TSUNAMI MODELLING IN A BUILT-IN COASTAL ENVIRONMENT WITH ADAPTIVE MESH RIFINEMENT AND VARYING BOTTOM FRICTION

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INTRODUCTION

The great Japan earthquake on March/11/2011provoked an extreme tsunami wave toward the northeastern Japanese coast. The tsunami inundation covered a wide range of territories stretching over 500 km^2 and caused devastating influences that claimed more than 15,000 lives (Mori et al. (2011)). Miyagi Prefecture, the closest mainland to the epicentre, received massive tsunami waves that reached over 40 m in run-up height. Prasetyo et al. (2019) aimed to reproduce the tsunami wave inundation in Onagawa Town of Miyagi Prefecture by building a physical model using Hybrid Tsunami Open Flume in Ujigawa Open Laboratory (HyTOFU) at Kyoto University to study the inundation process by measuring the wave height and arrival time. For that purpose, two wave types were used, the (Pump-type) hydraulic bore, and the (Piston-type) solitary wave. Also, 2D and quasi-3D (Q3D) models were tested for their robustness and applied to emulate tsunami propagation in the complex coastal city model.

In this study, we adopted adaptive mesh refinement (AMR) for its efficiency in tsunami modelling with Basilisk open-source flow solver for non-linear shallow water (Saint-Venant) equations and fully non-linear Boussinesq (Green-Naghdi) equations (Popinet (2015)). The numerical experiment was conducted to validate the model by comparing the wave height with the physical model experiment, the 2D, and Q3D model results by Prasetyo et al. (2019). Thus, the original conditions were applied, and the results agreed well with those obtained by Prasetyo et al. (2019). Furthermore, the Basilisk results were relatively more reliable in predicting the tsunami run-up in the built-in area of the Onagawa Town physical model. Also, the arrival time of the tsunami wave was efficiently predicted, especially in the case of the solitary wave.

METHODOLOGY

Basilisk open flow solver was used for tsunami modelling. The notations of the coding system provide the rigorous granularity to modify and manipulate the source code for a particular case of study. The framework of AMR in Basilisk solver depends on two methods to secure stability and efficiency, the prolongation process (interpolating values from coarser cells to finer cells), and the restriction process (interpolating values from finer to coarser cells), by implementing nested loops within the code (Popinet (2015)). Thus, the calculated values will be automatically inherited from parents' cells to children's cells and vice versa. This method ensures a systematic structure for the AMR by which the leading wave head is detected throughout the built-in region of the Onagawa physical model. The two approaches, the Saint-Venant (SV) solver and the Green-Naghdi (GN) solver were run over a quadtree adaptive mesh. The main difference between SV and GN is handling the vertical water pressure. In other words, the GN solver is the expansion of the SV solver to the next order $o(\mu^2)$ in terms of the shallowness parameter as follows:

$$\mu = h_0/L^2 \tag{1}$$

with h_0 the typical depth and L the typical horizontal scale. Thus, the GN equations have dispersive wave solutions. Generally, the source term of the governing equation of GN could be interpreted as:

$$S = \begin{pmatrix} 0 \\ -hg\partial_x z_b + h\left(\frac{g}{\alpha}\partial_x \eta - D_x\right) \\ -hg\partial_y z_b + h\left(\frac{g}{\alpha}\partial_y \eta - D_y\right) \end{pmatrix} \tag{2}$$

where, z_b is the terrain, $\eta = z_b + h$ is the free surface elevation, and α is the dispersion parameter.

RESULTS AND DISCUSSION

The numerical experiment was conducted to verify the model by comparing its results with those from Prasetyo et al. (2019). Thus, the same bottom friction was considered, 0.025 for the seaward and 0.013 for the built-in area. The tsunami was simulated over the original bathymetry of the Onagawa physical model (Figure 1), to mimic the experimental conditions.

