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# Spatial Variation of Damage due to Storm Surge and Waves during Typhoon Haiyan in the Philippines

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Field measurements and numerical simulations are used to assess the reasons for different types of water-related structural damage observed in Tacloban and Eastern Samar. Coastal Tacloban saw heavy damage due to wind waves riding atop storm surge, while inland Tacloban experienced much lighter damage because wind waves were not present (though inundation by surge soiled structures). Eastern Samar experienced little wind-induced or pressure-induced setup, but breaking-wave-induced setup over the reef combined with wave runup and infragravity motions caused heavy damage along the coast.

**Key Words :** storm surge, waves, wind, setup, hurricane, typhoon, Delft-3D, SWAN, inundation, runup

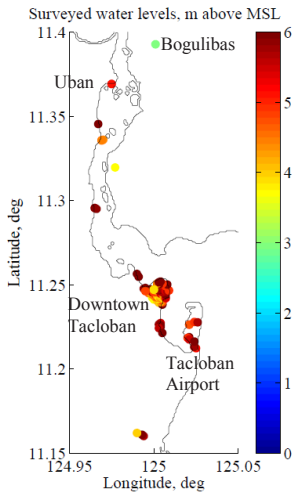
## 1. INTRODUCTION

Typhoon Haiyan struck the Philippines on November 8, 2013, caused over 6,000 casualties, displaced over 4 million people, and damaged or destroyed over 1 million houses<sup>1)</sup>. Due to the variety of bathymetric and topographic features in the region, degree and type of damage were dominated by site-specific mechanisms. These mechanisms include storm surge, surface waves, and winds. Furthermore, in different areas, the generation of storm surge was dominated by different physical mechanisms, either wind-induced setup or breaking-wave-induced setup. From January 16-24, 2014 a Tohoku University survey team investigated this damage, and carried

out numerical modeling to analyze the data obtained.

## 2. METHODOLOGY

Field measurements of water level were taken using a LaserTech TruPulse 200 rangefinder. Measurements were sighted with respect to sea level at the time, and later corrected to mean sea level (MSL) using the tidal database TPXO as boundary conditions for a Delft-3D simulation of the region. Near Tacloban (**Fig. 1**), these measurements were based upon water lines that were visible inside buildings and on witness accounts. In Eastern Samar (**Fig. 2**), water level measurements were based on debris runup lines, building damage, and witness accounts<sup>2)</sup>.

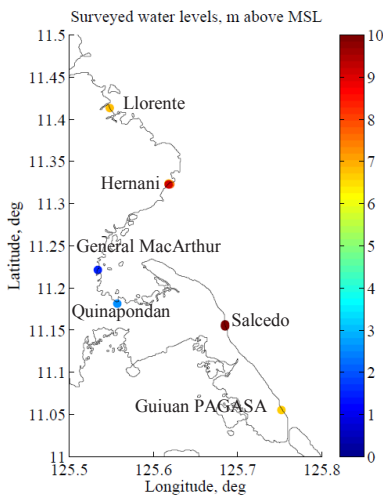


**Fig. 1.** Measured water level evidence near Tacloban. In Santa Rita (north of Bogulibas), witnesses reported no inundation.

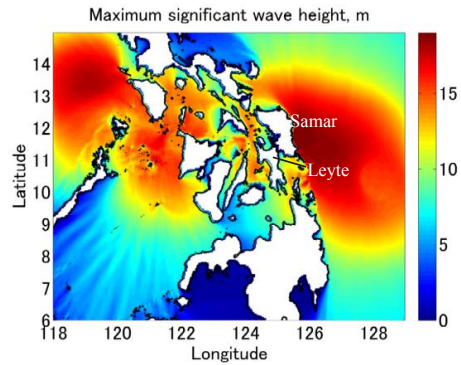
The behavior of Typhoon Haiyan was hindcast using typhoon track data from the Japan Meteorological Agency<sup>3)</sup>, which was input into Holland’s parametric hurricane model<sup>4)</sup> for air-pressure field estimation, followed by the moving-typhoon model of Fujii & Mitsuda<sup>5)</sup> as described in Veltcheva & Kawai<sup>6)</sup> for estimation of the wind field. The typhoon track data included data on location of the center of the storm, surface-level air pressure at the storm center, and maximum sustained wind speed  $v_{max}$  [m/s]. However, it did not contain information on the radius to maximum winds  $r_m$  [m], so the relation of Quiring<sup>7)</sup> is used to estimate this (Eq. 1).

