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Estimating Typhoon Haiyan's Wind Speeds Using Windicators

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Abstract – *Typhoon Haiyan of 2013, by the time it struck the Philippines, has been regarded as one of the strongest tropical cyclones. Yet there are discrepancies between the estimated maximum wind speeds reported by the weather agencies worldwide, causing widespread confusion. In the absence of credible in-situ wind speed measurements that will provide the storm's true strength, "Windicators" are analyzed. Windicator, coined from the terms wind and indicator, are existing simple structures of interest through failure analysis would directly provide an estimate of the wind speeds that brought the bending or even toppling of the structure. The study includes an expansive field survey on affected areas, excluding inundated areas, in Region VIII, where the storm made landfall at peak intensity. Computational Fluid Dynamics (CFD) was used to determine the wind speeds that initiated the failure, either yielding or localized buckling. The direction of failure/deformation is taken into account in order to establish an estimated time of failure, which in turn directly reflects on the proximity of the storm at the time of the arrival of the winds that caused the structural failure. Using digital image correlation of the satellite images or the gradient wind equation from the approximation of pressure profile of the storm, the radial profile of the storm, before and during landfall are established.This can then be used to estimate the winds on the cyclone's eyewall from the computed wind speed experienced by the windicator. The study determined through analysis of five windicators, that Typhoon Haiyan has 1-minute sustained winds of 351 kph, 10-minute sustained winds of 290 kph, both estimated intensities before landfall at Leyte, and a minimum central pressure of 872.2 mbar, using Holland's approximation and from the recorded pressure of 910 mbar from Guiuan Weather Station of PAGASA.*

Keywords—Windicators; Typhoon Haiyan; Forensic Structural Analysis; Computational Fluid Dynamics; Wind Engineering; Geophysical Fluid Dynamics

I. INTRODUCTION

Last November 8, 2013, Super Typhoon Haiyan (Philippine 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 several landfalls at its peak intensity.

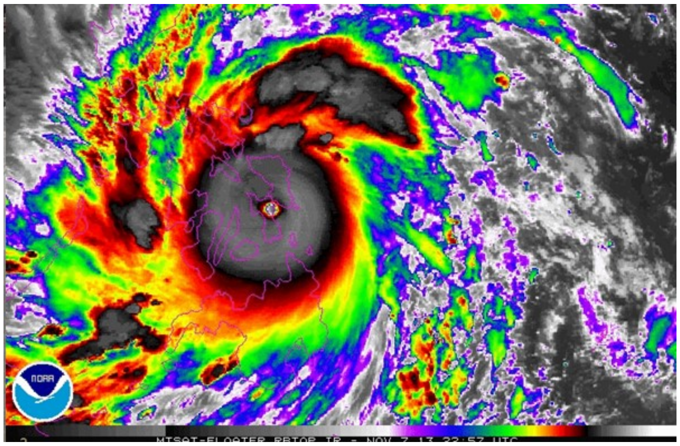


Figure 1. Infrared Image of Typhoon Haiyan(Source: National Oceanic and Atmospheric Administration [1])

The storm, with infrared image shown in Figure 1, has been regarded as the strongest storm in existence, surpassing the 1-minute sustained winds of 305 kph from Typhoon Tip (Philippine Name: Welpring) in 1979.It was estimated to have 1-minute sustained winds of 315 kph, which was assessed by the automated Advanced Dvorak Technique [2], which evaluated the storm's intensity by analyzing the intensity of the convection and the storm's shape. However, both the Japan Meteorological Agency (JMA) and the Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA), with their Doppler sensing techniques, estimated Haiyan's strength as having 10-minute sustained winds of 235 kph, which made Haiyan weaker compared to Typhoon Tip having recorded 10 -minute maximum sustained winds of 280 kph (JMA). 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 [3]. The difference of the estimates caused widespread confusion, as it put into question the preparedness of the affected areas against a storm of a caliber like Haiyan.

In-situ meteorological measurements were necessary to clear the discrepancy but unfortunately most of the weather instruments were damaged during the passage of Typhoon Haiyan. Only the barometric pressure readings from some areas remained. These were recorded during the full onslaught of Typhoon Haiyan at peak intensity namely: the 955.6 mbar [4] 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 [5].

