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Estimation of the Design Values of Local Wind-induced Loads Based on Short Wind Tunnel Experiments

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Abstract

In this research, the ensemble size effect on the estimation of design wind pressure coefficients was investigated. Long-term instantaneous pressure data over the surface of a high-rise building model was recorded in order to examine the formulation of nearly-true extreme value distribution characteristics. Tuple sizes of samples were then divided to different sets for the variations of tail characteristics and their corresponding scattering levels. Results showed that the appropriate estimation of wind pressure coefficients significantly depends on the stability of the samples.

Introduction

In the late 1970s and early 1980s, N. J. Cook (1980) put into words the basic question: what is the value of the loading coefficient that results in a design load of the desired design risk, given a wind speed of the same risk. This question implies that at least two sources for randomness of the wind load exist, which are: (1) the extreme wind speeds of specific events, such as storms, tropical cyclones, and downbursts et al; and (2) the extreme aerodynamic effects during an event.

Distribution models for extreme wind speeds have been widely discussed. Gumbel, Weibull, or Generalized Pareto Distribution is often utilized as a parent distribution to derive appropriate design wind speed along with a suitable target error probability. For the specification of the aerodynamic coefficient, sampling ensembles of extremes, decisive fractile of the distribution and the confidence level are equally important. Regarding the extremes from wind tunnel tests, Kasperski (2003) extended Cook's basic question into four specific problems, which are: what is the appropriate length of a single run, what is the minimum number of independent runs and what fractile of the extremes is required for the specification of the design wind load using what target confidence interval.

Normally, a wind tunnel test lasting for few minutes converts to several hours in full scale. For estimating design value under one-hour condition, only few samples are collected and may not keep the statistical stability. In this research, a long-term pressure measurement was firstly conduct to obtain an equivalently 1500 hour field scale data for the investigation of ensemble size effect. Then by fitting extreme pressure coefficients to generalized extreme value distributions, nearly true tail characteristics of distributions could be identified. Generation of ensemble sets was then carried out based on properly divisions of long-term data into different tuple sizes. Finally, the effect of different tuple sizes were analysed to indicate the uncertainty induced by few samples.

Experimental Setting

Wind pressure measurement test was conducted in a turbulent boundary layer wind tunnel located at Wind Engineering Research Centre in Tamkang University. A suburban terrain flow with power law index of 0.25 was simulated by properly equipped spires and roughness blocks and the vertical flow characteristics are shown in figure 1.

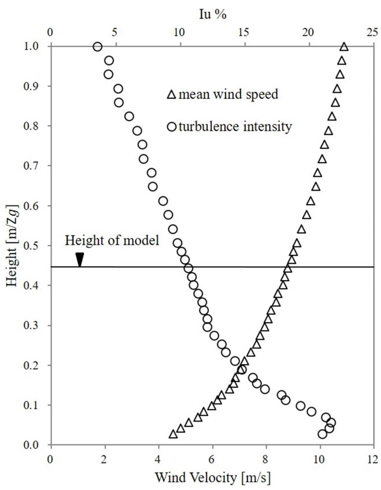


Figure 1 Vertical turbulent flow characteristics

A square prism model with aspect ratio of 6 was installed in the turbulent flow with one face normal to the wind. The diagram of the pressure tap distributions is shown in figure 2.

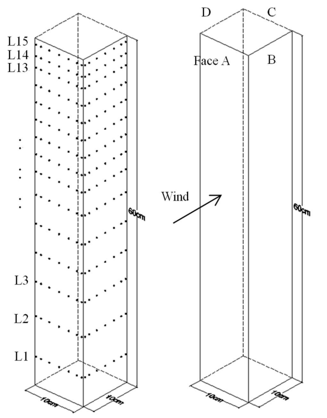


Figure 2 Diagram of square prism model

15 levels were manufactured with pressure tap arrangements and each level contains 28 taps. In total there are 420 pressure taps for further detailed examination. Similarity factors and other information for measurement are listed in table 1.