$$r_m = 1852(49.67 - 0.47v_{max}) \quad (1)$$

The hindcast pressure and wind fields are input



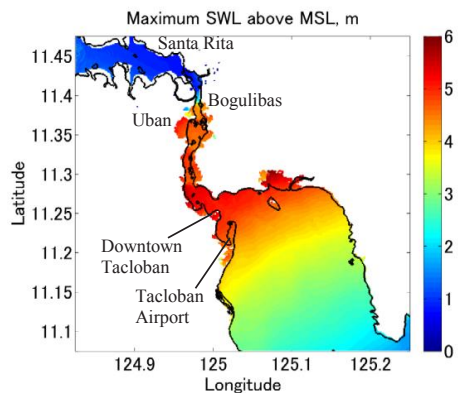
**Fig. 2.** Measured water level evidence in Eastern Samar.



**Fig. 3.** Maximum hindcast significant wave height throughout the Philippines during Typhoon Haiyan.

into a combined hydrodynamic and wave model to hindcast the water level and wave heights induced by the typhoon. The hydrodynamic model used is Delft-3D<sup>8)</sup> applied with only 1 layer in the vertical (thus the shallow water equations), and the spectral wave model used is SWAN<sup>9)</sup>. Delft-3D and SWAN are run together, with the hydrodynamic model repeatedly passing water level and current fields to the wave model, which calculates the wave field including the effects of currents and storm surge. The wave model in turn passes the radiation stress field back to the hydrodynamic model, which uses this information to calculate breaking-wave-induced setup and nearshore currents. Tides are included using the Global Tide database TPXO<sup>10)</sup> as a boundary condition to the hydrodynamic model.

Rough bathymetry was taken from GEBCO<sup>11)</sup> and topography from SRTM<sup>12)</sup>. Detailed bathymetry of Leyte Gulf was digitized from a nautical chart<sup>13)</sup>, and topography of downtown Tacloban and Tacloban Airport were surveyed during the January 2014 IRIDeS site visit. Nearshore coral reef topography east of Samar is not available, so the horizontal extents of reefs were digitized from Google Earth images, and a depth of 1 m relative to mean sea level was assumed. Model resolution is 2.5 km for the



**Fig. 4.** Maximum hindcast still water level near Tacloban.

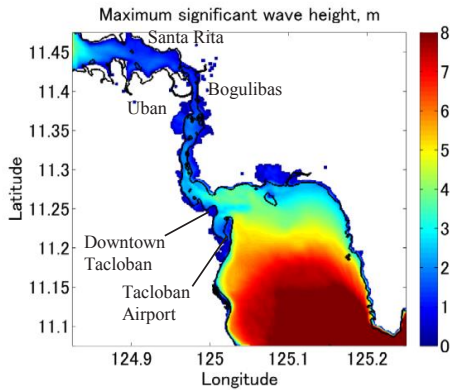


Fig. 5. Maximum hindcast significant wave height near Tacloban.

large domain (Fig. 3), 100 m for the Tacloban domain (Fig's 4-5), and 50 m for the Guiuan (Fig's 6-7) and Hernani (Fig's 8-9) domains. Manning's  $n$  was assumed to be 0.025 everywhere, though for more detailed inundation analysis in the future, this will need to be adjusted for land use.

