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Development of a near real-time forecasting system for storm surge and coastal inundation

Jong-Joo Yoon [†], **Jae-Seol Shim** [‡*]

[†] ChungNam Institute, Chungcheongnam-do training road 73-26, Gongju, South Korea

[‡] Korea Institute of Ocean Science & Technology(KIOST), 787 Haean-ro, Sangnok-gu, Ansan, South Korea

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ABSTRACT

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Climate change is resulting in an increase in disastrous effects, such as sea level rise, intensity and frequency of storms, abnormal waves, and storm surges, in densely populated coastal areas. In particular, the coast of Korea was repeatedly damaged by storm surge and subsequent inundation caused by the approach of strong typhoons. Therefore, it is desirable to accurately forecast storm surge height and coastal inundation. In this study, a rapid, near real-time forecasting system was developed for addressing coastal inundation. A primary study of this system for operational forecasting using typhoon advisories was conducted and applied for the 2012 typhoon Sanba. To develop this forecasting system, a systematic investigation of storm surge impacts to the Korean coast was conducted using the unstructured grid model, FVCOM. This model was employed to simulate near-future storm surges and their corresponding inundation characteristics. Observed surges and inland inundation data were used to validate the model with satisfactory results. In this forecasting system, full automatic computations according to typhoon advisories were conducted for each typhoon invasion and uploaded to the disaster warning system. Less than one hour from starting the calculation, all pre- and post-processing was completed using parallel clusters. We also collected field measurements to compare with simulated inundation results for typhoon Sanba. The forecasting simulation results agreed with the observational data. The system developed in this study could be useful as a pre-warning system to prompt preparation of detailed evacuation plans that address storm surge inundation problems.

ADDITIONAL INDEX WORDS: *Storm surge, Operational prediction system, TC96, FVCOM, Numerical simulation.*

INTRODUCTION

As the intensity and frequency of typhoons increase because of climate change, risk of inundation damage caused by storm surge in major coastal cities is likely to grow. These coastal disasters have a tendency to take place on a large scale and are hard to predict. Korea has extended the range of use of coastal areas through reclamation projects. Consequently, coastal disaster damage could increase significantly in those areas. In order to establish a coastal management plan to minimize disaster damage, it is necessary to develop technology for responding to coastal inundation.

Typhoon Maemi, which struck South Korea in September 2003, destroyed about $4.2 billion worth of property and resulted in 131 human casualties. In November 2013, typhoon Haiyan hit the Philippines and left about 8000 people dead. Therefore, it is urgent that measures to protect property and lives against these coastal disasters be established. The sole use of structures such as shore protection and coastal dykes, however, cannot completely prevent damages due to storm surges and high waves. In addition to these structural measures, non-structural hazard mitigation measures such as forecasting systems are also important because they allow people to promptly prepare for disaster and mitigate the scale of damage.

To accurately predict the areas that storm surge might affect, fine-grid ocean numerical models that comprehensively consider oceanic conditions such as tide, surge, and waves should be established in conjunction with accurate fine-grid meteorological model. GIS Database, which identifies geographical features of coastal areas by systematically combining land elevation and water level data, should also be deployed. In this study, we accurately simulated the typhoon wind field to estimate the surge height and predict inundation area during a typhoon landing. We established the storm surge model using simulated meteorological results. Based on the storm surge model, we operated the coastal inundation forecasting system, targeting major low-lying coastal areas. The system was designed to generate near real-time forecasting data regarding inundation while a typhoon was landed.

The U.S. has experienced massive damages from hurricanes over time. For this reason, the SLOSH (Sea, Lake, and Overland Surges from Hurricanes) model is run by the National Hurricane Center (NHC) under the National Oceanographic and Atmospheric Administration (NOAA) to forecast maximum wave height and probabilistic wave height throughout the

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*Corresponding author: jsshim@kiost.ac

country (Glahn *et al.*, 2009). Additionally, a storm surge forecasting system using the ADCIRC model is operated to predict storm surge in real-time as a storm approaches (Fleming *et al.*, 2008; Forbes *et al.*, 2010; Blanton *et al.*, 2012).

