even when the same experimental conditions are used. Only Model 1 modelled the random dispersion of debris by artificially intensifying turbulent diffusion in the present simulations (though Model 3 also has a function to consider the random dispersion of debris).

During the Tsunami Hackathon, the operators of Models 1, 2, and 3 ran four, two, three different cases, respectively, by varying numerical conditions to investigate the effects of parameters and improve the simulation results. Numerical condition used in each run can also be found in **Table 1** (alphabet inside the parenthesis shows each numerical condition).

5. Results

5.1. Hydrodynamics

Figure 2 shows the measured and simulated time history of the water surface elevation at the three wave gauges with no container models placed. The solid line represents the experimental results averaged over 20 repetitions. Stolle et al. [13] has already confirmed good repeatability of the tsunami-like bore generated by the same experimental setting.

The simulated results of Model 1 show good agreement with the experimental results, especially at WG3 and WG4. However, it should be noted that their simulated results were calibrated ones. More specifically, through the trial-and-error approach, the impoundment depth and Manning's roughness coefficient were adjusted to reproduce the generated tsunami well. Although the results of Model 4 also agree well with the measured results, they were also obtained through trial-and-error (the speed of the gate opening was adjusted). As Model 4 constructed a wall at the end of the flume in their simulations, the reflected wave was incorrectly recorded at WG3 and WG4. However, the present study only focused on the debris motion drifted from the initial position to at around $x = 6.70$ m. Thus, the effects of reflected waves are negligible.

There are two simulation results performed by Model 3; simulation with higher roughness coefficient ($n = 0.0296$, represented as 3(a)) and with smaller roughness coefficient ($n = 0.007$, represented with 3(b)–3(c)). As shown,