An important adjustment to the default SWAN setup was the use of an air-sea drag coefficient limiter of 0.003<sup>14),15)</sup> imposed on the drag law of Wu<sup>16)</sup>. This drag coefficient limiter is the result of multiple airborne sonde drop measurements in hurricanes<sup>15)</sup>, and is necessary to prevent the development of unphysical wave heights in the model.

### 3. RESULTS AND DISCUSSION

Storm surge was dominated by wind-driven setup near Tacloban and breaking-wave-induced setup in eastern Samar, because Tacloban is sheltered from waves but is sited at the head of a shallow bay, while Eastern Samar is directly exposed to the Pacific Ocean but the seabed drops off quickly to deep water. Fig. 3 shows maximum (in time) hindcast significant

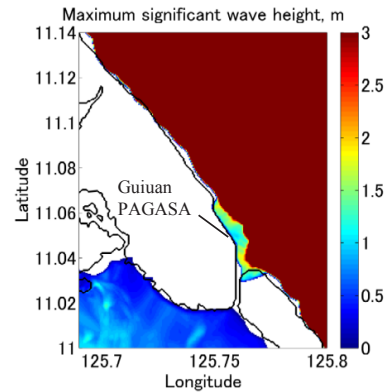


Fig. 7. Maximum hindcast significant wave height near Guiuan.

wave heights during the storm, reaching up to 19 m off Eastern Samar, and decreasing to less than 5 m in Leyte Gulf near Tacloban (Fig. 5). Fig. 4 shows the storm surge (wind-dominated) near Tacloban, including inundation of downtown Tacloban and Tacloban Airport. The 5-m surge extends up the San Juanico Strait to Bogulibas, then rapidly dissipates where the strait narrows. Comparing Fig. 1 with Fig. 4, modeled and measured surge levels near Tacloban agree well. In Eastern Samar, the agreement is not as good, because phase-dependent runup processes are not resolved (discussed below).

Damage along Tacloban's shoreline indicated waves atop the surge were strong enough to wreck reinforced concrete structures (Fig. 10, left), and to cause erosion near building foundations (Fig. 10, right). Near Tacloban harbor, ships atop the surge were pushed onshore by strong winds, flattening the communities they passed over (Fig. 11, left). Inland from the shoreline, damage resembled that of a slow, deep flood, with buildings soiled by floodwaters (Fig. 11, right).

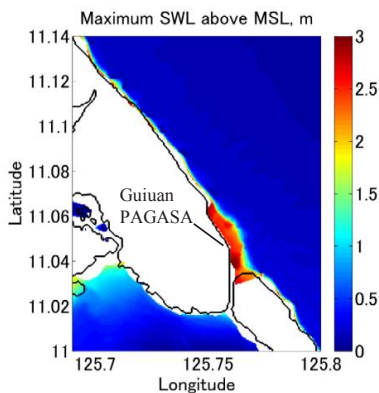


Fig. 6. Maximum hindcast still water level near Guiuan.

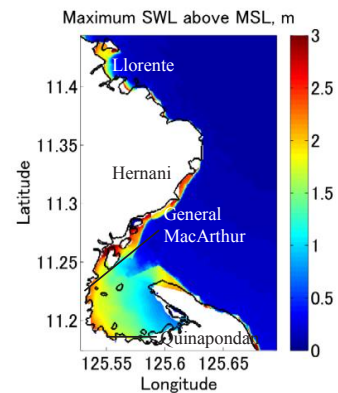


Fig. 8. Maximum hindcast still water level near Hernani.

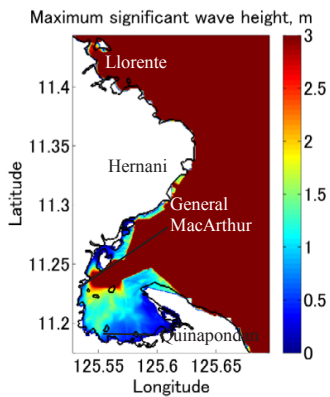


Fig. 9. Maximum hindcast significant wave height near Hernani.

