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Survey Report:

Numerical Simulation of Urban Inundation Processes and Their Hydraulic Quantities – Tsunami Analysis Hackathon Theme 1 –

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The detailed understanding of tsunami hazard risk using numerical simulations requires a numerical model that can accurately predict tsunami inundation phenomena on land. In such models, the structural effects are indirectly considered using the variation of bottom roughness as a proxy for the differences in building densities. Only a few studies have conducted intermodel tests to investigate tsunami inundation in complex coastal urban cities. During the tsunami analysis hackathon held in September 2020, eight research groups met to have a detailed discussion on the current urban inundation problems. In this study, we conducted an intermodel comparison of the numerical tsunami models, using the data from physical experiments that were performed on a detailed urban model. Our objective was to investigate the necessary conditions of an accurate numerical model based that can ensure high reproducibility and practicality. It was confirmed that the accuracy of topographic data is an important parameter for tsunami inundation simulations in complex urban areas. Based on the computational cost and accuracy, we suggest that a resolution of 1 cm of topographic data is a sufficient condition for tsunami inundation simulations on 1/250 scale model.

Keywords: tsunami analysis hackathon, tsunami inundation simulation, numerical models, topography data, reproducibility

1. Introduction

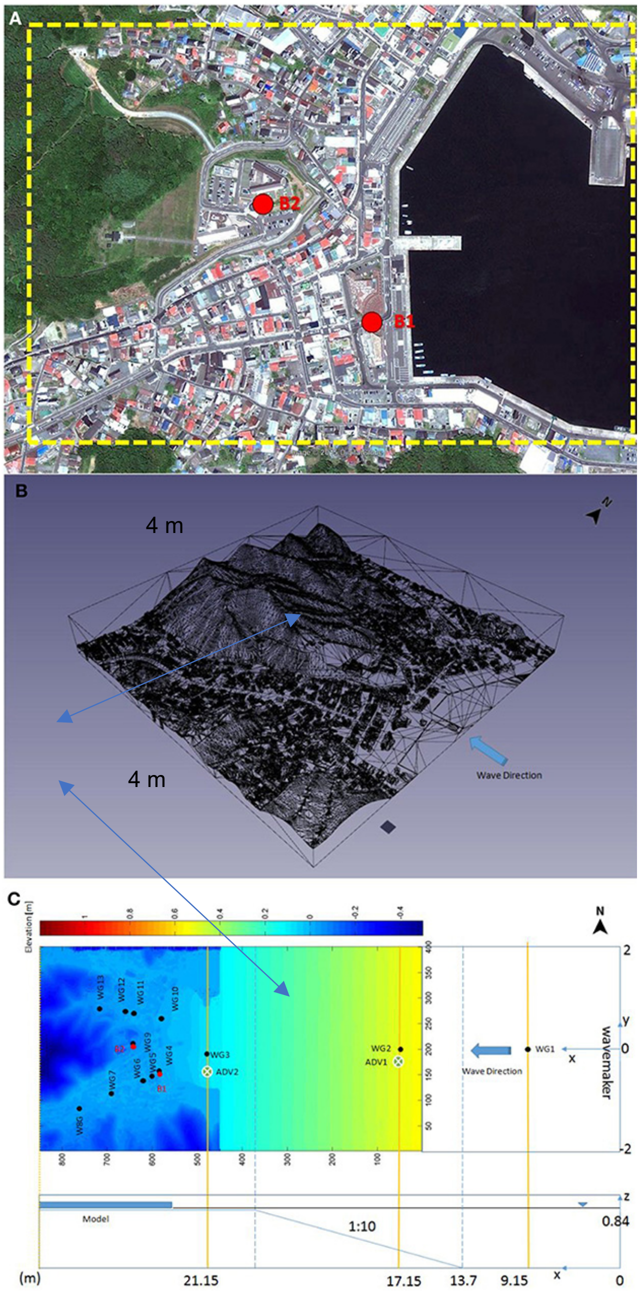
Computer simulations have become an indispensable tool in tsunami research and in the development of disaster prevention and mitigation practices. To study tsunami hazard and the associated risk assessment in detail using numerical simulation, it is essential to have a numerical model that can accurately predict tsunami inundation phenomena on land. Historically, tsunami inundation simulations use digital surface data that exclude buildings. The effect of structures is usually considered indirectly by evaluating the variation of bottom roughness as a proxy for the differences in building density. Only a few studies have conducted physical model tests to investigate tsunami inundation in complex coastal urban cities. For example, Tomiczek et al. [1] investigated the patterns of tsunami flow using complex arrays of box structures representing macro-roughness elements. The presence of an idealized macro-roughness obstacle can significantly affect the onshore wave propagation by changing the water surface profile compared to the configuration of bare Earth. Cox et al. [2] and Park et al. [3] conducted more detailed investigations on the effect of macro-roughness elements on inundation processes. They performed a physical modelling of tsunami run-up in Seaside, Oregon. The study used rectangular blocks as to represent buildings and residential houses on a flat topography. Prasetyo et al. [4] aimed to evaluate the physical processes of tsunamis by inundating a detailed and complex urban model, and verified the validity of the numerical model (two-dimensional and quasi three-dimensional planes) using the experimental results.

