

# Storm surge inundation simulations comparing three-dimensional with two-dimensional models based on Typhoon Maemi over Masan Bay of South Korea



Jae-Seol Shim†, Jinah Kim†, Dong-Chul Kim‡, Kiyoung Heo†, Kideok Do†, Sun-Jung Park ‡

† Coastal Disaster Research Center,  
Korea Institute of Ocean Science &  
Technology, 426-744, Ansan, Gyeonggi,  
Korea  
[jsshim@kiost.ac](mailto:jsshim@kiost.ac)  
[jakim@kiost.ac](mailto:jakim@kiost.ac)  
[kyheo21@kiost.ac](mailto:kyheo21@kiost.ac)  
[kddo@kiost.ac](mailto:kddo@kiost.ac)

‡ Technology R&D Institute  
Hyein E&C Co., Ltd., Seoul 157-861,  
Korea  
[skkkdc@chol.com](mailto:skkkdc@chol.com)  
[Nayana\\_sj@nate.com](mailto:Nayana_sj@nate.com)

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## ABSTRACT

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Severe storm surge inundation was caused by the typhoon Maemi in Masan Bay, South Korea in September 2003. To investigate the differences in the storm surge inundation simulated by three-dimensional (3D) and two-dimensional models, we used the ADvanced CIRCulation model (ADCIRC) and 3D computational fluid dynamics (CFD) model (FLOW3D). The simulation results were compared to the flood plain map of Masan Bay following the typhoon Maemi. To improve the accuracy of FLOW3D, we used a high-resolution digital surface model with a few tens of centimeter-resolution, produced by aerial LIDAR survey. Comparison of the results between ADCIRC and FLOW3D simulations shows that the inclusion of detailed information on buildings and topography has an impact, delaying seawater propagation and resulting in a reduced inundation depth and flooding area. Furthermore, we simulated the effect of the installation of a storm surge barrier on the storm surge inundation. The barrier acted to decrease the water volume of the inundation and delayed the arrival time of the storm surge, implying that the storm surge barrier provides more time for residents' evacuation.

**ADDITIONAL INDEX WORDS:** *Typhoon Maemi, digital surface elevation model, Reynolds-Averaged Navier-Stokes equations.*

## INTRODUCTION

A strong storm surge caused by Typhoon Maemi struck the southern coast of Korea on September 12, 2003. The Masan Bay area experienced the worst damage and suffered extensive flooding, induced by severe storm inundation. Thus, previous studies have been carried out to attempt a numerical prediction of the inundation by storm surges, to establish a prevention system in Masan Bay (Park et al. 2011). However, the resolution in topography is insufficient to represent the complex coastal structure when using the usual two-dimensional (2D) or three-dimensional (3D) hydrostatic assumptions. Therefore, we present a simulation of inundation from computational fluid dynamics (CFD) with a high-resolution topographic map of Masan Bay.

Typhoon Maemi made landfall over the Korean peninsula at 12 UTC on September 12, 2003, subsequently tracking along the southeastern coast of Korea (Figure 1). It moved into the East/Japan Sea and became an extratropical cyclone at 06 UTC on September 13, 2003. It is one of the most powerful typhoons that has struck Korea in terms of wind speed and air pressure. In particular, Masan city facing Masan Bay experienced the worst impacts of the storm-surge flooding, killing 32 people and

inflicting severe coastal damage. During the passage of the typhoon, with a central pressure of 950 hPa and a progression speed of 45 km h<sup>-1</sup>, a maximum surge height of about 2.3 m was recorded by a tide gauge at Masan Port. The residential and commercial areas facing Masan Bay were heavily flooded and subterranean facilities suffered from inundation by the storm surge (Yasuda et al. 2005).

In this paper, the coastal inundation generated by one of the largest recorded storm surges in Masan Bay is simulated using a 3D CFD model (FLOW 3D) and 2D ADvanced CIRCulation model (ADCIRC). The digital surface model (DSM) including the height and spatial information of buildings was made by airborne Light Detection and Ranging (LiDAR), and was used as input data for the storm-surge inundation model, namely, the 3D CFD model (FLOW 3D). In addition, the simulation result of ADCIRC is used as the boundary conditions for FLOW3D. The purpose of this study is to reproduce the storm surge inundation caused by the typhoon Maemi over Masan Bay, including the extreme inundation height and overflow into coastal land areas.

