Development of Fast-Calculation Storm Surge System and

Case Study of 2013 Typhoon Haiyan/Yolanda

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STORM SURGE

- Storm surge is a coastal flood of rising water commonly associated with low pressure weather systems:
  - Tropical cyclones
  - Storms
  - Typhoons
  - Hurricanes

- The two main meteorological factors contributing to a storm surge are:
  - Pressure gradient
  - Wind shear stress
Inundation induced by Storm Surges

- Destroy of homes and business
- Potential threat of coastal communities
- Damages of roads and bridges

Inundation induced by 2005 Hurricane Katrina. (http://www.stormsurge.noaa.gov/)

Tracks of all tropical cyclones in the northwestern Pacific Ocean between 1951 and 2014.
Taiwan – Catogory-4
Typhoon Dujuan
2015.09.15 – 2015.09.29

The lowest pressure of Typhoon Dujuan is 925 mb.
The highest 1—minute wind is 205 km/hr.

Hong Kong - Category-4 Typhoon Hagupit

Track of Typhoon Hagupit (HKO)

Hong Kong Local News

Copyright @ HKO (Huang and Huang, 2008)

Saltwater Intrusion
Records of Storm Surge at Victoria Harbour (Hong Kong)

Observed Water Level
Astronomical Tide
Storm Surge

香港天文台 (Hong Kong Observatory)
http://www.weather.gov.hk/m/article_uc.htm?title=ele_00184
Typhoon Haiyan was the strongest typhoon than tropical cyclones ever recorded, and devastated portions of Southeast Asia, particularly the Philippines, in early-November 2013.

Typhoon Haiyan: 'It was like the end of the world'.

Typhoon Haiyan was the strongest typhoon than tropical cyclones ever recorded, and devastated portions of Southeast Asia, particularly the Philippines, in early-November 2013.
1) Inundation height was measured at **5.9 m** near the San Juanico Bridge.

2) Sea wall damage at Tagpuro and the run-up height was about **6.9 m**.

3) Barangay Rosal area with a **5.0 m** storm surge inundation and damage to houses behind the 3.0 m sea wall.

*(Mas et al., 2015, Natural Hazards and Earth System SCI.)*
Our Goals for a Storm Surge Operational System

- Adopt large enough spherical computational domain to cover the complete typhoon life cycle and full storm surge propagation.
- Include nonlinear calculation, bottom shear stresses and shoaling effects in near-shore regions.
- Consider multi-scale storm surge propagation in both open ocean and coastal regions.
- Calculate high-resolution storm surge inundation area for risk assessment.
- Combine with the dynamic atmospheric model.
- Combine with the global tidal model.
- High-speed efficiency for the early-warning system.
The Introduction of CWB COMCOT-Surge Model

(COrell MUlti-grid COupled Tsunami Model – Storm Surge)

Nonlinear Shallow Water Equations on the Spherical Coordinate

\[
\frac{\partial \eta}{\partial t} + \frac{1}{R \cos \varphi} \left\{ \frac{\partial P}{\partial \psi} + \frac{\partial}{\partial \varphi} \left( \cos \varphi \cdot Q \right) \right\} = 0
\]

\[
\frac{\partial P}{\partial t} + \frac{1}{R \cos \varphi} \frac{\partial}{\partial \psi} \left( \frac{P^2}{H} \right) + \frac{1}{R} \frac{\partial}{\partial \varphi} \left( \frac{PQ}{H} \right) + \frac{gH}{R \cos \varphi} \frac{\partial \eta}{\partial \psi} - fQ + F^b = - \frac{H}{\rho_w R \cos \varphi} \frac{\partial P_a}{\partial \psi} + \frac{F^s}{\rho_w}
\]

\[
\frac{\partial Q}{\partial t} + \frac{1}{R \cos \varphi} \frac{\partial}{\partial \psi} \left( \frac{PQ}{H} \right) + \frac{1}{R} \frac{\partial}{\partial \varphi} \left( \frac{Q^2}{H} \right) + \frac{gH}{R} \frac{\partial \eta}{\partial \varphi} + fP + F^b = - \frac{H}{\rho_w R} \frac{\partial P_a}{\partial \psi} + \frac{F^s}{\rho_w}
\]

- Solve nonlinear shallow water equations on **both** spherical and Cartesian coordinates.
- **Explicit leapfrog Finite Difference Method** for stable and high speed calculation.
- **Multi/Nested-grid system** for multiple shallow water wave scales.
- **Moving Boundary Scheme** for inundation.
- **High-speed efficiency.**
(1). NOAA Benchmark Problem Validation

Compare with the Solitary Wave Run-up Experiments (Synolakis, 1986 and 1987).