The research status in Korea, however, was not mature compared to these developed cases. As such, an accurate and immediate storm surge forecasting system coupled with the storm forecast issued by the Korea Meteorological Administration (KMA) has begun development. The storm surge forecasting system suggested in this study has been run and used to predict the occurrence of inundation since 2012. While typhoons rarely directly affected the Korean Peninsula from 2013 to 2015, four typhoons hit the peninsula in 2012. Typhoon Sanba hit the southern coast in September 2012 and was expected to cause significant damage because its intensity and tracking path were similar to typhoon Maemi, which caused record-breaking coastal damage. In fact, massive damages and losses occurred in several low-lying areas on the southern coast of Korea due to storm surge and high waves.

In this study, we evaluated the performance of the inundation prediction system that was used when typhoon Sanba struck South Korea in 2012. We also conducted an inundation trace investigation for the areas damaged by inundation after the typhoon passed so as to estimate the system's applicability.

ESTABLISHMENT OF OPERATING SYSTEM

Operating storm surge prediction system

The storm surge and coastal inundation forecasting system predicts real-time storm surge conditions. Once a typhoon forms, several agencies, such as the KMA, Japan Meteorological Agency (JMA), and Joint Typhoon Warning Centre (JTWC), issue a real-time advisory and typhoon information every six hours. The typhoon advisory includes forecast information about tracking path and typhoon intensity.

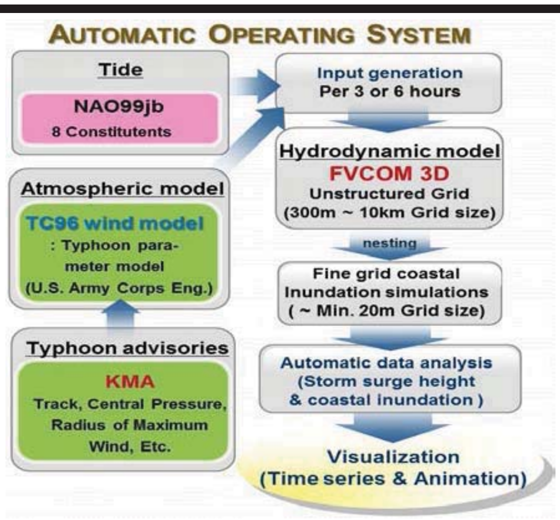

Figure 1. Flow chart of the near real-time storm surge inundation prediction system.

The storm surge forecasting system immediately executes a numerical ocean model, making use of the data in these typhoon advisories. The system generates 72-hour short-term prediction results in nearly real-time, including sea level with tides and surges, variation of currents, and areas likely to be inundated.

Figure 1 illustrates a flow chart of the near real-time storm surge inundation prediction system suggested by this study. During a typhoon, the meteorological data from a typhoon wind model (TC96) is used to estimate surge height. To simulate inundation caused by storm surge, an additional simulation is conducted for the nesting grid, extending computation coverage to low-lying coastal areas. A critical characteristic of this system is fast computing in response to typhoon warning updates. The system proposed in this study has relatively prompt forecasting capability; it can produce 72-hour prediction information within one hour of obtaining the typhoon data. The generated results are immediately sent to the local authority for coastal disaster prevention. The system continues to update the forecast results in accordance with typhoon advisory updates.

Typhoon wind model and storm surge model

To simulate the surge that occurs as a typhoon moves, accurate meteorological forecast data is essential. It is also important to choose a suitable sea-surface wind model to reproduce temporal and spatial variation of the typhoon wind field. Additionally, typhoon parameters necessary for calculating sea-surface wind need to be estimated accurately. For the ocean, there generally is not enough observation data readily available. Therefore, it is necessary to make use of satellite observation and numerical model analysis data in order to precisely analyze a typhoon. To estimate surge height, it is necessary to consider temporal and spatial data of sea-surface wind and atmospheric pressure field as external forces. In this study, TC96, which is a planetary boundary layer (PBL) model, was used to estimate wind and atmospheric pressure fields under typhoon conditions. Primary input parameters for TC96 comprised center position of typhoon, minimum center pressure, and radius of maximum wind. The TC96 wind model was introduced by Cardone *et al.* (1994) and Thompson and Cardone (1996), with support from the U.S. Army Corps of Engineers.