## 2D STORM SURGE

### PROPAGATION AND INUNDATION MODEL

The storm surge inundation model, ADvanced CIRCulation model (ADCIRC), is a continuous-Galerkin, finite-element, shallow-

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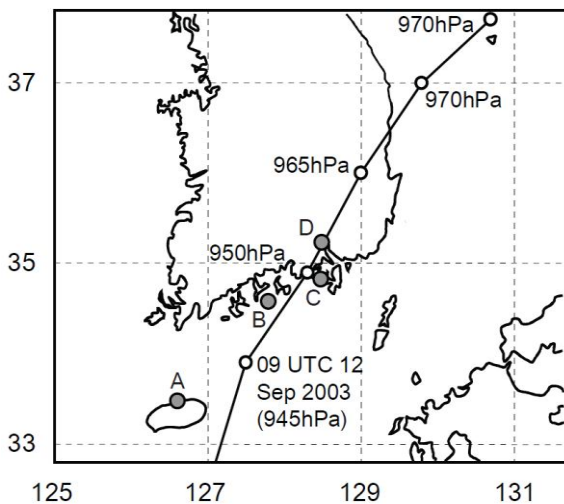


Figure 1. The best track and the central pressures of the typhoon Maemi from the Joint Typhoon Warning Center (JTWC). Open circles indicate the locations of the typhoon in 3 h intervals. Filled circles represent locations of the cited stations; A, B, C and D indicate Jeju, Yeosu, Tongyoung, and Masan, respectively.

water model that solves for water levels and currents at a range of scales (Westerink et al., 2008; Luetlich and Westerink, 2004; Atkinson et al., 2004; Dawson et al., 2006). The Generalized Wave Continuity Equation (GWCE) is used to predict water levels  $\zeta$  and the currents  $U$  and  $V$  are obtained from the vertically-integrated momentum equation assuming a closed water body. For a closed water body without consideration of evaporation, precipitation, and ground absorption, total water mass should be conserved during inundation. In the wind field of a typhoon, this study used the axis-symmetric hurricane model proposed by Holland (1980). ADCIRC computes water levels  $\zeta$  and currents  $U$  and  $V$  on an unstructured, triangular mesh by applying a linear Lagrange interpolation and solving for three degrees of freedom at every mesh vertex. In this study, the METIS domain-decomposition algorithm is applied to distribute the global mesh over a number of computational cores (Karypis and Kumar, 1999). This decomposition minimizes intercore communication by creating local sub-meshes in which the ratios of the number of vertices within the domain to the number of shared vertices at sub-mesh interfaces are small. This method also balances the computational load by creating local sub-meshes with a similar number of vertices; the local meshes decrease in geographical area as their average mesh size is decreased. In this study, we have configured the ADCIRC for a 2,200 km by 2,600 km square-shaped model domain with a grid size of 20-20,200 m in both  $x$  and  $y$  dimensions. Total number of elements is about 180,000 and the node number is about 100,000. The  $x$  coordinates are positive in the east direction and the  $y$  coordinates are positive in the north direction. Open boundary forcing is applied in the form of specifications based on NAO's tidal predictions (Matsumoto et al., 2000) along the model's open water boundary. In order to examine the boundary forcing, the ADCIRC model was run for 60 days in 2003 and the water level recorded by the Korea Hydrographic and Oceanographic Administration (KHOA) in this period. Figure 3 compares the simulated surge level and the recorded water level at four tidal stations. The simulation results have a good agreement with the recorded storm surge at all

studied stations. In addition, the simulation results were analyzed for 26 harmonic constants using the TIRA tidal analysis program (Murray, 1964). The tidal constituent and water level have a good agreement with data, meaning that the open boundary is well established.