Different numerical models of tsunami simulations are known to produce different results for identical inputs, resulting in a range of uncertainties. Lynett et al. [5] examined the sensitivity of tsunami-generated coastal current predictions for an intermodel set of simulations and found that shear- and separation-driven currents are quite sensitive to model physics and numerals. A tsunami analysis hackathon was conducted by Takahashi et al. [6] with the aim to improve the current tsunami simulation technology by comparing and discussing experimental data with developed numerical models.

This paper partly summarizes the results of the tsunami analysis hackathon that were obtained by comparing numerical tsunami models with the results of the inundation experiment based on a detailed urban model by Prasetyo et al. [4]. We also investigated the necessary conditions of the numerical model based on its reproducibility and practicality.

2. Tsunami Analysis Hackathon

The Tsunami Analysis Hackathon [6] was held online during 1st to 3rd September, 2020. There were nine themes that were discussed, including tsunami inundation and run-up, tsunami generation by non-seismic causes, tsunami pressure against coastal structures, sediment transport, and debris and floating object drift. Eight teams contributed to theme 1, and we presented and discussed every day. On day one, the simulation results were introduced using a pre-released dataset in the morning, and the necessary discussions were conducted in the afternoon. Subsequently, we confirmed the model setups and discussed the different ways to improve the simulation results. Following the discussion, we shared better topographic data, and each team modified the simulation conditions and re-executed the simulation to obtain better results. On the second and third days, presentations and discussions were repeated, and we agreed to continue further discussion even after the event. The details of the results and discussion are presented in the following sections.



Source: Prasetyo et al. [4].

Fig. 1. Experimental conditions: A: aerial photograph of Onagawa, Miyagi Prefecture; B: laser scan data; and C: topographical conditions.

3. Physical Model Experiment

A series of experiments were conducted by Prasetyo et al. [4] at Hybrid Tsunami Open Flume in the Ujigawa laboratory of Kyoto University (HyTOFU). The flume was 45 m long and 4 m wide, and could generate tsunami-like long-waves or irregular short waves using a combination of water pump, piston-type mechanical wave maker, and dam break gate system [7]. All experiments employed a wooden city model created based on the city center of Onagawa, Miyagi Prefecture (**Fig. 1**). The 3D city model included ports, buildings, and houses. It was constructed at a scale of 1 : 250 using standard triangulated language (STL) data provided by the Geospatial Information Authority of Japan, and it covers an area of 1 km from east to west and 1 km from north to south.

A 45 m long and 4 m wide experimental tank was used to generate long-periods or solitary wave type water level waveforms as offshore incident waves. A 1 : 10 planar slope, reaching the bottom of the flume, was connected at the eastern side of the model. To measure wave heights during the experiment, thirteen wave gauges (WGs) were set to cover the flume from offshore to onshore and over the city model. WG1 was set up near the wave maker to

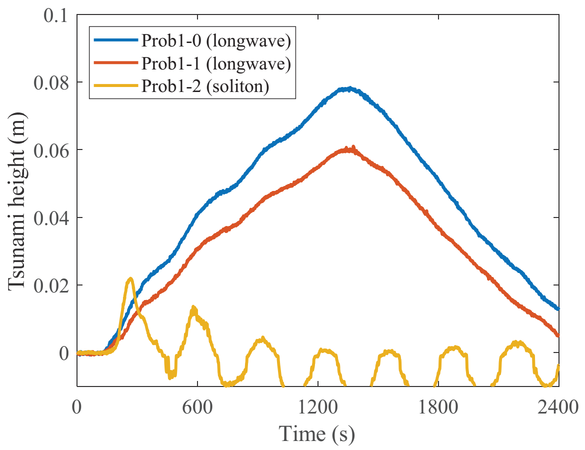


Fig. 2. Time series of water level at offshore wave gauge (WG2) for three input conditions (Prob1-0: prerelease data; Prob1-1: long period wave case; and Prob1-2: solitary wave case).

provide the initial wave condition. WG2 was set on the planar slope and WG3 was set at the port. WG4–8 were installed along the main street, while WG10–13 were set on narrower and steeper roads. WG9 was set on a hill, where the Onagawa Hospital is located. The time series of the velocity and pressure were also measured. The coordinates of the measurement locations are listed in **Table 4** in Appendix A.

The maximum discharge of the pump generator was 0.833 m^3/s, which is equivalent to a 0.1 m increase in the water surface elevation. The piston paddle was able to generate a solitary wave of up to 1.0 m height using a maximum 2.5 m stroke. Several tests were performed to achieve the target maximum inundation depths at the benchmark locations (B1 and B2 in **Fig. 1(a)**) for both solitary waves and hydraulic bore. Prasetyo et al. [4] reported a discharge of 0.133 m^3/s using a pump and a solitary wave amplitude 0.03 m with paddle. This study also uses the experimental results of discharge of 0.105 m^3/s by pump and solitary wave amplitude 0.02 m with paddle which data was kept secret from the research teams before hackathon.

4. Numerical Simulation

4.1. Data Provision

Eight research groups contributed to theme 1 of the tsunami analysis hackathon, and conducted numerical simulations of tsunami inundation to reproduce the experimental results by Prasetyo et al. [4]. Topography and bathymetry data obtained by the laser scanner were provided to the teams in advance. Experimental data, which were introduced in [4] and WG2 data for different conditions were also provided to the teams in advance, which are shown in **Fig. 2**. The other experimental results for different conditions were kept secret, and the simulation results were compared at the meeting. During the Tsunami Hackathon, the secret data were made publicly available, which were used for validation and discussion.