A 3-D finite-volume ocean model, FVCOM (Finite-Volume Coastal Ocean Model; Chen *et al.*, 2006) adopting a triangular grid was used to estimate storm surge. FVCOM employs the finite-volume method (FVM). FVCOM combines a numerical calculation flow of the finite-difference method (FDM) and a triangular unstructured grid system of the finite-element method (FEM). FVCOM balances the efficiency of discrete characteristics of FDM with the geometric flexibility of FEM. The wet/dry treatment method is also applied to simulate coastal inundation. Further model details are noted by Yoon and Shim (2013).

Mesh generation and boundary conditions

In the case of storm surge along Korea's southern coast, spatial variation tends to increase due to local geological influence. To better account for this spatial variation, fine-grid bathymetry data is required. To simulate storm surge height, it is particularly important to generate an exact water depth grid using bathymetry data.

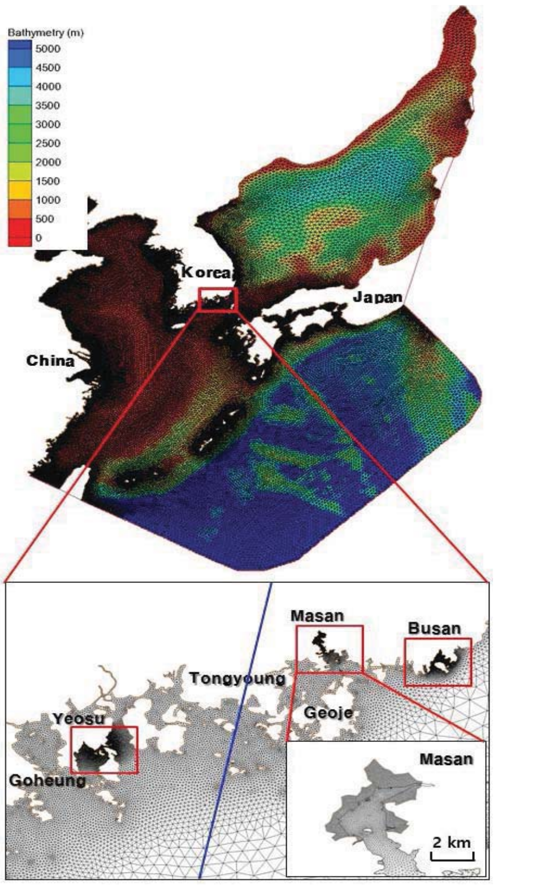

Figure 2. Overview of model domain, grid composition, and bathymetry distribution. Blue line represents moving track of typhoon Sanba.

Grid mesh used to simulate storm surge covered an extensive region including the Yellow, East (Japan), and East China Seas, as illustrated in Figure 2. The grid system was composed of unstructured triangular mesh in which the minimum grid size (close to the coastal area) was about 300–400 m. To simulate inundation in coastal land areas such as Yeosu, Masan, and Busan, the grid was extended to areas with elevations less than 10 m, and the minimum grid size was reduced to 20–30m. The total number of nodes was 136,570; the total number of elements was 258,482. Storm surge height was estimated in 3-D simulations. The vertical grid comprises eleven sigma layers. Water depth data were obtained from the digital nautical chart published by the Korea Hydrographic and Oceanographic Administration (KHOA); water depth data for areas outside the coastal area were obtained from ETOPO1 data (Amante and Eakins, 2008). Eight major tidal components of NAO99jb (Matsumoto *et al.*, 2000) were used as input to harmonic constants applied to open boundaries of the model.

OPERATION CASE OF STORM SURGE INUNDATION PREDICTION SYSTEM

Typhoon Sanba

Typhoon Sanba was the strongest typhoon that hit Korea in 2012. When it landed on the southern coast, it moved rapidly at speeds up to 43 km/hr. It had a maximum instantaneous wind speed over 40 m/s, barometric pressure of about 960 hpa, 60 mm/hr of heavy rain, and more than 1 m of maximum surge height during coastal landfall.

Figure 3. Cases of storm surge inundation damage in Masan by Typhoon Sanba, 2012.

