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Determination of Optimal Parameters for Wind Driven Rain CFD Simulation for Building Design in the Tropics

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Abstract

The study of wind driven rain is an important design consideration in the built environment. Numerical prediction of this phenomenon requires knowledge of wind speed, rain drop sizes and rain fall intensity among others. The wind speed and rain drop sizes are usually calculated from field measurements. Rainfall intensity is usually assumed to follow a generalized Pareto distribution. Studies have indicated that the rain drop sizes are a function of the rainfall intensity. From a design optimization perspective, it is unclear what value of rainfall intensity should be considered in the process. This paper seeks to examine that in detail. Rain over a simplified building is chosen as the representative test case. The results suggest that it is the lower rainfall intensities that are more critical to be considered in the design process. A combination of using both the median as well as the mean rainfall intensities is proposed for the same.

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Keywords: Wind driven rain, rainfall intensity, Eulerian, OpenFOAM, CFD

1. Introduction

Computer simulations are increasingly being used in the urban design process in varied climates. While in the higher latitudes, this translates to designing for the different seasons, the focus in tropical regions, particularly the ones very close to the equator, is usually different. The climate in these regions remains nearly the same throughout the year with some months being wetter than others.

Lately, Computational Fluid Dynamics (CFD) simulations have become a popular tool relied on by architects and designers in order to get the best possible design for natural ventilation.

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In tropical countries, a focus only on natural ventilation at the expense of other important factors would be detrimental to a design. One such factor to be considered is rain penetration. Tropical countries, particularly the ones close to the equator such as Singapore, experience considerable rainfall, and thus precipitation needs to be taken into account in the design.

One approach is to couple the rain simulations with wind, resulting in the concept of wind driven rain simulations. Interest in numerical rain simulations has existed since the 1990s. Choi had come up with a computational model for the modelling of rain, which he did by solving the equations of motion for droplets ([1]). Focus on the area was strengthened by the publication by Blocken and Carmeliet of their methodology, particularly on quantifying wind driven rain, in the early 2000s ([2]). Currently two main models for simulating wind driven rain exist: a. Lagrangian, where the droplets are modelled as particles and released ([1], [2]), and, b. Eulerian, developed by Kubilay ([3]) where the droplets belonging to a certain range of diameters are modelled in a single phase, with multiple phases being simulated in a single go ([4], [5]).

While extensive work has been done on each of the models and in wind driven rain simulations, particularly in the determination of droplet sizes and their incorporation into models, there are other equally important parameters that merit consideration. One such is the rainfall intensity, which in turn is linked to the raindrop sizes that are present during a precipitation activity, as detailed by Best in 1950 ([6]). It is worth noting that from a design point of view, factoring in the rainfall intensity seems more straightforward.

A review of the available literature indicate that the rainfall intensity experienced by a place can be quite varied, and particularly for tropical regions close to the equator like Malaysia and Singapore, the rainfall intensity follows a Generalized Pareto distribution as shown in 2010 ([7]).

The focus of this paper is on the rainfall intensity and the impact it has on designs. Particularly, the paper aims at establishing a suitable value of rainfall intensity that can be used by architects, designers, ESD consultants and CFD specialists in order to obtain a compromise between construction costs and the depth of penetration of rain. The focus thus is on determining *till where* water penetrates, as opposed to *how much* of it is present after a rain event.

The paper is organized as follows. The governing equations and methodology are presented in Section 2 while Section 3 details the geometry and the mesh. Results are presented and discussed in Section 4 and conclusions of the work are drawn in Section 5.

