Estimating Typhoon Haiyan's Wind Speeds Using Windicators and Post-Storm Wind Vulnerability Analysis on the Affected Areas

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ABSTRACT

On November 2013, there was widespread devastation over the Visayan Region due to the onslaught brought by Typhoon Haiyan, which was hyped as the strongest landfalling cyclone. Despite of that, a new benchmark for future disaster preparations cannot be established due to the discrepancies between various weather bulletins on how strong Haiyan really was, as well as the loss of vital meteorological data during Haiyan's passage. To remedy the shortage and discrepancy of Typhoon Haiyan's meteorological data, a forensic structural analysis was done on windicators through a field survey done on Leyte and Samar Island. Windicators are structural objects of interest whose structural failure will lead to estimating the magnitude of the winds that brought the failure, in this case, the strength of Typhoon Haiyan, which in turn was used to determine and re-assess the wind vulnerability of the regions affected, using also the historical wind data from Tacloban and Guiuan station, comparing with that to the current design wind speeds prescribed by the NSCP. The study determines through the analysis of four windicators, that before its landfall at Leyte Island, Typhoon Haiyan has 1-minute sustained winds of 351 kph, 10-minute sustained winds of 290 kph, and through the analysis of the reamining surface data, which corresponded well into forming a model of the storm, Typhoon Haiyan, before its landfall at Guiuan, Eastern Samar, has 10-minute sustained winds of 317 kph and 1-minute sustained winds of 352 kph, with minimum central pressures of 868.5 mbar and 872.2 mbar at 4:10 am and 5:10 am respectively. Statistical analysis determined that the existence of a storm like Typhoon Haiyan, regardless whether it would make landfall has a minimum recurrence period of 500 years and the event that such storm makes landfall has a minimum recurrence period of 5600 years on the areas affected.

Keywords: *windicators, typhoon haiyan; forensic structural analysis, computational fluid dynamics, wind engineering, geophysical fluid dynamics*

1. INTRODUCTION

Last November 8, 2013, Super Typhoon Haiyan (PAGASA Designated Name: Yolanda) struck the Visayan Region leaving catastrophic damages and record fatalities along its path, most notably the Eastern Visayan Region where the storm made landfalls at its peak intensity.

The storm was immediately hyped as the strongest storm to make landfall. But amidst the devastation and misery upon those affected, they were in confusion on how strong Typhoon Haiyan really was, with Joint Typhoon Warning Center (JTWC) estimating the 1-minute sustained winds to be about 315 kph through the Advanced Dvorak Technique (ADT) and Japan Meteorological Agency (JMA) and Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA) estimating the 10-minute sustained winds to be about 235 kph using the Doppler effect estimations. Taking into account the differences in the time-base of the wind averaging, using the recommendations of World Meteorological Organization (WMO) on the conversion factors between 10-minute averages and 1-minute averages, there was still a 55-kph difference between these estimates.

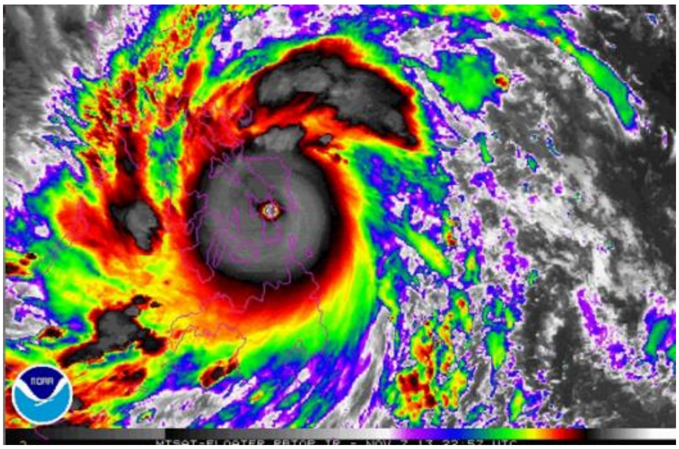


Figure 1: Infrared Image of Typhoon Haiyan

In-situ meteorological measurements were necessary to clear the discrepancy but unfortunately most of the weather instruments were damaged during the passage of TY Haiyan with only the barometric pressure readings from some areas remaining intact which were recorded during the full onslaught of Typhoon Haiyan at peak intensity namely: the 955.6 mbar barometric pressure reported at Tacloban Airport at 7:15 am, the 910 mbar barometric pressure reported at Guiuan Station at 5:10 am and the pressure readings from the barometer of the iCyclone team stationed in Hotel Alejandro in Tacloban City.

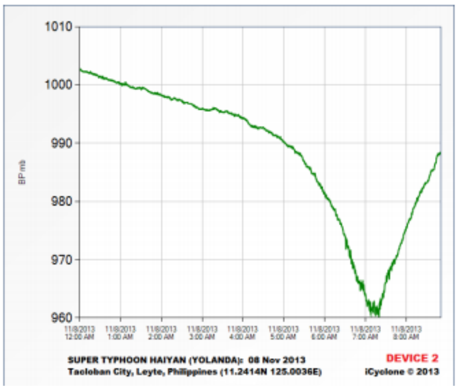


Figure 2: Barograph Reading on Tacloban City. A storm chaser team from iCyclone.com stationed at Hotel Alejandro in Tacloban City recorded the lowest pressure of 959.9 mbar at 7:20 am.

The flux of wind speed reading on weather stations was halted due to the fact that these stations were suffered physical damages from the winds of Typhoon Haiyan. Bantayan Island recorded winds of 77.4 m/s (278.6 kph) at 9:30 am (Nov 8, 2013, PST), which was recorded after Haiyan weakened considerably.