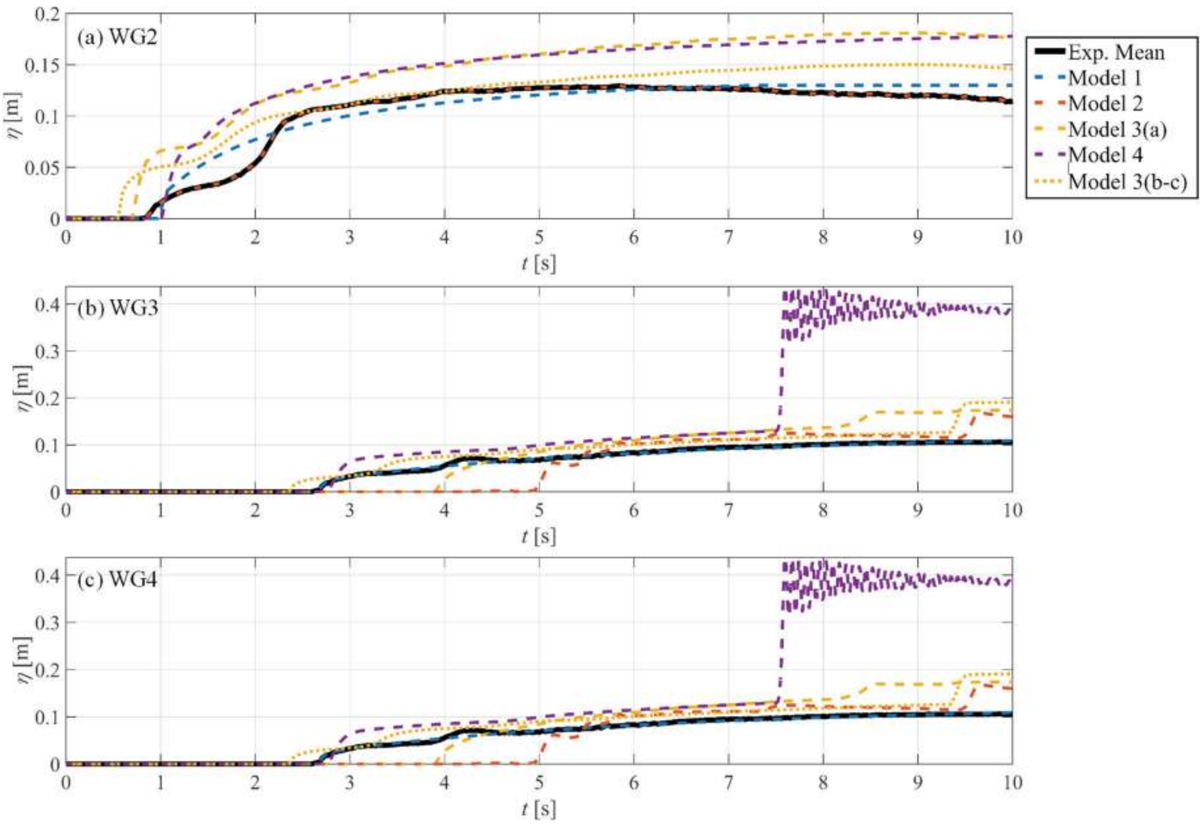

Fig. 2. Comparison of the time history of water levels at (a) WG2, (b) WG3, and (c) WG4.

the roughness coefficient had significant effects on the simulated results. Specifically, the arrival time of the tsunami at WG4 was changed by more than 1.0 s. However, the shapes of the water surface elevation resembled each other and the experimental results.

Although the shape of the water surface elevation was also reproduced by Model 2 relatively well, there are some discrepancies in the arrival time of the tsunami. Model 2 generated the tsunami by directly inputting the recorded water level at WG2 and did not perform any calibrations, which could be the reasons for the discrepancies.

5.2. Debris Trajectories

Figure 3 compares debris transport trajectories for each debris model. The experimental debris trajectories are shown with a black solid line, which corresponds to a mean trajectory over 17 repetitions, and black shaded area, corresponding to a 95% confidence interval. Although all measured debris trajectories are nearly in the form of a straight line, they slightly deviate to the negative x-direction. This trend was also observed in the other experiments performed at the same experimental facility [13, 61] and could be a result of the slight differences in the friction or topography over the flume bed. In all containers, the 95% confidence interval became larger as it propagated in the y direction. It is also worth mentioning that the debris initially located nearer the gate had a larger 95% confidence interval. As the debris closest to the gate was directly hit by the tsunami, the effects of diffusion were more significant, leading to larger deviation in the lateral direction.

The results of Model 1 consist of four lines, which show mean trajectories with four corresponding 95% confidence intervals. All results have slight deviations in lateral direction, which could be due the interactions with other containers and the effects of diffusion considered in Model 1. Overall, the simulated 95% confidence intervals agree relatively well with the experimental results. However, while the 95% confidence interval of Debris 3 was slightly underestimated, that of Debris 1 was slightly overestimated, meaning that the trend observed in the experiment (the 95% confidence interval of debris became wider when placed closer the gate) was not well reproduced. This is because uncertainty on the intensity of the diffusion was not considered in these simulations. As in Kihara and Kaida [39], uncertainty on the intensity of the diffusion should be considered in the future study. In addition, the result of Model 1(d) appears to have a narrower interval. As Model 1(d) neglected the effects of inertia force, the results suggest that the differences in acceleration between fluid and floating objects may play important roles in determining the deviation of debris transportation.

When focusing on the results of Model 2, although Debris 2 and 3 were transported in a straight line, Debris 1, located furthest from the gate, started to significantly deviate at around $y = 4.7$ m in Model 2(a). This is assumed to have occurred due to the effects of collision with other