Nomenclature

α_d phase fraction corresponding to diameter d
ε turbulent dissipation
κ von Karman constant (= 0.41)
μ_a viscosity of air
ν kinematic viscosity
ρ_w density of water
a constant used in drop size distribution equation
A constant used in drop size distribution equation
C_μ coefficient in k-ϵ equation
C_d drag coefficient
d droplet diameter
$F(d)$ fraction of liquid water in the air with raindrops of diameter less than d
f probability density of drop size distribution in air
f_h probability density of drop size distribution through a horizontal plane
g acceleration due to gravity (= 9.8 $\frac{m}{s^2}$)
k turbulent kinetic energy
n constant used in drop size distribution equation
P pressure
p constant used in drop size distribution equation
R_h horizontal rainfall intensity
Re_R relative Reynolds number
u^* frictional velocity
$u_{d,i}$ velocity of droplet of diameter d
u_i velocity of air
U wind velocity specified by log law profile
$v_t(d)$ terminal velocity of raindrop of diameter d
z height coordinate
z_0 aerodynamic roughness (= 1m)

2. Governing Equations and Methodology

2.1. Wind and Rain phases

The airflow is described by the incompressible Navier Stokes equations with turbulence modelled with using the Reynolds Averaged Navier Stokes (RANS) model with standard k-ε model ([8]). The equations for the same are as given in equations 1 and 2.

$$\frac{\partial \overline{u}_j}{\partial x_j} = 0 \tag{1}$$

$$\frac{\partial \overline{u}_i}{\partial t} + \overline{u}_j \frac{\partial \overline{u}_i}{\partial x_j} = -\frac{\partial P}{\partial x_i} + \nu \frac{\partial^2 \overline{u}_i}{\partial x_i \partial x_j} - \frac{\partial \overline{u'_i u'_j}}{\partial x_j} \tag{2}$$

For the k-ε model, the following coefficient values were used: $C_\mu = 0.09$, $C_1 = 1.44$, $C_2 = 1.92$, $\sigma_\epsilon = 1.3$

The rain simulations solve for the continuity and momentum equations of each phase, adopting the methodology used in [4]. The equations are given in equations 3 and 4:

$$\frac{\partial \alpha_d}{\partial t} + \frac{\partial \alpha_d \overline{u}_{d,j}}{\partial x_j} = 0 \quad (3)$$

$$\frac{\partial \alpha_d \overline{u}_{d,i}}{\partial t} + \frac{\partial \alpha_d \overline{u}_{d,i} \overline{u}_{d,j}}{\partial x_j} + \frac{\partial \alpha_d \overline{u'_{d,i} u'_{d,j}}}{\partial x_j} = \alpha_d g_i + \alpha_d \frac{3\mu_a}{\rho_w d^2} \frac{C_d Re_R}{4} (\overline{u}_i - \overline{u}_{d,i}) \quad (4)$$

The simulations are all solved in 3D space and are assumed to be steady. As the focus is to enable designers, architects, ESD consultants and CFD specialists to use such simulations to analyze designs, LES or other unsteady solution techniques are likely to be complex. Validation studies, involving steady RANS simulations, show results in agreement with field experiments as detailed in the work done by Kubilay ([4])

2.2. Raindrops

For rain, the raindrop size distribution is obtained from the work by Best in 1950 ([6]), while the terminal velocities of the raindrops along with their drag coefficients are obtained from the work by Gunn and Kinzer ([9]).

$$F(d) = 1 - \exp\left(-\left(\frac{d}{a}\right)^n\right) \qquad a = AR_h{}^p \qquad f(d) = \frac{\mathrm{d}F}{\mathrm{d}d} \qquad f_h(d) = \frac{f(d)v_t(d)}{\int_d f(d)v_t(d)\mathrm{d}d} \quad (5)$$

Equation 5 represents the mathematical relationship between raindrop diameters (d) and their probability density functions (f) and the same through a horizontal plane (f_h)

2.3. Methodology

In the current study, the steady state wind simulations are performed first followed by the rain simulations, which are also steady. The coupling between the wind and the rain is thus one-way, which is a reasonable assumption as the rain phase is very dilute ([4]). The discretization for the momentum equation in the wind simulation is of second order.

The current study adopts the droplet sizes as that used in [10] in their study of stadiums as being representative of the spectrum of raindrop sizes: 0.5mm, 1mm, 2mm and 5mm.