Tacloban Station, before being damaged by the storm surge, recorded winds of 77.7 m/s at 6:45 am. Guiuan Station, before halting its wind speed recording, recorded 10-minute sustained winds of 43 m/s (154.8 kph) peak winds of 53 m/s (190.8 kph) at 4:10 am, hours before its first landfall at Guiuan.

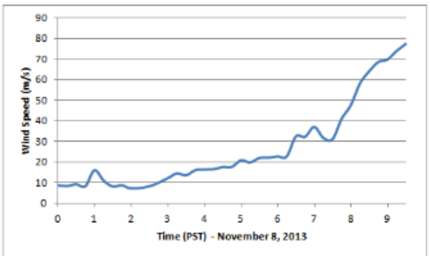


Figure 3: Wind Speed Reading – Bantayan Island

With these following premises given, a forensic structural analysis was performed to estimate the intensity of Typhoon Haiyan by the time it was making its landfalls to settle the discrepancy.

The forensic structural analysis performed on Windicators. Windicators, which were coined from terms 'wind' and 'indicators', are simple structural objects of interest whose failure leads to the computation of the wind speeds that brought the failure. Figure 5 shows the research framework using windicators.

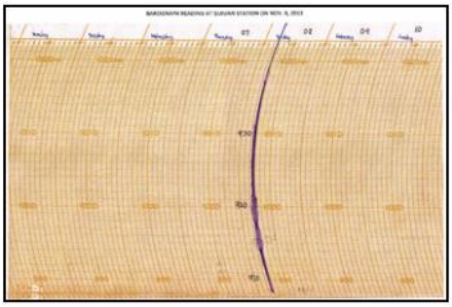


Figure 4: Barograph Reading – Guiuan Station (November 8, 2013). The lowest barometer reading of 910 mbar was recorded at 5:10 am. (Source: Climate Data Section - PAGASA and Guiuan Station Chief Marianito Macasa)

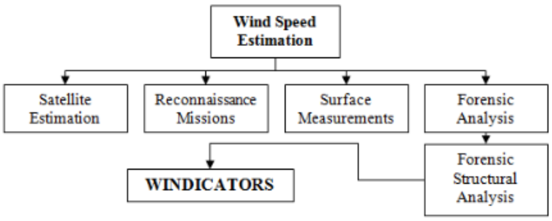


Figure 5: Conceptual Framework for Windicators

Figure 6: Research Framework

2. FORENSIC ANALYSIS

2.1 Field survey

Figure 7: Windicators (L to R: #4, #10, #9 and #8)

A field survey was performed on the affected areas. Non-inundated areas were surveyed to look for windicators. The area was further narrowed down to the area between Brgys. Guindapunan and San Jose in Palo, Leyte.

Figure 8: Windicators (L to R: #4, #10, #9 and #8) These were lamp posts installed in 2010 at Palo, Leyte. Windicator #9 was included in the study for verifications whether it was tampered or not.

The geogprahical coordinates, the geometric properties and samples trimmed from the structures were taken.

2.2 Material testing

The samples were taken back to the lab for material testing. Per ASTM A370-21419, a tensile test was performed on the samples.

Figure 9: Tensile test (right) on the sample (left)

Sample	Coupon #1	Coupon #2
Picture		
Gauge Length (in)	2.00	1.8125
Area (x 10^{-3} m^2)	0.00616	0.00777
f_{ult} (lbs)	6560	6800
σ_{ult} (MPa)	473.71	389.29

Table 1: Tensile test results

Based on the ultimate strengths of the samples and referring to AISC Table 2-1, the material is determined to be A36 steel.

2.3 Computational fluid dynamics (CFD)

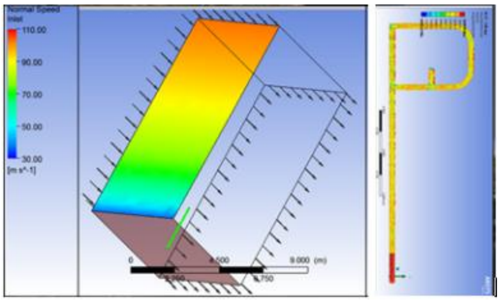


Figure 10: Wind simulation (left) and external pressures (right)

Using a finite-element modeler, winds were simulated over the structure following a logarithmic profile:

$$\bar{U}(z) = \bar{U}_{10} * \ln(z/z_0) * C_{SD}^{0.5}/0.4$$

$\bar{U}(z)$ – average wind speed at height z

z_0 – roughness length [1]

C_{SD} – surface drag coefficient [1]

$\bar{U}_{10}$ – average wind speed at height z=10 m

Equation 1

in order to obtain the external pressures applied on the structure using static wind load analysis. Using the external pressures caused by the wind, the internal forces in the member were determined. The von Mises stresses were used as the failure indicator, which was progressive yielding.