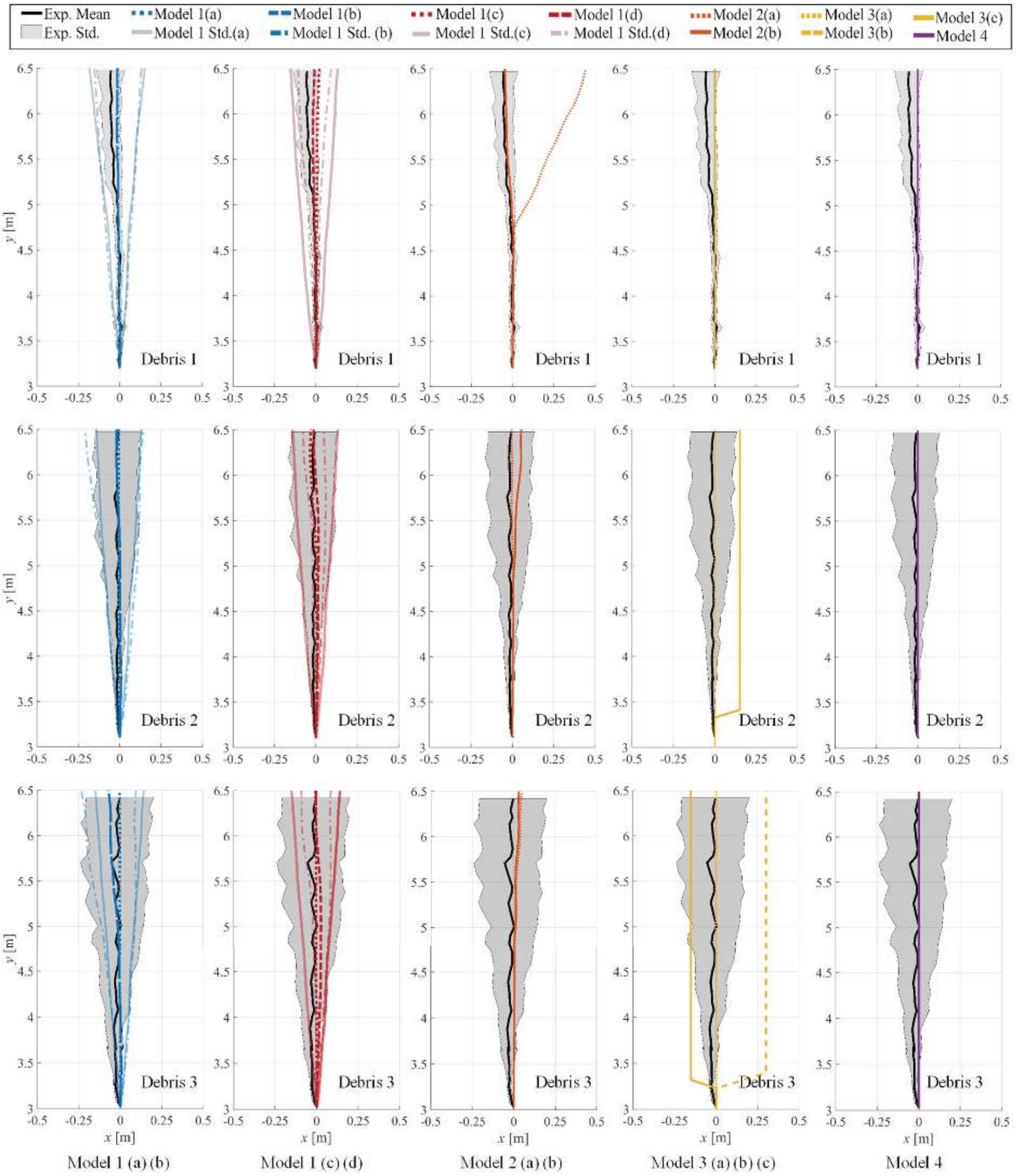

Fig. 3. Comparison of the experimental and numerically simulated debris trajectories.

debris, as the results in Model 2(b), which did not consider the interactions among debris, do not show such significant deviation.

In the results of Models 3 the significant lateral deviations of debris were observed in Models 3(b) and 3(c). The deviations could also be due to the fact that containers collided with each other in the simulations. However, while the numerical treatment of debris–debris interactions does not change between cases of Models 3, all the debris were simulated to move in a straight line in Model 3(a). Although further investigation is necessary to clarify the reasons, relatively smaller tsunami propagation speed, simulated in Model 3(a), resulted in relatively smaller debris velocities (as shown in Section 5.3), which may have influenced the interactions among debris.