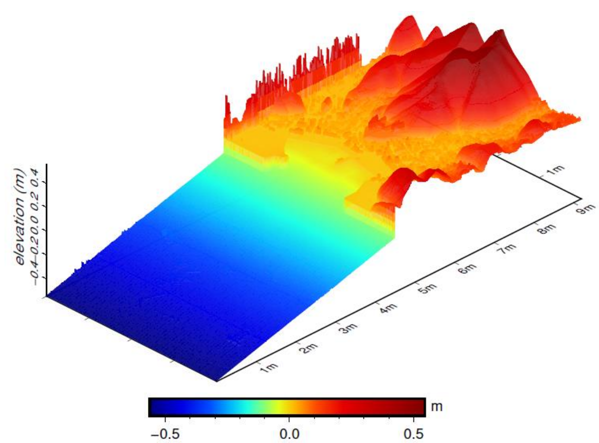

Figure 1 – The original bathymetry of the Onagawa physical model.

The numerical results from GN and SV agreed well with the wave heights of the experiment in the case of the hydraulic bore, Figure 2(A). Moreover, the results from GN and SV showed more robustness in predicting the arrival time and the run-up wave in the built-in area of the Onagawa physical model. In the case of solitary wave, the results of GN and SV proclaimed more efficiency compared to the results of 2D and Q3D to simulate the wave run-up in the complex model of Onagawa Town as depicted in Figure 2(B).

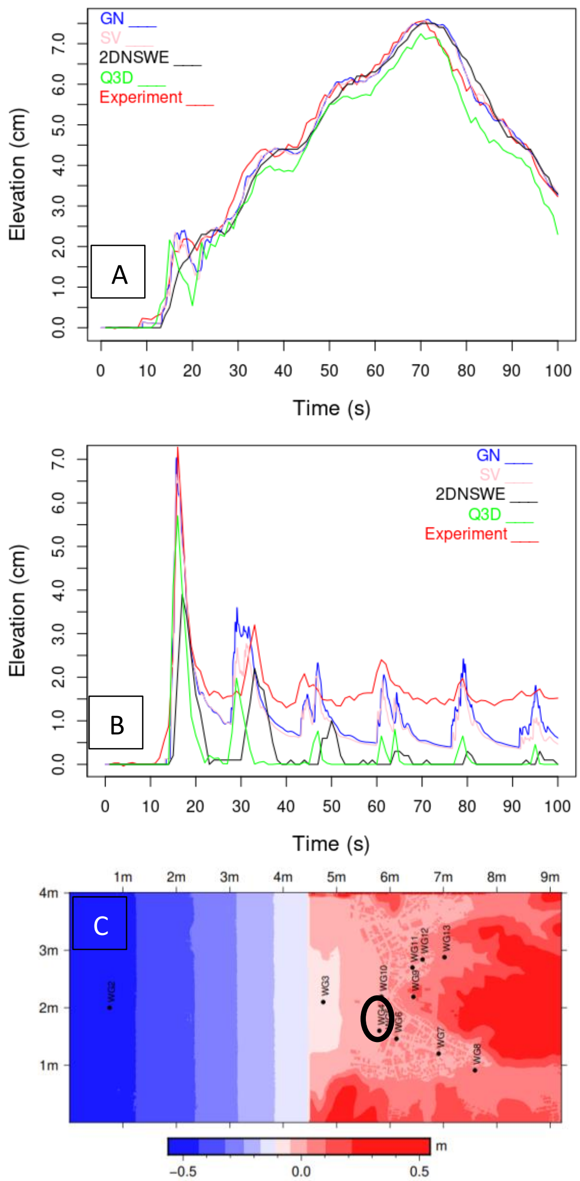

Figure 2 - Comparison among GN, SV, 2DNSWE, Q3D, and experimental results at WG4. A shows the case of hydraulic bore. B shows the case of solitary wave. C shows the position of WG4.