4.2. Numerical Models

Table 1 shows the summary of the numerical set up of the eight simulation models, which are the extended models of TUNAMI [8–11], JAGURS [12], and STOC [13–15]. All models were based on non-linear shallow water theory, and the conditions were mostly similar to a slightly different value under certain conditions. Each team tested their model using the rereleased data (Prob1-0 in **Fig. 2**). We compared the simulation results of the unreleased cases Prob1-1 and 1-2 during the Tsunami Hackathon.

5. Simulation Results

5.1. Laser Scanned Topography Data

5.1.1. Long Period Wave Case

Figure 3 shows the time series of water level at wave gauges for the case of long-period waves with laser-scanned topography data. The black line indicates the experimental results, while the colored lines indicate the simulation results. WG9 and 10 are not shown as no inundation occurred at WG9, which was located on the hill. Additionally, data were not recorded at WG10 due to plug out.

Although all models were slightly underestimated at WG3 (in the port) and overestimated at WG4 (in the quay), the variation tendency of the water level agreed well. All but one model showed differences at WG5 even though the water level difference was minor. On the other hand, most models exhibited delays in inundation propagation. Especially at WG8, within the inundation limit, it was observed that the delay of arrival time becomes longer. A similar trend can be observed in other areas (WG11–13), and it is more significant owing to the steeper road gradients and narrower width of the road is narrower in this area.

5.1.2. Solitary Wave Case

Figure 4 shows the time series of water level at wave gauges for the case of solitary wave simulated with laser-scanned topography data. WG9, 10, and 13 are not shown because no inundation occurred at WG9 and 13, and data were unrecorded at WG10 due to plug out.

Compared to the long period wave condition, except for one model, the water level time and arrival time agreed well with the experimental results. However, some models did not show any receding tsunami waves and reduction in inundation depth, especially at locations where the distance from the shore was long (WG6 and 7). In the steeper and narrower road areas (WG11 and 12), the discrepancy in the water level was significant, and the numerical models was overestimated by approximately two to three times higher than the experiment.

Table 1. Summary of numerical setup for each model.

<table>
<tr><th>Model code</th><th>IDEA (I)</th><th>NIPPON KOEI (NK)</th><th>TUNAMI NDA (TN)</th><th>TUNAMI IRIDeS (TI)</th><th>JAGURS TU (JT)</th><th>JAGURS MRI (JM)</th><th>JAGURS NIED (JN)</th><th>STOC CHUO (SC)</th></tr>
<tr><td>Governing equation</td><td colspan="7">Depth-integrated non-linear shallow water equations</td><td>Velocity-form NSWE</td></tr>
<tr><td>Spatial discretization</td><td colspan="7">Finite difference method</td><td>Finite volume method</td></tr>
<tr><td>Spatial differentiation</td><td colspan="8">Staggered C-grid</td></tr>
<tr><td>Temporal differentiation</td><td colspan="8">Leap-frog scheme</td></tr>
<tr><td>Convection terms</td><td>3rd order accuracy upwind</td><td colspan="7">1st order accuracy upwind</td></tr>
<tr><td>Friction term</td><td colspan="3">Semi-implicit</td><td>Simple implicit</td><td>Semi-implicit (combined)</td><td colspan="2">Semi-implicit (simple)</td><td>Semi-implicit</td></tr>
<tr><td>Wet/dry boundary</td><td colspan="5">Pressure gradient</td><td colspan="2">Pressure gradient and friction term</td><td>Pressure gradient</td></tr>
<tr><td>Time step</td><td>0.001 s</td><td>0.00025 s</td><td>0.001 s</td><td>Adaptive by 5th order Runge-Kutta method</td><td>0.001 s</td><td>0.0005 s</td><td>0.001 s</td><td>Adaptive (5×10^{-2}–5×10^{-6})</td></tr>
<tr><td>Mesh size</td><td colspan="7">0.01 m</td><td>3D: 0.01 m, 2D: 0.04 m</td></tr>
<tr><td>Grid number</td><td>920×400</td><td>845×400</td><td>845×400</td><td>920×400</td><td colspan="2">$845 \times 400 \times 2$</td><td>$(845+900) \times 400$</td><td>3D: $360 \times 260 \times 5$ 2D: 211×100</td></tr>
<tr><td>Velocity limiter</td><td>No limit</td><td>25 m/s</td><td>1.26 m/s</td><td>No limit</td><td colspan="3">$Fr = 2$</td><td>30 m/s</td></tr>
<tr><td>Tolerance depth</td><td>10^{-10} m</td><td>10^{-7} m</td><td>10^{-5} m</td><td>10^{-3} m</td><td>10^{-6} m</td><td>10^{-10} m</td><td>10^{-6} m</td><td>10^{-4} m</td></tr>
<tr><td>Roughness coefficient</td><td colspan="2">Sea: 0.025, land: 0.013</td><td>0.01</td><td>Sea: 0.025, land: 0.013</td><td colspan="3">0.025</td><td>Sea: 0.025 land: 0.013</td></tr>
<tr><td>Input value</td><td>Water level</td><td>Water level and discharge</td><td colspan="4">Water level</td><td>Extend flume to reproduce wave form</td><td>Water level</td></tr>
<tr><td>Input boundary</td><td colspan="4">Radiation</td><td colspan="2">Mirror</td><td>Imaginary flume</td><td>Radiation</td></tr>
<tr><td>Lateral boundary</td><td colspan="8">Wall</td></tr>
<tr><td>Outflow boundary</td><td>Radiation</td><td>Run-up</td><td colspan="5">Wall</td><td>Radiation</td></tr>
</table>