During typhoon Sanba, the storm surge inundation prediction system was operated with every typhoon information update (KMA) at 3 hours intervals. Typhoon data that were released at 7 AM (LST) on September 17, 2012, the moment before typhoon landing, were applied to this study. Tracks of typhoon Sanba looked similar to that of Maemi in 2003. These typhoons maintained their circular shape until landfall on the coast.

When typhoon Maemi arrived, extreme storm surge and high tide were observed in some areas around Yeosu, Masan, and Tongyoung (Figure 2). Similar to typhoon Maemi, typhoon Sanba was expected to cause significant inundation damage to major coastal cities because it was anticipated to come during high tide. Fortunately, the worst inundation damage was avoided because maximum storm surge height occurred just after high tide. Inundation damage, however, could not be avoided in some coastal regions near Masan and Tongyoung (Figure 3).

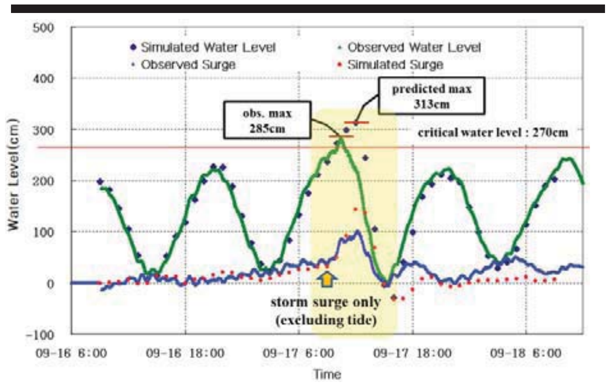

Figure 4. Comparisons of storm surge time variations at Masan tidal station during typhoon Sanba.

Results of storm surge inundation prediction

Figure 4 shows the predicted values of storm surge height for typhoon Sanba in Masan. This figure compares simulated results to observed data recorded by the tidal station. The estimated value of maximum water level including tide was about 313 cm at 12:00 PM (LST) on September 17, while the observed record was 285 cm at 10:30 AM on the same day. The prediction of maximum surge height excluding tide was simulated as 150 cm, while the observed record was 102 cm. Therefore, deviation of maximum surge height was about 48 cm.

The gap between observed and simulated results might be caused by several reasons. The first reason might be that recorded maximum surge height occurred one to two hours later than maximum tide level (during the ebb tide). Second, typhoon forecast data such as typhoon track and minimum central pressure (KMA), could contain errors. Third, primary external forces, such as wind and pressure field generated by the sea-surface wind model, might not exactly reproduce the meteorological field. Figure 5 compares the observed and simulated wind and air pressure time variations at Masan tidal station; wind speed was overestimated in comparison to the observed data.

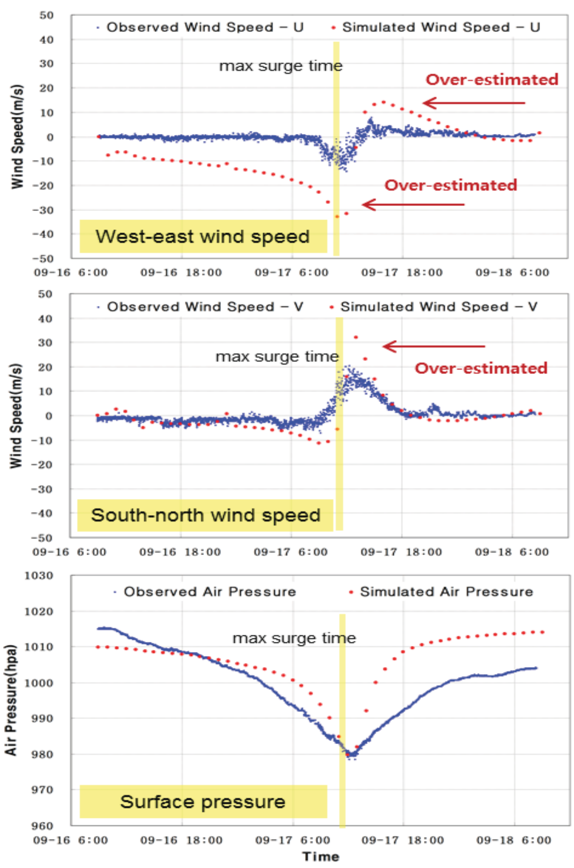

Figure 5. Comparisons between observed and simulated wind and air pressure time variations at Masan tidal station during Typhoon Sanba.