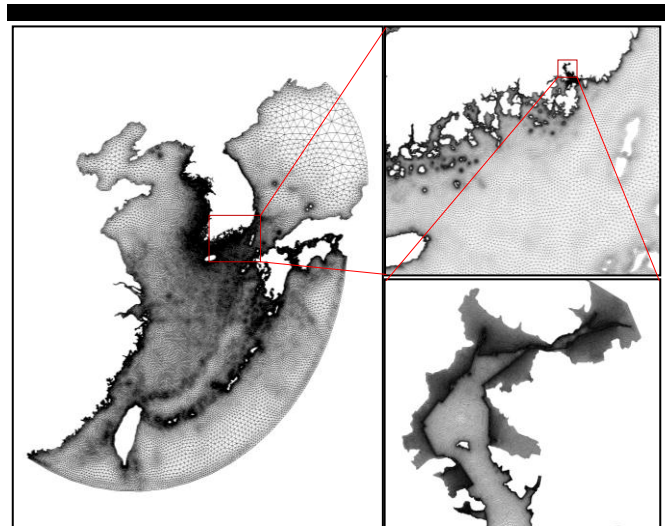


Figure 2. Model domain with FEM mesh for Typhoon Maemi.

Figure 4(a), (b), and (c) indicate the simulations by ADCIRC and FLOW3D, and the surveyed storm surge inundation map, respectively all for Masan Bay after the typhoon Maemi. These figures show that the 2D simulation does not take into consideration the complex topographic effects when predicting the inundation. In the following discussions, the 3D computational fluid dynamic model (FLOW 3D) is used to predict the inundation area across Masan Bay.

### 3D COMPUTATIONS OF STORM SURGE INUNDATION MODEL

To simulate the 3D wave field in the vicinity of inundation for the Masan area with high accuracy, the Reynolds-Averaged Navier-Stokes equations solved by the FLOW3D code (Hirt and Nichols, 1981; Flow Science, 2002) are used. FLOW3D utilizes a true volume of fluid (VOF) method for computing free surface motion and the fractional area/volume obstacle representation (FAVOR) technique to model complex geometric regions. A finite difference approximation is used for discretization of each equation. To describe turbulence in a viscous fluid, an updated version of the  $k-\epsilon$  model with renormalization group analysis is used (Yakhot and Orzag, 1986; Yakhot and Smith, 1992). This computer code has already been used to simulate tsunami waves (Choi et al., 2007, 2008a, b). In FLOW3D it is quite difficult to apply the boundary conditions because this model accepts only a single time-dependent boundary variable without customization of the codes. Thus, a representative boundary point was selected from the last domain of the ADCIRC model, which has the same position as the center at the southern extent of the FLOW3D domain.

In this study, we performed experiments for two case studies. For Case-1, two-dimensional three-dimensional simulation results are compared and analyzed for the inundation depth and area across the entire area of Masan port. For Case-2, that inundation

simulation was carried out for situations without a storm surge barrier, and with two types of barrier system, in order to analyze the effects of storm surge inundation disaster prevention or reduction facility systems such as barriers on the sea wall.

To improve the accuracy of inundation area prediction in the FLOW3D simulation, we used a digital surface model (DSM) with a vertical resolution of tens of centimeters, produced by an aerial LiDAR survey, as the topographic input data. The DSM represents the earth's surface including all objects on it such as terrain features, buildings, vegetation, power lines amongst others. It measures the height values of the first surface encountered by

