Local amplification of storm surge by Super Typhoon Haiyan in Leyte Gulf

Nobuhiro Mori1, Masaya Kato2, Sooyoul Kim3, Hajime Mase1, Yoko Shibutani1, Tetsuya Takemi1, Kazuhisa Tsuboki2, and Tomohiro Yasuda3

1Disaster Prevention Research Institute, Kyoto University, Uji, Kyoto, Japan, 2Hydrospheric Atmospheric Research Center, Nagoya University, Nagoya, Japan, 3Graduate School of Engineering, Tottori University, Tottori, Japan

Abstract

Typhoon Haiyan, which struck the Philippines in November 2013, was an extremely intense tropical cyclone that had a catastrophic impact. The minimum central pressure of Typhoon Haiyan was 895 hPa, making it the strongest typhoon to make landfall on a major island in the western North Pacific Ocean. The characteristics of Typhoon Haiyan and its related storm surge are estimated by numerical experiments using numerical weather prediction models and a storm surge model. Based on the analysis of best hindcast results, the storm surge level was 5–6 m and local amplification of water surface elevation due to seiche was found to be significant inside Leyte Gulf. The numerical experiments show the coherent structure of the storm surge profile due to the specific bathymetry of Leyte Gulf and the Philippines Trench as a major contributor to the disaster in Tacloban. The numerical results also indicated the sensitivity of storm surge forecast.

1. Introduction

Typhoon Haiyan was an enormous and extremely intense tropical cyclone that struck the Philippines, Vietnam, and nearby areas in November 2013, causing catastrophic damage. The minimum central pressure of Typhoon Haiyan was 895 hPa, and the maximum gust peak speed was over 90 m/s. Typhoon Haiyan was the 11th typhoon of such minimum central pressure recorded in the last 30 years in the western North Pacific Ocean and was the most powerful typhoon to make landfall to date [Schiermeier, 2013]. Typhoon Haiyan initially made landfall without any loss of power in Eastern Samar, the Philippines on 8 November 2013, at 4:40 AM local time (UTC +8). According to official statistics as of December 12, there were 5982 fatalities, with an additional 1799 missing and 27,022 injured [National Disaster Risk Reduction and Management Council, 2013]. In addition to loss of life, Typhoon Haiyan also caused extreme economic losses; the damage to infrastructure and agriculture damages were estimated at US$802 million. This is not the first severe storm surge in Tacloban area, and a similar typhoon with 4.5 m storm surge occurred in 1897.

Several severe storm surge disasters have been observed since 2000, such as Hurricane Katrina in 2005, Cyclone Nargis in 2008, and Hurricane Sandy in 2012. The minimum pressure of Typhoon Haiyan was 35 hPa lower than that of Hurricane Katrina at landfall [National Climatic Data Center, 2005], and such super typhoons are expected to increase both in number and intensity as a result of global climate change [Bender et al., 2010; Schiermeier, 2010]. As a result, flooding risks are expected to increase over time due to intensified tropical cyclone activity and accelerating sea level rise [Woodruff et al., 2013]. In developing countries, evacuation is the primary method for reducing the impact of natural disasters. Therefore, quantitative prediction of wind speed and storm surge is crucial. Such prediction is challenging for super typhoons; however, examination of this disaster can give insight into predicting and hindcasting for two major topics of research. The first is typhoon characteristics, and the second is local storm surge characteristics. There are several unknown factors when modeling characteristics such as central pressure of the eye, size, and track. Furthermore, previous studies on momentum transfer for high wind speeds in typhoons appear to contradict recent observations of super typhoons [Powell et al., 2003]. The near coast amplification of local storm surge characteristics (e.g., Proudman resonance, seiche, etc.) depends on the size and bathymetry of the bay. If the spatial distribution of the maximum water surface elevation can be obtained, it can be regarded for a proxy of validation for typhoon modeling. Forerunner surges sometimes occur with wide and shallow shelf conditions (see studies on Hurricane Ike by Kennedy et al. [2011] and on Hurricane Dennis by Morey et al. [2006]). The combination of several storm surge factors causes extreme changes in water surface level at particular locations. To understand these characteristics for Super Typhoon Haiyan in detail, to evaluate the current
performance of typhoon and storm surge prediction systems, to understand the reason why extreme storm surge occurred, and to guide reconstruction efforts of devastated areas, it is necessary to validate prediction models and analyze the local properties of storm surge.