λ_{Length} = 1/400	$\lambda_{velocity}$ = 1/6.7	λ_{Time} = 1/60
Power law index α		0.25
B (width)		0.1 m
D (depth)		0.1 m
H (height)		0.6 m
Mean wind speed at model height U_H		9.2 m/sec
Sampling rate F_s		200 Hz
Time interval Δt		0.005 sec
Recording time T		90,000 sec
Recording length L		18,000,000

Table 1 Experimental parameter settings

According to the time scale factor, the equivalent record time in full scale is 1,500 hour long, which should be long enough for distribution identification. On the other hand, according to Homes [1], an equivalent representative cladding length is 18.5 m, which is calculated by the multiplication of the time interval in full scale, 0.3 sec, and the mean wind speed at model height, 61.6 m/sec. Therefore, no moving averaging on pressure data was necessary in this study.

Generalized Extreme Value Distribution

Many distribution functions have been developed to meet the main features of various extreme events, such as Gumbel distribution (GD), Generalized Extreme Value Distribution (GEV), Generalized Pareto Distribution (GPD), and so on. In this study, Generalized Extreme Value Distribution is adopted to identify the shape parameters. Equation (1) defines the three-parameter function:

$$F(x) = exp\left[-\left(f_1 - sign(\tau)\cdot f_2 \cdot \frac{x-m}{\sigma}\right)^{\frac{1}{\tau}}\right] \tag{1a}$$

$$f_1 = \Gamma(1+\tau) \qquad f_2 = \sqrt{\Gamma(1+2\tau) - f_1^2} \tag{1b, 1c}$$

where m represents the mean value of extremes; σ represents the standard deviation value of extremes. τ is the shape parameter to determine the tail characteristics of the distribution and Γ is a Gamma function. When identifying the three parameters of the distribution, m and σ can be simply calculated from the ensemble set of all extremes and the shape parameter τ can then be fitted by the least square method. This distribution function is chosen not only because of its simplicity in defining three parameters, but also that the standard deviation value of extremes can be used to indicate the fluctuation level of extremes (σ / m).

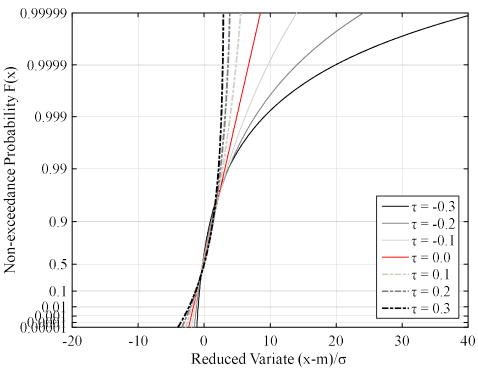


Figure 3 Generalized extreme value distributions for different shape parameters

In figure 3, several shape parameters are given to show their tail characteristics as an illustration. If $\tau > 0$, equation (1) approaches to Type III of GEV while if $\tau < 0$, equation (1) approaches to Type II of GEV. If $\tau = 0$, equation (1) converges to Gumbel distribution defined by equation (2):

$$F(x) = exp\left\{-exp\left[-\left(\gamma + \frac{\pi}{\sqrt{6}}\frac{x-m}{\sigma}\right)\right]\right\} \tag{2}$$

where γ = 0.577216 is Euler Constant.

Determination of Optimal Design Pressure Coefficients

Basic concept of design wind load can be interpreted as

$$w_{des} = \frac{1}{2}\rho_{des} v_{des}{}^2 c_{des} \tag{3}$$

where w_{des} is design wind load, v_{des} is design wind speed and c_{des} is design wind pressure coefficient. ρ_{des} is air density; however, in a common situation, ρ_{des} is usually assumed a constant value. To obtain the non-exceedance probability of design wind load, the convolution of design wind speed and the design wind pressure coefficient is attempted as equation (4):

$$p(w > w_{des}) = \int_{v=0}^{\infty} f_v(v)\cdot \int_{c=c_{lim}}^{\infty} f_c(c)dcdv \tag{4}$$

where $f_v(v)$ is probability density function of design wind speed v and $f_c(c)$ is probability density function of design wind pressure coefficient c. The lower integral limit $c_{\lim}$ in the inner integration part can be estimated by calculating design wind load and the true wind speed in the outer integration:

$$c_{lim} = \frac{2\cdot w_{des}}{\rho\cdot v^2} = \frac{v_{des}{}^2\cdot c_{des}}{v^2} \tag{5}$$

