MAPPING THE VULNERABILITY OF LOW-COST HOUSE ROOFS IN MALATE, METRO MANILA DUE TO EXTREME WIND SPEEDS

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ABSTRACT

Every year about fifteen to twenty typhoons enter the Philippine Area of Responsibility, causing devastating effects to residential structures in many parts of the country. The strong uplift force of the wind and the inadequate uplift resistance of the roof are the main reasons of roof failure during extreme wind speeds (typhoons). In this regard the authors investigated the probability of pullout and pullover failures of roof panels in low-rise residential structures when subjected to extreme wind speeds. The area studied is part of Malate Manila, Philippines, where many structures appear to be non-engineered or not designed according to applicable national structural codes. The extreme wind speeds were modeled using the generalized extreme value distribution (GEV) using 50 years of annual wind speed maxima from the Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA).

A survey was conducted on 42 residential houses in the study area. Galvanized iron roofs similar (rusted roofs) to the ones used in the study area were also tested for tensile strength. The roof panel resistance was obtained using the wind load provisions of the National Structural Code of the Philippines (NSCP 2010) while the wind uplift pressures for different typhoon return periods were obtained using NSCP 2010 and the GEV model. Finally the probability of failure for each roof was obtained by Monte Carlo simulation of the performance function, resistance minus load. The results obtained show that pullout failure is the main mode of failure attaining a maximum of 27.2% for a 150-year wind return period (200 km/h wind speed).

A risk curve was also obtained using the annualized expected loss and the average annual exceedance probability of the wind speeds. Finally a map in Geographic Information System (GIS) format was developed that can help local authorities identify house roofs that are vulnerable to strong typhoons. This hazard map may also help residents strengthen their roofs to lessen damage during typhoons.

Keywords: typhoons, probability of failure, generalized extreme value distribution, GIS

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1. INTRODUCTION

The Philippines is situated in the typhoon belt and thus experiences more than fifteen typhoons every year. In 2006 the infamous typhoon "Milenyo" struck the islands of Luzon, bringing about massive destruction to in various locations. It was considered the strongest typhoon to hit Metro Manila in 11 years, with gust wind speed reaching up to 160 kph with a sustained speed of 55 kph (PDI 2006). In 2011 a total of eleven typhoons struck the Philippines leaving 149,570 houses partially damaged with 38,380 houses totally damaged (NDRRMC 2011).

Among other structural components roof panel components and cladding exhibit least resistance against uplift forces and thus are most vulnerable to extreme wind loads (Cope 2004). Recent studies have also shown that wood frame structures of roofs are generally vulnerable to failure, with roof components failing incrementally with fluctuating wind loads (Morrison et al. 2012). Many roofs in the Philippines, especially in low income areas and in informal settlements, are built using wood frames and galvanized iron sheets for the roof. During strong typhoons these roofs are at risk to pullout and pullover failures. In this regard there is a need assess the vulnerability of house roofs to extreme wind speeds especially non-engineered roof construction.

The objectives of the study are: to assess the probability of failure of specific house roofs in Malate Manila and to develop a vulnerability map in GIS format showing the failure probabilities of the roofs under various wind speeds. The study area is in Malate Manila, specifically barangays 707 to 721 as shown in Figure 1. Only low-rise residential structures up to three stories high having galvanized iron sheet roofing on a wooden roof frame will considered. Furthermore, only roof dead load and wind loads are used for the analysis. Resistances are also only dependent on the fasteners installed in the roofing systems. The zone of influence, as based on the NSCP, is taken as the largest roof zone area indicated, to have a more accurate characterization of the roof.