In this study, Typhoon Haiyan and its related storm surge are estimated by a series of numerical experiments using numerical weather prediction models (NWPs) and a storm surge model. Comparisons of the estimated storm surges against satellite and ground observation data indicate possible typhoon characteristics and storm surges. We discuss the difficulty of quantitatively predicting storm surge of super typhoons based on perturbed analysis of TC tracks and the characteristics of local storm surge amplification in the Leyte Gulf and Tacloban areas.

2. Numerical Modeling and Observations of Typhoon and Storm Surge

Wind speed at height 10 m and sea level pressure are required to model storm surge. Two different NWPs, The Weather Research and Forecasting (WRF) model [Skamarock et al., 2008] and the Cloud Resolving Storm Simulator (CReSS) [Tsuboki and Sakakibara, 2002], were chosen for dynamic modeling of Typhoon Haiyan. Because the core of Typhoon Haiyan was deep and tight, higher spatial resolution was necessary for horizontal and vertical convection of the air. The spatial resolutions selected for the WRF and CReSS models were 1 and 4 km, respectively (Table A1). For WRF, a single-moment six-category microphysics scheme was used for cloud microphysics, and no cumulus cloud parameterization was applied. CReSS, a non-hydrostatic atmospheric model, was applied with formulated bulk cold rain cloud microphysics with no cumulus cloud parameterization. The domain sizes of WRF and CReSS were approximately 4000 × 2000 km mainly centered at 130°E and 10°N, and the sensitivity to domain size was examined by WRF simulations. The initial, lateral, and sea surface boundary conditions for WRF and CReSS were taken from the Final Operational Global Analysis by the National Centers for Environmental Prediction and Japan Meteorological Agency's Global Spectral Model. The downscaling of the typhoon by NWP could not control the track; therefore, data assimilation using spectral nudging (SN) was configured to use wavenumber 3, and lower components of analysis data were applied for several runs of the WRF simulations. There were 11 total NWP configurations generated by changing parameters such as the nesting, nesting time, and boundary conditions (Table A1). Storm surge was simulated using the surge-wave coupling model (SuWAT) reported by Kim et al. [2009]. The SuWAT model is based on a nonlinear shallow water equation that takes into account atmospheric pressure-driven surge, wind stress, and wave radiation stress. Three-domain two-way nesting was performed with spatial resolution from 0.1° (D1) to 0.00667° (D3). The final domain (D3) size was 2.0° × 2.0° with resolution of 740 m (Figure A1 and A2). The storm surge model considers wave-induced momentum effects and wave radiation effects but assumed vertical wall near the shoreline due to lack of information of land topography. The expected tidal level at 8:00 am on 8 November was 0.15 m; therefore, the astronomical tidal effects were excluded from the simulation for simplicity.

The performance of the NWP and storm surge simulation was validated against the observed typhoon track, pressure, wind speed, surges, and inundation height. The location of the typhoon’s eye, central pressure and wind radius were compared with satellite data [Digital Typhoon, 2013]. Figure 1 shows the track and minimum central pressure $P_{\text{min}}$ of Typhoon Haiyan for four different configurations. The four lines in the figure indicate tracks from satellite data, WRF with SN (0100), WRF without SN (0200, 0250, and 0550), and CReSS (sf). Although SN was applied for several WRF simulations, there is a ±50 km bias of the track in the north-south direction near Tacloban. As SN was only possible in the hindcast, the two predictions show 30–50 km different tracks; the sensitivity of this difference will be discussed later. The simulated time history of minimum pressure, $P_{\text{min}}$, and translation velocity generated by WRF-0250 and WRF-0550, which were the nested WRFs with SN by 1 km resolution, gave reasonable results against satellite data; however, this was not true for the radius of maximum wind speed, $R_{\text{max}}$ (Figure A3). These numerical results become more accurate if 1 km resolution nested NWP models are used.

