PHILIPPINE ENGINEERING JOURNAL
PEJ 2020; Vol. 41, No. 2: 39-54

Proposed Localized Wind-Driven Rain Test Parameters for Building Envelopes in Metro Manila

Homer Sadie and Nathaniel B. Diola
Institute of Civil Engineering, College of Engineering, University of the Philippines Diliman
Quezon City, 1101 Philippines

Abstract – *Rainwater intrusions in building envelopes have been recognized as the primary source of material deterioration inside buildings. These occurrences are partially attributed to wind-driven rain (WDR) scenarios. Local testing procedures and parameters to assess systems of building envelopes against WDR and its contributing leakage have not yet been established. After adapting international methodologies, a set of testing parameters are calculated. Parameters are pairings of spray rates and static pressures associated with return period for Metro Manila. The flow rates range from 5.89-16.05 L/min·m*^{2}*, while the static pressure pairings range from 90 to 481 Pa for considered return periods of 2, 5, 10, 20 and 30 years. These calculated values are generally higher than the endorsed minimum from several ASTM standards and comparable to other testing parameters used in other countries. Therefore, the usage of preset WDR test parameters from the ASTM standards, might not reflect the expected climate event specific for Metro Manila.*

Keywords – wind-driven rain, water leakage, static pressure, test parameters, Metro Manila

I. INTRODUCTION

One primary function of a building envelope is to protect the inhabitants and fixtures inside against severe weather or environmental conditions. Failure in performance of building facades is attributed to several reasons, one of which is the lack of understanding in the behavior of building envelopes compounded by certain climate conditions such as wind-driven rain (WDR). [1-4] Internationally, WDR is widely accepted as a potentially damaging source of moisture leakage inside a building. [5] Building enclosures in the Philippines are highly susceptible to WDR, as tropical cyclones pass through its Area of Responsibility (AR) on an average of 20 per year. [6]

Wind-driven rain is a term used to describe rain quantities or droplets being given a horizontal velocity component by the wind which interacts with building façades that sometimes induce water intrusions in the building envelope. [3,7] An illustration that portrays the physical condition of WDR can be seen in Figure 1.

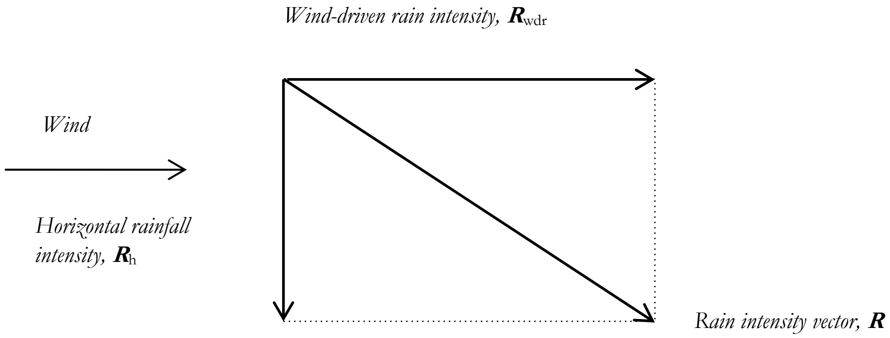


Figure 1. Rain intensity vector **R** and Wind-Driven Rain R_{wdr}

Rainwater intrusion is a continual threat to the durability and serviceability of building envelopes. [8,9] It is agreed that values of calculated loads for extreme events such as a 1 in 10-year rainstorm covers the effect of normal in-service conditions. [8,9] Distinction between two climate events are of significance to testing protocols such as: (1) spray rate – the amount of water impinging on the wall, related to the wind speed and rainfall intensity; and, (2) pressure difference across the wall – related to the wind speed. [4,9]

The present study has the main objective of quantifying the amount of water and the accompanying wind pressure as testing parameters for a test simulation of water-tightness of building components for a specific area.

Typically, WDR is not measured in weather stations. [10,11] For a detailed review of the measurement process of WDR, several works by Blocken and Carmeliet [3], Abuku et al. [8], and Sahal & Lacasse [5] are referred to. A development in a local testing facility that involves the use of equipment following specifications defined by the American Society for Testing and Materials (ASTM) test methods such as ASTM E331: Standard Test method for water penetration of exterior windows, skylights, doors and curtain walls by uniform static air pressure difference is underway. Refinement of such testing protocols and test parameters are currently being sought in consideration for the underpinnings of parameter development for selected ASTM standards.