Figure 3 shows a comparison between the numerical results and the experimental results at WG7. As presented in Figure 3(A), the GN and SV where more efficient in predicting the tsunami arrival time in the case of hydraulic bore compared to 2D and Q3D results. However, the wave height was slightly underestimated. The solitary wave case, Figure 3(B), showed reliable performance in predicting the arrival time and wave run-up compared to the numerical results of Prasetyo et al. (2019) where the tsunami run-up is adequately captured. The Pearson correlation test were conducted to verify the numerical results as presented in Table 1.

The GN solver performed well in terms of detecting the vertical deformation of the water surface and provided a well-solved wave propagation throughout the built-in area of Onagawa Town. However, it was computationally more expensive compared to the SV solver.

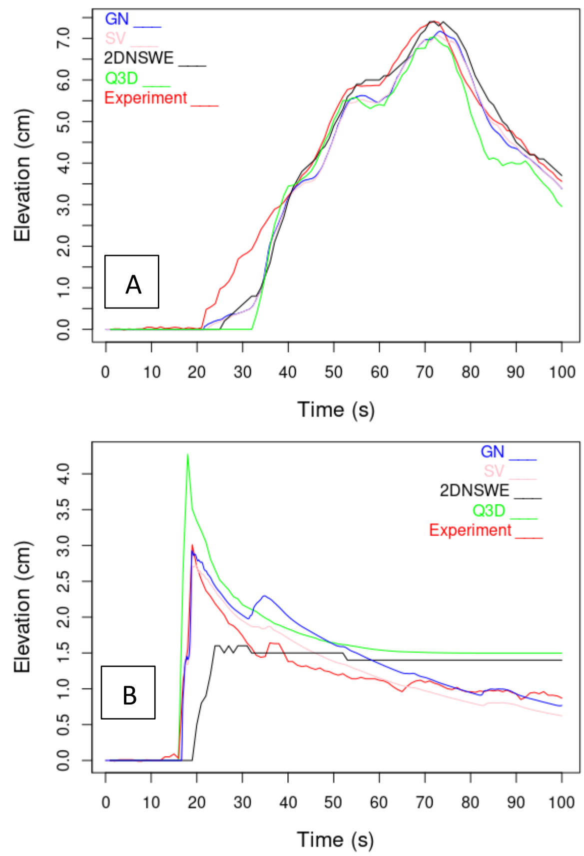

Figure 3 - Comparison among GN, SV, 2DNSWE, Q3D, and experimental results at WG7. A shows the case of hydraulic bore. B shows the case of solitary wave.

Table 1 - The Pearson correlation test results at WG4 and WG7 between the numerical results and the experimental results.

WG4				
Experiments	GN	SV	2DNSWE	Q3D
Hydraulic bore	0.99	0.99	0.99	0.99
Solitary wave	0.75	0.79	0.68	0.73
WG7				
Experimental	GN	SV	2DNSWE	Q3D
Hydraulic bore	0.98	0.98	0.98	0.98
Solitary wave	0.9	0.9	0.54	0.9

CONCLUSION

The numerical experiment of tsunami inundation in a complex coastal zone by Prasetyo et al. (2019) was

reproduced to test the efficiency of AMR methods using Basilisk open flow solver and to study the effect of varied bottom friction on tsunami run-up and arrival time. The two approaches with the non-linear shallow water (Saint-Venant (SV)) solver and the fully non-linear Boussinesq (Green-Naghdi (GN)) solver were run over a quadtree adaptive mesh. The numerical simulation was conducted on the original physical bathymetry model of the Onagawa Town, and two wave types were considered, (Pump-type) the hydraulic bore and (Piston-type) the solitary wave. The results agreed well with the experimental results and the results of 2D and Q3D. Furthermore, the results of Basilisk were relatively more efficient in predicting the arrival time in the built-in area of the Onagawa physical model in the case of the hydraulic bore. In the case of solitary waves, the results from Basilisk were more reliable in simulating the wave run-up in the urban area of the physical model.
The numerical model of Basilisk developed in this study could be implemented in real-time forecasting and tsunami early warning systems after improving the efficiency further and including more parameters.

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