2. PERFORMANCE FUNCTION

The performance function G, to assess the probability of pullout and pullover failure is shown in Equation (1) where R is the uplift resistance and S is the wind load.

$$G = R - S \tag{1}$$

R and S are both random variables and will be established later in this section. The probability of failure, shown in Equation (2), can be calculated by generating sample realizations of R and S by ordinary Monte Carlo simulation. In this equation, z is the total number of sample realizations of G while z_o is the number of realizations where $G < 0$.

$$P_f = P(G < 0) \approx \frac{z_o}{z} \tag{2}$$

2.1. Uplift load on purlin

The wind pressure on the roof panels is determined using Equation (3).

$$p = 0.8 q_h [GC_p - GC_{pi}] \tag{3}$$

The variable p is the typhoon wind pressure in kPa, GC_p is the external pressure coefficient (NSCP 2010 Fig.11B -15), GC_{pi} is the internal pressure coefficient (NSCP 2010 Fig. 207-5) and q_h is the velocity pressure in kPa that can be computed using Equation (4).

$$q_h = 47.3 \times 10^{-6} K_z K_{zt} K_d V^2 I_w \tag{4}$$

where K_z is the velocity pressure exposure coefficient (NSCP 2010 Table 207-4), K_{zt} is the topographic effect factor, K_d is the wind directionality factor (NSCP 2010 Table 207-2), and I_w is the importance factor (NSCP 2010 Table 207-3) and V is the basic wind speed corresponding to a 3-second gust speed at 10 m above ground in exposure category C. The total pressure on roof is then calculated by adding DL, the roof panel load (dead load) to q_h. Finally the uplift load per purlin, S_p, is determined using Equation (5), where T_A is the tributary width of purlin.

$$S_p = T_A \left(DL + q_h \right) \tag{5}$$

Figure 1: The area of study indicated by the broken line

2.2. Generalized Extreme Value (GEV) Distribution

The random variable V in the previous equation is modeled using the GEV distribution shown below

$$H(v) = \exp\left(-\left[1 + \frac{\xi}{\sigma}(v - \mu) \right]^{-1/\xi} \right) \tag{6}$$

The parameters μ, σ (>0) and ξ of the GEV distribution are obtained using maximum likelihood estimate (MLE) of the annual extreme wind speed data of a wind station nearest the study area.

2.3. Roof Panel Resistances

2.3.1. Pullout Resistance

The pullout resistance R_W shown below is employed which is suitable for nail-to-wood purlin connections (NDS 2005)

$$R_w = w \times p \tag{7}$$

W is the withdrawal load capacity in pounds per nail and p is the penetration of the nail in inches. The reference withdrawal, w (lb/in) is determined using Equation (8), where K_w is a constant,

$$w = K_w G^{5/2} D \tag{8}$$

G is the specific gravity of wood based on oven-dry weight and volume and D is the shank diameter of the nail in inches.

2.3.2. Pullover Resistance

For the pullover resistance, R_p, the equation shown below is employed.

$$R_p = 1.5 d_w F_{u1} t \tag{9}$$

F_{u1} is the tensile strength of the member in contact with screw head or washer in MPa, t is the thickness of material in mm and d_w is the diameter of the washer or the screw head in mm.

3. DATA

The annual extreme wind speed data used in this study is shown in Figure 2. This data is fitted