It is recognized that in performance testing or simulated water-tightness assessment of building components, such as window assemblies, the test parameters such as spray rates and pressure differences are based on the expected specific climate and a given return period. [10,12, 13]

II. METHODOLOGY

2.1 Methodologies for Test Parameter Development

Studies in WDR was pioneered by Hoppstead in 1995 and succeeding researches in different continents progressively continued with some researches focusing on improving the methodologies for test parameter development. [8,12]

The initial basis for the calculated local parameters used in this paper was developed by Choi [7,10] and its further developments by Sahal and Lacasse. [5] Choi’s methodology is based on analytically derived solutions and formulations from particular engineering principles. For a study in Turkey, Sahal and Lacasse [5] attempted a more integrated and systematic approach drawing from deeper experiences and wider data set from other studies and research. [5,7,10]

Table 1 presents the summary of the international procedures in acquiring water-tightness test parameters, spray rate and pressure difference. It also contains the primary proponents for each procedure of the testing parameters. The format of the table is inspired by the study of Sahal and Lacasse [5], its flexible structure lends to the listing of categories becoming a platform for comparison to other studies. The methodology is replicated by Branz [13] for New Zealand and by Krpan [12] for Canada. Essentially, the entire process can be seen as having three major stages namely: (1) gathering of the climate data, (2) estimating the intensity of wind-driven rain and (3) an analysis of extremes as adapted from the study by Branz. [13]

Table 1. Summary of methods in calculating testing parameters for water-tightness test

Steps	Description	Reference
1	Collection and analysis of Meteorological data: Typically gathered are hourly rainfall and coincident wind data from local meteorological stations	Choi 1996, Choi 1998
2	Selecting a suitable averaging time	New Zealand, Branz Study 2013,
2.1	Estimating short duration (1,5,10min) rainfall intensity based on step 1	Choi 1996, Choi 1998
2.2	Estimating short duration (1,5,10min) coincident wind speeds	Choi 1996; Choi 1998; New Zealand, Branz Study 2013
3	Estimating Driving Rain Intensity on Walls (based on steps 1-3)	Straube and Burnett 2000; New Zealand, Branz Study 2013
4	Analysis of Extreme Values	New Zealand, Branz Study 2013
4.1	Determining return periods of yearly driving rain extremes	Choi 1996; Choi 1998; Sahal and Lacasse 2008
4.2	Determining return periods of yearly coincident wind extremes	Choi 1996; Choi 1998; Choi 2000; Sahal and Lacasse 2008
5	Estimate of Dynamic Modes	Mayo 1998; Sahal and Lacasse 2008
5.1	Dynamic mode and estimate of pressure	Mayo 1998; Sahal and Lacasse 2008
5.2	Dynamic mode and test frequency	Mayo 1998; Sahal and Lacasse 2008

2.2 Test Parameter Calculations

2.2.1 Gathering Climatic Data for a specific location

In WDR studies, relevant climatic data such as rainfall intensity, wind speed and gust speed are gathered over certain periods of years at meteorological stations. These data are normally taken in hourly durations. [5,10] The number of years of gathered data is also a consideration, where a 10-year, 15-year or 30-year collection is deemed acceptable by other studies. [5,13] For this study, the data points are at a maximum hourly rainfall level determined by several gauging stations managed by the Effective Flood Control and Operation System (EFCOS). EFCOS is the only known institution that observes and records hourly rainfall data in Metro Manila. These data points are from a study by JICA in 2013 [14], in which the data had undergone quality checks using several criteria such as hydrograph and hyetograph compatibility for all available stations in Metro Manila. These data cover a limited duration, and this study only considers a period of 17 years (1994-2000). Necessary supplemental data such as mean wind speed and gust are obtained from the Port Area station of the Philippine Atmospheric Geophysical and Astronomical Services Administration (PAGASA). PAGASA has only a fixed 3-hour observation time, though manual recordings are conducted by weather observers. The recordings are considered to be 10-minute average wind speed with gust speed. [15,16]

In accordance to statistical concepts for testing criteria, several studies found it appropriate or sufficient to associate rainfall intensities and extreme wind with an averaging time of five (5) minutes. [10,13,17,18] This considers the random nature of wind and rain together, and that their mean values vary with an averaging period. [10] A 5-minute rain-water leak is already disturbing enough as it is and could correspond to a maximum rate of rainwater runoff from the surface of a wall.

2.2.2 Adapting a Suitable Averaging Time

Data taken within a short duration pertain to measurements taken for 1, 5 or 10-minute periods and correspond well to the accepted 5-minute application of climatic loading on a building envelope. If the gathered climatic data are already in the short duration resolution, then step 2 should be skipped, otherwise the equation below as proposed by Choi [10] should be used in approximating rainfall intensity:

$$r_i(t) \Big/ r_i\,(3600) = \left(3600 \big/ t\right)^{0.42} \qquad \textit{eq. 1}$$

where $r_i(t)$ is the average rainfall intensity for duration *t* seconds and $r_i(3600)$ is the hourly rainfall intensity. Equation 1 considers variation in values of rainfall intensity-duration-frequency from different locations or countries. However, forms of equations and shapes of curves from charts of intensity-duration are considered similar. This equation is accepted by several studies from different continents of the world, from North America, Europe, and Australia. [5,10,13]

Consequently, the coincident wind speed under short duration period is calculated using equation 2 (shown below). The coincident wind speed at roof height of a given building is determined by using the power law profile:

$$\frac{v(t) - v(3600)}{v(3) - v(3600)} = \frac{\ln\left({}^{t}/_{3600}\right)}{\ln\left({}^{3}/_{3600}\right)} \qquad eq.\ 2$$

where *v(t)* is the average wind speed for duration of *t* seconds, *v(3600)* is the hourly wind speed and *v(3)* is the *3* second gust speed. This simplified equation comes with the following assumptions: station height is normalized to 10-meters, a topographical factor of 1.0, and a ground roughness category of 1.0. As defined in related studies, a ground roughness of 1.0 pertains to a flat terrain with some isolated obstacles while topography factor 1.0 refers to an absence of valleys or gorges that produce funneling of the wind. [12,13]