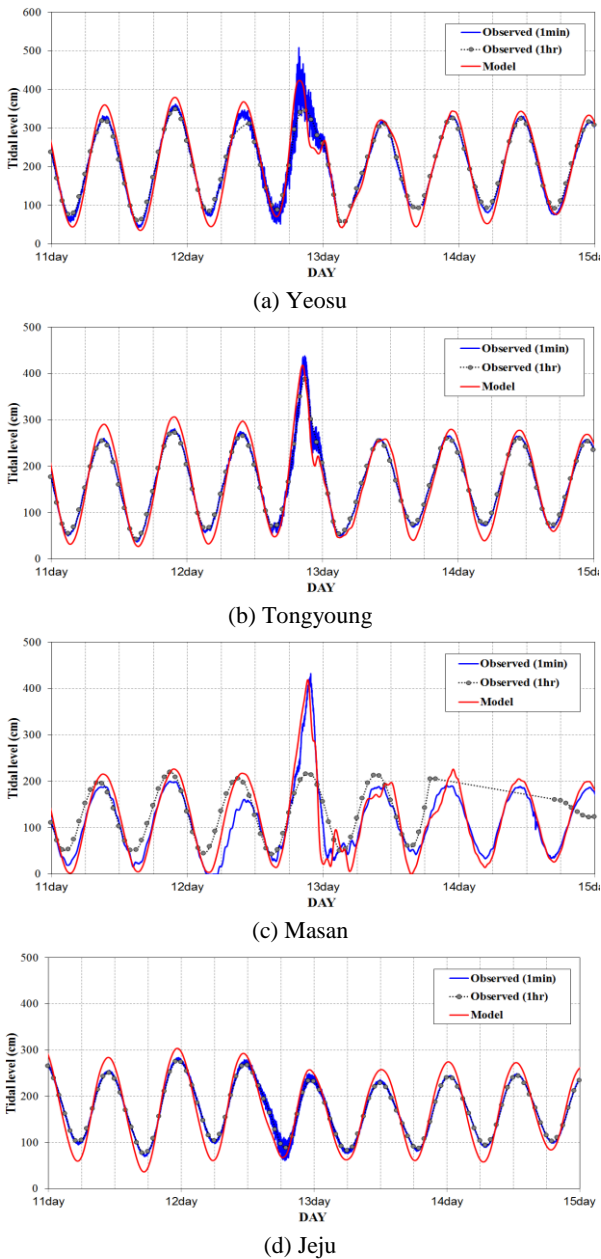
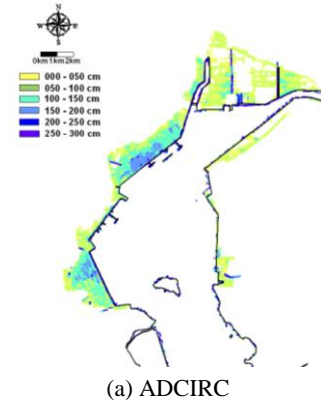
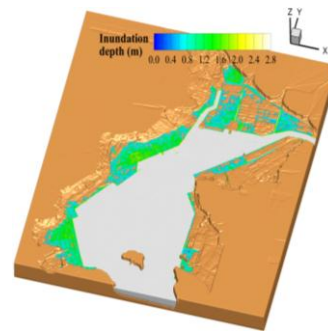


Figure 3. Validation of surge height for the four major tidal stations on the south coast of the Korea.



(a) ADCIRC



(b) FLOW3D



(c) Hazard map

Figure 4. Inundation depth results from (a) ADCIRC, (b) FLOW3D, and (c) inundation field surveying hazard map following typhoon Maemi.

aerial LiDAR to provide a topographic model of the Earth's modified surface.

[CASE-1]

The surface elevation contains two large crests with amplitude of around E.L. (+) 2.5 m. Numerical simulation shows that the article velocities in the simulated surge waves are up to  $2 \text{ m s}^{-1}$  in both directions and that overflow and inundation of the storm surge occurs over the seawall and inland. It can be clearly seen that seawater inundated the land area to a depth of about 3 m, and water propagated at a speed of up to  $2 \text{ m s}^{-1}$ . At around 1,200 seconds after the storm surge reached the front of the western part

of Masan port, it propagated into the harbor mouth. The surge wave then reflected and propagated into the harbor with a height of 2.3 m. After the storm surge propagated into the harbor mouth, after around 6,000 s, it reached the front of the northern area with an inundation depth of E.L.(+) 2.5m, and resultant overflow. Surge waves overflowed the seawall and propagated inland (Figure 5). Table 1 details the inundation area by inundation depth and the percentage of total inundation area given by the 2D and 3D flooding simulations. The results shows that the 2D and 3D flooding simulations underestimate the inundation area per depth in the 3D simulation by approximately 80% compared to the 2D simulation. The comparison of 2D and 3D simulations shows that the detailed information of building and topography has the effect of delaying seawater propagation and resulting in a reduced inundation depth and flooding area.