Simulated by COMCOT

(from NOAA Official Website)

(Wu, 2012)
(2). High-speed Calculation
CWB COMCOT-Surge Model can finish 48 hrs forecast in 30 mins and be used for the operational system.

The results has been published on Ocean Engineering *(Simon C. Lin et al., 2015).*
(3). Combine with the Atmospheric WRF/ TWRF Model

TWRF (Typhoon Weather Research and Forecasting Model)

- TWRF model is an atmospheric model adopted for operational forecasts by Central Weather Bureau in Taiwan.

- The TWRF model will start its simulation per 6 hours in a day at 00, 06, 12 and 18 UTC time respectively.
The tides are provided as complex amplitudes of earth-relative sea-surface elevation for eight primary (M2, S2, N2, K2, K1, O1, P1, Q1), two long period (Mf, Mm) and 3 non-linear (M4, MS4, MN4) harmonic constituents.

(Dushaw et al., 1997)
(5). High-Accuracy Tide Simulation

The bias is smaller than 0.1 m and RMSE is smaller than 0.4 m.

Validated Gauge Locations at Taiwan

The observed data and harmonic data are provided by CWB (Taiwan).
(6). Model Validation of 2015 Typhoon Soudelor

- Typhoon Soudelor was the strongest typhoon in Western North Pacific regions at 2015. According to the brief analysis, more than 4,000 thousands families lost their electricity during typhoon period and accumulative rainfall is more than 1,000 mm.

- Because of the destructive damages, economic loss and human casualties at Mariana Islands, Taiwan, and China, the name “Soudelor” was removed from the list of typhoon names and would not be used forever.

The flood in low-lying region at Ilan because of Typhoon Soudelor. (中央社記者沈如峰宜蘭縣)
Parabolic Drag Coefficient

\[ C_d = -a \left( V_p - 33 \right)^2 + c \]

(Peng and Li, 2015, Nature)
Comparison with Observed Data
2015.08.06 00:00 - 2015.08.09 06:00 (UTC)

The tide observed data are provided by our CWB in Taiwan.
Coastal Inundation Calculation

Our COMCOT storm surge model could also calculation the inundation area with nonlinear shallow water equations which considers nonlinear effects, bottom effects, and Coriolis effects inside.
The Case Study of 2013 Typhoon Haiyan

Source: Hong Kong Observatory
Nested Computational Domain

- Layer 01 can cover the complete typhoon life cycle of Typhoon Haiyan and the full storm surge propagation.
- Layer 02 can include the offshore hydrodynamic progresses of storm surge on the fine mesh domain.
The computational domain of Layer 03 and Layer 04 could cover the storm surge propagations in offshore and nearshore regions.
Combine with the Atmospheric WRF Model

- Asymmetric effect
- Topographic effect
- Hydrodynamic Pressure

The WRF simulations are provided by Dr. Chuan-Yao Lin, AAR Modeling Laboratory (Sinica).
Large computational domain to cover the complete storm surge propagation induced by Typhoon Haiyan with Coriolis effect.
Snapshots of Storm Surges in the Philippines
Maximum Simulated Storm Tides at Leyte Gulf
Storm Surge Operational System

Our COMCOT storm surge model has been the official operational system at the Central Weather Bureau this year.

- Meteorological Force: Parametric Typhoon Model or TWRF Model.
- Tidal Boundary Condition: TPXO 7.1 model.
- 48-HR Time Series for Storm Tide and Pure Tide at 34 specified locations.
- 2-dimensional model product.
1. Every forecasting includes two 96-HR computations, and one for storm tide (storm surge + tide) run and another for pure tide run.