The probability density function in the inner integration part can be replaced by probability distribution of design wind pressure coefficient c:

$$p(w > w_{des}) = \int_{v=0}^{\infty} f_v(v)\cdot\left[1 - F_c(c_{lim})\right]dv = p_{target} \tag{6}$$

where $F_c(c)$ is probability distribution of design wind pressure coefficient c. Equation (6) explains that the exceedance probability of design wind load is obtained by the convolution of the probability density function of design wind speed and the probability distribution of design wind pressure coefficient. In general, the exceedance probability of design wind load is assumed the same as the exceedance probability of design wind speed. Therefore, once the building classification and the target working life period are determined, the exceedance probability of design wind speed is confirmed. Then, by assuming a proper integration range of true wind speed, equality of equation (6) can be achieved by iterative calculation of design fractiles.

In figure 4, iteration results of design fractiles are demonstrated based on the same parameter assumptions adopted by Kasperski [2]. Table 2 lists the parameters substituted for the iterations. From these demonstration plots, the significance of shape parameters and coefficient of variation of pressure coefficient are revealed.

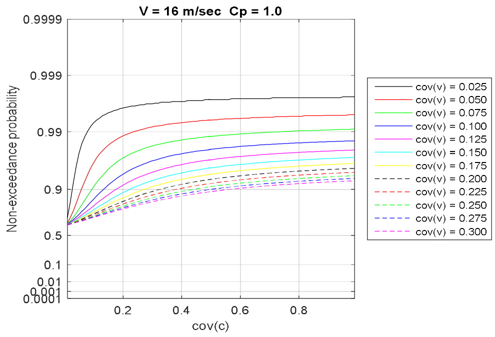
In table 2, the parameter, coefficient of variation, was calculated by equation (7) to indicate the fluctuation level of extreme pressure coefficients or extreme wind speeds.

$$c.o.v. = \left|\frac{\sigma_i}{m_i}\right| \tag{7}$$

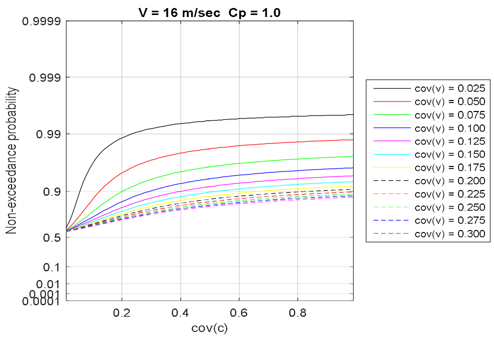
where i indicates the type of extreme values; in this study, coefficient of variation of extreme wind speeds is less concerned than coefficient of variation of extreme wind pressure coefficients.

p_{target}	0.001	Structural class: 3 Working life period: 50 years Ultimate limit state: 0.05
ρ	1.25 kg/m^3	Air density
m_v	16 m/sec	Mean value of extreme wind speeds
m_c	1	Mean value of extreme pressure coefficients
τ_v	0	Shape parameter of extreme wind speeds
τ_c	-0.2, 0.0, 0.2	Shape parameter of extreme pressure coefficients
$c.o.v.(v)$	2.5 – 30 %	Coefficient of variation of extreme wind speeds
$c.o.v.(c)$	0 – 1	Coefficient of variation of extreme pressure coefficients

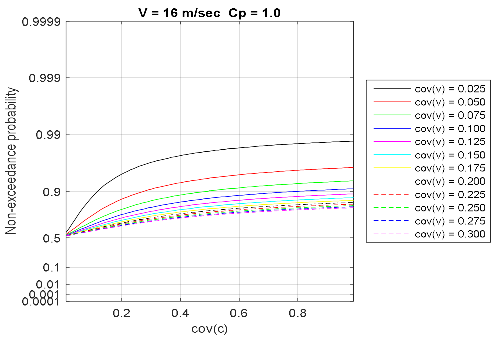
Table 2 Parameters adopted for demonstration of iteration results in figure 4 (Kasperski [2])



$\tau_v = 0$; $\tau_c = -0.2$



$\tau_v = 0$; $\tau_c = 0.0$



$\tau_v = 0$; $\tau_c = 0.2$

Figure 4 Demonstration iteration results based on Table 2 and basic concept of wind loads

Results and Discussions

Parameters for Optimal Design Pressure Coefficients

Representative pressure taps are selected for demonstration of variations of extreme value distributions due to locations. Locations of two selected pressure taps are plotted in red in figure 5. Besides, the torsional effect for 0.8H level height is also obtained by integrating the simultaneous pressure data of 28 pressure taps with their associated unit length for torsional force coefficients.