#### [CASE-2]

We examined the effects of the installation of a storm surge barrier on the inundation across Masan Bay, using FLOW3D with high resolution DSM data. The total simulated time is 30 minutes (1,800 s). Figure 6(a) shows inundation area and velocity without the storm surge barrier. In this simulation, most of the roads and building sites were inundated. In particular, the southern region of Masan port was seriously damaged because the elevation of this area is lower than in the northern region. This simulation result agrees well with the surveyed inundation map. Figure 6(b) shows the result of the numerical simulation when a storm surge barrier of 1 m height is installed across the entire seawall. The effect of the raised seawall is to decrease the volume of water involved in inundation. It also provides a longer evacuation time for residents because the storm surge barrier delays the arrival time of the storm surge. Figure 6(c) shows the inundation when a storm surge barrier of 1.7 m height was partially installed. The barrier is installed in the lower part of the revetment, an area that experienced severe inundation during typhoon Maemi. The simulation result shows that the partial installation of this storm surge barrier also decreases the inundation area. However, the water volume is focused on the part left open, so it still has the potential to endanger facilities and people. In order to improve the accuracy of the inundation simulation, observations of water velocity and inundation height at each site should be measured during the storm surge event. This study does not verify the water volume flux, but the 3D simulation is able to provide guidelines for evacuation routes.

### CONCLUSION & FUTURE WORK

In this study, we performed 2D and 3D numerical simulations of the storm surge and inundation over Masan Bay in South Korea. The result of the 2D hydrostatic finite-element model is in good agreement with the surveyed inundation map with regard to the

Table 1. Inundation area and percentage of total area by inundation depth, from the results of 2D and 3D simulations.

Inundation Depth (m)	2D Simulation (ADCIRC)		3D Simulation (Flow3D)		Comparison (2 vs.3D)	
	Area (m <sup>2</sup> )	%	Area (m <sup>2</sup> )	%	Area (m <sup>2</sup> )	%
0.0 ~ 0.5	806,300	24.4	515,100	19.0	291,200	63.9
0.5 ~ 1.0	1,613,300	48.9	1,456,700	53.7	156,600	90.3
2.0 ~ 1.5	651,400	19.7	549,400	20.3	102,000	84.3
1.5 ~ 2.0	155,900	4.7	151,800	5.6	4,100	97.4
2.0 ~ 2.5	71,600	2.2	38,600	1.4	33,000	53.9
<b>Total Area</b>	<b>3,298,500</b>	<b>100.0</b>	<b>2,711,600</b>	<b>100.0</b>	<b>586,890</b>	<b>82.2</b>