2.2.3 Estimate of the Driving Rain Intensity

With initial discussions by Lacy [19], subsequent developments by Straube and Burnett [11], and later by Sahal and Lacasse [5], the proposed driving rain intensity (L/m^2·min) on walls corresponds to equations 3 to 8 found below. In earlier studies, the driving rain intensity is indicated as the rain deposition rate on a vertical building face:

$$WDR = RAF \times DRF(r_h) \times \cos(\theta) \times V(h) \times r_h \qquad eq.\ 3$$

where *RAF* is the rain admittance factor, or a simplification factor transforming driving rain for some horizontal distance to deposited rain taking values from 0.3 to 1.0, $DRF(r_h)$ is the driving rain factor, r_h is the horizontal rainfall intensity (mm/min), θ is the angle of the wind to a line normal to the wall, *V(h)* is the wind speed at height of interest (m/s), and, r_h is the average rainfall rate on the ground (mm/m^2·min).

The rain admittance factor (RAF) considers the interaction of a building with driving rain in unobstructed wind conditions. Previous studies defined this as a factor accounting for building aerodynamics and angle of wind attack, even using computational fluid dynamics approach to determine its acceptable range of values. [10,11] RAF can take a value between 0.8 and 1.0 for low-rise buildings (i.e. <10m) on upper corners, or it can fall between 0.9 to 1.0 for tall buildings (i.e. >10m), as summarized by Sahal and Lacasse. [5]

The proportionality constant (driving rain factor) in equation 3 gives the relationship of horizontal rain to the vertical plane and is equivalent to:

$$DRF(r_h) = {}^{1}/_{V_t} \qquad eq.\ 4$$

where V_t is the terminal velocity of raindrops *(m/s).* The value of this terminal velocity is obtained by using the equation given below (equation 5) developed by Dingle and Lee, coming from laboratory studies and Doppler radar measurements and is claimed to possess an accuracy of +/- 2.5 % [10]:

$$V_t(\phi) = -0.16603 + 4.91884 \times \phi - 0.888016 \times \phi^2 + 0.054888 \times \phi^3 \le 9.20 \qquad eq.\ 5$$

where $V_t(\phi)$ is the terminal velocity of a raindrop diameter Φ in still air (m/s).

It is accepted, in accordance to the study by Straube and Burnett [11], that the raindrop size can be approximated by a function of rainfall intensity. Since the 1950's, field measurements and succeeding studies have produced an estimate of cumulative probability distributions of raindrop diameter as a function of rainfall intensity given by:

$$F(\phi) = 1 - exp\left\{-\left(\frac{\phi}{1.30 \times r_h^{0.232}}\right)^{2.245}\right\} \qquad eq.\ 6$$

where $F(\phi)$ is the cumulative probability distribution of drop diameters for a given rainfall intensity (mm/m^2·min) and an equivalent spherical raindrop diameter (mm). Sahal and Lacasse [5] added equations applicable for the determination of raindrop size identities such as the median (D_{50}) or the predominant drop size *(D_{pred})* of the rainfall intensity:

$$D_{50} = a \times\ 0.69^{1/n} \qquad eq.\ 7$$

$$D_{pred} = a \times \left(\frac{(n-1)}{n}\right)^{1/n} \qquad eq.\ 8$$

where $a = 1.30 r_h^p$, (r_h-average rainfall rate), p = 0.232, and n = 2.25

Equations 7 and 8 are also proposed by Lacasse and Cornick. [4]

2.3 Analysis of Extreme Values

Calculations of maximum chances of exceedance for calculated short duration (1) rainfall intensity and (2) coincident wind speed per year should be accomplished in the form of analysis-of-extremes. The procedure employed is suggested by Holmes [20] for climatic events, the basis of which is the Gumbel distribution. Choi [7,10] also applied this scheme in relation to a selected return period of interest.

The general procedures for the extreme value analysis are detailed below, as adapted from the study by Holmes [20]:

- the largest value of WDR or wind speed for each year are identified
- the identified values are ranked from smallest to largest
- each value is assigned with a probability of exceedance, equivalent to:

$$p = {}^{m}/_{N} + 1 \qquad eq.\ 9$$

where *m* is a data point and *N* is the size of the sample

- a reduced variate *(y)* is calculated from, assigning *c* as the intercept, and n as the gradient:

$$y = -ln\left(-ln(p)\right) \qquad eq.\ 10$$

- the values are then plotted against *y* and a linear regression curve were to be drawn to best fit

