Uncertainties in the Estimation of Local Peak Pressures on Low-Rise Buildings by Using the Gumbel Distribution Fitting Approach

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Abstract: The lack of a standard accepted method to estimate local peak pressure coefficients from wind tunnel data can lead to inconsistent definitions and interpretations, particularly because cost and time constraints associated with wind tunnel tests of low-rise buildings necessitate relatively short (equivalent full-scale) durations. This paper focuses on a Gumbel distribution fitting method widely used in practice. Because the sources of uncertainty regarding estimated peaks include the use of short-duration records (in practice) and the assumption that the observed peaks from wind tunnel pressure data are Gumbel-distributed, this is quantified in detail in terms of the parameters determining the required minimum record length. It is shown that 15 observed peaks can lead to local peak pressure estimates with adequate precision for many design scenarios. However, the conversion of peak coefficients from a short duration to those of a longer duration requires an increase in the number of observed peaks to maintain precision. **DOI: 10.1061/(ASCE)ST.1943-541X.0001556.** *© 2016 American Society of Civil Engineers.*

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Introduction

Many studies have presented estimates of peak pressure coefficients, Cp_{pk}, for the design of building components and cladding (C&C) in low-rise structures (e.g., Davenport 1964; Cook and Mayne 1979; Stathopoulos 1979; Dagliesh and Templin 1980; Sockel 1980; Peterka 1983; Kasperski 1997; Holmes and Moriarty 1999; Sadek and Simiu 2002; Holmes and Cochran 2003; Kasperski 2003). Considerable variation exists regarding the definition of and methodologies to estimate Cp_{pk}. These variations infiltrate wind-load design standards used around the world. Although there is a common thread in the use of scale models with boundary-layer wind tunnels as the basis for Cp_{pk} development, the lack of a standard accepted methodology and the dearth of clarity in supporting documentation inhibits the repeatability, transparency, and identification of best practices.

This paper addresses these issues in two parts. A historical and current-state-of-practice analysis is conducted via an exhaustive literature review to identify the evolution of and geographic differences in the estimation of Cp_{pk}. This is followed by analysis of a surface pressure data set from a low-rise residential-building model. Because of fitting a Gumbel distribution prevalence, the analysis focuses on fitting a Gumbel distribution to observed peaks. A parametric study is conducted to identify the uncertainties associated with the common use of relatively short-duration records as well as the selected Cp_{pk} estimation parameters. The duration in which a single peak is observed (t_{pk_g}) and the number of peaks observed (n_{pk_g}) are varied within a given fixed record length ($t_{\text{total}} = n_{pk_g} \times t_{pk_g}$) to determine combinations with acceptable uncertainty. The nomenclature used in the current study is summarized in the notation list.

Current and Historical Practice

A review of more than 150 journal and conference papers identified six different peak estimation methods: (1) a single worst peak method, which uses the single extreme value recorded during a sampling period; (2) an ensemble average method which averages several maxima (minima) taken from equal-length segments; (3) the Gumbel-fitting method, which uses several maxima (minima) to determine the parameters and then estimates the peak corresponding to a certain fractile level (F_{pk_frac}); (4) the Cook-Mayne method, which is discussed in greater detail below; (5) the translation method, which uses a full time series rather than observed peaks to obtain a peak cumulative distribution function (CDF); and (6) a peak factor method, which estimates a peak value as the sum of the mean value plus the standard deviation multiplied by a peak factor. The Gumbel-fitting method is similar to the Cook-Mayne method, with the peak fractile level fixed for the latter.

The review reveals that Cp_{pk} estimation methods have varied both by era and region. Table 1 shows the number of papers employing the different peak estimation methods stratified by decades. The simple worst peak method was dominant through the 1980s, after which the ensemble average and Gumbel-fitting methods began to emerge. The translation and peak factor methods were proposed in the early 2000s, whereas the peak observation method (such as the simple worst and ensemble average methods) and the Gumbel-fitting method continued to receive the bulk of attention.

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Table 1. Statistics of Peak Estimation Method Preference in Previous Studies Sorted by Decades

Method	1970s	1980s	1990s	2000s	2010s	Total
Simple worst	2	8	12	5	16	43
Ensemble average	1	1	12	12	16	42
Gumbel fitting	0	0	4	9	13	26
Cook-Mayne	0	1	1	2	16	20
Translation	0	0	0	2	6	8
Peak factor	0	0	0	1	4	5
Not mentioned	0	1	3	3	3	10
Other	0	0	1	2	2	5
Total	3	11	33	36	76	159

Table 2. Statistics of Peak Estimation Method Preference in Previous Studies Sorted by Region

Method	North/ South America	Europe	Asia	Oceania	Total
Simple worst	22	5	12	4	43
Ensemble average	18	2	16	6	42
Gumbel fitting	16	5	2	3	26
Cook-Mayne	0	9	11	0	20
Translation	6	0	2	0	8
Peak factor	0	2	3	0	5
Not mentioned	2	1	7	0	5
Other	3	0	1	1	10
Total	67	24	54	14	159

In the current era, the peak factor and translation methods are nominally increasing in use, but the simple worst, ensemble average, and the Cook-Mayne methods are still more frequent. Universities and research facilities that only recently began to engage in wind engineering tend to use the simple worst and peak factor methods, which explains their recent resurgence despite their lack of a statistical basis. It is also worth noting that some papers did not reveal the specific Cp_{pk} estimation methods used. Table 2 presents the same data stratified by region, offering both the distribution of methods and the relative volume of papers.

Beyond those described in Tables 1 and 2, several peak estimation methods are seen in the literature, such as fitting the peak to the Type III Extreme value distribution (Kasperski 2003), Generalized Pareto distribution with peaks over threshold data (Simiu and Heckert 1996; Holmes and Morarity 1999; Holmes and Cochran 2003), and the methods suggested for wind velocity estimation, for example, the method of independent storms (Harris 2009). Although these methods may be able to estimate peaks with higher accuracy and are based on sound theory, those listed in Tables 1 and 2 appear to be preferred because of their simplicity and their relatively shorter sampling time requirements.

Table 3 summarizes whether design codes explicitly define Cp_{pk} and the methodology to determine it and whether documentation is referenced. Only ISO 4354 (ISO 2009) clearly defines Cp_{pk} and its estimation method. Australia/New Zealand and Japan have published guides (AWES 1994; BCJ 2008) wherein the recommended estimation method is explained, which seem to be helping to reduce the variability of employed peak estimation methods in this region (Table 2). For North and South America, no recommendations are made, nor are calculation methods provided. In Europe, the Cook-Mayne method is dominant in the literature (Table 2). In the Eurocode, the Cook-Mayne method is employed for the calculation of structural design loads, but C&C loads appear to be calculated using simple worst peaks (Geurts et al. 2001, 2013).