Although the storm wind, pressure, and water surface elevation peaks during Typhoon Haiyan were not directly observed due to loss of electric power at several measurement locations, the comparison of simulated results with in situ observations of wind speed at 10 m height $U_{10}$, $P_{\text{min}}$, and water surface elevation indicates that the simulations had 50–200% error, depending on the specific variables and locations used.
However, the initial growth of $U_{10}$, $P_{min}$, and water surface elevation were qualitatively well simulated by the numerical models. The typhoon radius $R_{max}$ was 50–100 km, equivalent in size to San Pedro and San Pablo Bay (Leyte Gulf). Therefore, comparing the results with in situ data is sensitive to typhoon track, which has the same magnitude of error (Figure 2).

The accuracy of storm surge is more difficult to validate due to the lack of available data. There are few recorded tidal data sets because of damage to instruments and loss of electric power during Typhoon Haiyan, but the initial decrease of water surface level at Tacloban was well simulated by the WRFs with SN (Figure A5). From a comparison of the time histories of surge level between the available observation data for the locations, the results of the numerical models are more scattered in Tacloban (near the typhoon center) than in Masbate (on the outer edge of the typhoon). These different effects may affect the ratio of pressure- to wind-driven storm surge, and storm surge may be more sensitive to these effects than to the typhoon scale itself. The predictions (without data assimilation) by WRF and CReSS failed to estimate the water surface elevation, indicating the difficulty of predicting the extreme storm surge that occurred during Typhoon Haiyan. The spatial distribution of the maximum water surface level caused by storm surge is spatially limited to within the northwestern part of Leyte Gulf. For example, Figure 2 shows the maximum surge in domain 3 (D3) for the case of WRF-0550 with land inundation survey data [Tajima et al., 2014] with authors’ survey. The surveys were conducted following the post-event tsunami survey IOC-UNESCO manual [IOC-UNESCO, 1998], and the data can be classified into inundation height and runup height. The inundation heights were selected to minimize local land side amplification effects for comparison. The pressure-driven storm surge was approximately 1.1 m and was limited to within 50 km from the eye. However, the area affected by wind-driven storm surge was several times larger than that affected by the pressure-driven surge. Areas where maximum storm surge exceeded 3 m were mainly limited to the Tacloban area. The maximum water level at Tacloban was estimated to be 5.15 m by the best case (WRF-0550) and is in good keeping with the post-survey data measured from watermarks remaining on the land. Although the numerical simulation is the mean of a 740 × 740 m square mesh nearest to coast without storm surge inundation and wave runup on the land, the best-case simulation gave reasonably accurate predictions of the lower envelope of increase and decrease of maximum water surface level trends near the Tacloban area (Figure A6). The wave radiation stress increases the storm surge up to 0.3 m near the Tacloban due to shallow bathymetry of Leyte Gulf, but wave runup effects were severe at the Pacific side of Samar Island (Figure A7). The hindcast and prediction of maximum water surface level are sensitive to NWP results, and the mean error of maximum water surface level between the numerical results and the post-survey data ranged from 1.08 to 4.15 m depending on...
NWP configuration (Table 1). The mean error of predicted maximum water surface level was largest at 2.37 and 4.15 m in the no-data-assimilation cases of WRF and CReSS, respectively. The WRF series with SN also indicate that the sensitivity of hindcast maximum water surface level, the error of 38–219%, depends on the configuration of the numerical setup. These factors make it difficult to quantitatively forecast or hindcast the storm surge during Typhoon Haiyan.