5.1.3. Discussion

In the Tsunami Hackathon, we discussed the reason for the discrepancy in delay of arrival time for the long period case and the absence of receding tsunami wave for the solitary wave case. We assumed that the laser-scanned topography data might have insufficient accuracy, especially on narrow roads between complex buildings. **Fig. 5** shows a comparison between laser-scanned data and STL data. As evidenced in the figure, the laser-scanned data does not efficiently reproduce the straight roads and buildings, and has unsmoothed slopes. Thus, the teams decided to use STL data as topography data on land, which was used when the experimental model was constructed, and additional simulations were conducted.

5.2. STL Topography Data

5.2.1. Resolution of STL Topography Data

Figure 6 shows the 3D topographic images obtained using laser-scanned and STL data with different resolutions. As shown in **Fig. 6(a)**, roads and buildings were not accurately reproduced by laser-scanned data. On the other hand, roads were obvious in the STL topography data. As far as the differences in the resolution were concerned, a grid size of 1 mm precisely reproduced the shape of the buildings, while a grid size of 1 cm made the building edge uneven although the road widths were imaged sufficiently well.

5.2.2. Long-Period Wave Case

Figure 7 shows the time series of water level at wave gauges for the case of long-period waves with STL topography data with 1 cm resolution (**Fig. 6(b)**). The black line indicates the experimental results, while the colored lines indicate the simulation results. WG9 and 10 are not shown because there was no inundation or data.

As shown in the panels of WG5–7, the simulation results along the main street agree well with the experiment in terms of inundation depth and arrival time. Even at WG8, most models could simulate inundation in the area farther from the shore sufficiently well. On the other hand, discrepancy remained and simulation results of the inundation depth were overestimated by approximately 1.5 times at WG11–13, where the road is narrower and steeper.

5.2.3. Solitary Wave Case

Figure 8 shows the time series of the water level at wave gauges for the case of solitary waves with STL topography data. Compared with the results of the laser-scanned data (**Fig. 4**), the reproducibility of the model

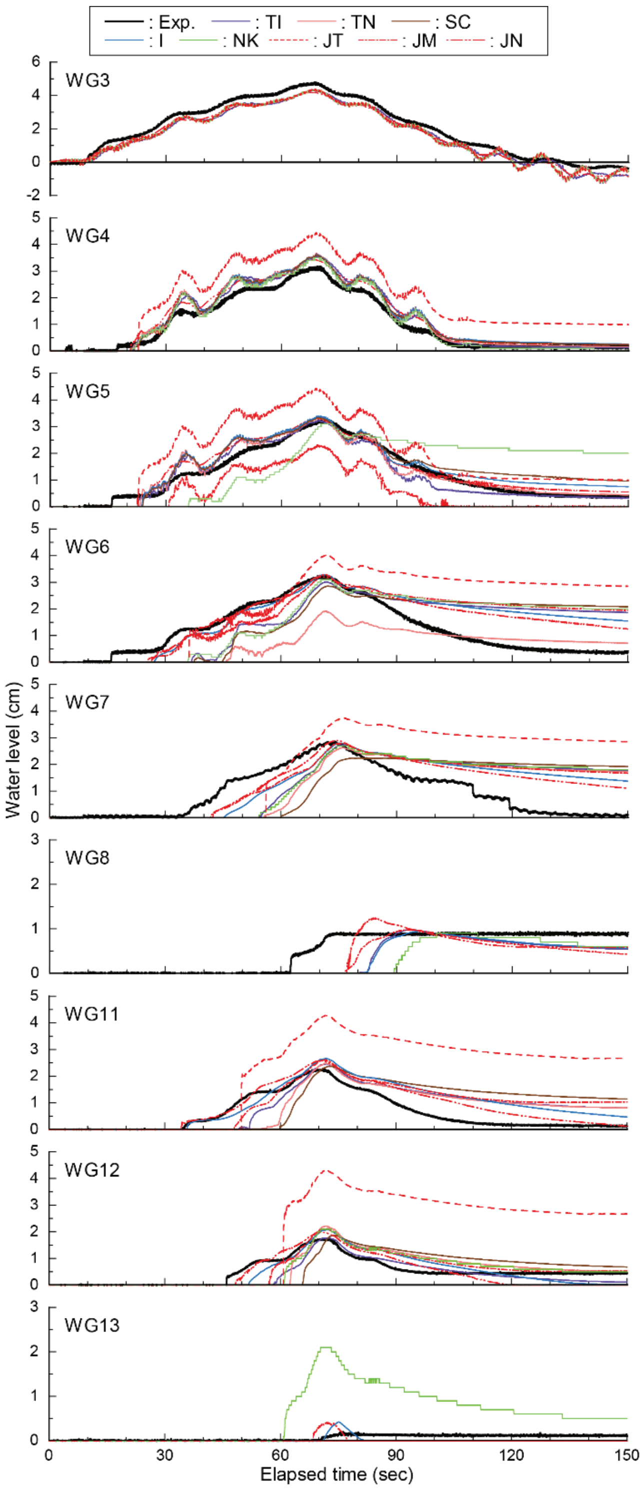


Fig. 3. Time series of water level at wave gauges for the case of long period wave with laser scanned topography data (black: experiment data, model codes were indicated in **Table 1**).