Table 3. Peak Estimation Method Described in National Codes

Authority	Design code	Explicit explanation of peak estimation in code	Possible method used for calculating design value in codes	Detail of calculation method
Australia/ New Zealand	AS/NZ Standard (AS/NZS 2002)	No	Ensemble-averaged based on AWES (1994)	$n_{pk_g} = 6$, $t_{pk_g} = 10$ min–3 h (full-scale)
Canada	NBCC (NBCC 2010)	No	Single measured peak based on Stathopoulos (1979)	N/A
Europe	BS-EN 1991-1-4 (BS 2005)	No	Single measured peak based on Stathopoulos (1979), see Geurts et al. (2013)	N/A
ISO	ISO 4354 (ISO 2009)	80% fractile value of the extreme aerodynamic coefficient assuming the peaks follow a Gumbel distribution	N/A	n_{pk_g}: n/a, $t_{pk_g} = 10$–60 min (full-scale), $F_{pk_frac} = 80\%$
Japan	Building Standard of Japan, AIJ Recommendations (AIJ 2004)	No	Ensemble average of several peaks based on BCJ (2008)	$n_{pk_g} = 6 - 15$, $t_{pk_g} = 10$ min (full-scale)
United States	ASCE 7 (ASCE 2010)	P_{max} in $Cp_{max} = P_{max}/q_{ref}$ is "maximum instantaneous pressure measured over the sampling period" (ASCE/SEI49-12)	Ensemble average of several peaks with some adjustment for intermediate roof slope based on Stathopoulos et al. (2001)	$n_{pk_g} = 6$, $t_{pk_g} = 10$ min (full-scale)

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Fig. 1. Statistics of parameters for Gumbel-fitting method used in previous studies: (a) peak sampling duration in full scale; (b) peak sampling duration in model scale; (c) number of peaks observed; (d) peak fractile level

The lack of a standard Cp_{pk} definition or estimation methodology presents obvious weaknesses regarding repeatability because different researchers/practitioners produce different Cp_{pk} estimates given an identical data set. With respect to the Gumbel-fitting method, the required parameters are the number of peaks (n_{pk_g}), sampling duration (t_{pk_g}), and peak fractile level (F_{pk_frac}) that defines Cp_{pk}. Fig. 1 shows the lack of consistency among studies that use the Gumbel-fitting method. This is, at least in part, attributable to the fact that the averaging period for peak wind speed differs regionally. Table 3 and Fig. 1 also indicate that, in some codes and manuals, parameters are proposed as a range instead of a single value. For example, the Cook-Mayne method employed the Gumbel fitting approach and its parameters are calculated with the Lieblein BLUE method, using (generally) 16 maximal (minimal) values (n_{pk_g}) whose evaluation time is between 10 and 60 min in full scale (t_{pk_g}), with 78% of peak fractile level (F_{pk_frac}) using conversion to change the evaluation time to a longer one (Cook 1982, 1985). Similarly, ISO 4354 Annex D provides an equation [Eq. (D.1)] to estimate Cp_{pk} from wind tunnel data using the assumption that the peaks follow a Gumbel distribution. The mean and weighted root-mean-square (RMS) values of a series of sequential peaks, each observed over a duration of $t_{pk_g} = 60$ min, are added to provide the Cp_{pk} defined as the 80% fractile corresponding to a reference period of 60 min. ISO 4354 also provides an equation [Eq. (D.3)] to utilize peaks observed from a duration of $t_{pk_g} = 10$ min to estimate the 60-min Cp_{pk} defined at the 80% fractile. Thus, ISO 4354 provides t_{pk_g} and F_{pk_frac}. The required number of peaks (n_{pk_g}) to determine the mean and RMS in ISO 4354 Eq. (D.1) or Eq. (D.3) influences the uncertainty of the Cp_{pk} estimate but is not specified.

Study Objectives

The objective is to quantify, via a parametric study, the uncertainties associated with the Gumbel-fitting method to estimate Cp_{pk}. The estimated peak is denoted Cp_{pk_g} for clarity. The Gumbel-fitting method is selected because of its wide use in practice, its simplicity, and its advantages over single or ensemble-averaged peak methods with respect to stability and the ability to select a target fractile. The accuracy of the method has been demonstrated relative to other methods (e.g., Harris 2001; Kasperski 2009; Peng et al. 2014). The current study focuses on low-rise buildings because the relatively large model scales used in such studies lead to relatively long sampling durations. The parametric study is conducted in the context of the relatively short test durations (equivalent full-scale durations of 15–20 min per wind direction) typically employed for low-rise wind tunnel testing in practice.

Long (30-h equivalent full-scale) wind tunnel pressure records were collected for a 1/50-scale model of a residential structure. The full-scale companion structure is located in the Florida Panhandle; measured pressure time histories were obtained for it during Hurricane Ivan in 2004 (Liu et al. 2009). The long-duration wind tunnel data provide an empirical benchmark to compare the Cp_{pk} estimation using the Gumbel and ISO 4354 approaches applied to short-duration segments of long-duration records. Quan et al. (2009) performed a study with similar goals regarding the identification of an acceptable t_{pk_g}, but used much shorter data records and did not quantify uncertainty originating from the variation in t_{pk_g}. In addition, the current study explicitly identifies the influence of t_{pk_g} and n_{pk_g} on the accuracy and precision of Cp_{pk_g}, providing practitioners with guidance regarding the selection of Cp_{pk} estimation parameters in the framework of uncertainty bounds.

Wind Tunnel Testing and Selection of Taps for Analysis

The wind tunnel experiments were conducted in Boundary Layer Wind Tunnel II at the University of Western Ontario (UWO). A single-story residential house was modeled at a scale of 1/50 and placed in suburban terrain exposure ($z_0 = 0.23$ m). Details can be found in Kopp and Gavanski (2010). The surface pressures acting at each tap on the roof were measured at the average reference wind speed of V_{ref} (14.5 m/s) and rereferenced to mean roof height (4.3 m). A sampling rate of 400 Hz for 3 h (model scale) was used. Assuming a full-scale wind speed at a 10-m height in suburban terrain ($z_0 = 0.23$ m) of 32 m/s (velocity scale = 1/5), the sampled data are equivalent to 30 h in full scale (time scale = 1/10) at a sampling rate of 40 Hz. The pressure coefficient (Cp) data were digitally low-pass-filtered at 200 Hz (model scale). No corrections

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Fig. 2. Plan view of the building model, with the locations of Taps 1–4 indicated; arrow indicates wind direction used in the analysis

Fig. 3. Skewness and kurtosis pair of Cp data measured at 493 taps

were made for missing energy in the wind tunnel data at large scales/low frequencies.