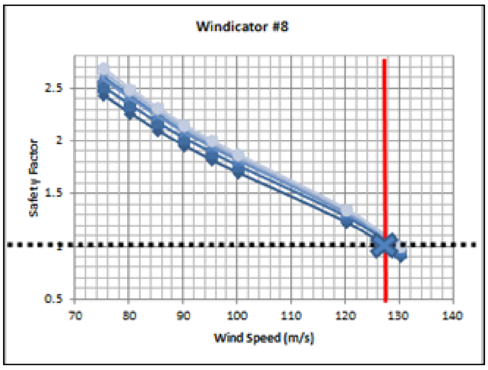


Figure 11: Wind speed v safety factor - #8

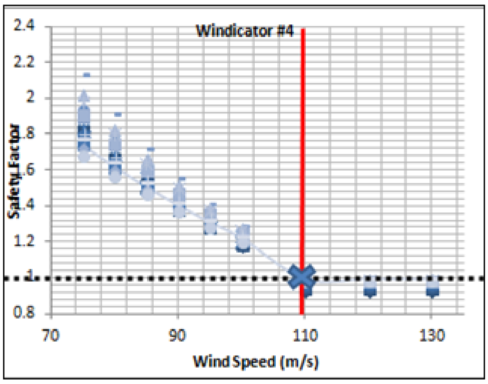


Figure 12: Wind speed v safety factor - #4

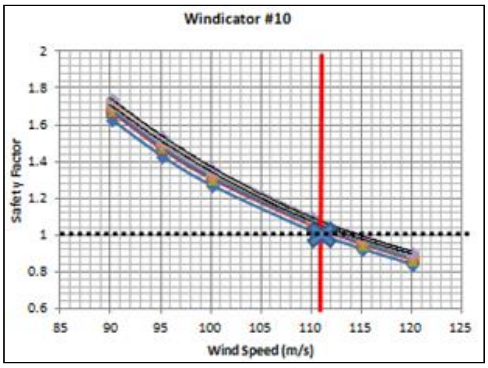


Figure 13: Wind speed v safety factor - #10

The terrain was considered a rough terrain ($z_0 = 0.5$ m and $C_{SD} = 0.019$) for the analysis. On Figures 11 to 14, the safety factor (Yield Stress/von Mises stress) on leeward elements and the wind speed were plotted. The winds simulated were considered to be a 3-second gust and therefore must be converted to 10-minute sustained averages using the conversion factors recommended by WMO. (Table 2)

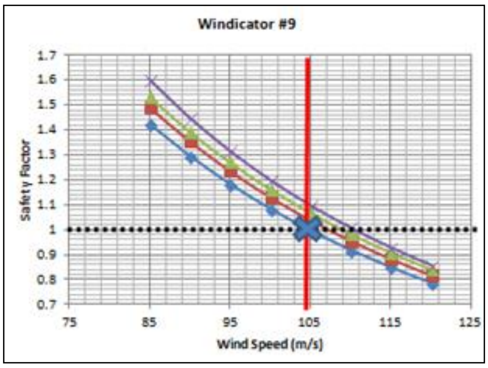


Figure 14: Wind speed v safety factor - #9

Windicator	Gust (m/s)	10-min sustained wind (m/s)
#4	109.43	65.95
#8	127.4	76.77
#9	104.77	63.11
#10	**113.48**	**68.36**

Table 2: Results of CFD analysis

2.4 Geophysical Fluid Dynamics

To determine the time of arrival of the winds, the direction of failure of the structures was estimated from the location of the compressive elements, which were considered to be on the leeward side of the winds, and the tensile elements on the structure's cross-section.

Next was to consider the effect of the Ekman Spiral, which is the change in direction of the winds as it descends from the boundary layer, where:

$$u\ (z) = U_{gr}*(1-(e^{-\beta}\cos(\beta))$$

Equation 2

$$v\ (z) = U_{gr}\ e^{-\beta}\sin(\beta)$$

Equation 3

$$\beta = z * (f/(2*v_e)$$

u – magnitude of the wind tangential to the pressure isobars.

v – magnitude of the wind n to the pressure isobars.

f – Coriolis parameter

v_e – Eddy viscosity (constant on rotating bodies)

The height of the boundary layer (H_{abl}), which is dependent on the roughness length (z_0) and the Coriolis parameter (f), is determined by using (1) on the equation of Lettau (1959) :

$$H_{ABL} = e^{(2.5\left(f{z_0}^{-0.09}\right)+\ln(z_0))}$$

Equation 4

The height of the Ekman layer (H_{ekman}), which is dependent on the roughness length and the Eddy viscosity (v_e), is determined by equating (3) to zero:

$$H_{ekman} = \pi * (2*v_e/f)^{0.5}$$

Equation 5

Due to the circular geometry of Typhoon Haiyan, which had a Dvorak rating of T8.1, the gradient winds were assumed to be parallel to the pressure isobars. At 4:10 am in the morning, the direction of the gradient wind over Guiuan – Station was estimated to be N 42.08°E. The PAGASA Station recorded the direction of the surface wind at that time to be at N 30°E. Using the directional differences of the wind at that time and coinciding the Ekman layer to the Atmospheric Boundary Layer, the eddy viscosity (v_e) was computed to be equal to 0.719144 m^2/s.

Typhoon Haiyan's storm track was interpolated from 6-hour intervals into 1-minute intervals. Using the computed eddy viscosity, Equations (2), (3), (4) and (5), the time of failure was estimated based on the direction of failure and the windicators' location (Figure 14). With the time of failure being estimated the distance from the storm's center at the time of failure was estimated on each windicators.