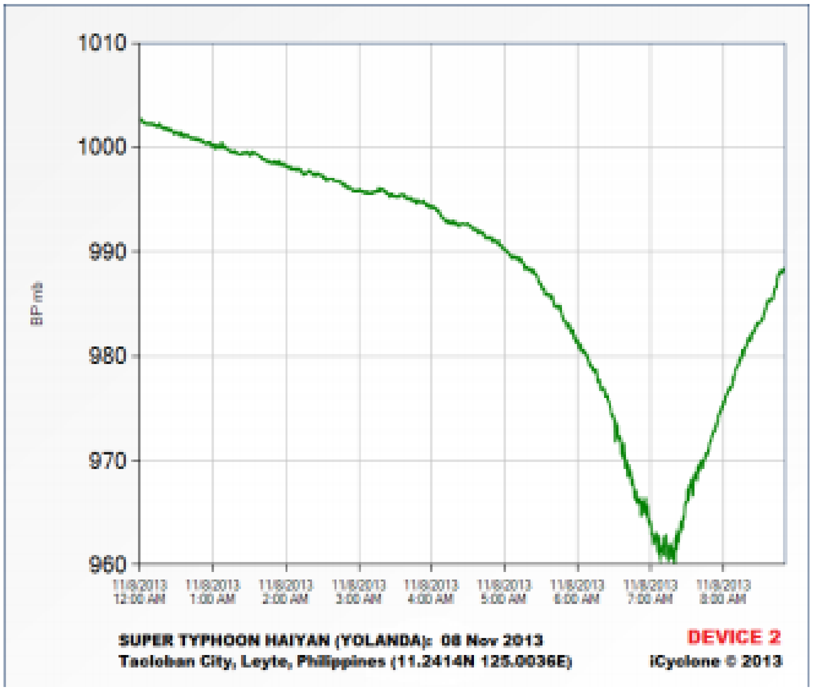


Figure 2. Barograph Reading in Tacloban City [3]

The recording of wind speeds by weather stations was abruptly stopped because these stations suffered physical damages from the winds of Typhoon Haiyan. Bantayan Island recorded winds of 77.4 m/s at 9:30 am (Nov 8, 2013, PST) as shown in Figure 3, which was recorded after Haiyan weakened considerably. Guiuan Station, before the recording of wind speed was stopped, recorded winds of 53 m/s at 4:10 am, hours before its first landfall at Guiuan.

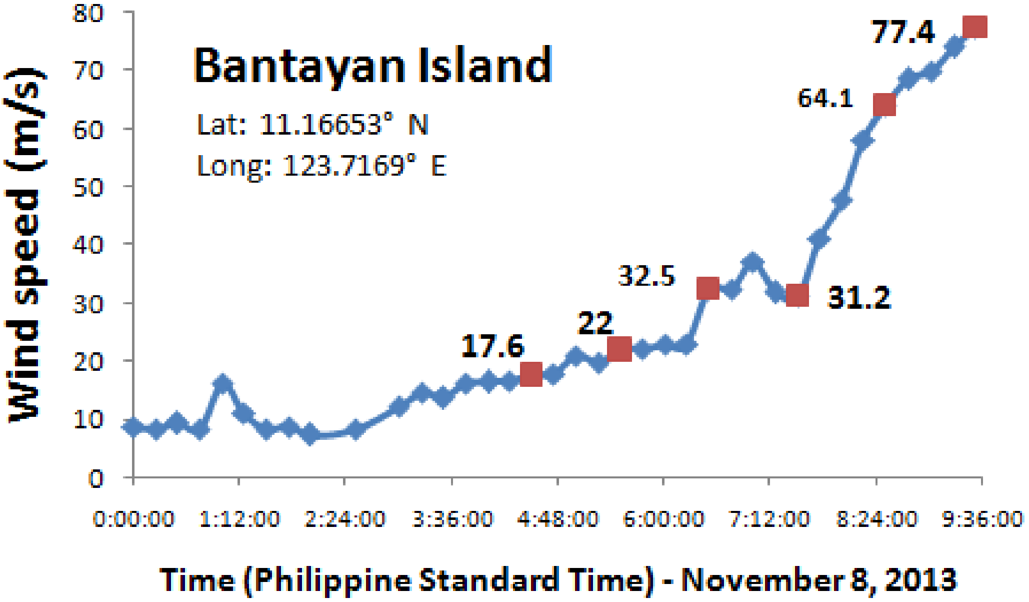


Figure 3. Wind Speed Reading – Bantayan Island [Source: DOST – Advanced Sciences and Technology Institute (ASTI)]

With the satellite estimation techniques causing confusion on the wind speed estimates, the reconnaissance missions ceasing by the mid-1980's in the Western Pacific, and with ground surface measurements abruptly stopped during the storm's passage, only the forensic analysis [6][7] of windicators remains as a viable option to estimate its wind speeds(Figure 4). Windicators, which was coined by combining terms 'wind' and 'indicators', are simple structural objects of interest whose failure provides anestimate of the wind speeds that caused the failure. These, in turn, would provide estimates of the intensity of Typhoon Haiyan by the time it made landfall.