Fig. 2 shows the plan of the scale model with all tap locations marked. Because it is known that positive and negative pressures tend to have different characteristics in the upper tail of the distribution (Peterka and Cermak 1975), the current analysis focuses on negative pressure because of the practical importance of roof loads. The methodology is first developed and applied to the four taps labeled in Fig. 2 to allow a detailed presentation of results. The methodology is then applied to all 493 taps. The approach wind direction isolated for analysis is identified in Fig. 2.

The four taps in Fig. 2 were chosen as a broad statistical representation of the available data with respect to higher moments as quantified by the coefficients of skewness (s) and kurtosis (k). Fig. 3 is a plot of $s-k$ pairs for all 493 taps, with the four taps in Fig. 2 highlighted. In order to examine the applicability of the suggested combination of t_{pk_g} and n_{pk_g} in terms of non-Gaussian characteristics, the $s-k$ pairs are stratified into four groups based on their kurtosis values ($10 \le k$, $5 \le k < 10$, $4 \le k < 5$, $k < 4$). The four selected taps include both mildly (Taps 1 and 2) and strongly (Taps 3 and 4) non-Gaussian behavior. Table 4 provides summary statistics for each of the four selected taps.

Table 4. Statistics of Cp at the Four Taps Identified in Fig. 2

Statistics	Tap 1	Tap 2	Tap 3	Tap 4
Mean	−1.69	−1.36	−0.33	−0.29
Maximum	0.34	0.58	1.47	1.56
Minimum	−12.9	−9.98	−9.26	−6.79
SD	0.90	0.66	0.33	0.31
COV	0.53	0.48	1.00	1.09
Skewness	−1.34	−1.18	−2.64	−2.26
Kurtosis	5.69	5.41	21.04	15.47

Methodology and Results

Evaluation of the Gumbel Model for Approximating the Peak CDF

The cumulative distribution function (CDF) for the Gumbel distribution is

$$F_g = \exp\{-\exp[-\alpha(Cp - U)]\} \tag{1}$$

where α and U = shape parameters to be selected based on the observed peaks.

The 30-h-long (full-scale) Cp time histories at each of the four selected taps were divided into 100 segments, each 18 min long, from each of which a peak (i.e., minima) was collected ($n_{pk_g} =$ 100 peaks with $t_{pk_g} = 18$ min). These peaks were ordered from smallest to largest of their absolute values and allocated the plotting position expressed as

$$F_{\text{emp}} = i/(N+1) \tag{2}$$

where i = peak rank in ascending order; and N = total number of peaks.

The empirical CDFs were compared with the Gumbel CDF models, where the Gumbel parameters are calculated from the observed peaks using the Gumbel plot, method of moments, maximum likelihood, and expanded generalized least-squares (GLS) methods [i.e., Lieblein BLUE (Lieblein 1974; Hong et al. 2013)]. The empirical and the Gumbel-modeled CDFs are shown in Fig. 4. The horizontal gray lines indicate 50, 80, 90, and 99% fractile levels based on the empirical CDF. Approximation with a Gumbel distribution is generally acceptable. These results justify the use of the Gumbel-fitting approach, but also indicate that some error is associated with the Gumbel assumption. The expanded GLS method is used to select the Gumbel parameters if the number of peaks (n_{pk_g}) is 100 or fewer. Otherwise, maximum likelihood is employed. The independence of observed peaks is addressed in the next section.

Effects of t_{pk_g} and n_{pk_g} on Peak Estimation Uncertainty

Approach

The influence of duration (t_{pk_g}) and number of observed peaks (n_{pk_g}) on the accuracy and precision of a single peak pressure coefficient estimate (Cp_{pk_g}) is examined. This uncertainty quantification can be used to optimally select the appropriate t_{pk_g} and n_{pk_g} for a fixed wind tunnel testing time or to select an appropriate wind tunnel testing time ($t_{\text{total}} = t_{pk_g} \times n_{pk_g}$) based on a desired level of uncertainty.

The available stationary 30-h (equivalent full-scale) wind tunnel records from each of the four taps were divided into subrecords. A Gumbel model was fit to the observed peaks in a given subrecord

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Fig. 4. Observed values of Cp_{pk_g} for $t_{pk_g} = 18$ min and $n_{pk_g} = 100$, and fits to the Gumbel distribution using several methods: (a) Tap 1; (b) Tap 2; (c) Tap 3; (d) Tap 4

using an assigned t_{pk_g} and n_{pk_g}. The 80% fractile was obtained from the Gumbel model to estimate Cp_{pk_g} in order to be consistent with ISO 4354. There is no standard, uniformly accepted or applied definition of an appropriate fractile, as evidenced in Table 3. Additionally, the majority of, but not all, studies in Fig. 1 that did cite a specific definition used a 78% fractile. Hence, an 80% fractile was selected per ISO 4353. Given the lack of a standard, however, the peak fractile level of 80% is somewhat arbitrary and further research is required to determine an appropriate benchmark value for it. A motivation for this work is to demonstrate that developing a standard is essential and that quantifying uncertainty regardless of peak definition, estimation method, and duration is important. In this manner, multiple Cp_{pk_g} associated with given t_{pk_g} and n_{pk_g} were created for each 30-h record, providing a measure of the magnitude, accuracy, and precision of Cp_{pk_g} as a function of tap location, t_{pk_g}, and n_{pk_g}.

In addition to the Cp_{pk_g}, an empirical peak value, Cp_{emp}, was calculated for each tap and an assigned t_{pk_g} using observed peaks from the 30-h record. The corresponding probability was calculated using Eq. (2), and a peak fractile level of 80% was selected as the Cp_{emp} in this study. Because more peaks can be obtained with smaller t_{pk_g} and a fixed wind tunnel data length (i.e., 30 h), Cp_{emp} with smaller t_{pk_g} can be estimated with more peaks and therefore greater accuracy. To obtain a Cp_{emp} value that reflects only the difference in sampling length but not the number of peaks, a fixed number of observed peaks were employed for the calculation of Cp_{emp} regardless of t_{pk_g}. This was selected to be 60, which is the number of observed peaks obtained with $t_{pk_g} = 30$ min.