The results of Model 4 indicate that all three containers were transported in a nearly straight line (i.e., the significant lateral deviations were not observed) despite the fact that the collision among debris should also have been simulated in Model 4. Contrary to Models 2 and 3, Model 4 (and Model 1) expressed debris–debris interaction by adopting the spring-dashpot system (instead of

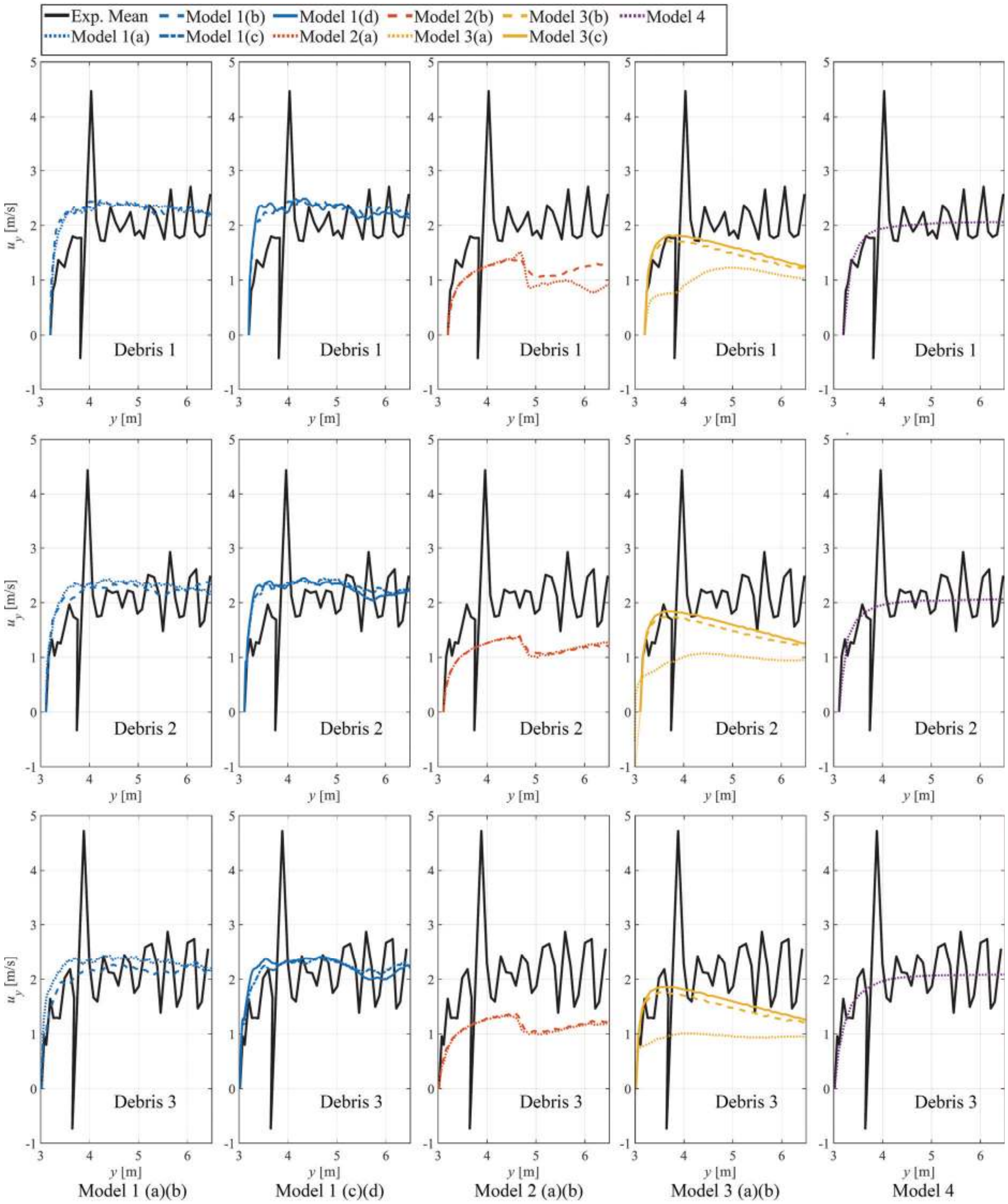

Fig. 4. Comparison of debris velocities.

solving a momentum conservation equation). This difference in numerical treatment could be the reason why debris were not unreasonably deviated in the results of Model 4.