For wind driven rain, a quantity called 'wet' is examined. This is a binary variable, taking the value of 0 if a cell in the computational domain is dry and 1 if it is wet, which is determined by looping over all the phase fractions being simulated and determining if the value of any of the phase fractions (α_d) in that cell is above a certain threshold. In the simulations performed, the threshold value has been strict: if a phase fraction is more than 0.01% of the maximum phase fraction value for that phase in that particular cell, then the cell is marked as 'wet'. This is expressed in mathematical terms by equations 6 and 7.

$$wet = \begin{cases} 0 & \sum_d wet_d = 0 \\ 1 & otherwise \end{cases} \quad (6)$$

$$wet_d[i] = \begin{cases} 1 & \alpha_d[i] > 0.0001\max(\alpha_d), \quad for \quad cell \quad i \\ 0 & otherwise \end{cases} \quad (7)$$

For the wind simulations, the profile of the wind ($U(z)$) is given by the standard log law (equation 8). The values of turbulent kinetic energy (k) and turbulence dissipation (ε) are also computed based on the values used for the log profile of the velocity (equation 8). In the current study, a single wind speed is chosen, corresponding to the recorded and documented data over a thirty year time period by the National Environment Agency (NEA) in Singapore. The chosen datapoint corresponds to the North wind, with a velocity of 2m/s at a reference height of 15m. The reference speed and height are consistent with the requirements established in the guidelines for CFD ([11]) by the Building and Construction Authority (BCA) of Singapore. Aerodynamic roughness (z_0) is taken to be 1m, a reasonable assumption for a city-state, with predominantly urban built-up areas. Equivalent sand grain roughness and associated parameters are computed using the relations established by Blocken ([12]), particularly for the different CFD codes.

$$U(z) = \frac{u^*}{\kappa} \ln\left(\frac{z + z_0}{z_0}\right) \qquad k(z) = \frac{u^{*2}}{\sqrt{C_\mu}} \qquad \varepsilon(z) = \frac{u^{*3}}{\kappa(z + z_0)} \tag{8}$$

In equation 8, u^* represents the frictional velocity, while z represents the vertical coordinate. The other parameters are as defined in the nomenclature section.

For the wind simulations, on the top and lateral sides, symmetry boundary condition is imposed. On the ground and the building walls, no-slip is specified, while the front and back act as the inlet and outlet respectively. The solvers for velocity, turbulent kinetic energy and turbulent dissipation were the smoothSolver with Gauss-Seidel as the smoother. For pressure, the solver used was the Geometric Algebraic Multi-Grid (GAMG). The convergence criteria for each of the variables was set to 1e-4. For k and ε, bounded Gauss upwind scheme was used, while for the momentum, the bounded Gauss linearUpwindV grad(U) scheme was used.

For the rain simulations, the boundary conditions similar to the ones used by Kubilay in ([4]) are used. The velocity and phase fraction of the rain phases were solved with the Preconditioned Bi-Conjugate Gradient solver (PBiCG) with the Diagonal Incomplete Lower Upper (DILU) method used as the preconditioner. The bounded Gauss upwind schemes were used in these simulations.

For the rainfall intensities, observations and data recordings reported in Johor Bahru are used ([7]), particularly for the mean (2.66mm/hr) and extreme (36.2mm/hr). In order to study the trend, the following rainfall intensities are also used: 0.1mm/hr, 0.2mm/hr, 0.5mm/hr, 1mm/hr, 5mm/hr, 10mm/hr and 100mm/hr, where the rainfall intensity is roughly doubled every time.

3. Geometry and Mesh

In the current study, two sets of geometry are studied. The first consists of a single square block 30m long and wide. The height of the block is 15m and the block is raised from the ground by a height of 5m. The block is raised in an effort to model the void deck spaces that are typically found in the public housing buildings in Singapore. The dimensions of the block roughly represent a five to six storied public housing building.

Ledges of varying lengths are added to this basic building geometry to study the penetration depth of rain under different rainfall intensities. The geometries vary from a situation with no ledge (Case A) to ledges of lengths 1.5m (Case B), 3m (Case C) and 4.5m (Case D) respectively as shown in Figure 2.