With this approach, multiple 80% fractile peaks can be obtained for $t_{pk_g} = 2$, 5, and 10 min. In this case, the mean was treated as Cp_{emp}. For example, for $t_{pk_g} = 10$ min, 180 observed peaks ($n_{pk_g} = 180$) can be obtained from the 30-h record. Using the first set of 60 peaks with the probability calculated from Eq. (2), an 80% fractile peak was calculated. This was repeated two more times using the rest of the data, and the mean of the three 80% fractile peaks was denoted Cp_{emp}. This empirical estimate, Cp_{emp}, is typically not available in practice because wind tunnel records are much shorter than 30 h. Thus, Cp_{emp} provides a unique point of comparison for benchmarking the accuracy and precision of the Gumbel-based Cp_{pk_g} estimated. Following Peng et al. (2014), the standard error (SE) of the random variable Cp_{emp} was calculated at the fractile level of 80% based on the Maritz-Jarrett method (Wilcox 2012). The SE was also calculated using a fixed number of peaks (60) regardless of t_{pk_g}, and the mean of the peaks was denoted as SE for the specific t_{pk_g}. The value $Cp_{\text{emp}} \pm 3\ SE$ represents a 99% confidence interval against which to compare the Cp_{pk_g} (Krishnan 2006).

This study considers five values of t_{pk_g} and four values of n_{pk_g} at each of the four taps (Fig. 2). The length of the subrecord needed to create a single sample of Cp_{pk_g} (t_{total}) and the number of Cp_{pk_g} samples produced for a given combination from the 30-h record (n_{peak}) are provided in Table 5.

The independence between peaks was examined by calculating the autocorrelation of the individual Cp time series to determine a time lag that would imply independence between sequential peaks. The results suggest that 40 s (full scale) is a very conservative minimum time lag to apply. Strictly speaking, with the exception of Gaussian variables the vanishing autocorrelation function does not prove independence. However, the pressure peaks are a product of wind field gusts, and the wind field is very nearly Gaussian. By this proxy argument and the very long (40-s) time lag applied, it is reasonable to infer that peak gusts separated by a 40-s time lag are

Table 5. Combinations of Parameters Used in the Statistical Analysis

Cell content: t_{total} (min) (n_{peak})		t_{pk_g} (min)				
		2	5	10	20	30
n_{pk_g}	5	10 (180)	25 (72)	50 (36)	100 (18)	150 (12)
	10	20 (90)	50 (36)	100 (18)	200 (9)	300 (6)
	15	30 (60)	75 (24)	150 (12)	300 (6)	450 (4)
	30	60 (30)	150 (12)	300 (6)	600 (3)	900 (2)

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independent. It was found that less than 10% of the sequential observed peaks had a time interval of less than 40 s for the case of $t_{pk_g} = 2$ min. Using t_{pk_g} larger than 2 min (as the majority of the analyses do) would produce an even lower occurrence of sequential peaks within the 40-s interval. It is concluded that the frequency of occurrence of nonindependent sequential peaks is much smaller than 10% in this study and, thus the effects are minor.

Results

Fig. 5 shows the result from one column in Table 5, the $t_{pk_g} =$ 20-min case. The four columns in each plot correspond to the four n_{pk_g} values in Table 5, and each plot presents the results from a different tap. The Cp_{pk_g} from the individual subrecords within a given 30-h record are plotted as closed circles. The average among all Cp_{pk_g} samples in a column ($\bar{C}p_{pk_g}$) is shown as the open circle. The 95% probability range among all Cp_{pk_g} samples in a column is presented as the cross (denoted U_{pk_g}) when the number of estimated peaks (n_{peak}) is more than 60 (such as the combination of $t_{pk_g} = 2$ min and $n_{pk_g} = 30$). If n_{peak} is less than 3 (such as a case of $t_{pk_g} = 30$ min and $n_{pk_g} = 30$), simple maximum and minimum values of Cp_{pk_g} are plotted instead of 95% bounds. The empirical value, Cp_{emp}, was calculated using the 30-h record for the tap and presented along with the ±3-SE range (U_{emp}), which corresponds to a 99% confidence interval, shown as the solid and dashed horizontal gray lines.

Results of all cases in Table 5 are presented in *condensed form in* Fig. 6. $\bar{C}p_{pk_g}$ is the open circle with 95% bounds (refer to the legend). Cp_{emp} and its bounds ($U_{\text{emp}} = Cp_{\text{emp}} \pm 3$ SE) are the horizontal solid and dashed gray lines, respectively.

General observations are first made regarding the magnitude, precision, and accuracy of Cp_{pk_g} estimated from the subrecords. The magnitude of Cp_{pk_g} increases with t_{pk_g} for any given n_{pk_g}, as does the magnitude of Cp_{emp}, observed as the upward trend moving from left to right for each of the four plots in Fig. 6. The precision of Cp_{pk_g} improves with the increasing number of observed peaks (n_{pk_g}). This is qualitatively viewed as inversely proportional to the U_{pk_g} range (the crosses in Fig. 5), observed as the left-to-right trend in any plot in Fig. 5 and the left-to-right trend for any given t_{pk_g} in Fig. 6.

The mean-square-error (MSE) quantification of the difference between the individual estimates of Cp_{pk_g} and the empirically evaluated benchmark Cp_{emp} for each tap was calculated using

$$\text{MSE} = \frac{1}{n_{\text{peak}}} \sum_{i=1}^{n_{\text{peak}}} (s_i)^2 \tag{3a}$$

where

$$s_i = \begin{cases} Cp_{pk_g,i} - (Cp_{\text{emp}} + 3 \times \text{S.E.}), & (Cp_{pk_g,i} > Cp_{\text{emp}} + 3 \times \text{S.E.}) \\ 0, & (Cp_{\text{emp},j} - 3 \times \text{S.E.} < Cp_{pk_g,i} < Cp_{\text{emp}} + 3 \times \text{S.E.}) \\ (Cp_{\text{emp}} - 3 \times \text{S.E.}) - Cp_{pk_g,i}, & (Cp_{pk_g,i} < Cp_{\text{emp}} - 3 \times \text{S.E.}) \end{cases} \tag{3b}$$

and n_{peak} = number of Cp_{pk_g} samples at a given combination of t_{pk_g} and n_{pk_g} (parenthetical values in Table 5).

The results are not presented here (because of space limitations), but MSE is generally observed to decrease as n_{pk_g} increases. However, there is no clear monotonic trend between MSE and t_{pk_g}.