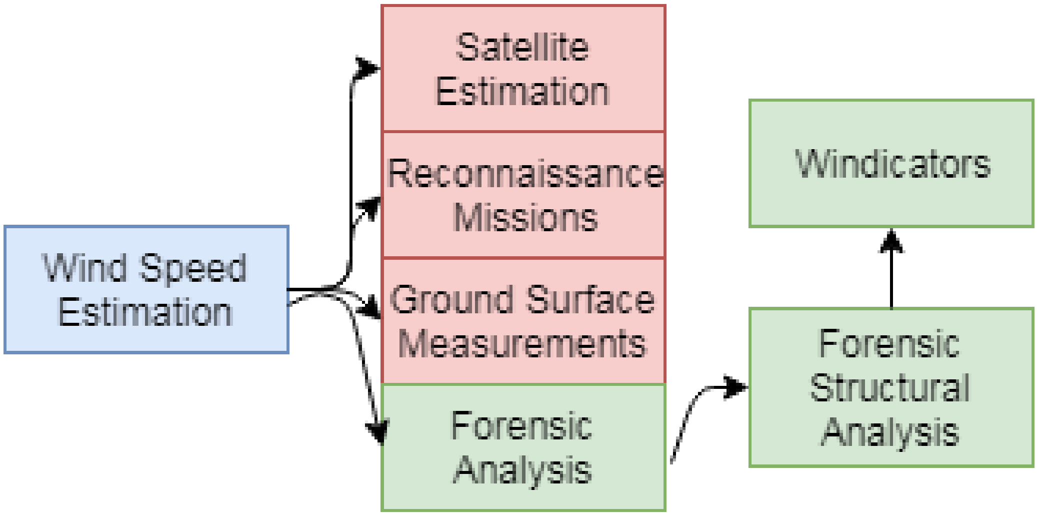


Figure 4. Conceptual Framework

II. FORENSIC ANALYSIS

A. Field Survey

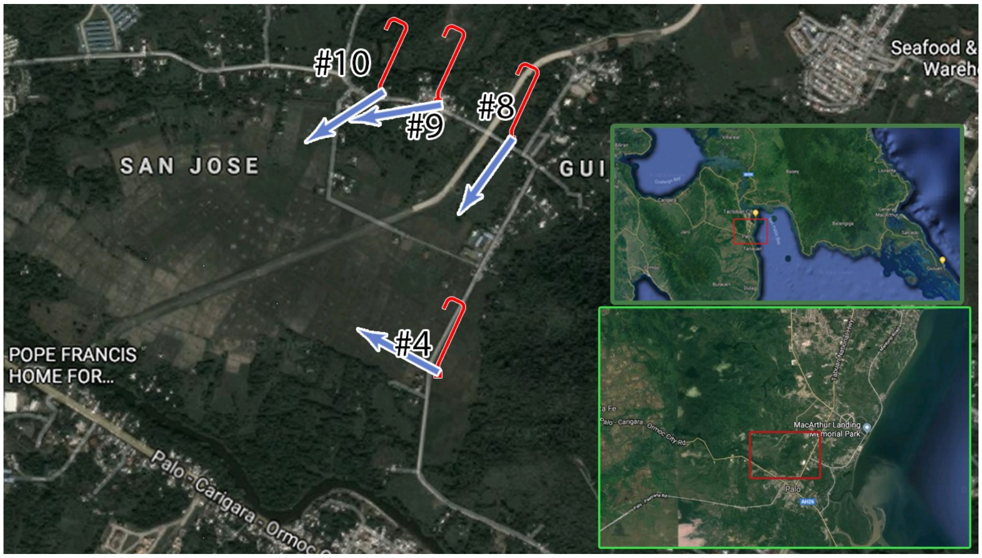


Figure 5. Location of the Windicators in Palo, Leyte[Source: Google Maps]

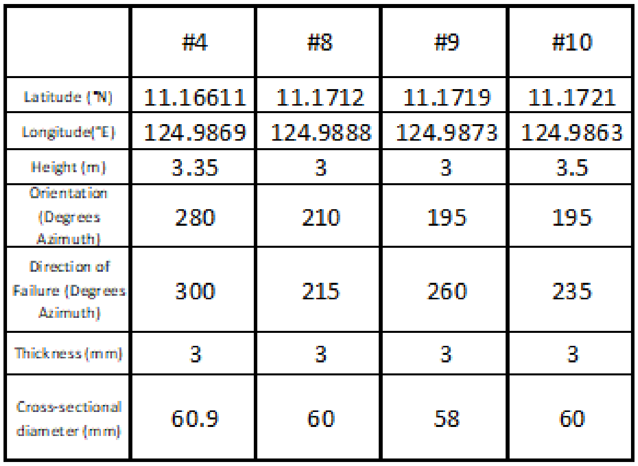
A field survey was performed on the affected areas. Non-inundated areas were surveyed to look for windicators. The area was further narrowed down to the areas between Brgys. Guindapunan and San Jose in Palo, Leyte (Figure 5).

The windicators selected are street lamp posts that have the shape of the letter P, peculiar only the area. Listed in Table 1 are the geographical coordinates and the geometric properties of samples takenfrom the windicators.

Figure 6. Windicators (L to R: #4, #10, #9 and #8)

To take into account the possible tampering of the samples, Windicator #9, which was being used as an anchor for the residents’ clothesline, was included in order to determine how the tampering would affect the analysis.

Table 1. WINDICATOR DETAILS



	#4	#8	#9	#10
Latitude (°N)	11.16611	11.1712	11.1719	11.1721
Longitude(°E)	124.9869	124.9888	124.9873	124.9863
Height (m)	3.35	3	3	3.5
Orientation (Degrees Azimuth)	280	210	195	195
Direction of Failure (Degrees Azimuth)	300	215	260	235
Thickness (mm)	3	3	3	3
Cross-sectional diameter (mm)	60.9	60	58	60

B. Material Testing

The samples were taken back to the lab for material testing. In accordance with ASTM A370-21419, a tensile test was performed on the samples, using a Universal Testing Machine (UTM). Figures 7 and 8 show the sample taken from a windicator and coupons tested in the UTM.