In the second set, a block of similar dimensions but with no ledge is introduced upstream of the building of interest at a distance of 30m (corresponding to one building length). This is mainly to understand the effect of interactions between buildings and to see if it has an impact on the choices made for the chosen block. To be consistent, the labelling convention for the block of interest in the second set is kept the same as that of the first: ledges of lengths 1.5m. 3m and 4.5m are tagged Case B, Case C and Case D respectively.

The domain follows the blockage ratio guidelines specified in [13]: in each direction, the ratio of the dimension of the building of interest to that of the length of the domain in that direction does not exceed 17%.

The mesh consists purely of hexahedral elements with the mesh near the region of interest reading a size of 0.5m in all three directions. The geometry and the mesh are shown in Figure 1.

All simulations have been performed with the use of the open source code OpenFOAM [14]. In particular, the wind driven rain simulations have been done using a modified version of the windDrivenRainFoam solver developed by Kubilay in [3].

4. Results and Discussion

The results from the different cases are shown in Figures 3 through 9 and is also detailed in Table 1. In the figures, red indicates 'wet' regions and blue indicates 'dry' regions. The cut planes are taken through the centre of the block(s).

The work by Best shows the distribution of the raindrop size as a function of intensity. It is immediately clear that at lower rainfall intensities, the droplets tend to be mainly of the small size, while for the higher intensities, the probability shifts towards the larger droplets.

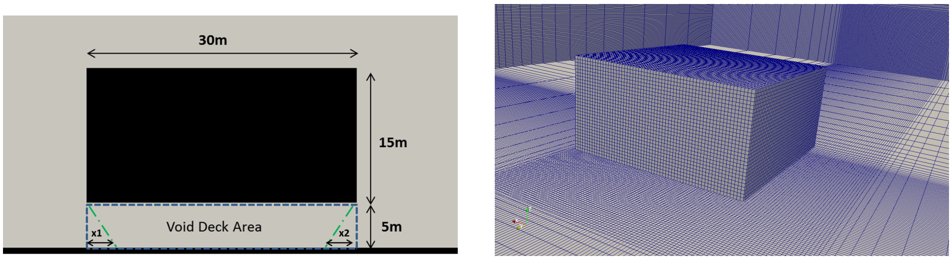

Fig. 1. (a) Geometry (Penetration Depth = x1+x2); (b) Mesh

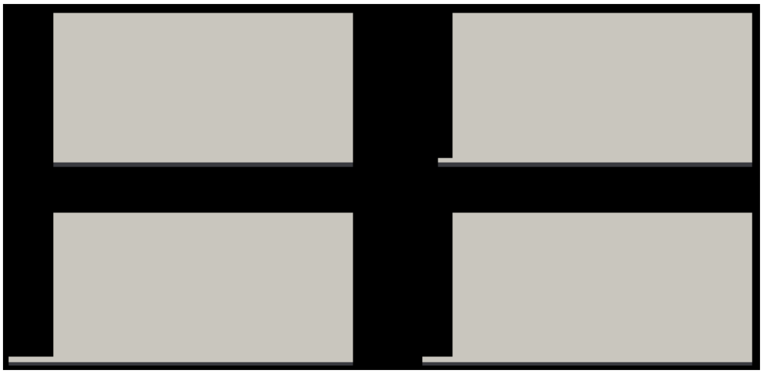

Fig. 2. Cases (clockwise from top left) Case A, Case B, Case C and Case D

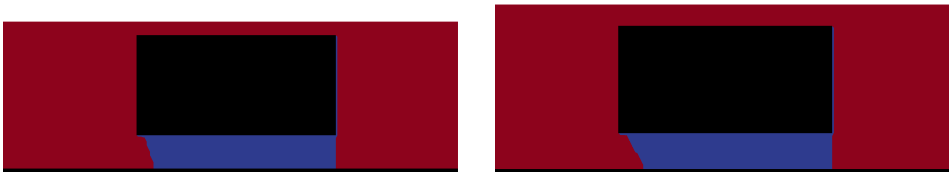

Fig. 3. Wet area, Case A, Single Building (a) $R_h = 36.2mm/hr$; (b) $R_h = 0.1mm/hr$