Maximum surge height simulated by the inundation prediction system was overestimated compared to the observed data; this was because simulated wind speed data was overestimated. To improve this wind simulation error, we refined the typhoon sea-surface wind model by noting that wind speed passing through the land surface could be mitigated by land surface friction (Yoon el al., 2014). This refinement improved the accuracy of the inundation prediction system.

Figure 6 shows the distribution of the maximum inundation area and height simulated by the inundation prediction system during typhoon Sanba. The simulation predicted that inundations up to 1 m would occur at Dong-Seodong, Jung-Angdong, Hae-Undong, and Bong-Amdong, which are located in low-lying coastal zones. Fortunately, the actual inundation was less than predicted since the strength of the typhoon was reduced upon landing. The data generated by this prediction system was immediately sent to the local authority so that it could be used to predict locations and times where damage might occur. The data was also used to issue warnings that allowed local residents to evacuate safely from the risky area.

Field Investigation of Damage by Surge Inundation (Masan)

Inundation caused by typhoon Sanba affected an extensive area along the southern coast of Korea, including Masan, Jinhae, Tongyoung, and Yeosu. The situation may have worsened in low-lying areas when seawater backflow occurred because sewage pipes, which are connected to the ocean, fully filled with seawater, especially at high tide. If heavy rainfall coincided with the typhoon, cities flooded severely even without storm surge inundation. Some coastal areas facing open sea without breakwater, like Yeosu, experienced significant damage by inundation due to wave overtopping. In this study, an inundation trace survey was conducted for Masan, Tongyoung, Jinhae, and Yeosu immediately after typhoon Sanba so that a wide variety of post-disaster data could be collected, including statements by eyewitnesses and photos taken when the region was inundated. This data could be useful for determining the accuracy of the inundation prediction model.

Figure 6 illustrates the distribution of inundated areas at Masan where the worst flooding damage happened. In this investigation, we explored the spatial distribution of major inundated areas and boundaries, however, we did not obtain precise inundation height due to lack of a digital altimeter. According to Figure 6, which compares observed and simulated inundation area, the simulation reproduced the inundation area well at industry complex zones like Bong-Amdong and residential and retail zones such as Dong-Seodong, Jung-Angdong, and Hae-Undong.

The primary characteristic of low-lying coastal zones is that rainfall easily causes flooding because sewage pipes connected to the sea fill with seawater at high tide and cannot release water. Inundation occurring under these circumstances is highly likely to lead to significant expansion of damages because there is no outlet for excess water. To overcome this problem, it will be necessary to apply the integrated numerical model including coastal inundation and urban flooding in the next step.