- the value for the given return period is X_R :

$$X_R = c + n\{-log_e[-log_e(1 - {}^{1}/_{R})]\} \qquad eq.\ 11$$

where R is the return periods

A statistical analysis of extremes for the wind speed should also be considered for the test pressure parameter. [7,10] It is reasonable to use the equivalent pressure of the wind speed as the test parameter pressure. However, we have initially assumed that there is a co-dependence between wind and rain, therefore, that relationship should be considered. It is observed that high values of driving rain intensity frequently occur with low wind speed other than the maximum average wind speed. As a solution, Choi [10] proposes using a threshold value of 5 mm/h for WDR as paired with wind speeds that will be considered. The said threshold condition pertains to occasions where cladding is wet enough for potential water leakage. This condition is later refined by Lacasse and Cornick [4] as a rate of 1.8 mm/hr, corresponding to ordinary experienced rainfall for most common storms. In the absence of verifying activities, the same threshold value of 1.8 mm/hr is used in this study, as implemented by other studies. [4,12] The pressure parameter can now be determined using the following equation, in consideration of the given wind speed (V, m/s):

$$pressure = C_p \times {}^{1}/_{2} \times \rho \times V^2 \qquad eq.\ 12$$

where ρ is the air density (kg/m^3), and Cp is the pressure coefficient, often taken as 1.0 by several researches in test parameter development. [5,10] The calculated pressure is known to be applicable to both static and dynamic modes. [5]

The outlined steps in Table 1, from steps 1 to 4.2, will yield the desired test parameters in terms of spray rates (L/m^2·min) and a static pressure differences (Pa) across a certain wall or test set-up. These test parameters are necessary to assess the water ingress/infiltration based on the short duration driving rain intensity and pressure under several assumptions made for *RAF*, θ, and ϕ.

2.4 Dynamic Mode Test Parameter Estimates

The dynamic mode estimation of pressure values is proposed by Mayo [17] and is applied by Sahal and Lacasse [5] in their research. It adopts the condition that the applied pressure, considering variation of amplitude, should be equivalent to 1/3 with the mean value of pressure as shown in equation 13:

$$P_c = {}^{P_m}/_{3} \qquad eq.\ 13$$

where P_c is the applied pressure and P_m is the mean pressure value.

An alternative procedure for pressure calculation is provided using the root-mean-square value of available wall pressure measurements. The range of pressure coefficients is 0.1 to 0.3, and the value of the root-mean-square of *sine* is 0.707 multiplied to its amplitude. Therefore, the range of values for the amplitude corresponding to the pressure coefficient is within 0.14 to 0.42, leading previous studies to suggest that the pressure amplitude can be taken as 0.33 in value. [5,17] This condition could be met by adopting the following range of dynamic pressure test parameters:

$$P_{max} = P_m + (0.33 \times P_m), \qquad \textit{eq. 14}$$

$$P_{min} = P_m - (0.33 \times P_m). \qquad \textit{eq. 15}$$

The test's dynamic frequency is selected at 5 seconds or 0.2 Hz pressure variations. It is based on the phase compatibility of the response of the wall with the pressure difference due to the wind. This remaining set of equations could be used if dynamic loads are to be needed in the test protocols.

2.5 Comparison of test parameter findings

Accepted values from international codes and guidelines regarding water infiltration/penetration in various building envelopes or components are summarized in Table 2. Table 3 details the main values presented on the gathered international studies with the methodology almost similar to the procedures discussed in this study. These tables are compiled through data from several researches and actual protocols. [4,5,7,10,12,13,23,24]

Table 2. Summary of Current Water Penetration Standards and Related Relevant Parameters

Standard	**Description**	**Spray Rate** ($L/m^2\cdot min$)	**Pressure** (in Pascal)		**Duration** (in minutes)	
			Uniform Static	Cyclic Static	Spray	Pressure
AAMA 501.3, 1994	American Architectural Manufacturers Association	3.4	137, 300-600 or 20% of d.w.p*		15	15
AS/NZS 4284,1995	Australian and New Zealand Standard Institution (static & dynamic)	3	300		5	15
		3		150-300 or 300-600 or 0.3-0.6*structural test pressure	15	5 for each
NZS 1170, 2003	Standards New Zealand	3	455	455-910		
SS 381, 1996	Singapore Standard (static and dynamic	4	240 or 30% of d.w.p		20	15
		3.5		137 or 300-600 or 20% of d.w.p	15	15
CWCT, 1996	Center for window and cladding technology (static & dynamic)	3.4	300 or 450 or 600 or 0.25 of d.w.p		40 (for 300 Pa level)	25 (for 300 Pa level)
		3.4	300 or 450 or 600 or 0.25 of d.w.p		15	15
ASTM 331, 2000	American Society for Testing and Materials	3.4	137		15	15
BS EN 12155	British Standards Institution	2	150 or 300 or 450 or 600 or >600		50 (for 600 Pa level)	35 (for 600 Pa level)
NT Built 421	Nordtest Standard	2.7		200 or 400 or 600 or 800 or 1100		10 for each spray
CSA A 440.1, 1998	Canadian Standards Association	3.4		137-three cycles	15	5-each cycle
ASTM E 514, 2014	American Society for Testing and Materials	2.3	500		240	240
AAMA 501.1, 1994	American Architectural Manufacturers Association	3.4		137 or 300-600 or 20% of d.w.p.	15	15
BS ENV 13050 2001	British Standards Institution	2		150 or 300 or 450 or 600 or > 600	---	---