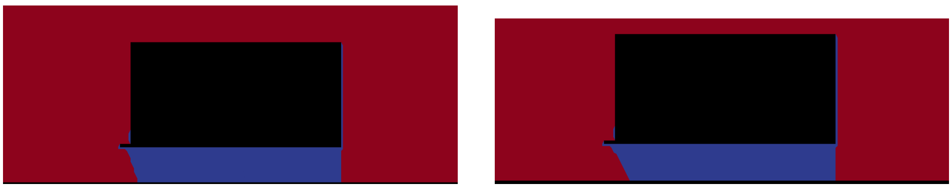

Fig. 4. Wet area, Case B, Single Building (a) $R_h = 36.2mm/hr$; (b) $R_h = 0.1mm/hr$

As a result of having higher mass (and consequently higher inertia), the larger drops tend to fall down as straight as possible and are not affected much by the mean flow. The current simulations do not take into account wind gusts and consequently behaviour of droplets under those conditions cannot be commented upon. Smaller raindrops are more susceptible to be carried by the wind into spaces leading to wetting of those areas.

It is clear that for design purposes, the smaller raindrops are more important, especially under steady wind assumptions. This translates to the lower intensities of rain being the more critical ones. However, it is also clear that designing for the lowest intensity would likely result in overdesign of the space. To find a suitable rainfall intensity that can be used, a cost function that weights equally the length of the ledge and the corresponding penetration dept is defined (equation 9). The penetration depth refers to how much of the 30m void deck length gets wet.

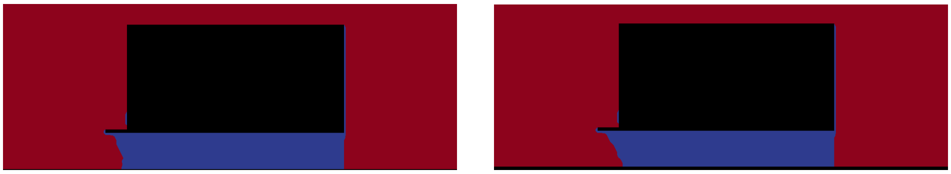

Fig. 5. Wet area, Case C, Single Building (a) $R_h = 36.2mm/hr$; (b) $R_h = 0.1mm/hr$

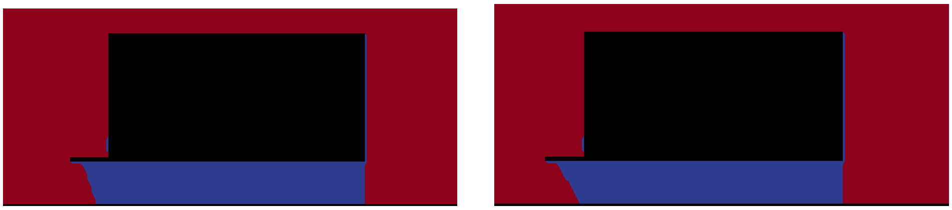

Fig. 6. Wet area, Case D, Single Building (a) $R_h = 36.2mm/hr$; (b) $R_h = 0.1mm/hr$

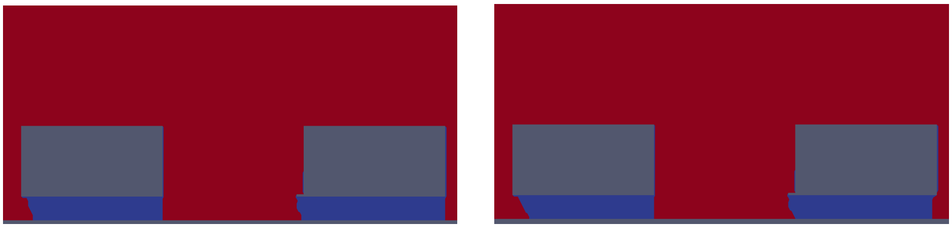

Fig. 7. Wet area, Case B, Two Buildings (a) $R_h = 36.2mm/hr$; (b) $R_h = 0.1mm/hr$