The accuracy of Cp_{pk_g} is quantified by the difference between $\bar{C}p_{pk_g}$ and Cp_{emp}. No clear trend as a function of t_{pk_g} and n_{pk_g} is observed in the error between the open circle and the gray solid line in any plots in Fig. 6. Hence, the magnitude and precision of Cp_{pk_g} are influenced by t_{pk_g} and n_{pk_g}, respectively, whereas accuracy is not clearly influenced for the range of t_{pk_g} and n_{pk_g} values used in this study.

Accuracy has little meaning without knowledge of the associated precision because measurement durations for typical applications of the Gumbel estimate of Cp_{pk} provide a single sample rather than multiple samples by which $\bar{C}p_{pk_g}$ can be quantified. Therefore, some quantitative observations regarding the influence of n_{pk_g} on precision are offered. Cp_{pk_g} precision for different n_{pk_g} varies with taps and t_{pk_g}. A change in n_{pk_g} from 5 to 10 significantly increases the precision of Cp_{pk_g} and reduces the occurrence of Cp_{pk_g} samples that fall outside the U_{emp} range (gray dashed lines in Fig. 6).

These observed trends validate known concepts from extreme value theory. The contribution of this study is a detailed quantification of the uncertainty involved in common practice, where relatively short-duration records are used and the opportunity to observe precision and accuracy (via multiple Cp_{pk_g} and the empirical Cp_{emp}) is not typically available.

Precision quantification provides guidelines for the selection of n_{pk_g} required to achieve acceptable precision—for example, this could be defined as the case where U_{pk_g}, which is the 95% bound on the estimated Cp_{pk_g}, is contained within U_{emp}, which is the 99% confidence interval associated with Cp_{emp}. In Fig. 6, the n_{pk_g} that achieves $U_{\text{emp}} > U_{pk_g}$ is different depending on t_{pk_g} and tap locations, and it is difficult to find a clear trend in their relationships. When n_{pk_g} needs to be selected for unspecified values of $t_{pk_g}, n_{pk_g} = 30$ can satisfy the relationship of $U_{\text{emp}} > U_{pk_g}$ for all four taps. Although $U_{\text{emp}} > U_{pk_g}$ can still be achieved for many cases in Fig. 6 with $n_{pk_g} = 15$, it cannot be achieved with $n_{pk_g} = 10$ for more than half of the cases considered in Fig. 6. With $n_{pk_g} = 5$, there is no case that satisfies the $U_{\text{emp}} > U_{pk_g}$ relationship regardless of t_{pk_g} and tap location.

The analysis just described is expanded to all 493 taps in Fig. 7, wherein the difference between U_{pk_g} and U_{emp}, defined in the following equations, divided by $|Cp_{\text{emp}}|$ is presented as a function of $|Cp_{\text{emp}}|$ for the combinations of $t_{pk_g} = 30$ min and $n_{pk_g} = 10$ and 15 in this analysis.

$$e_j = \begin{cases} U_{pk_g_\text{upper},j} - U_{\text{emp_upper},j}, & (U_{pk_g_\text{upper},j} > U_{\text{emp_upper},j}) \\ 0, & (U_{\text{emp_lower},j} < U_{pk_g_\text{lower},j}, U_{pk_g_\text{upper},j} < U_{\text{emp_upper},j}) \\ U_{\text{emp_lower},j} - U_{pk_g_\text{lower},j}, & (U_{pk_g_\text{lower},j} < U_{\text{emp_lower},j}) \end{cases} \tag{4}$$

where j = tap number.

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Fig. 5. Plots of Cp_{pk_g} for all n_{pk_g} with $t_{pk_g} = 20$ min, from single-tap Cp time histories at the 4 selected taps in Fig. 2: (a) Tap 1; (b) Tap 2; (c) Tap 3; (d) Tap 4; shown are estimated values of Cp_{pk_g} (closed circle) and its mean, $\bar{C}p_{pk_g}$ (open circle), and 95% probability range, U_{pk_g} (cross); also included are peak values from the empirical distribution, Cp_{emp} (solid gray line), and U_{emp} range (dashed gray line)

Fig. 6. Plots of Cp_{pk_g} for all n_{pk_g} and t_{pk_g} from single-tap Cp time histories at the 4 selected taps in Fig. 2: (a) Tap 1; (b) Tap 2; (c) Tap 3; (d) Tap 4; values shown are the mean of the estimated peak, $\bar{C}p_{pk_g}$ (open circle) and 95% probability range, U_{pk_g} (star, closed circle, cross, and square); also included are peak values from the empirical distribution, Cp_{emp} (solid gray line), and U_{emp} range (dashed gray line)

Recall that U_{pk_g} is the 95% probability range among individual Cp_{pk_g} at a given tap. The uncertainty range U_{emp} in Figs. 5 and 6 is also a function of the individual tap, so e can be calculated for each tap and presented as a percentage.

With $n_{pk_g} = 10$, $|e/Cp_{\text{emp}}|$, for most of the taps are within 20% range except for those with low-magnitude peaks and low kurtosis values. Large $|GCp|$ values defined for C&C in ASCE7 7-10 (ASCE 2010) are approximately 3 (noting that the code values are area averages). Using the conversion method of St. Pierre et al. (2005), this corresponds to values of approximately 3.6 for the Cp values used in the current analysis, which are referenced to mean hourly wind speed measured at 10 m in height in suburban terrain. Considering the differences in target peak fractile levels, $|Cp_{\text{emp}}| \approx 4$ may be the magnitude level that needs to be focused

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Fig. 7. Plots of peak values from the empirical distribution, Cp_{emp} (horizontal axis), and the difference between U_{pk_g} and U_{emp}, e, divided by Cp_{emp} (vertical axis) for all 493 taps for $t_{pk_g} = 30$ min: (a) $n_{pk_g} = 10$; (b) $n_{pk_g} = 15$

on in the current study. For the large majority of taps with peaks at this magnitude level ($|Cp_{\text{emp}}| > 4$), $|e/Cp_{\text{emp}}|$ is within a 10% range, with $n_{pk_g} = 15$ showing no significant improvement obtained by increasing n_{pk_g} to values greater than 15 except for peaks with low magnitude and low kurtosis values. Fig. 7 also includes a mean and standard deviation of mean-square error quantification (MSE_{mean}, MSE_{STD}, respectively) using

$$\text{MSE}_{\text{mean}} = \frac{1}{n_{\text{tap}}}\sum_{j=1}^{n_{\text{tap}}}\text{MSE}_j$$

$$\text{MSE}_{\text{STD}} = \sqrt{\frac{1}{n_{\text{tap}}}\sum_{j=1}^{n_{\text{tap}}}(\text{MSE}_{\text{mean}} - \text{MSE}_j)^2} \tag{5}$$

where MSE_j = MSE defined in Eq. (3*a*) at Tap j; and n_{tap} = the number of taps (493).