Figure 2. Maximum water surface elevation predicted by WRF-0550.
Based on the best case in comparison with different variables, the numerically estimated minimum pressure, radius of maximum winds, maximum mean wind speed, translation speed, and maximum surface water level of the typhoon at the landfall are 906 hPa, 55 km, 65 m/s, 28 km/h, and 5.15 m, respectively. The maximum intensity of the typhoon was reached at landfall, which gave catastrophic impact on the Leyte Gulf area. The estimated errors of minimum central pressure by different configurations are 24 hPa maximum (Figure A3), but the maximum difference of water surface level is 4.42 m (Table 1). Such larger differences of water surface elevation occurred due to differences of typhoon track estimation and resultant storm surge amplification.

### 3. Local Amplification of Storm Surge

The characteristics of storm surge depend on atmospheric conditions and bathymetry. There are several mechanisms that generate extreme water surface elevation during a storm surge. Wind-induced surge results from a surface current generated by the friction of the water surface and wind, and it can be regarded as a mass transport of water from offshore to onshore. Pressure-induced surge is generated by atmospheric pumping caused by atmospheric depression near the eye, generating two different wave modes. One is convex-shaped water surface elevation, traveling with the typhoon, and the other is a forerunner, which has faster surface movement than the typhoon itself [Nielsen et al., 2008; Kennedy et al., 2011]. Pressure-induced surge is mainly a long-wave phenomenon, and therefore there is no mass transport from offshore to onshore. Assessing the magnitude of each component is important to comprehending the local and macro-scale behavior of storm surge.

Figure 3 shows a time series of surface elevation, velocity components, and instantaneous and accumulated mass fluxes along the north-south line A (lon. 125°38′.00E, Figure 2a) at the mouth of Leyte Gulf. The small-amplitude water oscillation and water flowing from the Pacific entered the bay more than 2 days before the typhoon landfall. The accumulated total mass of the water entering from the Pacific Ocean (solid line in Figure 3a) was \(1.00 \times 10^{14} \text{m}^3\), which is about 1.2% of the total water volume of the Leyte Gulf (dash-dotted line in Figure 3c) at landfall. Therefore, the role of the forerunner and wind-induced surge was not very significant in increasing water surface elevation in Leyte Gulf. The time history of latitudinal velocity and mass flux shows rapid positive (northward) and negative (southward) change before landfall. This result indicates that the water mass circulated clockwise before landfall but became anticlockwise after the landfall. The few hours of oscillation in water surface elevation and velocity components reflect the local oscillation of water surface inside the bay.

The characteristics of water surface elevation along the typhoon track contribute to local enhancement of storm surge in Leyte Gulf. Figure 4 shows frequency spectra of different locations from the Pacific Ocean to Leyte Gulf (see the location and time history in Figure A8). The water surface elevations were a single soliton-like shape and had no significant peak frequency in the Pacific Ocean. However, the water surface began to oscillate as the peak water surface elevation increased in Leyte Gulf. The amplification of surface elevation near the coast is significant compared to that offshore. The peak frequency of the spectrum occurs at 4.6 h, which corresponds to the first mode of the seiche’s period \(T\) for a standing wave of \(L = 112.4 \text{km}\) oscillation with the mean water depth of Leyte Gulf (\(h = 75 \text{m}\)).

\[
T = \frac{4L}{\sqrt{gh}}
\]  

Here, \(g\) is the acceleration due to Earth’s gravity. The node is the Philippine Trench, and antinode is the east coast of Leyte. Simply measured, Leyte Gulf is about 90–140 km in length, and the development of seiches can be expected,