Windicator	Gust (m/s)	10-min sustained wind (m/s)	Time of Failure	Distance from the storm's centre (km)
#4	109.43	65.95	7:50 AM	30.57
#8	127.4	76.77	6:41 AM	35.93
#9	104.77	63.11	7:20 AM	24.41
#10	**113.48**	**68.36**	**7:02 AM**$^{+}$	**27.31**

Table 3: Time of failure and storm's proximity

2.5 Maximum Wind Speed Estimation

An analytical model of Typhoon Haiyan was formulated using the equations of Holland (1980) for the gradient wind profile and the pressure profile, the pressure (p) vs radial distance (r):

$$U_{gr} = -\frac{|fr|}{2} + \sqrt{\left(\frac{fr}{2}\right)^2 + \frac{(p-p_0)AB}{\rho_{air} r^B}\exp(\frac{-A}{r^B})}$$

Equation 6

$$\frac{p-p_o}{p_n-p_o} = \exp(\frac{-A}{r^B})$$

Equation 7

Using the pressure points discussed at section A and from Figure 2, and assuming the pressure on the outer edges of the storm to be at 1000 mbar based on the RDAP of the Haiyan from JTWC, on (7), the values of A and B were determined to be equal to 2445717313577890000 and 4.14868822191798 respectively. Using (6) to the data from Windicator #10 yielded a value of 68.39 m/s, relatively close to the 68.36 m/s 10-min sustained wind speeds on Windicator #10.

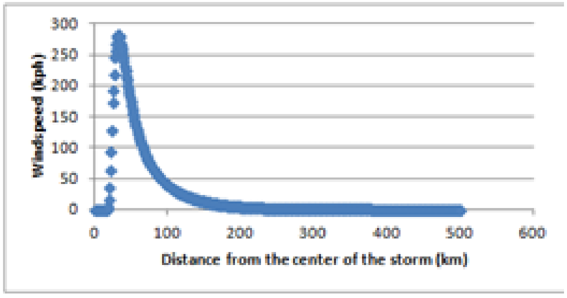


Figure 15: Velocity profile of TY haiyan (7:02 am)

Equation (6) was used not only to determine the maximum wind speeds and the minimum central pressure of Typhoon Haiyan at the time of failure of the windicators (Figure 13).

	#4	#8	#9	#10
Time of Failure (UTC)	2350	2241	2320	2302
10-minute sustained winds (kph)	**239.6**	**290.81**	371.82	**281.67**
1-minute sustained winds (kph)	**289.91**	**351.87**	449.90	**340.83**
Percent Deviation from JTWC(1-min)	**8.65%**	-10.48%	-	**-7.58%**
Percent Deviation from JMA/PAGASA(10-min)	19.17%	71.55%	-	23.57%
Minimum Central Pressure	922 mbar	888 mbar	500~ mbar	895 mbar

Table 4: Summary of values

The data from Windicator #9 returned erroneous values from the model. Windicator #9, before the survey was conducted, was being used as an anchor to the residents' clothesline, therefore the direction of failure may be compromised thus causing errors on the comparison to the model.

Using the 910 mbar pressure reading on Guiuan station at 5:10 am on (7), the minimum central pressure of Typhoon Haiyan at that time was estimated to be equal to 872.2 mbar, corresponding to a 10-minute maximum sustained winds of 317 kph and 1-minute sustained winds of 352 kph. The 10-minute sustained winds of 43 m/s and the peak gust of 53 m/s from the Guiuan Station taken at 4:00 am and 4:10 am respectively both returned 10-minute maximum sustained winds of 325 kph and 1-minute maximum sustained winds of 352 kph, corresponding to a minimum central pressure of 868.5 mbar, for Typhoon Haiyan.

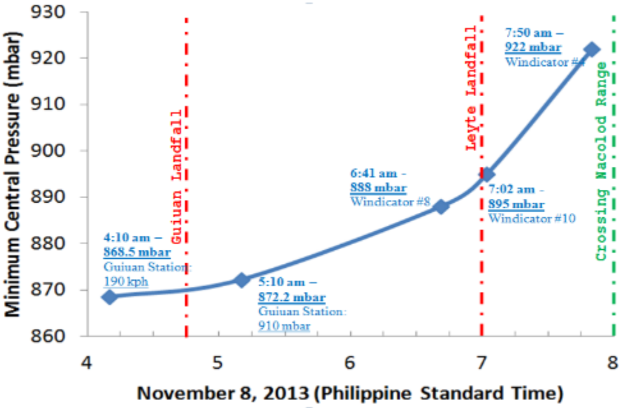


Figure 16: Minimum central pressure vs time

The conversion of the 77.7 m/s data from Tacloban Station, which was located at an isthmus which account for a sea type exposure, at 6:45 am to 10-min sustained winds, and putting it to the analytical model returned 10-minute maximum sustained winds of 290 kph, almost the same as Windicator #8 which failed around the same time.

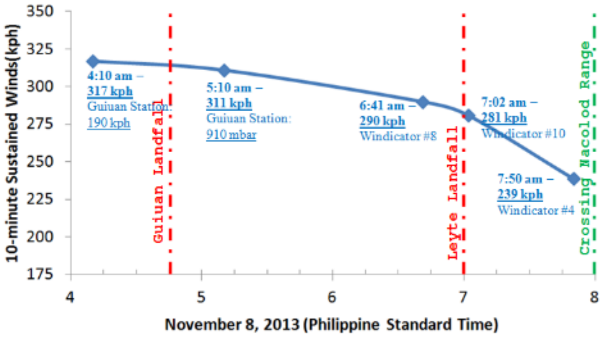


Figure 17: Maximum sustained winds vs time

Summing up the data on the timelines of Figure 16 and Figure 17 showed how Typhoon Haiyan drastically weakened over time. Terrain analysis reveals the limits of the analytical model which was valid until Typhoon

Haiyan crossed the Nacolod Range (a mountain range with 1000+ m mountains) of Leyte, causing disruption of the storm's structure as shown by the comparison of the analytical model and the synthesis of the data from Bantayan Island at Figure 18.