* d.w.p.-design wind pressure

Table 3. Summary of Current Water Penetration Parameters for International Studies at 10-year return period

Standard	**Description**	**Spray Rate** ($L/m^2 \cdot min$)	**Pressure** (in Pascal)		**Duration** (in minutes)	
			Uniform static	**Cyclic static**	**Spray**	**Pressure**
Airport Site, Metro Vancouver Canada. Krpan 2013	Based on the methodology by: Choi 1998; Sahal & Lacasse 2008	0.95	202	---	15	15
New Zealand, Branz Building Research Levy 2013	Based on the methodology by: Choi 1998; Sahal & Lacasse 2008	0.94-5.55	135-692			
Istanbul, Turkey. Sahal and Lacasse 2008	Based on the methodology by: Choi 1998; Mayo 1998; and, Straube & Burnett 2000 (static & dynamic)	0.9	308		15	15
		0.9		206-410		
Sydney Australia, Choi 1998	Based on the methodology by: Choi 1998 and Choi 1994; Lacy 1965 and 1975	2.43	410		15	15

III. RESULTS AND DISCUSSIONS

The assumptions adopted for the calculation of the test parameters are the following: rain admittance factor (RAF) is taken as 0.9, (which follows the proposal by Straube and Burnett [11] and the development of test parameters by Branz [13] and Sahal & Lacasse [5], wind direction is normal to the wall of the building facade, translating to theta θ being taken equal to 0 and $cos(0)=1$, and calculated height of WDR values is at 10-m, based on the World Meteorological Organization anemometer height.

Omni-directional analysis is not employed. This adoption translates to discounting the wind direction or variation of wind on different directions. The wind direction is also considered normal to the wall.

The Generalized Extreme Value analysis (GEV) of Type I is used to obtain reliable results. It is noted that if the function is not a Type I distribution, but rather a Type III distribution, then the expected values are already overestimated.

Using the Gumbel distribution and 17 data points for maximum rainfall intensity and wind speed from 1994 to 2010, Figure 2 was developed. The hourly data are transformable as stated in steps 2 and 2.1 (Section 2.2.2). The Type I distribution fit the points, and these points fit a straight line (R^2=0.908). The aforementioned steps 1 to 4.2 were applied in order to come about the given values shown in Table 4 and Figure 3.

Table 4. Calculated Values of Water Penetration Testing Parameters

RETURN PERIOD	PREDICTED WDR (LITER/MIN ·M^2)	PREDICTED AVERAGE PRESSURE (PA)
2	5.89	89.6
5	9.03	144.2
10	12.05	259.6
20	14.00	324.4
30	16.05	480.8

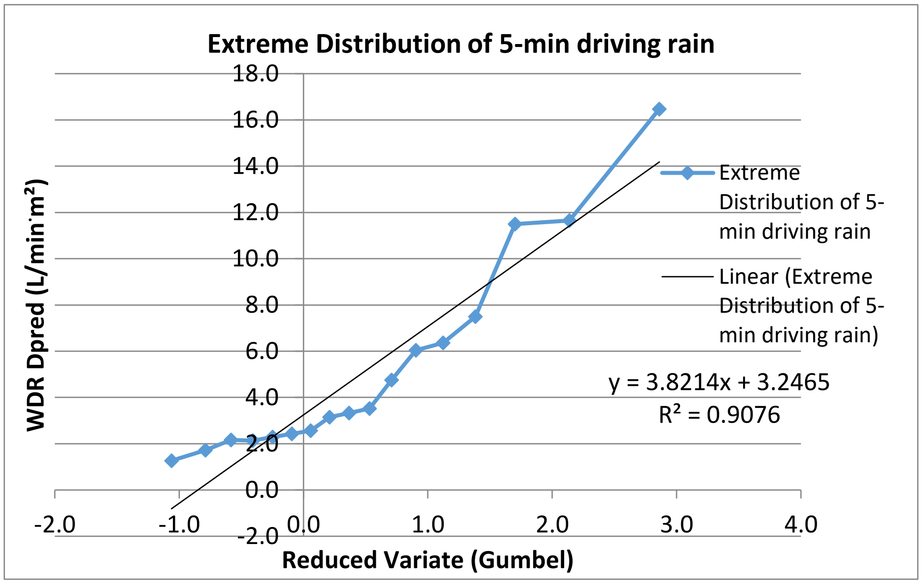


Figure 2. Extreme value distribution of a 5-minute Driving Rain Intensity, for analysis of return period.