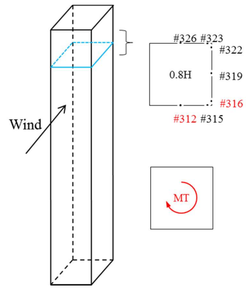


Figure 5 Locations of selected pressure taps for discussions

For each pressure tap, 1500 extremes are extracted to calculate the mean and the standard deviation value and then to fit the generalized extreme value distribution for shape parameter. Coefficient of variation in equation (7) is calculated and the iteration process of optimal design coefficients based on the following parameters in table 3 is carried out. Table 4 lists the estimated results based on Table 3 for two selected pressure taps and the torsional effect.

p_{target}	0.001	Structural class: 3 Working life period: 50 years Ultimate limit state: 0.05
ρ	1.15 kg/m^3	Air density
m_v	61.6 m/sec	Mean value of extreme wind speeds
τ_v	0	Shape parameter of extreme wind speeds
$c.o.v.(v)$	12 %	Coefficient of variation of extreme wind speeds at building height

Table 3 Parameters adopted for iteration process in this study

	τ_c	m_c	$c.o.v.(c)$	$c_{p,des}$/ $c_{f,des}$
Tap 312	0.023	1.684	0.047	1.698
Tap 316	-0.070	-2.297	0.118	-2.444
Torsional effect at 0.8H	0.059	0.259	0.100	0.268

Table 4 Estimated results for selected cases

Ensemble Size Effects on Estimation of Design Coefficients

In order to discuss the ensemble size effect on the design pressure coefficients, tuples of 3, 5, 10, 15, 20, 50 and 100 are picked up randomly but not repeatedly from 1500 records. Furthermore, the same number of set is fixed for each tuple size. Table 5 lists the tuple sizes and corresponding number of sets. For instance, if the tuple size is selected as 20, there will be 75 divided sets and the records will not be repeated among them. Selection process is repeated for 20 times to obtain 1500 generated sets. The 20 records in the first selection process will not be the same as any 20 records in other selection process. Figure 7 shows the variations of estimation results of those selected cases.

Tuple size	Divided sets	Repeat time	Total generated sets
100	15	100	1500
50	30	50	1500
20	75	20	1500
15	100	15	1500
10	150	10	1500
5	300	5	1500
3	500	3	1500