Figure 7. A sample taken from a windicator

Figure 8. Flattened coupons that were cut from the sample, namely Sample 1 (left) and Sample 2 (right)

Table 2. TENSILE TEST RESULTS

	Gauge Length (in)	Area (mm^2)	Ultimate Strength (lbs)	σ,ult (MPa)
Sample 1	2.0000	6.1600	6560.0000	473.7100
Sample 2	1.8125	7.7700	6800.0000	389.2100

Based on the ultimate strengths of the samples and referring to AISC Table 2-1, the material was identified to be A36 steel. Due to limitations in the number of samples, a deterministic approach instead of a probabilistic one was used in representing the properties of the material for analysis.

C. Computational Fluid Dynamics (CFD)

To provide information about how wind flows in given situations, Computational Fluid Dynamics (CFD) was used to determine the external pressures experienced by the structure under a simulated wind flow.

CFD employs the continuity equation (1) to numerically determine the balance of mass within the domain as illustrated in Figure 10, and the Navier-Stokes equation (2) to numerically determine the balance of forces within the same domain, which in turn would determine the external pressures.The turbulence model used was the Reynolds Averaged Navier Stokes model, and to improve the mixing length model, the k-epsilon model was used, which considered the turbulent kinetic energy as well as the energy dissipation.[8]

$$u_{i,i} = 0 \qquad (1)$$

$$\rho \frac{\partial u_i}{\partial t} + \rho u_{i,j} u_j - (\mu + \mu_T) u_{i,jj} = -\frac{\partial p}{\partial x_i} \qquad (2)$$

Where

u_i = wind speed with respect to the x_i-axis
ρ = density of air
μ = viscosity
μ_T= turbulence viscosity

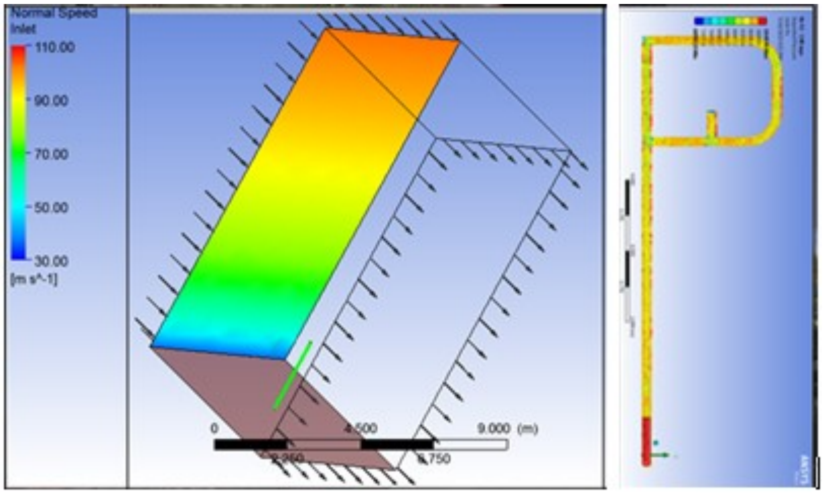


Figure 9. Wind Simulation (left) and External Pressures (right)

Using CFD, wind loads were simulated over the structure following the logarithmic law [9] for the wind speed profile in order to obtain the external pressures applied on the structure using static wind load analysis as shown in Figure 9.

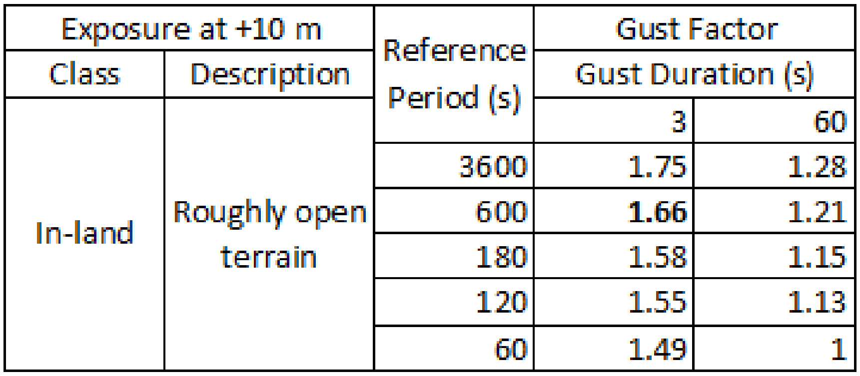
$$\bar{U}(z) = \frac{C_{SD}^{\;0.5}}{0.4} \times \bar{U}_{10} \times ln(\frac{z}{z_0}) \tag{3}$$

$\bar{U}(z)$ – average wind speed at height z
z_0 – roughness length (m) [3]
C_{SD} – surface drag coefficient [3]
$\bar{U}_{10}$ – average wind speed at height z=10 m

Using the external pressures, the forces and moments induced in the windicator were determined. The von Mises stresses were used as the failure indicator, which was progressive yielding. It was assumed that yielding propagates once the onset failure was reached, which was the safety factor (ratio of the yield stress to the von Mises stress) becoming less than 1 for the critical elements of the structure, which are situated on the leeward side of the base of the structure.