5.3. Debris Velocity

Debris velocities in the flow direction (y-direction) were obtained from the time history of the position of each debris. **Fig. 4** compares the obtained results. The experimental results include significant oscillations and even display negative values when debris started to move. This was due to difficulties in tracking debris motion from the recorded images. Specifically, when the tsunami reached debris, some water splashed up in the air, which hindered accurate recording of the incipient motion of debris. Thus, such significant oscillations (including maximum and minimum debris velocities) would be the results of experimental recording errors rather than the actual phenomena. Although Debris 3 had slightly higher velocity at the beginning (as they directly received hydrodynamic forces), all debris moved with almost the same speed after around $y = 4.0$ m.

The simulated results of Model 1 slightly overestimated the experimental results regardless of the simulated cases. As expected, the effects of varying coefficients for drag and inertia forces influenced the moving speed of Debris 3 more significantly. Essentially, when a smaller drag coefficient was used in the simulation, the moving speed of Debris 3 slightly reduced and moved closer to the experiment (see Model 1(b)).

The simulated results of Model 2 underestimated the debris velocities in the experiment. This underestimation could be attributed to their underestimation of the propagation velocity for the generated tsunami-like bore (which can be inferred from their lower reproduction of the time histories of water surface elevation recorded in the experiment, as shown in **Fig. 2**). The moving speed of debris was reduced near $y = 4.5$ m, which was assumed to have occurred due to the negative forces acting on the debris from the collision with the false bed (friction forces).

The importance of properly modelling of tsunami front was also confirmed from the results of Model 3. Model 3(a), which underestimated the propagation velocity (see **Fig. 2**), also underestimated the debris velocity. In contrast, Models 3(b) and 3c, which improved the propagation speed with a lower Manning's roughness coefficient, reproduced the debris velocity well at the early stages of debris displacement. However, the debris velocity gradually reduced after $y = 4.0$ m, which could also be due to the overestimation on the effects of collision force with the false bed.

The simulated results of Model 4 show good agreement with the experimental results for all debris during the entire recorded time. The main reason could be that Model 4 reproduced the generated tsunami-like bore relatively well. The big difference between Model 4 and the other models is that it considers the effects of the presence of debris on a flow field (i.e., two-way model).

6. Discussion and Conclusions

In the present study, an inter-model comparison for tsunami debris simulation model was performed as part of the Tsunami Hackathon. The blind benchmarking experiment, which recorded the transport of three container models under a tsunami-like bore, was conducted. Then, four different numerical models were employed to reproduce the experimental results.

Before the event, each modeler submitted their simulation results, which, for the current manuscript, correspond to the results of Model 1(a), Model 2(a), Model 3(a), and Model 4, respectively. On the first day of the event, the submitted numerical results were discussed and further parametric studies were decided to be conducted, producing additional, new simulation results. On the second day, the results of the parametric studies, the differences between the four models, possible future studies to further validate and to improve the tsunami debris simulation models were discussed. Overall, the discussions carried out during the three-day event and the conclusions derived from the present study are summarized below.

It was first confirmed that accurate modelling of the flow field generated by tsunami inundation is essential to simulate the transport of floating objects accurately. Especially, for the cases of debris placed on the ground, it is important to properly model the tsunami front shape and inundating speed. A dam-break wave, which resembles a tsunami bore propagating over a coastal plain, was used as the incident tsunami. Numerical treatment of a tsunami front has been known to significantly influence the inundating tsunami bore [62, 63]. Kawasaki et al. [64] also reported that the front of a dam-break wave was not well reproduced by the assumption of [58], of which all four simulation models were adopted, which could be one of the reasons why calibration was necessary to more accurately reproduce the generated tsunami. Further study on the detailed modeling of a tsunami front would eventually aid in proper modelling of the movement of tsunami debris.