| Pmin [hPa] | Umax [m/s] | Mean Error [m] | RMSE [m] | Max Diff to WRF-0550 [m] | SN |
|-----------|-----------|----------------|----------|-------------------------|----|
| WRF-0100  | 929.2     | 59.0           |          |                         |    |
| WRF-0200  | 928.8     | 56.9           |          |                         |    |
| WRF-0250  | 907.3     | 62.7           |          |                         |    |
| WRF-0280  | 911.6     | 62.0           |          |                         |    |
| WRF-0550  | 906.0     | 65.4           |          |                         |    |
| CReSS-sf  | 954.2     | 51.8           |          |                         |    |
| CReSS-s1sf| 915.0     | 68.8           |          |                         |    |
due to the shallow water depth of 75 m inside the bay and the sudden change in water depth to 10,000 m at the eastern boundary along the Philippine Trench. Therefore, the local amplification of water surface elevation near Leyte’s east coast due to seiche motion can be expected, even though the mass flux from the Pacific Ocean to the bay was not significant. Moreover, it is difficult for long wave components to enter and exit Leyte’s eastern boundary. The hindcast numerical results indicate a few peaks of water surface elevation with several hours interval along the east coast of Leyte, which is in agreement with local eyewitness reports following our survey.

Figure 3. Water surface elevation, velocity components, and instantaneous and accumulated mass flux from the Pacific Ocean to Leyte Gulf along line A in Figure 2. (a) Water surface elevation, longitudinal (U), and latitudinal (V) depth-integrated velocity; (b) longitudinal and latitudinal mass flux ($F_x$ and $F_y$, respectively); (c) accumulated longitudinal and latitudinal mass flux ($F_x$ and $F_y$, respectively) and total mass increase (TV). In all graphs, red corresponds to longitudinal measurements, and blue lines correspond to latitudinal measurements.

Figure 4. Spectra of simulated water surface elevation from the outside to inside Leyte Gulf (colored lines indicate the different references points shown in Figure A8, and black vertical lines indicate a resonance frequency of 50, 100, or 200 km oscillation).
The numerical experiments omitting the Pacific Ocean show a 1 m decrease of peak surface level but give a spatial profile rather similar to that of the water surface in Leyte Gulf (data not shown). Such local oscillation can be often observed for a storm surge in a semi-enclosed coastal location (e.g., storm surge in Osaka Bay due to Typhoon Jane in 1951). The local oscillation maximizes if surface wind blows over the longest fetch to Tacloban. Typhoon Haiyan ran rather parallel to the east-west direction; therefore, it was not the worst possible case for its given wind speed and atmospheric pressure. The local increase of water surface elevation by any typhoon can be expected from the geological structure of Leyte Gulf to be maximum near Tacloban. Therefore, careful consideration of these factors during reconstruction of the Tacloban area will be necessary to avoid future disasters.

4. Discussion and Conclusions

A series of numerical simulations of atmospheric conditions and storm surge were conducted for Typhoon Haiyan. The best hindcast using NWPs and a storm surge model indicated that the maximum wind radius of Haiyan was 50–60 km and that the storm surge near Tacloban was 5 m. The best hindcast results agree with satellite and in situ observations.

The differences between different NWP configurations indicate the difficulty of dynamic projection of a super typhoon and related storm surge simulations. First, we found that the minimum central pressure, track, and maximum storm surge of Typhoon Haiyan were difficult to estimate without additional a priori observational data based on the difference between without assimilation (WRF-0100 and CReSS) and with assimilation (the others; see Table 1). The accuracy of minimum central pressure was sensitive to SST, the model resolution, and NWP models themselves. The appropriate SST and finer spatial mesh (horizontal 1 km) significantly improved the minimum central pressure of the typhoon, specially. Furthermore, the accuracy of storm surge does not depend on the accuracy of atmospheric field, directly, although the hindcast results by the NWPs were estimated as $U_{10}$ more than 50 m/s (Table 1). The correlation between the minimum pressure and maximum wind speed at Tacloban is 0.89, but the correlations between the mean errors of water surface elevation from measured inundation height and the minimum pressure or maximum wind speed are decreased to 0.60 and 0.34, respectively. The accuracy of the storm surge hindcast has a weak relation with the accuracy of mesoscale and local-scale atmospheric fields. Based on the analysis of best hindcast results, the accumulated total mass due to water inflow from the Pacific Ocean was about 10% of the total volume, and seiche oscillation of water surface elevation was significant inside Leyte Gulf. The peak frequency of water surface elevation occurred at 4.6 h, which corresponds to the first mode of 112 km seiche oscillation for the mean depth of Leyte Gulf. The numerical experiments show the coherent structure of storm surge as it relates to the seafloor bathymetry of Leyte Gulf and the Philippines Trench. The seiche of Leyte Gulf enhanced the storm surge, and it is one of difficulties and sensitivities of the hindcast of this event in addition to typhoon track hindcast. However, the storm surge in Leyte Gulf can be amplified by particular typhoon track due to seiche, potentially.