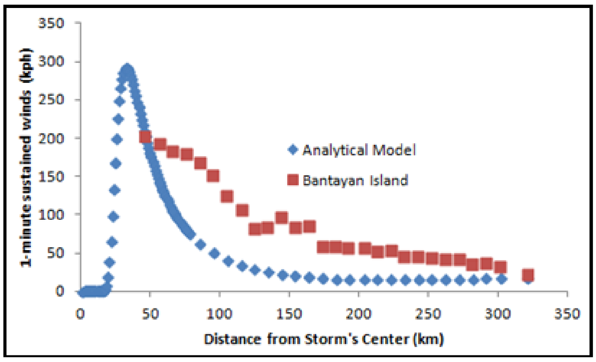


Figure 18: Bantayan island vs the analytical model

3. STATISTICAL ANALYSIS

The study analyzes the historical data from the PAGASA Synoptic Stations in the Visayan Region as shown in Figure 18 and Table 5.

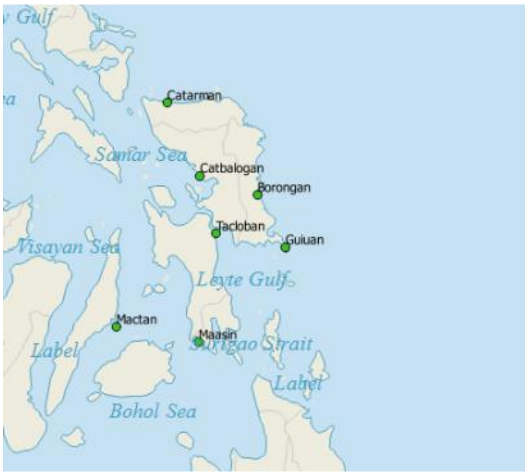


Figure 19: Location of the PAGASA stations analysed

STATION	PERIOD OF COVERAGE	HISTORICAL MAXIMUM WINDS
Borongan	1963-2010	52 m/s
Catarman	1951-2010	54 m/s
Catbalogan	1951-2010	59 m/s
Guiuan	1973-2012	72 m/s
Maasin	1972-2010	52 m/s
Mactan	1972-2010	55 m/s
Tacloban	1973-2012	62 m/s

Table 5: Details about the pagasa stations

Using the historical data, extreme value functions are formulated using the methods of Gumbel (Type I) and Gringorten (Type II) :