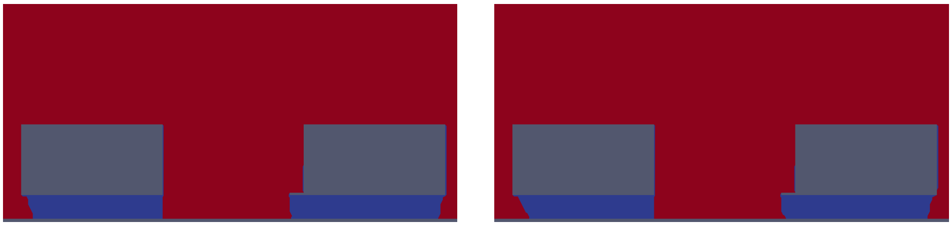

Fig. 8. Wet area, Case C, Two Buildings (a) $R_h = 36.2mm/hr$; (b) $R_h = 0.1mm/hr$

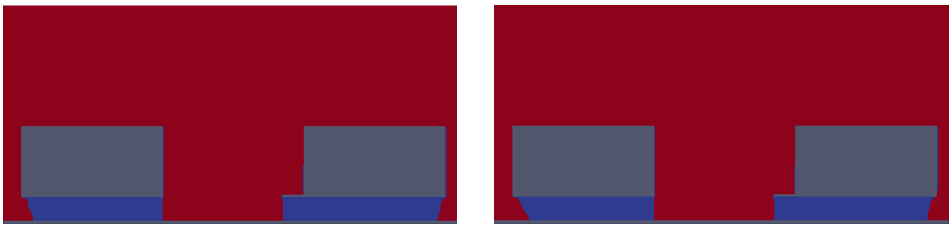

Fig. 9. Wet area, Case D, Two Buildings (a) $R_h = 36.2mm/hr$; (b) $R_h = 0.1mm/hr$

$$cost = \text{Length of ledge} + \text{Depth of penetration} \tag{9}$$

With the cost function as defined in equation 9, Table 2 is obtained.

Table 1. Dry region (Max 30m) for different scenarios -1 building

R_h (mm/hr)	Case A	Case B	Case C	Case D
0.1	26.5	28	29.5	30
0.2	26.5	28	29.5	30
0.5	27.5	29	30	30
1	27.5	29	30	30
2.66	27.5	29	30	30
5	27.5	29	30	30
10	27.5	29	30	30
36.2	27.5	29	30	30
100	27.5	29	30	30

Table 2. Evaluation of simple cost function: Cost=f(Penetration Depth, Ledge Length)

R_h (mm/hr)	Case A	Case B	Case C	Case D
0.1	3.5	3.5	3.5	4.5
0.2	3.5	3.5	3.5	4.5
0.5	2.5	2.5	3	4.5
1	2.5	2.5	3	4.5
2.66	2.5	2.5	3	4.5
5	2.5	2.5	3	4.5
10	2.5	2.5	3	4.5
36.2	2.5	2.5	3	4.5
100	2.5	2.5	3	4.5

It is clear from Table 2 that an equal weighting of the length of the ledge as well as the penetration depth states that no ledge (Case A) and a ledge of 1.5m (Case B) are the optimal solutions. In each case, the worst performance, as can be expected, is from the lowest rainfall intensity which causes the smaller sized droplets to penetrate further into the space.

However, from a design point of view, the performance on the space would in general have a greater weightage than just the construction cost. As a result, if the weighting is done differently (equation 10), such that there is more onus on reducing the penetration depth, then the results bear a pattern such that it is easier to determine an optimal design solution (Case C) as can be seen from Table 3.

$$cost = 0.33 \text{ x Length of ledge} + 0.67 \text{ x Depth of penetration} \tag{10}$$

Table 3. Evaluation of simple cost function: Cost=f(0.67xPenetration Depth, 0.33xLedge Length)

R_h (mm/hr)	Case A	Case B	Case C	Case D
0.1	2.345	1.835	1.325	1.485
0.2	2.345	1.835	1.325	1.485
0.5	1.675	1.165	0.99	1.485
1	1.675	1.165	0.99	1.485
2.66	1.675	1.165	0.99	1.485
5	1.675	1.165	0.99	1.485
10	1.675	1.165	0.99	1.485
36.2	1.675	1.165	0.99	1.485
100	1.675	1.165	0.99	1.485

Examining the results of the two building scenario, yields some unexpected results, particularly in the performances and effect of the ledges in keeping the void deck area dry.