The terrain was considered a rough terrain (z_0 = 0.5 m and C_{SD} = 0.019) [3] for the analysis. On Figures 10 to 13, the safety factor (ratio of the yield stress to the von Mises stress[10]) of some leeward elements vs the wind speed are plotted(the yellow area indicating the range of values from the other critical elements). The winds simulated were 3-second gust and therefore must be converted to 10-minute sustained averages(Table 4) using the conversion factors recommended by WMO (using Table 3). Because the exposure was inland the conversion factor used was 1.66.

Table 3. CONVERSON FACTORS RECOMMENDED BY WMO [3]



Exposure at +10 m		Reference Period (s)	Gust Factor	
Class	Description		Gust Duration (s)	
			3	60
In-land	Roughly open terrain	3600	1.75	1.28
		600	**1.66**	1.21
		180	1.58	1.15
		120	1.55	1.13
		60	1.49	1

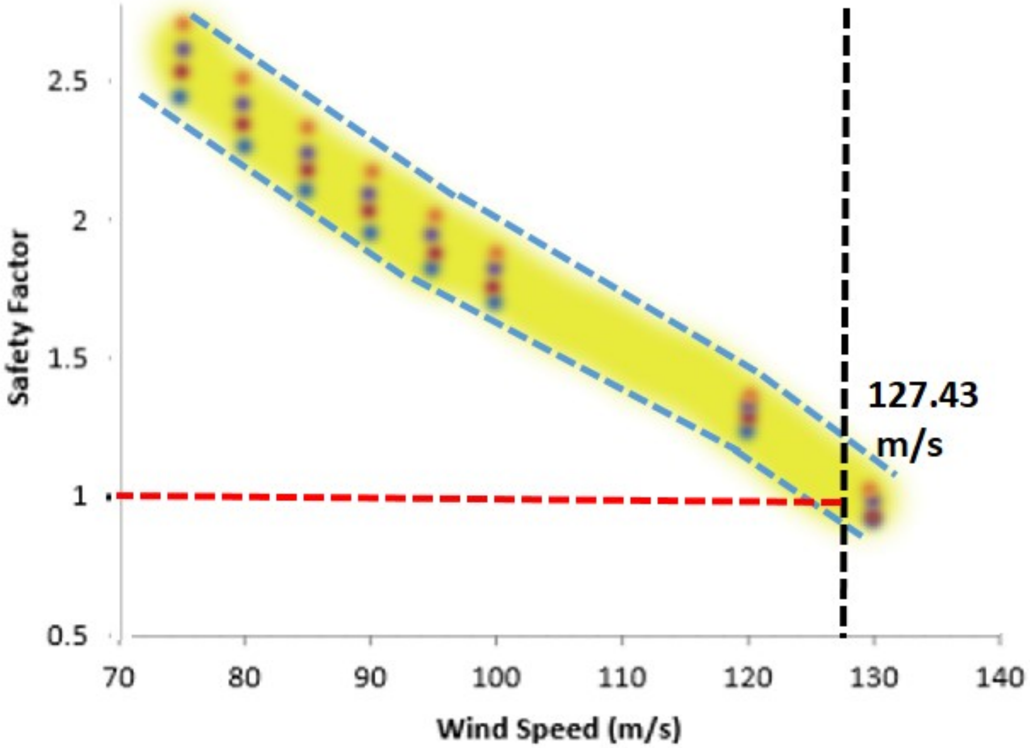


Figure 10. Wind Speed v Safety Factor for Windicator #8

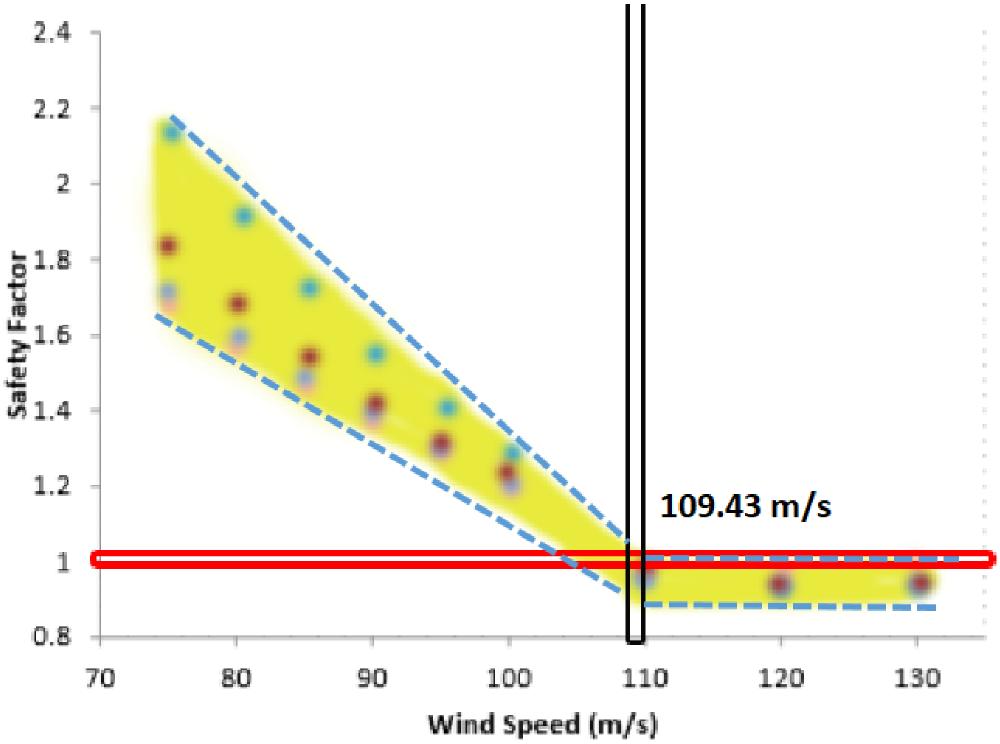


Figure 11. Wind Speed v Safety Factor for Windicator #4

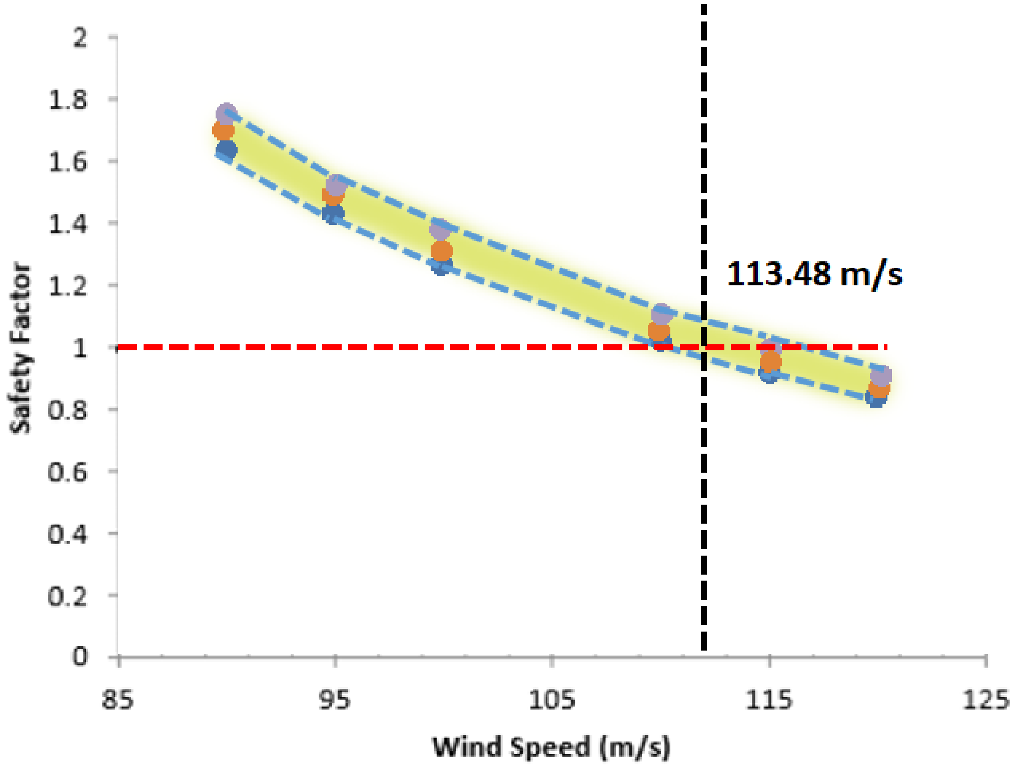


Figure 12. Wind Speed v Safety Factor for Windicator #10

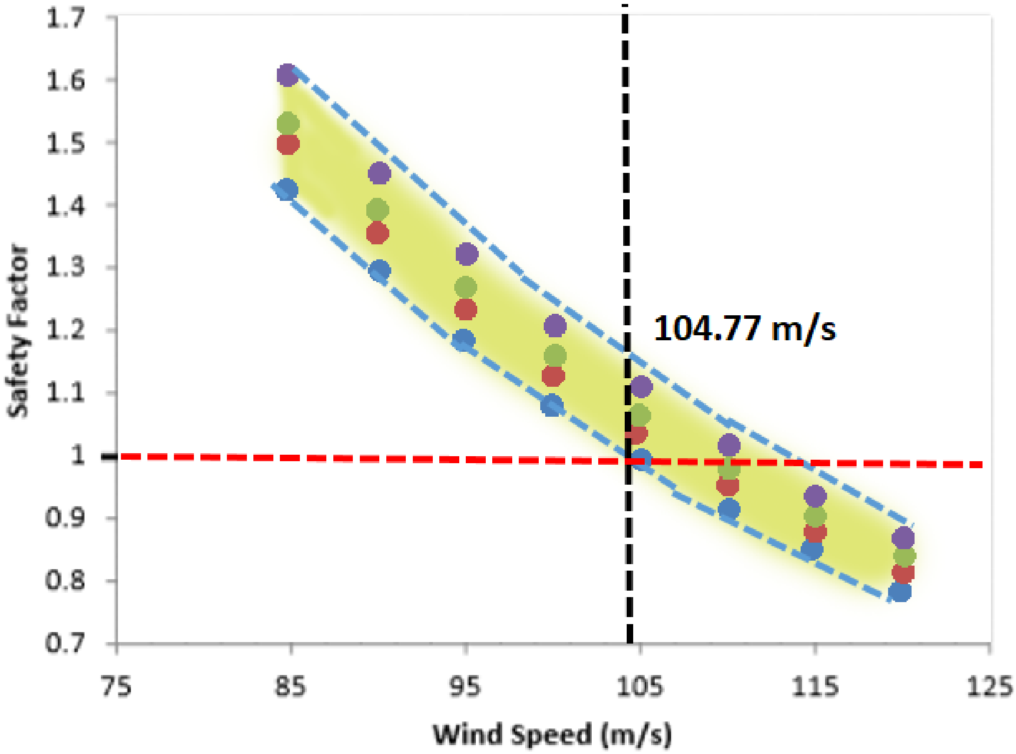


Figure 13. Wind Speed v Safety Factor for Windicator #9

Table 4. Results of CFD Analysis

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**