This is the reason why the similar storm surge disasters occurred in 1897 and 2013.

References

Bender, M. A., T. R. Knutson, R. E. Tuleya, J. J. Sirutis, G. A. Vecchi, S. T. Garner, and I. M. Held (2010), Modeled impact of anthropogenic warming on the frequency of intense Atlantic hurricanes, Science, 327, 454–458.

Digital Typhoon (2013), Typhoon images and information. [Available at http://www.digital-typhoon.org/]

IOC-UNESCO (1998), Post-Tsunami Survey Field Guide, 1st ed., Intergovernmental Oceanographic Commission Manuals and Guides, Paris, France.

Kennedy, A. B., U. Gravois, B. C. Zachry, J. J. Westerink, M. E. Hope, J. C. Dietrich, and R. G. Dean (2011), Origin of the Hurricane Ike forerunner surge, Geophys. Res. Lett., 38, L08608, doi:10.1029/2011GL047090.

Kim, S. Y., T. Yasuda, and H. Mase (2009), Numerical analysis of effects of tidal variations on storm surges and waves, Appl. Ocean Res., 30(4), 311–322.

Morey, S. L., S. Baig, M. A. Bourassa, D. S. Dukhovsky, and J. J. O’Brien (2006), Remote forcing contribution to storm-induced sea level rise during Hurricane Dennis, Geophys. Res. Lett., 33, L19603, doi:10.1029/2006GL027021.

National Climatic Data Center (2005), Hurricane Katrina, Special Report, NOAA-NCDC, Asheville, N. C. [Available at http://www1.ncdc.noaa.gov/pub/data/sealevel/specialreps/Hurricane-Katrina.pdf.]

National Disaster Risk Reduction and Management Council (2013), Re effects of Typhoon “Yolanda,” SitRep 60, NDRRMC, Quezon City, Philippines. [Available at http://www.ndrrmc.gov.ph/attachments/article/1125/Update%20SitRep%20No.60.pdf.]

Nielson, P. S., D. Byre, D. P. Callaghan, and P. A. Guard (2008), Transient dynamics of storm surges and other forced long waves, Coastal Eng., 55(8), 499–505.

Powell, M. D., P. J. Vickery, and T. A. Reinhold (2003), Reduced drag coefficient for high wind speeds in tropical cyclones, Nature, 422, 279–283.

Schiermeier, Q. (2010), Most powerful hurricanes on the rise, Nature, doi:10.1038/news.2010.24.
Schiermeier, Q. (2013), Did climate change cause Typhoon Haiyan?, Nature, doi:10.1038/nature.2013.14139.
Skamarock, W. C., J. B. Klemp, J. Dudhia, D. O. Gill, O. M. Barker, M. G. Duda, X. Y. Huang, W. Wang, and J. G. Powers (2008), A description of the Advanced Research WRF Version 3. NCAR Tech. Note, 475, p. 113, National Center for Atmospheric Research, Boulder, Colo.
Tajima, T., et al. (2014), Initial report of JSCE-PICE joint survey on the storm surge disaster caused by Typhoon Haiyan, Coastal Eng. J., 56, doi:10.1142/S0578563414500065, in press.
Tsuboki, K., and A. Sakakibara (2002), Large-scale parallel computing of Cloud Resolving Storm Simulator, in High Performance Computing, edited by H. P. Zima et al., pp. 243–259, Springer, New York.
Woodruff, J. D., J. L. Irish, and S. J. Camargo (2013), Coastal flooding by tropical cyclones and sea-level rise, Nature, 504, 44–52.