2. There are 48-HR warm-up and 48-HR forecast at each storm tide run.
## Comparison with Other Operational Storm Surge Model

<table>
<thead>
<tr>
<th>Model</th>
<th>Country</th>
<th>Resolution</th>
<th>Coordinate</th>
<th>Grid System</th>
<th>Inundation</th>
<th>Nonlinear Tidal Effect</th>
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<td>Structured</td>
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<td>Spherical/ Cartesian</td>
<td>Nested-Grid System</td>
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</tbody>
</table>

- Solve **spherical nonlinear** shallow water equation directly with Coriolis effect.
- Cover complete storm surge propagation from open oceans to coastal regions.
- Calculate **high-resolution storm surge inundation**.
- **Tide warm-up** is stable and low-time consuming.
- The resolution in coastal regions can be promoted easily and be separately calculated in **nested-grid scheme**.
- Bathymetry and elevation data are easily to be input.
- The resolution can be modified easily.
Tide Validation of COMCOT-SURGE Model
(2016.09.11 00:00 – 2016.09.15 00:00)

Toucheng
大武
Anping
頭城
安平
2016 Category-5 Typhoon Nepartak in Taiwan

Our COMCOT storm surge model has been to the official operational system at CWB, Taiwan since Typhoon Nepartak.
Storm surges could be calculated for 2-day predictions and only spends 1.0 hr on a PC-level computational resources.
People live in these areas need to pay attention to the storm surge inundation.

Surge and Wave in Taiwan
(http://news.rthk.hk/rthk/ch/component/k2/1271353-20160708.htm)
Severe Typhoon Meranti in 2016

Typhoon Meranti was one of the most intense tropical cyclones on record. Impacting the Batanes in the Philippines, Taiwan, as well as Fujian, China in September 2016.

Best-track parameters of Typhoon Meranti

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<tr>
<th>Year</th>
<th>Month</th>
<th>Day</th>
<th>Hour</th>
<th>GPS Latitude (°)</th>
<th>GPS Longitude (°)</th>
<th>Lowest Central Pressure (hPa)</th>
<th>Radius of Maximum Winds (km)</th>
<th>Max Sustained Wind Speed (m/s)</th>
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Forecast Product (1)
Maximum Storm Surge

2016年莫蘭蒂颱風
颱風警報單時間：2016031308

(颱風資料庫提供)
Contribution of Wind Shear Stress and Pressure Gradient

2016 Typhoon Meranti

Wind Shear Stress (Taisi)
Max Wind surge = 0.45 m
Max Pressure surge = 0.5 m

Wind Shear Stress (Nanwan)
Max Wind surge = 0.1 m
Max Pressure surge = 1.2 m
Contribution of Wind Shear Stress and Pressure Gradient

2016 Typhoon Meranti

Max Pressure surge = 0.7 m
Max Wind surge = 0.3 m

Max Pressure surge = 0.7 m
Max Wind surge = 0.1 m
3-D Demonstration of Storm Surge Modeling in Deep-water Regions
Storm Surge Model Products

• High-Resolution Potential Inundation Area
  • Storm Surge Inundation Area
  • Pure Tide Inundation Area

• Predicted Water Elevations at Specified Tidal Stations
  • Storm Surge
  • Tide
  • Storm Tides (Storm Surge + Tide)

• Maximum Water Elevations in Coastal Regions
  • Maximum Storm Surge
  • Maximum Tide
  • Maximum Storm Tide (Storm Surge + Tide)
Conclusion

• Our CWB COMCOT storm surge model:
  ✓ Adopt the large computational domain to cover the complete typhoon life cycle and full storm surge propagation.
  ✓ The resolution in coastal regions can be promoted easily and be separately calculated in nested-grid scheme.
  ✓ Combine with the dynamic atmospheric WRF/TWRF model.
  ✓ Combine with the global TPXO tidal model.
  ✓ Calculate high-resolution storm surge inundation.
  ✓ High-speed calculation for the operational system.
  ✓ It has been the official operational system at Central Weather Bureau from 2016.

Maximum Simulated Storm Tides at Leyte Gulf, Philippines.

Thanks for your listening.
Welcome for comments and questions.