The statistics of MSE are dramatically reduced by increasing n_{pk_g}. Considering the magnitude of $|Cp_{\text{emp}}|$, the error defined in Eq. (3*b*) is less than 1% of $|Cp_{\text{emp}}|$ on average for $n_{pk_g} \geq 10$. This means that most of the estimated peaks are within U_{emp} ($= Cp_{\text{emp}} \pm 3$ SE) regardless of tap location. The effects of t_{pk_g} on the relationship between U_{emp} and U_{pk_g} are not clearly seen in Fig. 6. However, by expanding the analysis to 493 taps, as shown in Fig. 7, it was found that $U_{\text{emp}} > U_{pk_g}$ can be achieved with less n_{pk_g} for smaller t_{pk_g}. Thus, the observations made previously are also applicable to $t_{pk_g} < 30$ min.

For a fixed time frame in a wind tunnel experiment (t_{total}), reducing t_{pk_g} provides a means to increase n_{pk_g} and thus the precision of the resulting Cp_{pk_g}. However, the magnitude of the estimated Cp_{pk_g} is only significant in reference to the duration in which it is quantified (t_{pk_g}). Results from experiments using different t_{pk_g} cannot be directly compared absent a common frame of reference. It is confirmed in the next section that Cp_{pk_g} based on a given t_{pk_g} and n_{pk_g} can be converted to an equivalent Cp_{pk_g} for the same n_{pk_g} and another (larger) t_{pk_g}. This conversion comes at the cost of some loss of precision and accuracy.

Evaluation of t_{pk_g} Conversions

The selection of t_{pk_g} in practice is driven largely by the need to provide a sufficiently large n_{pk_g} within a fixed total sampling time (t_{total}). A relatively short-duration t_{pk_g} is typically used because of the preference for wind tunnel testing times of 15–60 min, particularly for the larger model scales used for low-rise buildings. A conversion for Cp_{pk_g} among various t_{pk_g} evaluated by Cook and Mayne (1979) allows the estimate of Cp_{pk} using limited data (large n_{pk_g}, small t_{pk_g}) followed by a conversion of Cp_{pk_g} from a smaller t_{pk_g} to a larger t_{pk_g} that can serve as a common frame of reference (e.g., design). Cook and Mayne (1979) presented a conversion for Gumbel parameters (α, U):

$$\alpha_T = \alpha_t \tag{6}$$

$$U_T = U_t + \ln(T/t)/\alpha_t \tag{7}$$

where α_T and U_T = Gumbel parameters for $t_{pk_g} = T$; and α_t and U_t = Gumbel parameters for $t_{pk_g} = t$ (where $T > t$).

The Gumbel parameters are fitted to the observed peaks using a t_{pk_g} of t min and then converted to parameters for an equivalent $t_{pk_g} = T$-min Gumbel distribution. This allows conversion between different t_{pk_g}, T, and t under the condition that both T and t are long enough to ensure the statistical independence of peaks (Cook 1985) and ideally lie in the spectral gap range—that is, 10–60-min (Van de Hoven 1956; Cook 1982, 1985)—so that peaks are due only to turbulence effects and not to changes in the storm or another large-scale environmental factor.

The efficacy of this conversion [Eqs. (6) and (7)] was investigated by Cook (1982, 1985). The n_{pk_g} is unknown (not reported), and durations of $T = 60$ min and $t = 10$ and 1 min were examined. It was found that agreement between the measurements for the $T = 60$ min and the data predicted from $t = 10$ min is very good, whereas the use of $t = 1$ min resulted in overestimates of 10–20%. Using the current data set, Eqs. (6) and (7) are investigated as a function of n_{pk_g}. The precision of the conversion from t_{pk_g} values smaller than 10 min but larger than 1 min is also investigated. These two issues were not examined in previous studies and are critical to the objective of selecting n_{pk_g} and t_{pk_g} with known uncertainty for a given fixed test time, t_{total}.

In wind tunnel studies, 60 min is commonly used for high-rise buildings as the duration of the measurements, consistent with the averaging time of the wind velocities [the averaging time for a basic wind velocity and the evaluation time for Cp_{pk} should be the same (Cook and Mayne 1979; Cook 1982)]. In hurricanes, wind speeds are rarely stationary for such a long duration, with 10–15 min being more typical. It is important that the peak pressures being assessed are directly related to turbulence effects and that the physical processes are stationary, meaning that meteorological effects do not play a role. $T = 60$ min is at the upper bound of reasonable

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Fig. 8. Cp_{pk_g} values for $t_{pk_g} = 60$ min ($Cp_{pk_g_60}$) and the ratio of $Cp_{pk_g_60}$ and $Cp_{pk_g_t}$ values for $t_{pk_g} = 2$, 5, and 10 min converted to 60 min using Eqs. (6) and (7) ($Cp_{pk_g_2}$, $Cp_{pk_g_5}$, $Cp_{pk_g_10}$) (vertical axis), and the ±10 and 20% ranges of estimated values (horizontal dashed gray lines)

duration associated with peak wind speeds in a storm and so was selected in the current study.

A set of Gumbel parameters ($U_{60\ \mathrm{min}}$, $\alpha_{60\ \mathrm{min}}$) was calculated for all 493 taps using $n_{pk_g} = 30$ and $t_{pk_g} = 60$ min, and the 80% fractile Cp_{pk_g} samples were estimated using these Gumbel parameters (denoted $Cp_{pk_g_60}$). Another set of Gumbel parameters (U_t, α_t) was calculated for each tap using $t_{pk_g} = 2$, 5, and 10 min and $n_{pk_g} = 10$, 15, and 30 ($t_{\mathrm{total}} = 10$–600 min subrecords), and converted to 60-min equivalents using Eqs. (6) and (7). Peaks calculated in this way are denoted $Cp_{pk_g_t}$, where t can be 2, 5, and 10. For each tap, the ratio between $Cp_{pk_g_60}$ and $Cp_{pk_g_t}$ is calculated as a range using the maximum and minimum estimated peaks of $Cp_{pk_g_t}$ (Fig. 8) as a function of $|Cp_{pk_g_60}|$. The broken horizontal lines in the figure indicate ±10% and ±20% ranges of $|Cp_{pk_g_t}|/|Cp_{pk_g_60}|$. The reduced number of peaks (n_{pk_g}) and the sampling duration (t_{pk_g}) associated with shorter records results in a loss of precision. In addition, taps with large kurtosis values have less variation in $|Cp_{pk_g_t}|/|Cp_{pk_g_60}|$. Focusing on peak coefficients with magnitudes larger than 4, combinations of $n_{pk_g} =$ 15 and $t_{pk_g} \geq 10$ min, $n_{pk_g} = 30$ and $t_{pk_g} \geq 5$ min can estimate $Cp_{pk_g_t}$ that are within 20% of difference from $Cp_{pk_g_60}$ for most of the taps.