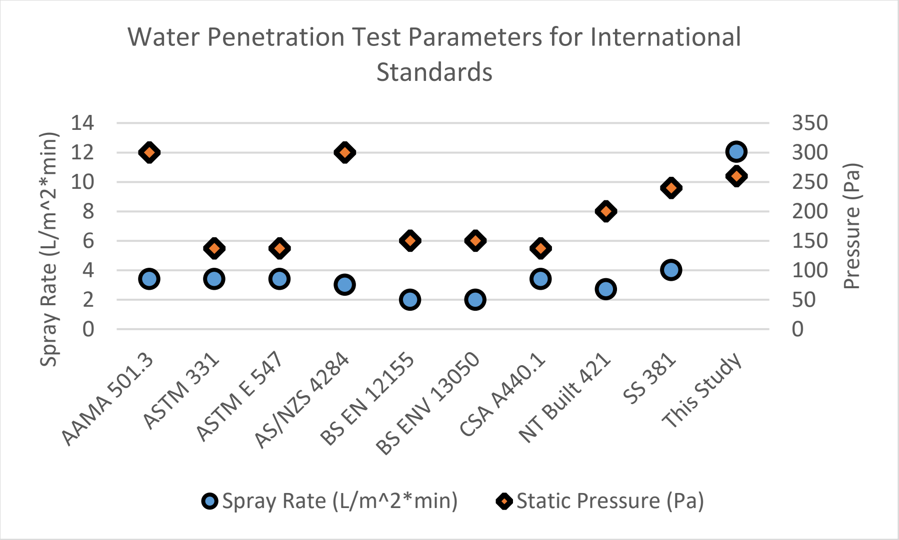


Figure 3. Water Penetration Testing Parameters for International Standards at a 10-year return period with the included value from this study.

By virtue of serviceability consideration, test loads are not expected to exceed 30-years in a building life, therefore a tail end 30-year return period was selected. [4,5] Most of the listed WDR calculation studies consider a 10-year return period. Figure 3 compares the testing parameters from various international standards together with the results of this study for a 10-year return period.

The calculated WDR spray rate test parameter ranges from 5.89- 16.05 *L/min·m*^{2} when considering return periods of 2 to 30-years. These calculated values are dominantly higher in comparison with the accepted values in countries such as Canada, New Zealand, and Australia (see Tables 2 and 3). The majority of the standard spray rates recommended internationally has a value of 3.4 *L/min·m*^{2} (at a 10-year return period), including those from several ASTM standards (i.e. ASTM E331 and ASTM E514), British standards (BS EN 12155), and Singaporean standards (SS 381-1996), as shown in Table 2.

A similar extreme value analysis for the calculation of test pressures was conducted, using data points for yearly extreme wind events from 1994 to 2010, with accompanying rain conditions. [4,13] The calculated test (static) pressures, and the paired (second) water penetration test parameters, range from *90Pa to-481 Pa*. The highest calculated value in the selected area is less than the maximum value found from other studies, and it is within the range of other test values accepted internationally. Also, a number of other international standards possess or prescribe static pressure loads of 600 Pa or greater. It is emphasized that several ASTM standards (i.e. ASTM E331 and ASTM E514) endorse a minimum of 137 Pa in the absence of any calculated values.

IV. CONCLUSIONS AND RECOMMENDATIONS

A set of wind-driven rain testing parameters were calculated using procedures and methodologies from international studies in test protocol development. From several studies that propose individual compatible procedures, five (5) sets of water penetration parameters were calculated and results are presented in Table 4. They portray pairings of spray rates and static pressures for pressure differences associated with return periods for Metro Manila.

Several ASTM water-tightness standards (i.e. ASTM E331 and ASTM E514) endorse minimum values for spray rates and pressure differences in the absence of calculated values. This study proposed localized test parameters that better replicate or estimate the climate condition of Metro Manila. The calculated values are generally higher than the prescription of at least two ASTM protocols cited here. Differences in obtained values for area-specific calculations in comparison with standard test parameters are anticipated, as observed also by previous studies.

Several factors such as the rain admittance factor can be further studied in order to refine the calculated test parameters.

REFERENCES

[1] Choi, Edmund CC. 1993. Simulation of wind-driven rain around a building. In: Journal of Wind Engineering and Industrial Aerodynamics. Elsevier.46 & 47. 721-729.

[2] Choi, Edmund CC. 1994. Characteristics of the co-occurrence of wind and rain and the driving-rain index. In: Journal of Wind Engineering and Industrial Aerodynamics. Elsevier. 53. 49-62.

[3] Blocken B, and Carmeliet J. 2004. A review of wind-driven rain research in building science. In: Journal of Wind Engineering and Industrial Aerodynamics. Elsevier. 92(13): 1079-1130.

[4] Lacasse MA, and Cornick SM. 2005. A review of climate loads relevant to assessing the water tightness of walls, windows and wall-window interfaces. In: Journal of ASTM International. Vol. 2, No. 10.

[5] Sahal N, and Lacasse M. 2008. Proposed method for calculating water penetration test parameters of wall assemblies as applied to Istanbul, Turkey. In: Building and Environment. Elsevier. 43 1250-1260.

[6] Asian Pacific FRIEND: Rainfall Intensity Duration Frequency (IDF) Analysis for the Asia Pacific Region, International Hydrological Programme. 2008.

[7] Choi, Edmund CC. 1996. Methodology for establishing the water penetration testing criteria. In: School of Civil and Structural Engineering Nanyang Technological. Singapore.

[8] Abuku M. et. al. 2009. Impact, absorption and evaporation of raindrops on building facades. In: Building and Environment. 44: 113-124.