The effects of changing drag coefficient and inertia coefficient on the movement of tsunami debris were deduced from the results of Models 1(b)–1(d) and Models 3(b) and 3(c). The relative velocity and relative acceleration are used to calculate drag or inertia force, respectively. Thus, these effects become more significant when debris are accelerated by being entrained in a tsunami or decelerated owing to the presence of structure or touching the ground. In the present study, the differences in these coefficients were confirmed to influence debris moving speed and trajectory. More specifically, larger drag coefficient and smaller inertia coefficient slightly increased the debris velocity when they started to move.

The debris–debris interaction was also found to significantly influence simulated results. In the results of Models 2 and 3, which solve the momentum conservation equations to determine the velocity of debris after touching other debris, some debris incorrectly deviated in lateral direction (x-direction in the present study). In contrast, such significant deviation in the lateral direction was not observed in Models 1 and 4, which adopted a spring and dash-pod system to simulate debris–debris interaction. Originally, the approach to use momentum conservation equations for debris–debris interaction was constructed considering the interactions between drifted ships in the sea [28]. Thus, further consideration would be necessary to extend the applicability of this approach to the objects initially located on the ground.

Considering the facts that the results of Model 4 agree well with the experimental results, two-way coupling simulation could be important to reproduce the debris transport appropriately. Resistance force against debris could be neglected when the debris is small. However, the present results suggest that they should be included when the debris size is relatively large, such as shipping containers used in the present study. Past studies (e.g., [65, 66]) have also reported that the effects of debris on a flow field is important to reproduce debris transport more accurately.

Despite the above findings, there are some limitations in the present study. The authors acknowledge that as the simulated hydrodynamics are different according to each simulation model, it is difficult to solely evaluate the performance of numerical modelling of tsunami debris. Thus, it would be meaningful for each modeler to simulate the transport of debris, using the same flow field generated by a tsunami in the future. Having the experimental dataset with detailed spatiotemporal flow fields associated with debris motion could work as an ideal benchmarking for tsunami debris simulation models. Using such an ideal dataset, it is important to perform more thorough parametric studies, which will aid to identify the most influential parameters (among those shown in **Table 1**) to simulate tsunami debris motions. Although the present study only compared 2D simulation models, it would also be worthwhile to compare 3D simulation models. Such comparisons can clarify the limitations of 2D models. Since 3D models can also simulate debris impact force, which is another important issue that has been addressed and discussed in other literature (e.g., [67–69]), it would also be meaningful to check their performance in terms of debris loading.

Finally, the authors would like to point out the importance of probabilistic approaches to assess the tsunami debris impact. Many of the existing studies reported that the results obtained through the laboratory experiments slightly differed even when repeated with the same experimental conditions. Kihara and Kaida [39] proposed a probabilistic approach on debris collision, and random diffusion was considered by incorporating intensified turbulent diffusion, as partially applied to Model 1. Recently, Stolle et al. [61] proposed an empirical equation to estimate variations in debris trajectory, using normal distribution function. It is therefore important to investigate how this stochastic nature should be expressed in numerical modelling.

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Academic Societies & Scientific Organizations:
- Japan Society of Civil Engineers (JSCE)
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- Y. Shigihara, T. Kita, T. Tada, and H. Yagi, "Proposal of tsunami risk map for vessel evacuation and application to Tokyo Bay," J. of Japan Society of Civil Engineers, Ser. B2 (Coastal Engineering), Vol.73, No.2, pp. I_415-I_420, 2017.
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Academic Societies & Scientific Organizations:
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Selected Publications:
- H. von Häfen, J. Stolle, I. Nistor, and N. Goseberg, "Side-by-Side Entrainment and Displacement of Cuboids due to a Tsunami-like Wave," Coastal Engineering, Vol.164, 103819, 2021.
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- American Society of Civil Engineers (ASCE)
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