simulations was found to be significantly improved, and the time and height of elevation and declination of the water level agreed precisely with the experiment. The problem of receding tsunami waves also improved. On the other hand, the narrow and steep road areas of WG11

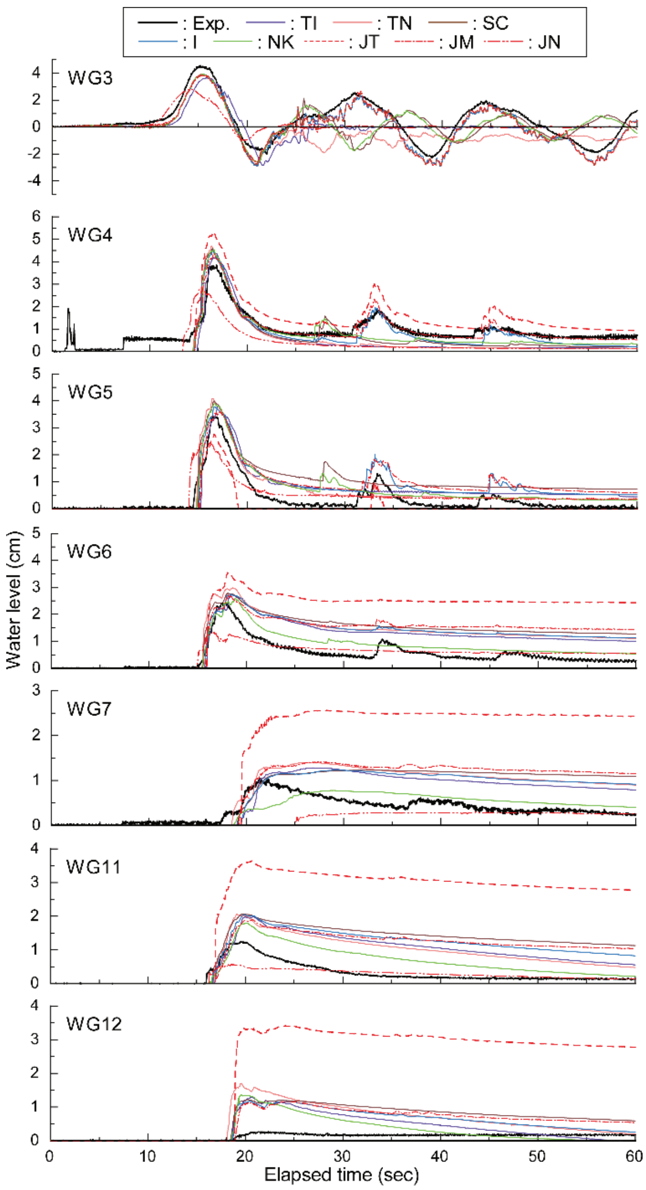


Fig. 4. Time series of water level at wave gauges for the case of solitary wave by laser scanned topography data (black: experiment data, model codes were indicated in **Table 1**).

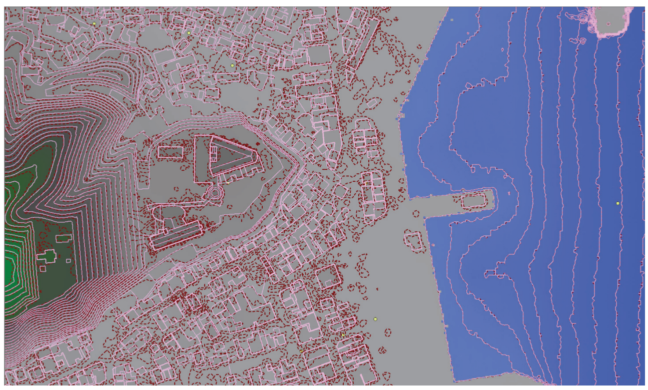
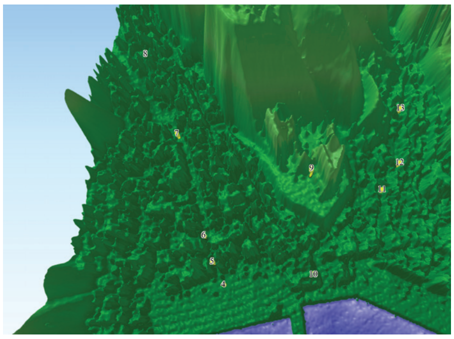
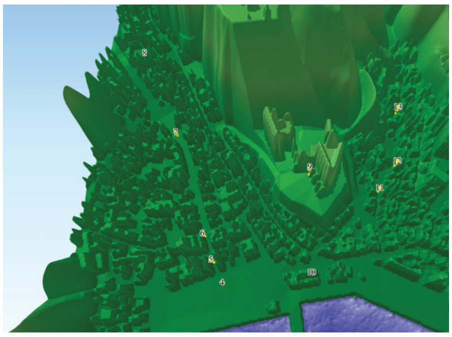