[9] Lacasse, Michael A. et al. 2009. Water Penetration of Cladding Components—Results from Laboratory test on Simulated Sealed Vertical and Horizontal Joints of Wall cladding. In: Journal of ASTM International. Vol. 6, No. 6.

[10] Choi, Edmund CC. 1998. Criteria for Water Penetration Testing, Water leakage through building facades, ASTM STP 1314, R.J. Kudder and J.L Erdly Eds. American Society for Testing and Materials. 3-19.

[11] Straube JF, and Burnett EFP. 2000. Simplified prediction of Driving Rain Deposition. In: Proceeding of International Building Physics Conference. Eindhoven. 375-382.

[12] Krpan, Ronald. 2013. Wind-driven Rain on buildings in Metro Vancouver: Parameters for Rain Penetration Testing of Window Assemblies. MA Thesis. Concordia University. Quebec, Canada.

[13] Research, Branz Building. 2013. Study Report 300: An analysis of Wind-driven Rain in New Zealand. Tech.rep. Branz, Ministry of Business Innovation, and Employment. New Zealand.

[14] JICA –DPWH: The Study of Water Security Master Plan for Metro Manila and its Adjoining Areas, Final Report. 2013.

[15] Aquino, Ronwaldo Emmanuel R. 2005. Philippine Wind Information for Engineering, Research, and Mitigation. COE-Short Term Fellowship Report, Tokyo Polytechnic University. Japan.

[16] Rosaria, Nicetos E. 2001. Estimation of Extreme Wind Speeds for the development of Wind Zone Map for the Philippines. MS Thesis. University of the Philippines.

[17] Mayo A.P. 1998. To develop a European Standard dynamic weather tightness test for curtain walling, Task 4-compare the conditions produced by existing test methods with the standard test conditions. In: Building Research Establishment.

[18] Choi, Edmund CC. 2000. Variation of Wind-driven Rain Intensity with Building Orientation. In: Journal of Architectural Engineering. 6:122-128.

[19] Lacy R.E. 1965. Driving-rain maps and the onslaught of rain on buildings. In: Proceedings of the RILEM/CIB symposium on moisture problems in buildings, Helsiki, Finland.

[20] Holmes, J.D. 2001. Wind Loading of Structures, Spon Press.

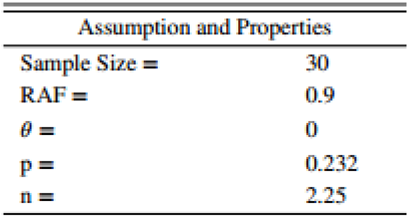
[21] ASTM E331-00: Standard Test Method for Water Penetration of exterior windows, skylights, doors and curtain walls by uniform static air pressure difference (2009).

[22] ASTM E514M-14 Standard Test Method for Water Penetration and Leakage Through Masonry (2014)

APPENDIX

Table A.1

Assumptions and properties in calculating preliminary values in WDR parameters



Assumption and Properties	
Sample Size =	30
RAF =	0.9
θ =	0
p =	0.232
n =	2.25

Table A.2 **Raw and calculated data for spray rate test parameter with extreme value analysis**