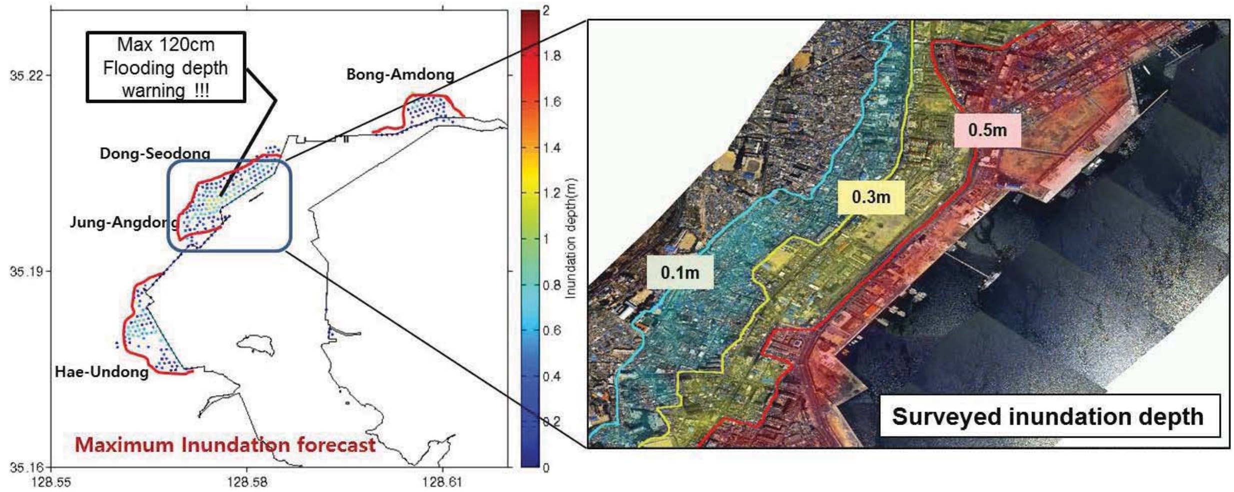

Figure 6. Simulated (dotted color) and observed (red line) inundation area at Masan during Typhoon Sanba.

CONCLUSION

In this study, we established a near real-time prediction system for estimating surge height and the storm surge inundation. The system is expected to forecast damages during typhoon landings on the Korean Peninsula. Applicability of this system was examined by comparing observed and simulated surge height for typhoon Sanba on September 17, 2012. The spatial distribution of inundated areas was relatively accurately simulated with respect to the observed data. It should be noted, however, that some errors occurred in the estimation of surge height. If we can improve the accuracy of sea-surface wind generation by investigating the cause of the error, the ability of this system to predict coastal disaster damages by simulating near future inundation will significantly increase.

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LITERATURE CITED

Amante, C., and Eakins, B.W., 2008. *Etopo1 1 arc-minute global relief model: procedures, data sources and analysis*. National Geophysical Data Center, Boulder, Colorado, NOAA Technical Memorandun NESDIS NGDC-24, 25 p.

Blanton, B.; McGee, J.; Fleming, J.; Kaiser, C.; Kaiser, H.; Lander, H. & Kolar, R., 2012. Urgent computing of storm surge for North Carolina's coast. *Procedia Computer Science*, 9, 1677-1686.

Cardone, V.J.; Cox, A.T.; Greenwood, J.A. and Thompson, E.F., 1994. Upgrade of tropical cyclone surface wind field model. US Army Corps of Engineers, *Waterways Experiment Station*, Miscellaneous paper CERC-94-14, 101 p.

Chen, C.; Beardsley, R.C. and Cowles, G., 2006. An unstructured grid, finite-volume coastal ocean model (FVCOM) system. *Oceanography- Washington Dc - Oceanography Society*, 19(1), 78-89.

Fleming, J.G.; Fulcher, C.; Luettich, R.A.; Estrade, B.D.; Allen, G.D. and Winer, H.S., 2008. A real time storm surge forecasting system using ADCIRC. *Estuarine and Coastal Modeling X*, 373-392.

Forbes, C.; Luettich Jr, R.A.; Mattocks, C.A. and Westerink, J.J., 2010. A retrospective evaluation of the storm surge produced by Hurricane Gustav (2008): Forecast and hindcast results. *Weather and Forecasting*, 25(6), 1577-1602.

Glahn, B.; Taylor, A.; Kurkowski, N. and Shaffer, W.A., 2009. The role of the SLOSH model in National Weather Service storm surge forecasting. *National Weather Digest*, 33(1), 3-14.

Matsumoto, K.; Takanezawa, T. and Ooe, M., 2000. Ocean tide models developed by assimilating TOPEX/POSEIDON altimeter data into hydrodynamical model: a global model and a regional model around Japan. *Journal of Oceanography*, 56(5), 567-581.

Thompson, E.F. and Cardone, V.J., 1996. Practical modeling of hurricane surface wind fields. *Journal of Waterway, Port, Coastal, and Ocean Engineering*, 122(4), 195-205.

Yoon, J.J. and Shim, J.S., 2013. Estimation of storm surge inundation and hazard mapping for the southern coast of Korea. *Journal of Coastal Research*, Special Issue No. 65, pp. 856-861.

Yoon, J.J.; Shim, J.S.; Park, K.S. and Lee, J.C., 2014. Numerical experiments of storm winds, surges, and waves on the southern coast of Korea during Typhoon Sanba: the role of revising wind force. *Natural Hazards and Earth System Science*, 14(12), 3279-3295.