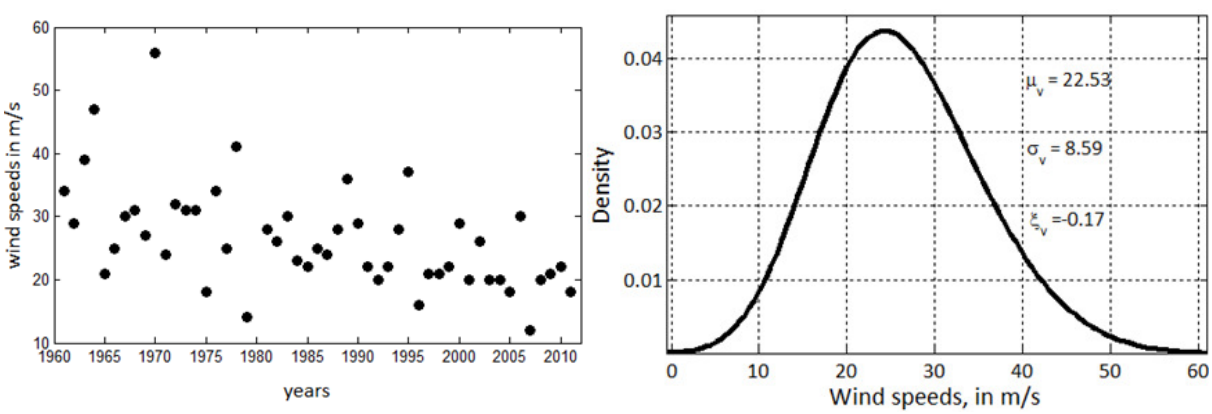

Figure 2: Extreme wind speed data at a wind station and its GEV distribution fit

to the GEV distribution and the parameters (shown in Figure 2) were estimated using MLE. The statistics of the random variables used in obtaining roof resistance are shown in Table 1. Some of these parameters were obtained through material testing in the laboratory.

Table 1: Statistics of the random variables

Random Variable	μ	σ	*Distribution type*
p	1.71	0.44	Normal
G	0.67	0.18	Normal
D	0.16	10.0	Normal
d_w	19.9	1.18	Normal
F_{u1}	147.43	55.63	Normal
t	0.79	0.099	Normal
K	1380		Deterministic

Forty-two residential houses were surveyed in the study area comprising of twenty-five mono slopes and seventeen gable type residential roofing.

4. RESULTS

Sample realizations of 10,000 points were R and S including basic wind speed v from the GEV model. These values were then used to determine the probability of pullout and pullover failures (see Figures 4 and 5). This specific case involves a mono slope type of roof with a nail spacing of 45 cm and an in-plane purlin spacing of 0.60 m. The values of the other variables are as follows: K_Z = 0.7, K_w = 1380, K = 1.0, K_Zt = 0.70, K_d = 0.85, I_w = 1.0, P_w = 0.60, GC_p = -1 and GC_{pi} = -0.55. The roof panel dead load is taken as 0.14 kPa. Based on these values the pullover and pullout failure probabilities are 0.003 and 0.051, respectively

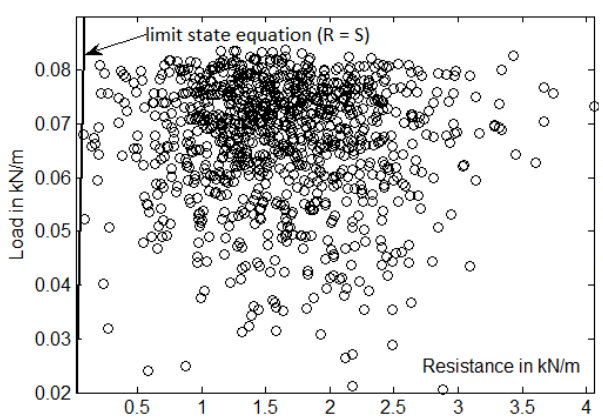

Figure 4: Pullover failure sample realization

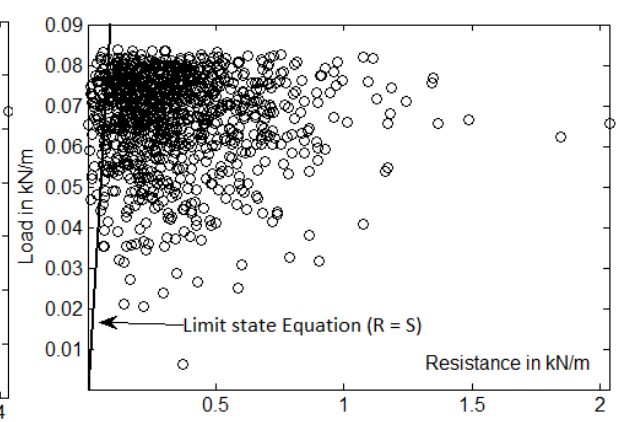

Figure 5: Pullout failure sample realization

Return wind speeds corresponding to 50, 75, 100, and 150 years were also obtained from the GEV model. These were used to determine the probability of pullout and pullover and are summarized in

Tables 2 and 3. These tables only show selected houses, including the houses with maximum and minimum probabilities of failure for each failure mode.