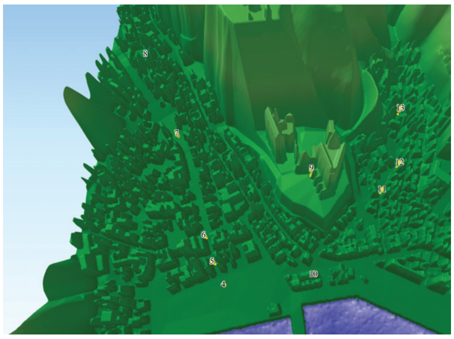
Fig. 5. Comparison of topographic data between laser scan and STL (red broken line: laser scan; and pink solid line: STL).



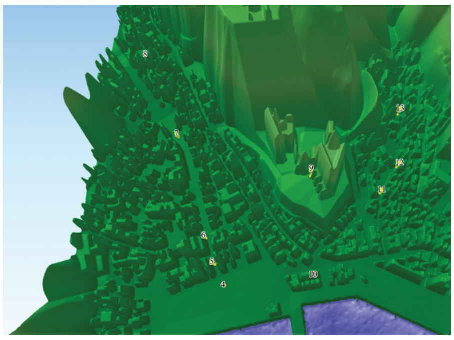
(a) Topography obtained using laser-scanned data at a resolution of 1 cm



(b) Resolution of 1 cm



(c) Resolution of 5 mm



(d) Resolution of 1 mm

Fig. 6. Topography data at different resolutions.

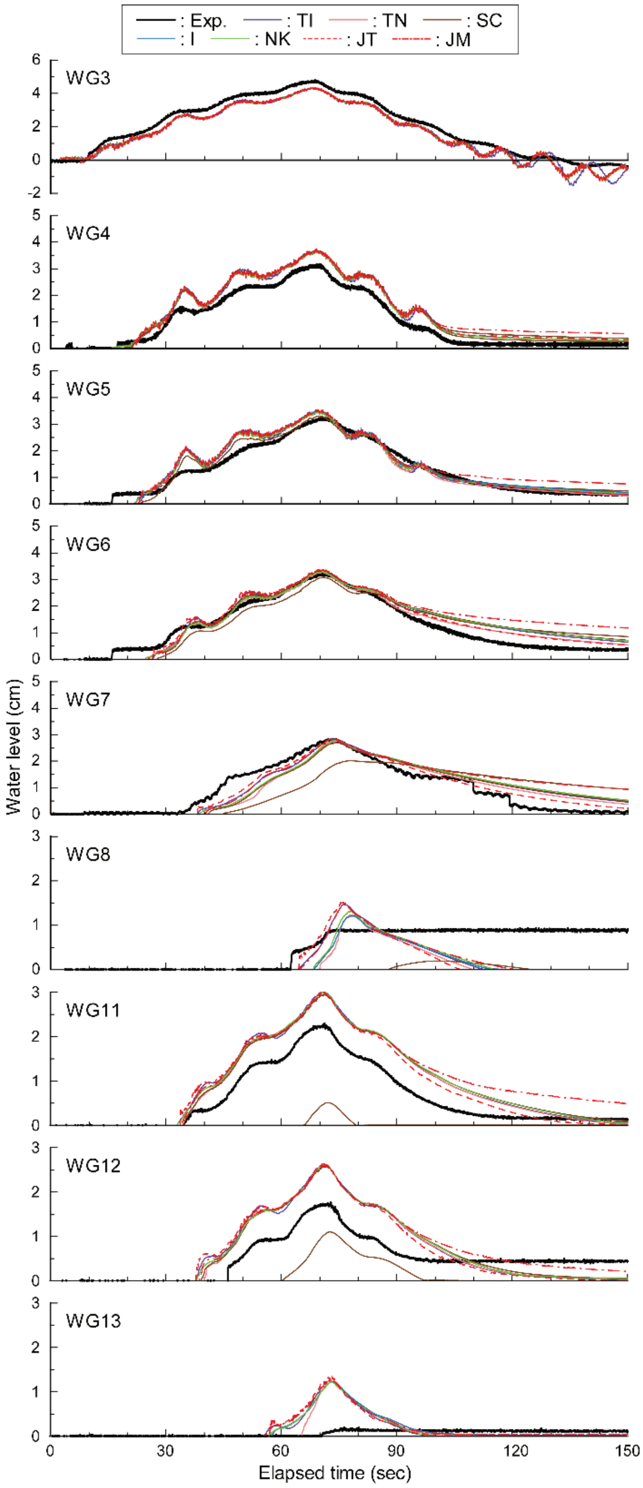


Fig. 7. Time series of water level at wave gauges for the case of long period wave with STL topography data (black: experiment data).

and 12 were over-estimated, similar to the long period wave case.

5.2.4. Discussion

To compare the performance of each model, the index for comparing the waveforms, i.e., the variance reduction (VR) parameter proposed by Yamamoto et al. [16] was employed.