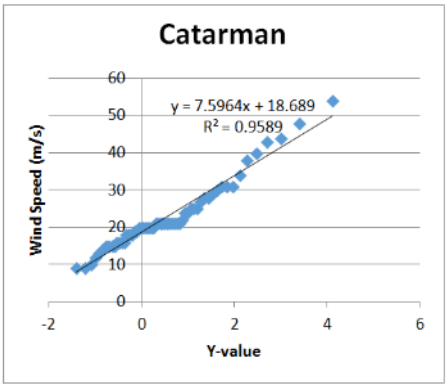


Figure 20: Type I distribution – Catarman

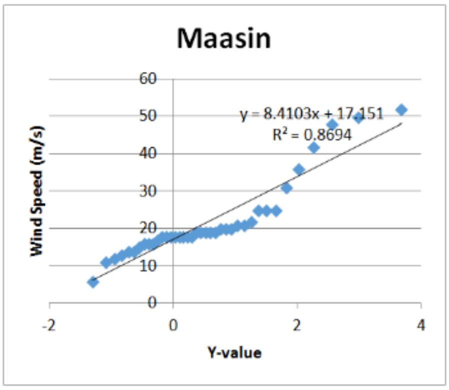


Figure 21: Type I distribution – Maasin

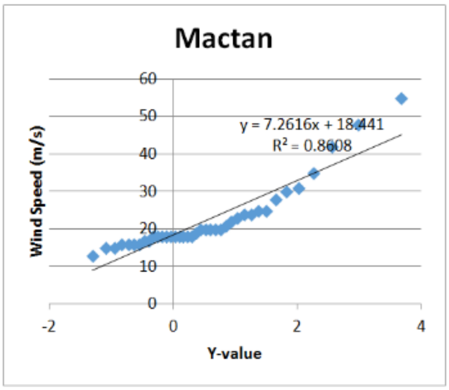


Figure 22: Type I distribution – Mactan

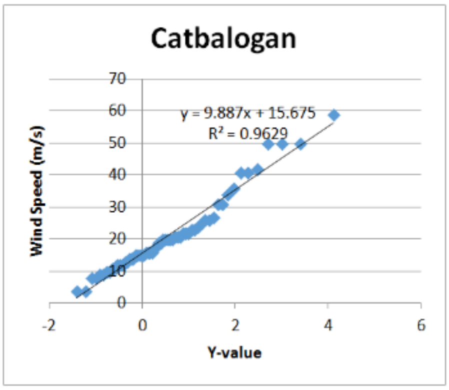


Figure 23: Type I distribution – Catbalogan

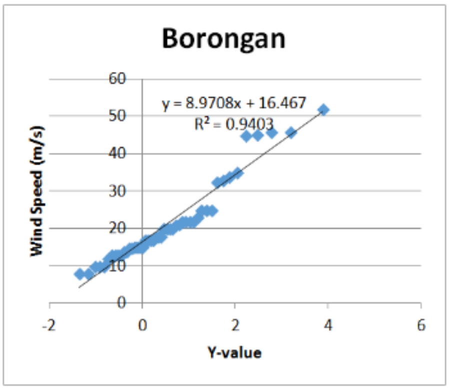


Figure 24: Type I distribution – Borongan

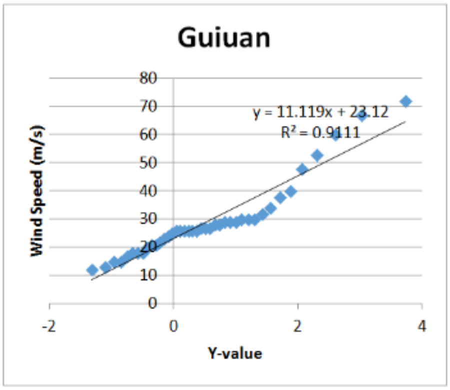


Figure 25: Type I distribution – Guiuan

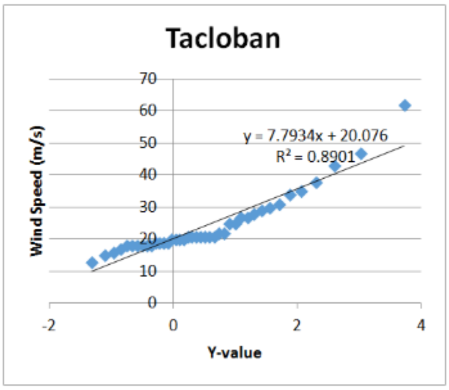
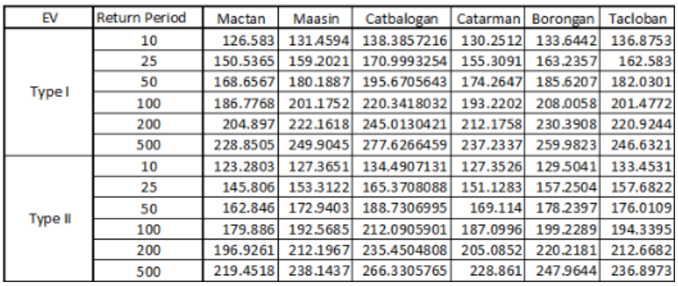


Figure 26: Type I distribution – Tacloban

Station	Daily Max			
	Type I		Type II	
	A	B	A	B
Mactan	18.44143	7.261625	18.52069	6.828771
Maasin	17.15099	8.410334	17.26715	7.865964
Catbalogan	15.6749	9.886965	15.80301	9.361444
Catarman	18.68947	7.596423	18.77932	7.207723
Borongan	16.46741	8.97078	16.60539	8.411409
Tacloban	20.07591	7.793412	20.1574	7.345179
Guiuan	23.11989	11.11882	23.26805	10.42299

Table 6: Shape values for the extreme value functions

Using the shape values for the extreme value functions on Table 6, the expected largest wind speed in the following return periods can be obtained as shown in Table 7.



EV	Return Period	Mactan	Maasin	Catbalogan	Catarman	Borongan	Tacloban
Type I	10	126.583	131.4594	138.3857216	130.2512	133.6442	136.8753
	25	150.5365	159.2021	170.9993254	155.3091	163.2357	162.583
	50	168.6567	180.1887	195.6705643	174.2647	185.6207	182.0301
	100	186.7768	201.1752	220.3418032	193.2202	208.0058	201.4772
	200	204.897	222.1618	245.0130421	212.1758	230.3908	220.9244
	500	228.8505	249.9045	277.6266459	237.2337	259.9823	246.6321
Type II	10	123.2803	127.3651	134.4907131	127.3526	129.5041	133.4531
	25	145.806	153.3122	165.3708088	151.1283	157.2504	157.6822
	50	162.846	172.9403	188.7306995	169.114	178.2397	176.0109
	100	179.886	192.5685	212.0905901	187.0996	199.2289	194.3395
	200	196.9261	212.1967	235.4504808	205.0852	220.2181	212.6682
	500	219.4518	238.1437	266.3305765	228.861	247.9644	236.8973

Table 7: Largest winds on the following return periods (in kph)

Using largest winds over the return periods of 10, 25, 50 and 100 years, basic wind speed maps are made :

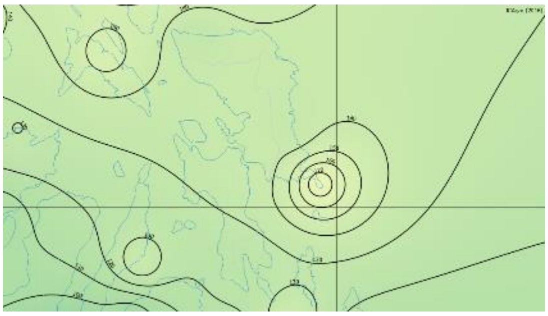


Figure 27: Basic Wind Speed Map – 10-year return period (Values are in kph)

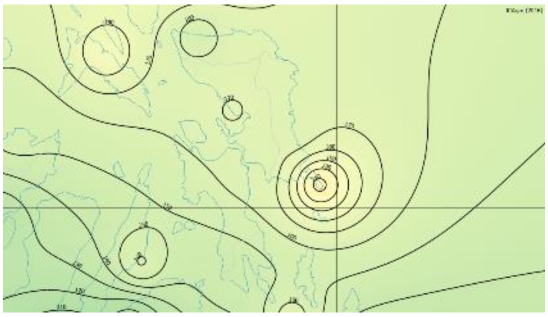


Figure 28: Basic Wind Speed Map – 25-year return period (Values are in kph)