Table 2: Sample probabilities of pullout failure (in percent)

Roof Type	House #	180 km/h	200 km/h	50-year	100-year	150-year	GEV
Mono slope	3	19.76	27.73	17.4	23.8	26.8	1.48
	10	16.98	23.92	15.2	20.0	23.6	1.17
	26	6.56	11.82	3.4	7.6	11.4	0.48
	37	1.95	4.96	1.8	3.0	3.6	0.26
Gable	8	2.82	6.76	1.8	4.0	4.6	0.29
	12	1.27	3.48	1.0	1.8	2.6	0.21
	27	3.35	7.68	2.0	4.6	6.0	0.3
	36	0.26	0.58	0.4	0.4	0.8	0.11

Table 3: Sample probabilities of failure in pullover (in percent)

Roof Type	House #	180 km/h	200 km/h	50-year	100-year	150-year	GEV
Mono slope	3	0.69	0.85	0.8	0.8	0.8	0.41
	10	0.61	0.77	0.6	0.8	0.8	0.41
	26	0.52	0.56	0.2	0.4	0.4	0.36
	37	0.49	0.52	0.2	0.2	0.2	0.35
Gable	8	0.49	0.52	0.2	0.2	0.4	0.34
	12	0.46	0.51	0.2	0.2	0.2	0.34
	27	0.45	0.47	0.2	0.2	0.4	0.35
	36	0.42	0.45	0.2	0.2	0.2	0.33

For the pullout failure mode, the resistance mainly depended on nail penetration, number of nails per purlin, and number of purlins. The average nail spacing for most of the houses is 30cm and the number of purlins varies from 5 to 18. The probabilities of failure for mono slope roofs have an average of about 12%, 18% and 1% while gable roofs have 1%, 3% and 0.2% for specific wind speeds of 180 km/h, 200 km/h and from the GEV simulation, respectively. Based on the results for pullout failure, mono slope roofs are generally more prone to failure than gabled roofs.

In terms of pullover, this failure mode also had the same behavior as the pullout failure mode: mono slope roofs still have greater values for probabilities of failure than gable type roofs in this failure mode. The values obtained for pullover failure are relatively smaller than pullout failure, thus clearly identifying pullout failure as the governing failure mode.

5. RISK CURVE

The costs of reconstruction of the roof panels per house, based on the probabilities of failure that governed, between the pullover and pullout failure, are then estimated. The estimation of cost gives a summary of the equivalent cost of damage in percentage corresponding to the probability of failure for each house roof. It is computed by getting the equivalent roofing area, adjusted by an overlap ratio for the galvanized iron roofing sheets of 5.25 percent (Fajardo 1995). Using the individual house data, and the average cost of repair materials from local hardware, the maximum cost is around 7000 Philippine Pesos for House #14 under a 150-year return extreme wind speed.

The total cost of reconstruction for all 42 houses for each return period can then be obtained. The four loss-probability pairs are then fitted to an exponential function as shown in Figure 6