Geophysical Fluid Dynamics

To determine the time of arrival of the winds that caused failure of the windicator, the direction of failure of the structures was estimated from the location of the elements that experienced compressive failure, which were on the leeward side of the base of the windicator cross-section [11].

Next was to consider the effect of the Ekman Spiral, which is the change in direction of the winds as it descends to the boundary layer [12], where:

$$u\ (z) = U_{gr} \times (1 - (e^{-\beta} cos(\beta)) \tag{4}$$

$$v\ (z) = U_{gr} \times e^{-\beta} \times sin(\beta) \tag{5}$$

$$\beta = z\ (\frac{f}{2v_e}) \tag{6}$$

u – magnitude of the wind speed tangential to the pressure isobars.
v – magnitude of the wind speednormal 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 bysubstituting(3) on the equation of Lettau (1959) [8]:

$$H_{ABL} = e^{(2.5(f z_0{}^{-0.09})+\ln(z_0)} \tag{7}$$

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 equation (5) to zero:

$$H_{Ekman} = \pi\sqrt{\frac{2v_e}{f}} \tag{8}$$

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 of November 8, 2013, 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 (4), (5), (6) and (7), the time of failure was estimated based on the direction of failure and the windicators' location (Figure 5). Using the estimated time of failure of the windicators, the distance from the storm's center at the time of failure was estimated for each windicator.