Table 4 details the values for the two building case for Case B, Case C and Case D as highlighted earlier.

Table 4. Dry region (Max 30m) for different scenarios -2 buildings

R_h (mm/hr)	Case B	Case C	Case D
0.1	29	28	28
0.2	29	28	28
0.5	30	28.5	28
1	30	28.5	28
2.66	30	28.5	28
5	30	28.5	28
10	30	28.5	28
36.2	30	28.5	28
100	30	28.5	28

Performing calculations (equation 10) similar to the ones in Tables 2 and 3 yield the data in Tables 5 and 6.

Table 5. Evaluation of simple cost function: Cost=f(Penetration Depth, Ledge Length)

R_h (mm/hr)	Case B	Case C	Case D
0.1	2.5	5	6.5
0.2	2.5	5	6.5
0.5	1.5	4.5	6.5
1	1.5	4.5	6.5
2.66	1.5	4.5	6.5
5	1.5	4.5	6.5
10	1.5	4.5	6.5
36.2	1.5	4.5	6.5
100	1.5	4.5	6.5

Table 6. Evaluation of simple cost function: Cost=f(0.67xPenetration Depth, 0.33xLedge Length)

R_h (mm/hr)	Case B	Case C	Case D
0.1	1.165	2.33	2.825
0.2	1.165	2.33	2.825
0.5	0.495	1.995	2.825
1	0.495	1.995	2.825
2.66	0.495	1.995	2.825
5	0.495	1.995	2.825
10	0.495	1.995	2.825
36.2	0.495	1.995	2.825
100	0.495	1.995	2.825

The computations obtained in Tables 5 and 6 serve to highlight what was seen in Figures 7 through 9. While the ledge remains effective in its localized region, in a multi-building approach, it causes rain to enter from the leeward side, which in the end forces re-evaluating which of the ledges is in fact truly effective. However, even in the two building case, the greatest penetration is due to the lowest rainfall intensity, which remains consistent with what was observed in the single building case.

As has been shown in [7] that the rainfall intensities typically follow a Generalized Pareto distribution, it would seem based on the above simulations and result tabulation that the rainfall intensity to be considered in the design stage should be derived from that.

In addition to the mean value, a value for the rainfall intensity that might be more useful for design might be the median of the distribution of the rainfall intensity. By assuming a simple Pareto distribution (instead of a generalized one), and keeping 0.1mm/hr as the lowest possible rainfall intensity, 2.66mm/hr as the mean of the observations (as recorded at Johor Bahru, Malaysia), the median rainfall intensity can be worked out to be 0.2mm/hr, which has also been considered in the list of values and whose results are similar to that of the lowest rainfall intensity case.

The combination of using the mean and the median would theoretically allow for a broad spectrum of the scenarios to have been accounted for. Based on the Pareto distribution, the mean intensity would not be exceeded more than 3% of the time, while the median intensity would not be exceeded 50% of the time.

5. Conclusions

In the current paper, CFD wind driven rain simulation work has been done to show the impact of the parameters on the result obtained for WDR studies, in particular the effect of the rainfall intensity. It was seen that counter-intuitively, it is the lower rainfall intensity that requires significant attention, particularly in relation to the penetration depth of a rain event. Hence, with available data on rainfall intensities, the pragmatic strategy is to compute both the mean and the median rainfall intensities and use both to determine penetration depths. The presence of surrounding buildings may have unexpected consequences on a design that has been optimized for a single unit. Comprehensive studies need to be undertaken to ensure the validity of the optimized result in a different scenario.

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