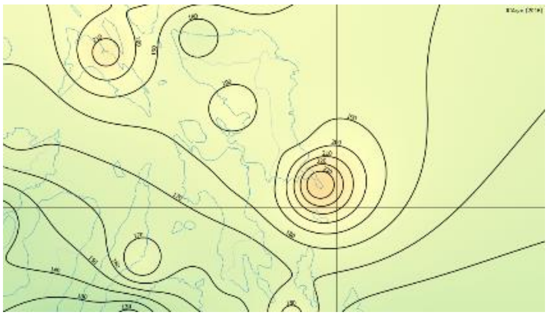


Figure 29: Basic Wind Speed Map – 50-year return period (Values are in kph)

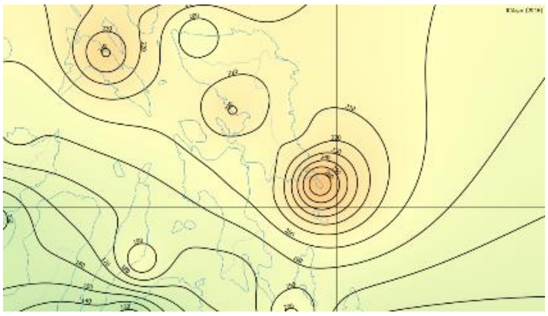


Figure 30: Basic Wind Speed Map – 100-year return period (Values are in kph)

The estimated and recorded wind speeds were also used to produce a wind exposure map brought by Typhoon Haiyan.

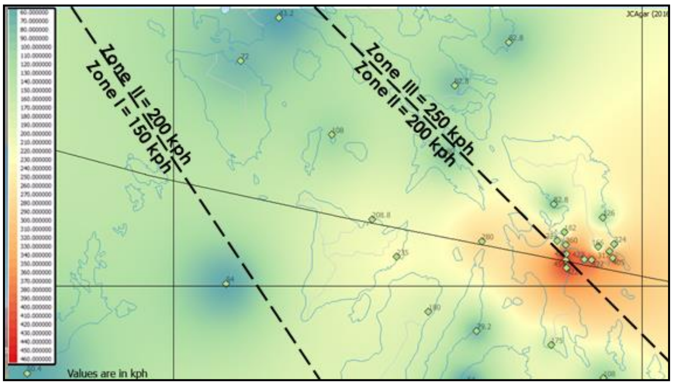


Figure 31: Wind Vulnerability Map of Typhoon Haiyan compared to the wind zones on NSCP (Values are in kph; Lower bound – 60 kph; higher bound – 460 kph)

Many of the areas had exceeded the basic design wind speed recommendations in the National Structural Code of the Philippines with the areas under Zone II experiencing gust more than 300 kph and areas under Zone I experiencing gust more than 400 kph, therefore, even engineered structures built in accordance to the NSCP were damaged.

Also using the values on Table 6, the return period of the winds experienced by Windicator #8 is obtained. Through the Type I extreme value functions, the 127 m/s winds experienced by Windicator #8 give return period values with the least being from the extreme value function from Guiuan Station which is approximately 5600 years. The return period is greater than the design life of the engineered structures.

Furthermore, using the least value expected for the highest pre-landfall wind speeds, highest wind speed recorded after the Leyte landfall in Bantayan Island, 77.4 m/s (278.6 kph), the return periods were computed to be at least 1650 years for Tacloban, and 140 years for Guiuan, also exceeding already the prescribed design life for engineered structures on the areas affected.

In terms of typhoon strengths, a statistical analysis was also done on the historical data of typhoon strength using the data from Japan Meteorological Agency, spanning from 1977-2014, excluding Typhoon Haiyan.

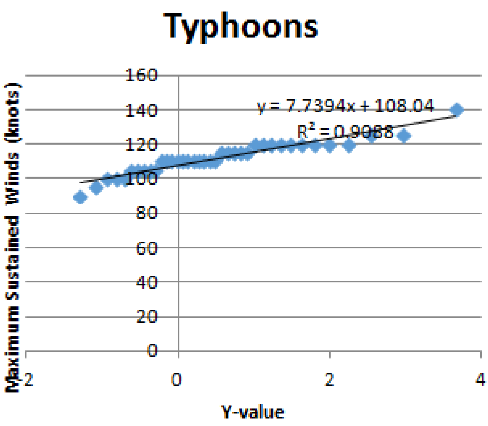


Figure 32: Type I analysis (Gumbel)

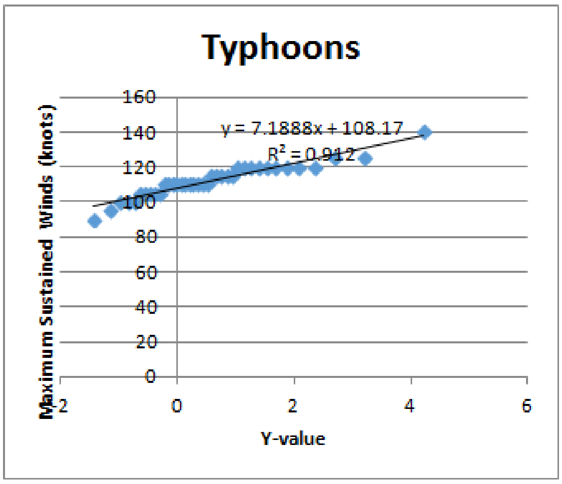


Figure 33: Type II analysis (Gringorten)

4. CONCLUSION

The study concludes that Typhoon Haiyan, before its landfall at Guiuan, has 10-minute sustained winds of 317 kph and 1-minute sustained winds of 352 kph. At its landfall at Leyte, Typhoon Haiyan has 10-minute sustained winds of 290 kph and 1-minute sustained winds of 351 kph. The minimum central pressures were determined to be 872.2 mbar at 5:10 am and 868.5 mbar at 4:10 am.