In light of these results, the analysis used to produce Figs. 5 and 6 was appended with an additional step. The individual estimations of Cp_{pk_g} (80% fractile) for various t_{pk_g} and n_{pk_g} listed in Table 5 were converted to an equivalent $t_{pk_g} = 60$-min value using Eqs. (6) and (7). Cp_{emp} was then calculated from the empirical CDF using $t_{pk_g} = 60$ min and $n_{pk_g} = 30$. The results are shown in Fig. 9.

The study sought to minimize the wind tunnel test time, t_{total}, required to achieve acceptable precision, in which the 95% bounds of the $Cp_{pk_g}(U_{pk_g})$ are contained within U_{emp} ($= Cp_{\mathrm{emp}} \pm 3$ SE), including the influence of the conversion [Eqs. (6) and (7)] for different t_{pk_g} and n_{pk_g} combinations.

With the exception of Tap 2, the use of $t_{pk_g} = 2$ and 5 min produces large uncertainty regardless of n_{pk_g}. By increasing t_{pk_g} to 10, 20, and 30 min, the $U_{\mathrm{emp}} > U_{pk_g}$ relationship can be achieved using n_{pk_g} of 30, 15, and 10, respectively, with a few exceptions. The combination of t_{pk_g} and n_{pk_g} that satisfies the $U_{\mathrm{emp}} > U_{pk_g}$ relationship requires longer t_{total} than that selected based on the applicability of Eqs. (6) and (7) in Fig. 8.

The examination was expanded to all 493 taps, and the results are presented in Fig. 10 with $n_{pk_g} = 10$, 15, and 30 and $t_{pk_g} = 5$, 10, and 20 min. The variation in $|e/Cp_{\mathrm{emp}}|$ changes with both n_{pk_g} and t_{pk_g}. As expected, large n_{pk_g} values, with a smaller extrapolation of t_{pk_g}, lead to more accurate results. The question to be answered is what is sufficient. Considering the other uncertainties in developing design wind loads, a 95% probability range covering approximately ±10% for the large-magnitude coefficients should be acceptable in practice, given that the overall expected coefficient of variation for wind loads on structures is about 35% (Ellingwood 1999). At this level, random variations in peak pressures would not significantly alter the reliability of the final answer. Therefore, viewing Fig. 10 with this acceptable range in mind, and focusing

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Fig. 9. Plots of Cp_{pk_g} for all n_{pk_g} and t_{pk_g} from single-tap Cp time histories at the 4 selected taps (Fig. 2) with conversion to $t_{pk_g} = 60$ min using Eqs. (6) and (7): (a) Tap 1; (b) Tap 2; (c) Tap3; (d) Tap 4; values shown are the mean of the estimated peak, $\bar{C}p_{pk_g}$ (open circle) and 95% probability range, U_{pk_g} (star, circle, cross, and square); also included are the peak values from the empirical distribution, Cp_{emp} (solid gray line), U_{emp} range (dashed gray line), and 95% probability range of ISO peaks calculated with $t_{pk_g} = 10$ and 60 min for various n_{pk_g}, $U_{pk_g_ISO}$

Fig. 10. Plots of peak values from the empirical distribution, Cp_{emp} (horizontal axis), and the difference between U_{pk_g} and U_{emp}, e, divided by Cp_{emp} (vertical axis) for all 493 taps

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Fig. 11. Plots of peak values from the empirical distribution, Cp_{emp} (horizontal axis), and (a) difference between U_{pk_g} and U_{emp}, e, divided by Cp_{emp} (vertical axis), where U_{pk_g} is calculated using the Gumbel-fitting approach for $t_{pk_g} = 10$ min and $n_{pk_g} = 30$ converted to 60 min using Eqs. (6) and (7); (b) difference between $U_{pk_g_ISO}$ and U_{emp} divided by Cp_{emp} (vertical axis), where $U_{pk_g_ISO}$ is calculated using ISO 4354 Eq.(D.3) for $t_{pk_g} = 10$ min and $n_{pk_g} = 30$ for all 493 taps in Fig. 2

on the coefficients with magnitudes of approximately 4 and higher, $t_{pk_g} = 5$ or 10 min can be used with $n_{pk_g} = 30$ and $t_{pk_g} = 20$ min with $n_{pk_g} \geq 15$. The results are not presented, but $t_{pk_g} = 2$ min and $n_{pk_g} = 5$ cannot be selected regardless of n_{pk_g} and t_{pk_g}, respectively. Thus, for $T = 60$ min, the minimum wind tunnel test duration is approximately 150 min using $t_{pk_g} = 5$ min with $n_{pk_g} = 30$. The extrapolation of t_{pk_g} by approximately an order of magnitude using $n_{pk_g} = 30$ therefore leads to sufficiently accurate results. This implies, for example, that for $T = 10$ min, one can use $t_{pk_g} = 1$ min with $n_{pk_g} = 30$ for a total sampling duration of approximately 30 min.

ISO 4354

In the ISO 4354 peak estimation method, which was introduced earlier, the mean and standard deviation of the observed peaks are translation and dilation parameters in the estimation of Cp_{pk}. The ISO 4354 Annex D equations [Eqs. (D.1) and (D.3)] provide an estimate of the 80% fractile Cp_{pk} for a reference period of 1 h. These estimates are included in Fig. 9 as the two rightmost columns in each plot. $U_{pk_g_ISO60}$, which is the same as U_{pk_g} but calculated from the estimated Cp_{pk} using ISO 4354 Eq. (D.1), is less than U_{emp} for most of the taps when $n_{pk_g} > 10$, but requires a wind tunnel testing time of at least 10 h. The ISO estimates based on $t_{pk_g} = 10$ min are very similar to those of the Gumbel-fitting approach for $t_{pk_g} = 10$ min. That is, the Gumbel-fitting approach and the method in ISO 4354 are almost identical with regard to the uncertainty associated with a common t_{pk_g}, and no obvious advantage to using the ISO approach was identified.