Table 5. TIME OF FAILURE AND STORM'S PROXIMITY

Windicator	Gust (m/s)	10-min sustained wind (m/s)	Time of Failure in Nov 8, 2013 (PST)	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**

E. 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) [13]:

$$U_{gr} = -\frac{|fr|}{2} + \sqrt{\left(\frac{fr}{2}\right)^2 + \frac{(p-p_o)AB}{\rho_{air}\, r^B}\exp\left(\frac{-A}{r^B}\right)} \tag{9}$$

$$\frac{p-p_o}{p_n-p_o} = \exp\left(\frac{-A}{r^B}\right) \tag{10}$$

Using the pressure points discussed at section I and from Figure 2, and assuming the pressure on the outer edges of the storm to be at 1000 mbarinequation (10) based on the estimates of JTWC, the values of A and B were determined to be equal to 2445717313577890000 and 4.14868822191798, respectively. Using the data from Windicator #10 in equation (9) yielded a value of 68.39 m/s, relatively close to the 68.36 m/s 10-min sustained wind speeds on Windicator #10, based from Table 4.

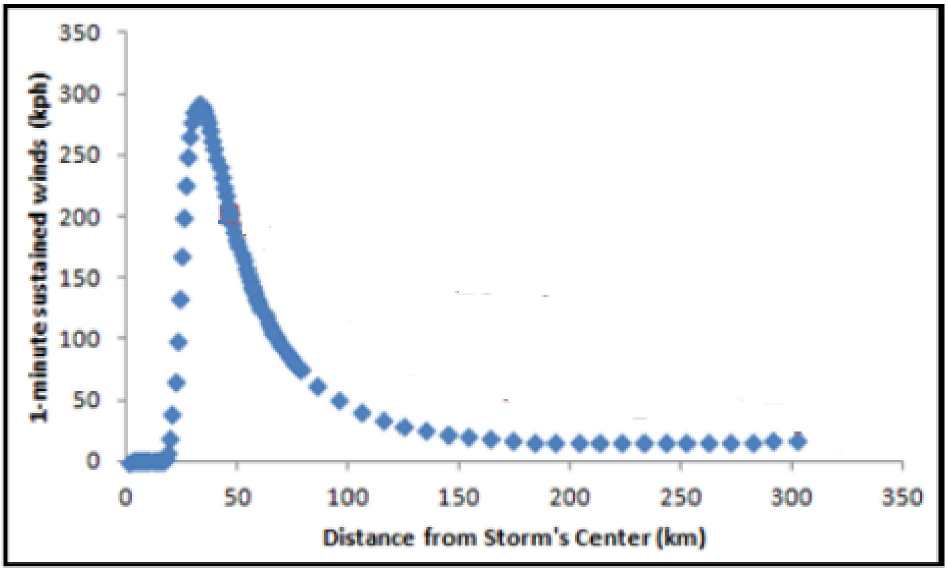


Figure 14. Velocity Profile of TY Haiyan (7:02 am)

Equation (9) was used not only to determine the maximum wind speeds but also the minimum central pressure of Typhoon Haiyan at the time of failure of the windicators (Table 6) [14].