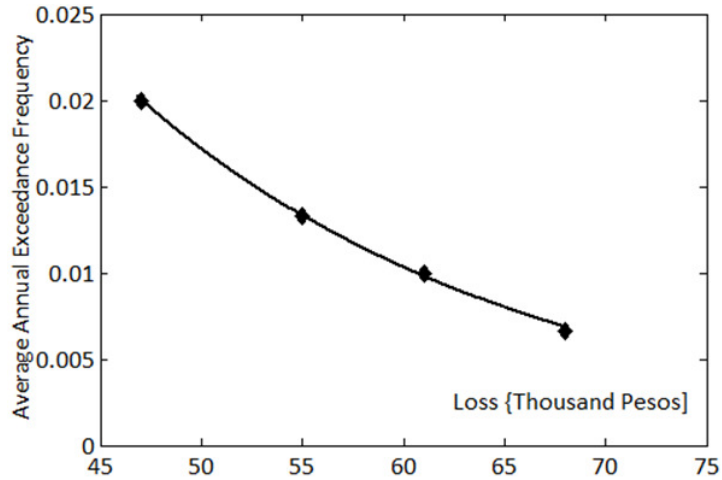

Figure 6: Risk curve for the area of study

6. GIS MAP

Finally the results are stored in a GIS database which is matched with real-world coordinates where the data recorded include the address, latitude, longitude, roof height, type of design of roof and the pullout and pullover probabilities and the reconstruction cost considering all the *n*-year return periods.

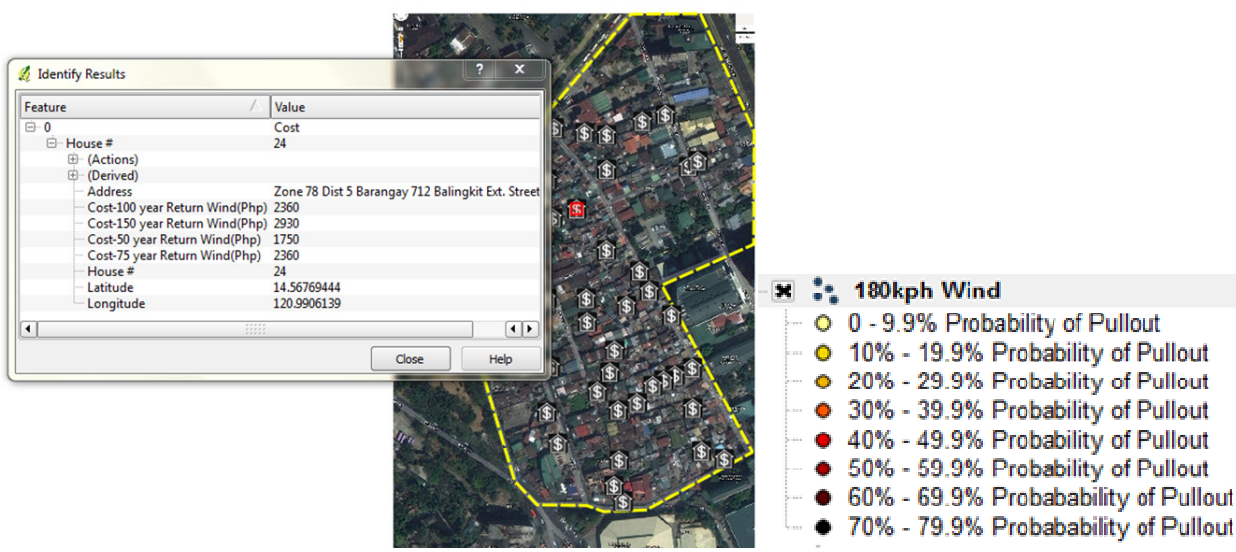

Figure 7. Probability of failure in GIS database

Figure 7 shows a typical feature of the developed GIS database. The circular markers represent the range of probabilities of failure for the *n*-year return wind speed. These markers are located in the

map in the locations of the specific houses under the study, and would change in color for each wind speed to represent the range of probability of failure the house is in under a particular wind speed.

7. CONCLUSIONS

This study highlights the need to study pullout and pullover probabilities of failure of house roofs especially for non-engineered structures and for informal dwellings. The result show that pullout failure governs and the inadequacy should therefore be strengthened. The extreme loads are also increasing in magnitude in recent years, with the strongest typhoon recorded at 160 km/h. In this case these is a big chance that design wind speed for old structures value will be exceeded and would mean a higher probability of failure of roofs.

With the knowledge on likelihood of roofs failure under *n*-year extreme wind speeds and the data summarized in a GIS format, this will help residents as well as local authorities mitigate these risks of roof failure during strong typhoons.

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