		using logarithmic duration relationship				prediction of terminal velocity					using D50		using Dpred		RETURN PERIOD ANALYSIS Ranked Values					
	Date	Hourly Rainfall Intensity (mm/hr)	Rainfall (mm/5-mins)	Wind Speed - average hourly(m/s)	Coincident Wind speed, 5-min (m/s)	DRF (s/m) from D_{pred}	Vt (m/s) from D_{pred}	a	D_{pred}		WDR (L/m² min)		WDR (L/m² min)		WDR (L/m² min)	Gumbel Probability	Reduced Variate	Cumulative Probability Distribution Function	**R** for cumulative distribution	**UR**
1	9/7/2010 18:00	24.3	69.002	3.0	1.949	0.130	7.686	3.472	2.674	8	3.018	8	3.149	1	1.267	0.056	-1.061	0.187	1.229	4.036
2	9/26/2009 11:00	70.0	198.772	6.0	3.897	0.118	8.463	4.438	3.417	17	16.038	17	16.475	2	1.718	0.111	-0.787	0.225	1.290	4.220
3	10/28/2008 6:00	50.0	141.980	3.0	1.949	0.121	8.243	4.104	3.161	12	5.851	12	6.041	3	2.161	0.167	-0.583	0.265	1.360	4.422
4	5/29/2007 20:00	26.7	75.817	2.0	1.299	0.129	7.764	3.549	2.733	5	2.191	5	2.283	4	2.143	0.222	-0.408	0.263	1.357	4.414
5	9/9/2006 21:00	24.6	69.854	6.0	3.897	0.130	7.697	3.482	2.681	13	6.104	13	6.367	5	2.283	0.278	-0.248	0.276	1.382	4.482
6	5/17/2005 19:00	25.1	71.274	2.0	1.299	0.130	7.713	3.498	2.694	3	2.072	3	2.161	6	2.421	0.333	-0.094	0.289	1.407	4.550
7	11/29/2004 21:00	40.6	115.287	2.0	1.299	0.124	8.093	3.911	3.012	9	3.216	9	3.331	7	2.564	0.389	0.057	0.303	1.434	4.623
8	5/27/2003 13:00	26.9	76.385	10.0	6.495	0.129	7.771	3.555	2.737	15	11.031	15	11.493	8	3.149	0.444	0.210	0.358	1.559	4.943
9	8/13/2002 11:00	53.5	151.918	1.0	0.650	0.121	8.290	4.169	3.211	4	2.077	4	2.143	9	3.331	0.500	0.367	0.376	1.603	5.049
10	7/19/2001 19:00	45.0	127.782	2.6	1.689	0.122	8.168	4.005	3.085	11	4.598	11	4.755	10	3.517	0.556	0.531	0.394	1.650	5.160
11	8/2/2000 18:00	65.0	184.574	1.0	0.650	0.119	8.417	4.362	3.359	7	2.493	7	2.564	11	4.755	0.611	0.708	0.510	2.040	5.971
12	3/9/1999 8:00	27.5	78.089	3.0	1.949	0.128	7.789	3.573	2.751	10	3.376	10	3.517	12	6.041	0.667	0.903	0.618	2.618	6.924
13	10/22/1998 18:00	29.5	83.768	6.0	3.897	0.127	7.845	3.632	2.797	14	7.198	14	7.490	13	6.367	0.722	1.123	0.643	2.799	7.180
14	6/16/1997 17:00	42.0	119.263	1.0	0.650	0.123	8.118	3.942	3.036	2	1.659	2	1.718	14	7.490	0.778	1.381	0.719	3.563	8.102
15	9/9/1996 15:00	30.0	85.188	1.0	0.650	0.127	7.859	3.646	2.808	1	1.218	1	1.267	15	11.493	0.833	1.702	0.891	9.163	11.711
16	10/1/1995 3:00	35.0	99.386	8.0	5.196	0.125	7.980	3.779	2.910	16	11.222	16	11.648	16	11.648	0.889	2.139	0.895	9.522	11.858
17	7/25/1994 13:00	28.5	80.928	2.0	1.299	0.128	7.818	3.603	2.774	6	2.325	6	2.421	17	16.475	0.944	2.862	0.969	32.373	16.535

Table A.3 **Raw and calculated data for static pressure parameter with extreme value analysis**

	Date	Windspeed (m/s)	Gust Speed (m/s)	V, Short Duration wind Speed (5-min) (m/s)	Dry Bulb Temperature (°C)		Ranking of Max Windspeed Values (m/s)	Air Density, ρ	Gumbel probability	Reduced Variate	Cumulative Probability Distribution Function	**R** for cumulative distribution	**UR**
1	10/18/2010	6.00	14.00	8.80	28.00	1	6.855	1.174	0.0556	-1.061	0.0000	1.000	9.938
2	7/16/2009	4.00	13.00	7.15	26.10	2	7.453	1.175	0.1111	-0.787	0.0001	1.000	9.938
3	8/20/2008	3.00	14.00	6.86	27.40	3	8.804	1.172	0.1667	-0.583	0.0008	1.001	9.941
4	8/6/2007	4.00	12.00	6.80	27.20	4	8.855	1.177	0.2222	-0.408	0.0047	1.005	9.955
5	5/13/2006	8.00	12.00	9.40	25.40	5	9.505	1.178	0.2778	-0.248	0.0175	1.018	10.000
6	8/12/2005	7.00	17.00	10.50	25.70	6	9.804	1.180	0.3333	-0.094	0.0474	1.050	10.110
7	6/29/2004	9.00	17.00	11.80	29.00	7	9.804	1.180	0.3889	0.057	0.1006	1.112	10.313
8	5/28/2003	8.00	18.00	11.50	26.30	8	10.505	1.181	0.4444	0.210	0.1772	1.215	10.627
9	7/8/2002	7.00	26.00	13.66	27.40	9	11.505	1.179	0.5000	0.367	0.2714	1.373	11.057
10	7/4/2001	9.00	20.00	12.86	27.10	10	11.505	1.179	0.5556	0.531	0.3743	1.598	11.595
11	10/28/2000	10.00	24.00	14.91	25.00	11	11.804	1.168	0.6111	0.708	0.4769	1.912	12.228
12	7/23/1999	7.00	16.00	10.15	26.80	12	12.556	1.173	0.6667	0.903	0.5724	2.339	12.940
13	10/14/1998	8.00	21.00	12.56	27.90	13	12.855	1.176	0.7222	1.123	0.6568	2.914	13.717
14	5/26/1997	8.00	18.00	11.50	26.20	14	13.659	1.174	0.7778	1.381	0.7285	3.683	14.545
15	7/24/1996	6.00	16.00	9.50	26.60	15	14.907	1.184	0.8333	1.702	0.7877	4.710	15.413
16	11/3/1995	17.00	37.00	24.01	25.30	16	15.659	1.183	0.8889	2.139	0.8354	6.075	16.313
17	10/21/1994	9.00	28.00	15.66	25.30	17	24.010	1.183	0.9444	2.862	0.8733	7.891	17.237