The wind vulnerability map during the passage of Typhoon Haiyan revealed that the current wind design specifications were not enough to prevent damage to structures.

Using statistical analysis over the historical data of Typhoon strengths and using the maximum sustained winds estimated in the forensic analysis, the existence of storms with the same intensity, whether it will hit land or not, on the Northwestern Pacific Basin as Typhoon Haiyan was analyzed to have a return period of 500 years.

Using statistical analysis over the historical data on weather stations in the Visayan Region, the winds brought by Typhoon Haiyan has a return period of possibly more than 5600 years over the affected areas.

REFERENCES

[1] Y. OKUDA, H. KIKITSU, H. OKADA, M. MATSUI, Y. TAMURA, M. TSUCHIYA, M. YAMAMOTO, K. HAYASHIDA and K. KONDO, 'High Wind Damages in Miyako Islands under Typhoon Maemi (2003)', Wind Engineers, JAWE, vol. 2003, no. 97, pp. 49-60, 2003.
[2] H. KIKITSU, K. FUJII and Y. WAKIYAMA, 'High Wind Damages in Hachijo Island under Typhoon 15th, 2003', Wind Engineers, JAWE, vol. 2004, no. 98, pp. 55-64, 2004.
[3] J. Morgerman, 'Super Typhoon HAIYAN in Tacloban City & Leyte, Philippines', iCyclone.com, vol. 1, no. 1, 2015.
[4] J. Masters, 'Haiyan's True Intensity and Death Toll Still Unknown | Dr. Jeff Masters' WunderBlog', Wunderground.com, 2015. [Online]. Available: http://www.wunderground.com/blog/JeffMasters/comment.html?entrynum=2580. [Accessed: 10- Nov- 2015].
[5] Upload.wikimedia.org, 2015. [Online]. Available: https://upload.wikimedia.org/wikipedia/commons/2/2f/Typhoon_Haiyan_2013_making_landfall.gif.[Accessed: 10- Nov- 2015].
[6] B. Cushman-Roisin and J. Beckers, Introduction to geophysical fluid dynamics. Waltham, MA: Academic Press, 2011.
[7] C. Dyrbye and S. Hansen, Wind loads on structures. Chichester: J. Wiley, 1997.
[8] T. Olander and C. Velden, 'The Advanced Dvorak Technique: Continued Development of an Objective Scheme to Estimate Tropical Cyclone Intensity Using Geostationary Infrared Satellite Imagery', Wea. Forecasting, vol. 22, no. 2, pp. 287-298, 2007.
[9] V. Dvorak, 'Tropical cyclone intensity analysis using satellite data', 1984.

[10] C. Risien and D. Chelton, 'A Global Climatology of Surface Wind and Wind Stress Fields from Eight Years of QuikSCAT Scatterometer Data', J. Phys. Oceanogr., vol. 38, no. 11, pp. 2379-2413, 2008.
[11] B. Harper, J. Kepert and J. Ginger, 'Guidelines for converting between various wind averaging periods in tropical cyclone conditions', World Meteorological Organization, p. 1555, 2010.
[12] J. Holmes, Wind Loading of Structures, 2nd ed. Hoboken: Taylor & Francis Ltd. Methodological Peace, 2007.
[13] Z. Zhang, J. Li and P. Zhuge, 'Failure Analysis of Large-Scale Wind Power Structure under Simulated Typhoon', Mathematical Problems in Engineering, vol. 2014, pp. 1-10, 2014.
[14] G. Holland, 'An Analytic Model of the Wind and Pressure Profiles in Hurricanes', Mon. Wea. Rev., vol. 108, no. 8, pp. 1212-1218, 1980.90(12-15), pp.1555-1568.
[15] T. Fujii, J. Maeda, N. Ishida and T. Hayashi, 'An analysis of a pressure pattern in severe Typhoon Bart hitting the Japanese Islands in 1999 and a comparison of the gradient wind with the observed surface wind', Journal of Wind Engineering and Industrial Aerodynamics, vol. 90, no. 12-15, pp. 1555-1568, 2002.
[16] C. Yoo and S. Lee, Stability of structures. Amsterdam: Butterworth-Heinemann, 2011.
[17] B. Brookes and E. Gumbel, "Statistical Theory of Extreme Values and Some Practical Applications", The Mathematical Gazette, vol. 39, no. 330, p. 341, 1955.
[18] I. Gringorten, "A plotting rule for extreme probability paper", J. Geophys. Res., vol. 68, no. 3, pp. 813-814, 1963.
[19] N. Lakshmanan, S. Gomathinayagam, P. Harikrishna, A. Abraham and S. Chitra Ganapathi, "Basic wind speed map of India with long-term hourly wind data", CURRENT SCIENCE, vol. 96, no. 7, 2009.
[20] National structural code of the Philippines. [Manila?]: ASEP, 2010.
[21] J. Agar, J. Hernandez and W. Mata, “Estimating Typhoon Haiyan’s Wind Speeds Using Windicators”, Undergraduate Thesis, 2015