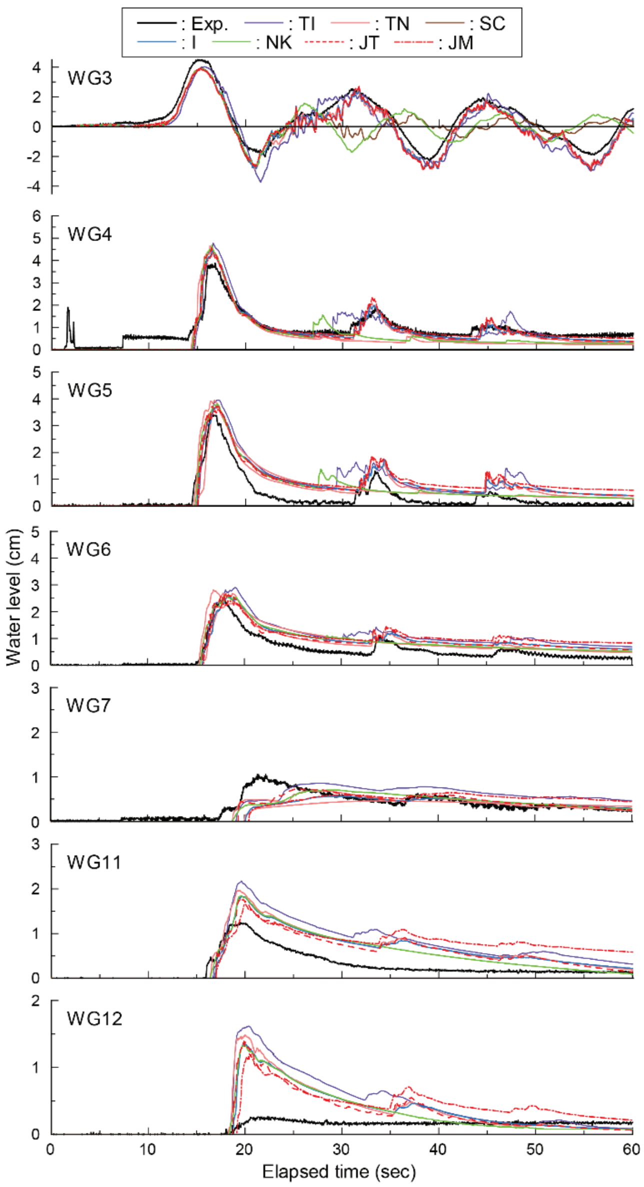


Fig. 8. Time series of water level at wave gauges for the case of solitary wave by laser scanned topography data (black: experiment data).

$$\mathrm{VR} = 1 - \frac{\text{Difference}}{\text{Reference amount}} \quad \cdots\cdots\cdots \quad (1)$$

The results of the two cases for tsunami input conditions (Prob1-1 and Prob1-2) and on and post-hackathon were compared. As shown in **Table 2**, most models exhibited better VR in the solitary wave case (Prob1-2) compared to that in the long-period wave case (Prob1-1). The overall VR of post-hackathon was improved compared to that during the hackathon. This is because post-hackathon used STL topographic data, and it showed significant improvement for both the cases of input tsunami waves compared to the results obtained with laser scanned data during the hackathon.

To discuss the effect of resolution on STL topography data, the time series of water levels at WG6 and 7 were plotted for the resolutions of 1 cm, 5 mm, 2.5 mm (**Fig. 9**).

Table 2. Comparison of model performance by variance reduction (VR).

		TI	TN	SC	I	NK	JT	JM	JN
Prob1-1	On	0.82	0.96	0.97	0.99	0.56	0.81	0.99	0.99
	Post	0.78	0.91	0.83	0.91	0.92	0.92	0.92	
Prob1-2	On	0.95	0.92	0.95	0.96	0.93	0.63	0.96	0.87
	Post	0.93	0.94	0.95	0.96	0.95	0.95	0.97	

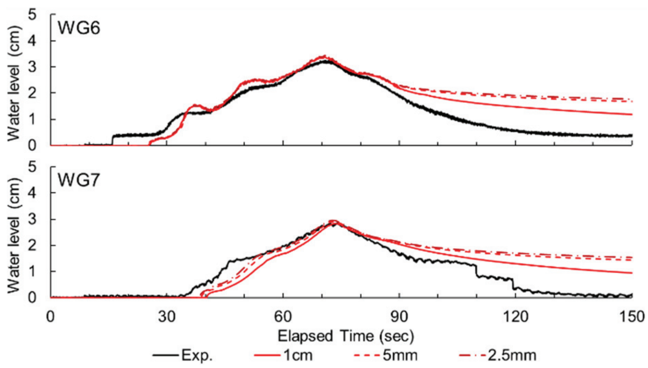


Fig. 9. Comparison of the time series of water level with different resolutions of STL topography data (black: experiment data).

Table 3. Computation time for different resolution.

dx	*dt*	Time
1 cm	0.0005 s	7 minutes
5 mm	0.0005 s	28 minutes
2.5 mm	0.00025 s	4 hours 7 minutes
1 mm	0.0001 s	65 hours 46 minutes

As shown in the figure, the overall tendency of the temporal water level variation did not change, and the peak water level was almost the same, although a slight improvement in the arrival time was observed at WG7. **Table 3** shows the computation time obtained by the supercomputer MRI-JMA at the different resolutions. Considering the computational cost and accuracy of the results, we can conclude that a resolution of 1 cm is sufficient for conducting practical simulation on 1/250 scale model.