Table 5 Tuple sizes and corresponding generated sets

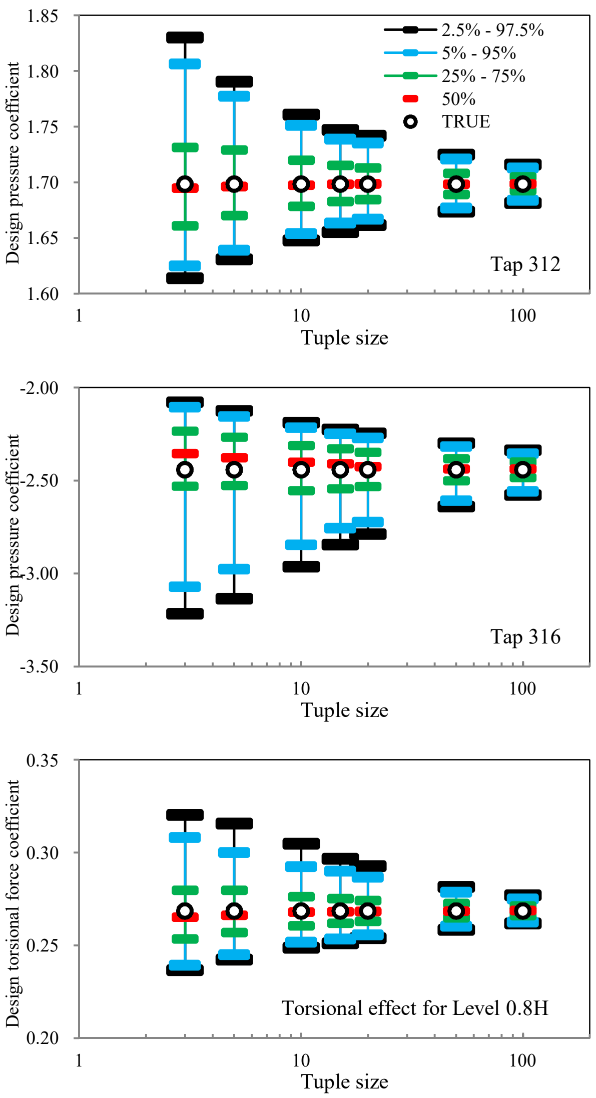


Figure 7 Tuple size effect on estimated pressure/force coefficients

For lower tuple size selected, the variations of estimated pressure coefficients have larger distribution ranges of values, especially the longer tail of the distribution in the same sign as mean values. As the tuple size increases, their patterns gradually change from skewed distribution to normal distribution. In the case of tap 316, the difference by taking tuple size of 3 is up to about 1.1 ~ 1.6 for 2.5% - 97.5% interval. The tail of the estimated extremes with different sizes strongly depends on the coefficient of variation from their original extremes.

As for the resultant torsional effect, the largest estimation could be 0.32 if the tuple size is 3 for 2.5% - 97.5% interval. The distribution of estimated results is similar to that of tap 312. Nevertheless, the bulk is much larger than single tap probably due to the effect of those significantly varying negative pressures.

Adjusting Factor Proposed for Ensemble Size Effects

The adjusting factor is obtained as the 25%-fractile over the nearly true value. Applying the adjusting factor to the obtained estimation results pushes the confidence to 75%.

As shown in figure 8, the adjusting factor obviously depends on the variation coefficient. For the extremes having the largest variation coefficient (tap 316), the adjusting factors exceed the 5%-limit for ensembles sizes up to 10, i.e. based on the knowledge of the true design value, it can be conclude that 15 runs are required to estimate an appropriate design value with 75% confidence allowing for a mismatch of 5%.

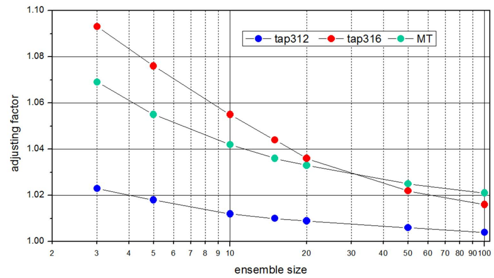


Figure 8 Adjusting factors against ensemble sizes

Applying the adjusting factor leads to an increasing probability for over-estimating the design value. Take tap 316 for example in figure 9, if tuple size is 3, the probability of over-estimating the design value by at least 10% is 0.334 and by at least 20% is 0.141. With tuple size of 15, there is still a probability of 0.217 for a mismatch larger than 10%. The appropriate adjusting factor pushed the estimated value to the appropriate confidence for any ensemble size. The information on the probability of over-estimation allows evaluation if larger tuple sizes should be performed to reduce the probability of a considerable uneconomic design. Nevertheless, the final adjusting factor in a standard will be different since it requires the effects of the unknown variation coefficient in case of small ensemble sizes.

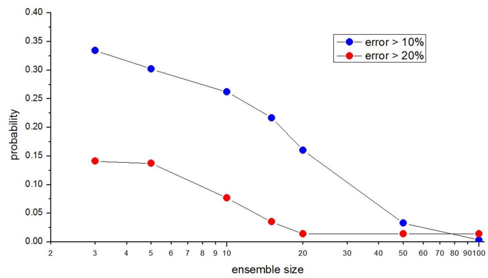


Figure 9 Adjusting factors against ensemble sizes

Conclusions

The appropriate estimation of design coefficients significantly depends on the background knowledge of the samples once the wind tunnel test is well organized. One of the keys to achieve this goal – the ensemble size effect has been presented.

Acknowledgments

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