On the steep coast of Eastern Samar, wind- and pressure-driven storm surge were small (less than 1 m in height; figures illustrating this are omitted due to manuscript length limitation), but breaking-wave-induced setup over the broad coral reefs in these areas generated a surge up to 3 m high (Fig. 6 and Fig. 8). Waves on top of this wave-induced setup (Fig. 7 and Fig. 9) wrecked structures (Fig. 12 and Fig. 13) and transported concrete and coral debris up to 50 m inland.

An important item that this surge and wave modeling has not resolved, however, is the tsunami-like behavior of the flood captured on film in Hernani<sup>17)</sup>. Monserrat et. al.<sup>18)</sup> describe meteo-tsunamis, which are bore-like seiches that can cause destruction similar to that of a tsunami. If the present phenomenon is indeed a meteo-tsunami generated by the travelling low-pressure system (the typhoon), the Delft3D shallow water model should have reproduced it. The lack of this effect in the model result indicates that either the local topography/bathymetry data is insufficient, the hurricane model is not sufficiently resolving the pressure field, or a meteo-tsunami did not occur. Indeed, Hibiya and Kajiuira<sup>19)</sup> show that me-



Fig. 10. Typical damage along the coast south of Tacloban Airport (left), and along the coast of downtown Tacloban (right). In both locations, waves were present.



Fig. 11. (Left) Homes demolished by drifting ships near Tacloban Harbor. (Right) Typical soiling inland in downtown Tacloban, where only surge (no waves) was present.

teo-tsunamis might only occur for storms propagating across shallow shelf seas, though such a shelf is not present off Eastern Samar.

Alternately, if the bore that struck Hernani is related to wave phenomena (infragravity waves such as surf beat, for instance), which the phase-averaged SWAN wave model can not resolve, a phase-resolving wave model such as the 2-dimensional Boussinesq model BOSZ<sup>20)</sup> must be implemented via further nesting under SWAN. 1-dimensional studies<sup>21),22)</sup> show surf beat and wave runup are most likely the cause of the phenomenon seen in Hernani.

#### 4. CONCLUSIONS

In Tacloban, severe structural damage and scour of foundations was observed only along the coast, where waves were present. Further inland, even though inundation was deep, structural damage was relatively mild, likely because buildings here are very porous, with water readily flowing in through doors and windows. This prevented buoyancy or lateral hydrostatic forces from forming, so that most water-related damage inland was not structural. Hydrodynamic forces due to rapid flow also were not excessive, as flow speed on inundated land in Tacloban did not generally exceed 2 m/s (Fig. 14).

In Eastern Samar, damage was extensive, but



Fig. 12. Damage to a concrete foundation near the Guiuan PAGASA station.



Fig. 13. Damage to the coral-fill Hernani seawall.

wind-driven setup was small. Breaking-wave-induced setup together with infragravity motions resulted in extreme runup heights and inundation extents. Work with the phase-resolving models OpenFOAM<sup>22)</sup> and BOSZ<sup>20)</sup> is underway to resolve the dynamic infragravity motions observed in Hernani.

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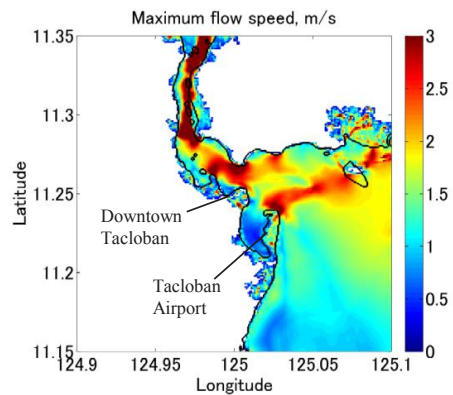


Fig. 14. Maximum hindcast flow speed near Tacloban.

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