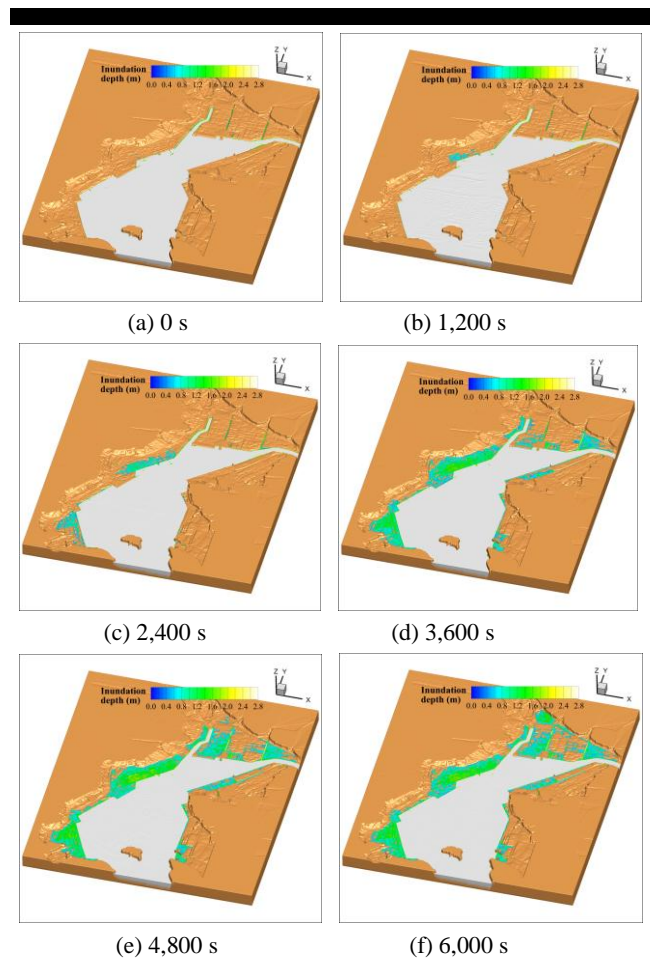


Figure 5. Inundation depth results computed by Flow3D at each time period following arrival of storm surge wave at harbor mouth.

inundation area. However, the 2D simulation does not successfully simulate the maximum inundation height above 3.0m observed in Masan Bay, because the effect of the complex topography on the inundation process is not considered. The result of the 3D simulation shows the inundation process with vertical velocity and the effects of complex topography including many buildings and roads, and that these play an important role in surge inundation and propagation inland. In addition, the 3D numerical model with detailed DSM data is able to reproduce the characteristics of surge inundation well in this coastal area. Thus, 3D numerical models should be used in the future for the prediction of storm surge characteristics on the steepest coasts and for estimation of storm surge inundation risk in such areas. Numerical simulation models

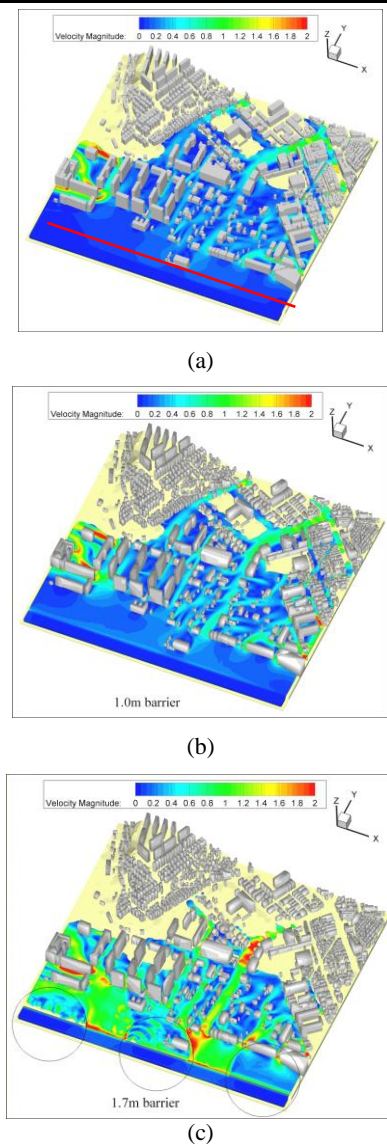


Figure 6. Maximum inundation field in simulations with (a) no barrier on the seawall (red line), (b) a 1 m barrier across the entire sea wall, and (c) a 1.7 m barrier partially installed on the seawall.

for storm surge inundation can be developed to study and prevent storm surge disasters on the coasts near large ports. Various inundation processes such as those induced by overflow, overtopping and dike breach are incorporated into this model. This model is used to estimate information necessary for the prevention of storm surge disasters, such as inundation area and inundation depth at Masan Port. With this inundation simulation, coastal protection works consisting of hard and soft countermeasures, such as an inundation map combined with the GIS, can be designed.

In future research, a modification of the roughness coefficient in the 2D model is necessary to appropriately reflect the effect of various topographical characteristics. It is possible to apply further conditions of land use and building density by using the high resolution DSM. Moreover, appropriate storm surge prevention

facilities for Masan Bay can be formulated, following simulation of the different locations and effects of storm surge barriers, to determine their suitability.

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