6. Conclusions

This study conducted an intermodel comparison of the tsunami inundation processes in complex urban areas as a part of the tsunami analysis hackathon program 2020. The numerical model results were compared with the results of an inundation experiment conducted by Prasetyo et al. [4]. The simulation results obtained using laser-scanned data showed discrepancies between the models, and the reproducibility of the inundation process was insufficient. On the other hand, the results obtained using STL topographic data showed significant improvement for both the cases of input tsunami waves compared to the results obtained using laser scanned data. It was confirmed that the accuracy of topographic data is significantly important for tsunami inundation simulations in complex urban areas. From the viewpoint of computational cost and accuracy, a resolution of 1 cm of topographic data is sufficient as a reasonable condition for practical tsunami inundation simulation.

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Table 4. Location of wave gauges and pressure sensors.

Water level	x [m]	y [m]	Pressure	x [m]	y [m]
WG2	0.75	2.00	P1	5.52	2.86
WG3	4.75	2.10	P2	5.84	2.55
WG4	5.80	1.60	P3	5.98	2.57
WG5	5.94	1.53	P4	6.07	2.53
WG6	6.12	1.46	P5	6.14	2.60
WG7	6.91	1.20	P6	5.97	2.20
WG8	7.59	0.91	P7	5.99	3.83
WG9	6.44	2.19	P8	6.01	2.10
WG10	5.84	2.19	P9	6.47	2.17
WG11	6.42	2.70	P10	6.91	2.88
WG12	6.61	2.84	P11	5.80	1.66
WG13	7.02	2.88	P12	6.00	1.40
			P13	6.38	1.28
			P14	6.59	1.20
			P15	5.74	1.00
			P16	6.11	2.25
			P17	5.95	2.48
			P18	6.21	2.58

Appendix A. Coordinates of Sensors of Provided Data

The coordinates of wave gauges and pressor sensors of provided data are provided in **Table 4**. Photographs of the overall Onagawa model and sensor locations are shown in **Fig. 10**.

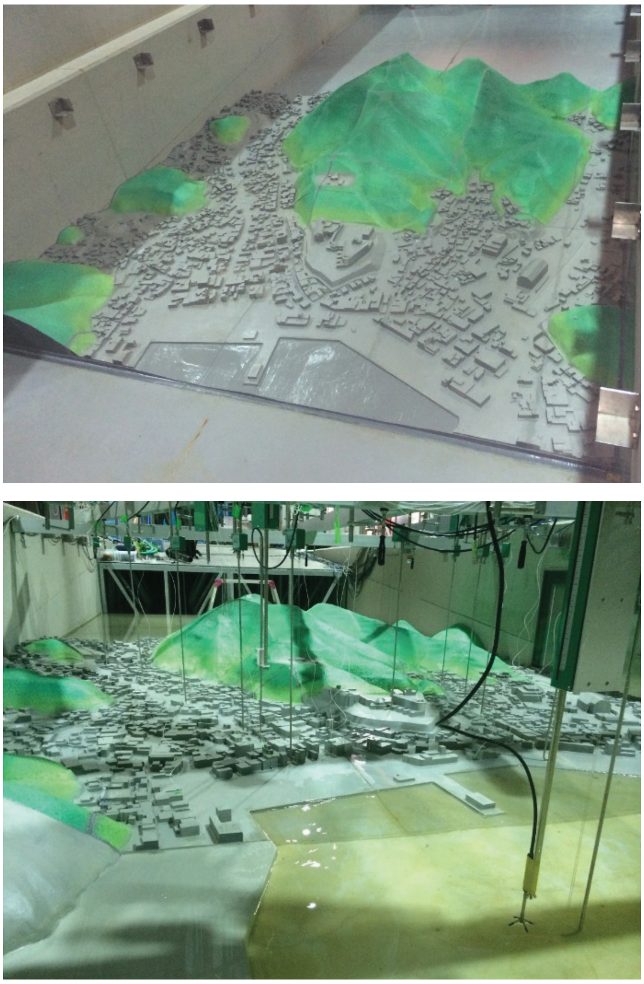

Fig. 10. Onagawa model.

Appendix B. Time Series of the Spatial Distribution of Tsunami Inundation

B.1. Long Period Wave Case

Figures 11 and **12** show intermodel comparison of time series of spatial distribution of inundation processes. The input tsunami condition is the long period wave case Prob1-1 and topographic data is STL data of 1 cm resolution.

B.2. Solitary Wave Case

Figure 13 shows the intermodel comparison of the time series of spatial distribution data for the inundation processes in the following cases: solitary wave condition Prob1-2. Topographic data is STL data with 1 cm resolution.

Fig. 11. Time series of spatial water level for the case of long period wave ($t = 20$–60 s; code name from the left to right: I, NK, TN, JT, and JM).

Fig. 12. Time series of spatial water level for the case of long period wave ($t = 70$–110 s; code name from the left to right: I, NK, TN, JT, and JM).

Fig. 13. Time series of spatial water level for the case of solitary wave (t = 20–60 s; code name from the left to right: I, NK, TN, JT, and JM).

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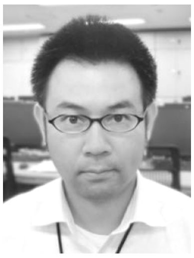

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