Table 6. Summary of Values

	#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

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 causing errors in comparison to the model.

Using the 910 mbar pressure reading on Guiuan station at 5:10 am in equation (10), the minimum central pressure of Typhoon Haiyan at that time was estimated to be equal to 872.2 mbar, which entailed 10-minute sustained winds of 311 kph.

Also using the 190 kph wind speed data recorded at Guiuan station at 4:10 am in equation (9) yielded a minimum central pressure of 868.5 mbar, which entailed 10-minute sustained winds of 317 kph.

III. SUMMARY

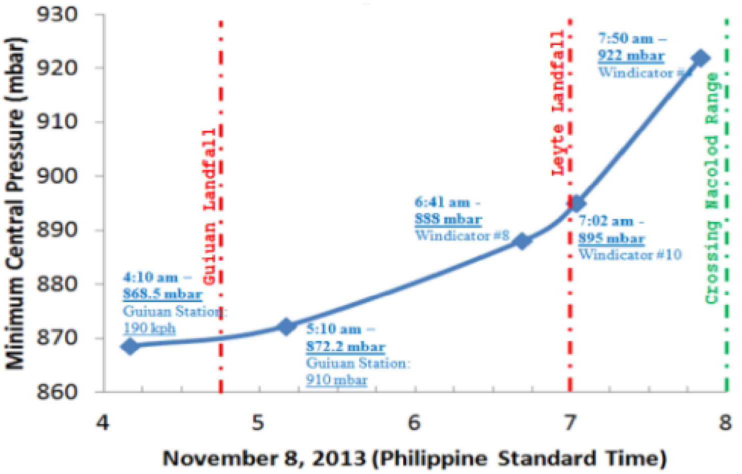


Figure 15. Minimum Central Pressure vs Time

The minimum central pressure, the barometric pressure measured at the storm's center, is a physical factor that has also been used in meteorology to assess the strength of tropical cyclones. The lower minimum central pressure implies a stronger tropical cyclone, as well as it's capacity to induce storm swells – a phenomenon where differences in atmospheric pressure caused sea levels on the storm's center to rise. The timeline of the minimum central pressure of Typhoon Haiyan is plotted in Figure 15.

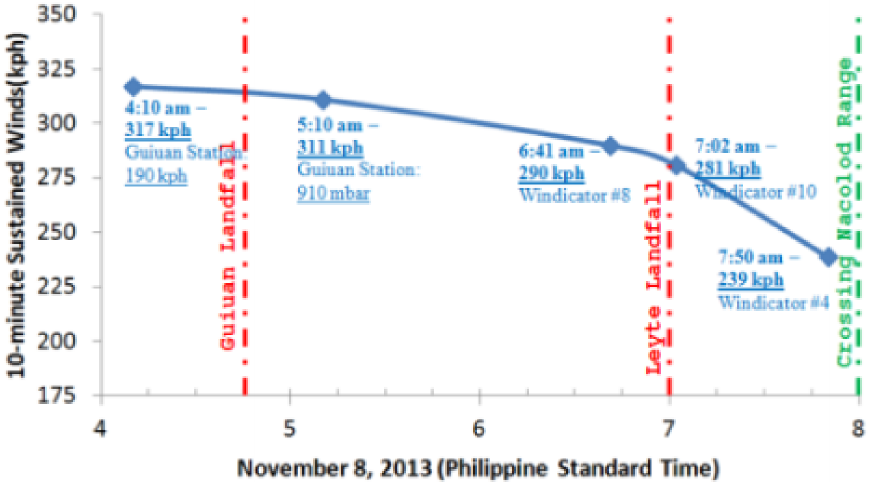


Figure 16. Maximum Sustained Winds vs Time

On the other hand, the magnitude of the maximum wind speed is related to the pressure gradient. Steeper pressure gradients imply higher maximum sustained winds. The maximum sustained winds vs time is plotted in Figure 16. Taking into account the direction of the winds proved to be vital in determining the strength of Typhoon Haiyan as it gives a clue on the proximity of the cyclone at the time the windicators experienced those winds.

Also taking into account the direction of the failure proved to be crucial in determining whether the structure was tampered before the forensic analysis as a mismatch with the storm model was observed.

With the storm's wind and pressure profile derived from the remaining meteorological data and verified using the windicators, the maximum winds can be reflected from the minimum central pressure. Figure 16 showed the timeline of the maximum sustained winds. Strong winds induce physical effects on the sea as sea levels rise. That effect is called a storm surge. Both the storm swell and the storm surge caused the catastrophic rise in the sea level that day that caused the deaths of many people.

Through Figures 15 and 16, the study managed to capture how Typhoon Haiyan weakened as it made its approach and as it traversed through land.

The study concludes conservatively from the windicators that Typhoon Haiyan has 10-minute sustained winds of 290 kph and 1-minute sustained winds of 351 kph with a minimum central pressure of 872.2 mbar, although projections from the remaining in-situ data suggest that the Typhoon Haiyan might be stronger, nevertheless, the strength of Typhoon Haiyan was proven to be unprecedented, way beyond the scale of the disaster preparations that were made.

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