To validate this conclusion, the comparison between the Gumbel-fitting and ISO approaches was expanded to all 493 taps for the combination of $t_{pk_g} = 10$ min and $n_{pk_g} = 30$ ($t_{\text{total}} = 300$ min), shown in Figs. 11(a and b), respectively. The statistics of MSE between Cp_{emp} and estimated peaks were also calculated using Eq. (3) with $n_{\text{tap}} = 493$ and $n_{\text{peak}} = 6$. The results from the two methods are visually very similar, with the Gumbel-fitting approach showing slightly lower MSE values. Overall, a clear advantage between the two methods was not identified because both use the same observed peaks and have similar results and uncertainty for a common t_{pk_g}.

Effects of Area Averaging

Thus far, the analyses have focused on local Cp time histories measured at single taps. The previous section applied a metric of $U_{pk_g} < U_{\text{emp}}$ ($Cp_{\text{emp}} \pm 3$ SE) to suggest that $t_{pk_g} = 5$ min and $n_{pk_g} = 30$ ($t_{\text{total}} = 150$ min) result in acceptable precision in the estimation of an 80% fractile peak with a 1-h reference duration. This was the case using the Gumbel-fitting approach for observed peaks with the conversion to 60-min-equivalent Cp_{pk_g}.

Aggregate loads over larger areas are typically of significant concern in determining design loads for both the main wind force–resisting system and components and cladding. It is well known that the magnitude of the peak is reduced when area averaging is considered (e.g., Kopp et al. 2005). It is also known that the probability distribution of the area-averaged pressure differs from that of its individual components when the area becomes larger (e.g., Stathopoulos 1979). This section considers whether the n_{pk_g} and t_{pk_g} necessary to achieve desired Cp_{pk_g} accuracy and precision are altered when area-averaged pressures are analyzed.

A series of 30-h time histories were constructed via area averaging of multiple adjacent taps, as was done in Gavanski and Uematsu (2014). It was not possible to conduct a tributary area analysis for Tap 3 because of its location on the roof. The size and number of larger areas vary with the tap. Following the analysis of single-tap Cp time series, Cp_{pk_g} values (80% fractile) were estimated from the area-averaged time histories for various t_{pk_g} and n_{pk_g}, and then converted to an equivalent $t_{pk_g} = 60$-min value. Cp_{emp} was then calculated from the empirical CDF of each area-averaged time history using $t_{pk_g} = 60$ min and $n_{pk_g} = 30$.

Fig. 12 presents area-averaged results in a format similar to that in Fig. 9 for $n_{pk_g} = 10$, 15, and 30. The assigned n_{pk_g} is constant in a given figure (3 figures per tap). The columns in each plot correspond to the area used for averaging and the number of taps employed for the calculation of area-averaged Cp time series. The cases where the smallest (base) tributary area was considered used Cp time series at only one tap; therefore, the results are the same as in Fig. 9.

As expected, the magnitude of Cp_{pk_g} is reduced as the area increases, to a degree substantially dependent on location. Observing the relationship between Cp_{emp} and U_{pk_g}, there seem to be more cases where U_{emp} ($Cp_{\text{emp}} \pm 3$ SE) begins to contain U_{pk_g} as the area increases for large n_{pk_g} regardless of tap location [Figs. 12(c, f, and i)]. For example, with $n_{pk_g} = 30$, although it is necessary to have a t_{total} of 150 min ($t_{pk_g} = 5$ min) for single-tap Cp time series in order to have a relationship of $U_{pk_g} < U_{\text{emp}}$ at Taps 1, 2, and 4, t_{total} can be reduced to 60 min ($t_{pk_g} = 2$ min) for area-averaged Cp time series. However, for small n_{pk_g}, the relationship of U_{pk_g} and U_{emp} does not necessary improve and in some cases becomes worse as the area increases.

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Fig. 12. Plots of Cp_{pk_g} for $n_{pk_g} = 10$, 15, and 30 and all t_{pk_g} from area-averaged Cp histories at the 3 selected taps with conversion to $t_{pk_g} = 60$ min using Eqs. (6) and (7); values shown are the mean of the estimated peak, $\bar{C}p_{pk_g}$ (open circle), and 95% probability range, U_{pk_g} (triangle, circle, cross, square, and x); Also included are the peak values from the empirical distribution, Cp_{emp} (solid gray line), and U_{emp} range (dashed gray line)

Conclusions

The purpose of this study is to highlight the strong influence of duration and peak sampling frequency on uncertainty. Although the sensitivity of uncertainty is undoubtedly a function of estimation method, the duration-precision trade-off issue is universal. The wind tunnel practitioner employing a different estimation method and peak definition may not be able to utilize the specific quantifications here, but can benefit from exposure to the issue and the simple uncertainty quantification scheme of this study rather than the nominal results.

The accuracy and precision of peak pressure coefficient estimation procedures were investigated using wind tunnel time-series data obtained on the roof of a low-rise building. In particular, uncertainties due to the use of short-duration records (which occurs often in practice) are investigated in order to identify the combination of duration in which a single peak is observed (t_{pk_g}) and the number of observed peaks (n_{pk_g}) necessary to achieve various levels of precision that minimize total sampling duration within acceptable error bounds. For any sampling time, t_{pk_g}, 30 observed peaks ($n_{pk_g} = 30$) were required for the difference between true (Cp_{emp}) and estimated peaks (Cp_{pk_g}) to have a 95% probability of being within ±10% of each other (except for taps with relatively small-magnitude peak values). However, if only the larger-magnitude suctions are of primary concern, using $n_{pk_g} = 15$ yields a similar precision. Thus, for many design scenarios, if no extrapolation to other sampling times is required, the use of $n_{pk_g} = 15$ is likely to be sufficient.

When particular sampling times are required, the combination of t_{pk_g} and n_{pk_g} needs to be investigated. In the current work, the desired sampling duration for the peak, T, was assumed to be 60 min, consistent with earlier studies and design standards. The conversion of Gumbel parameters, derived from peaks observed from a series of subsets with duration t_{pk_g} less than 60 min, to those associated with $t_{pk_g} = T = 60$ min, was applied to the peak estimation procedure. Precision was evaluated in terms of both t_{pk_g} and n_{pk_g}. Errors and uncertainty increase when the extrapolation procedure is used such that extrapolating from $t_{pk_g} = 2$ min to $t_{pk_g} = 60$ min (i.e., a factor of 30) with $n_{pk_g} = 30$ leads to differences between the true and estimated peaks having a 95% probability of being within ±20% of each other for the majority, although certainly not all of the taps. However, for the extrapolation from $t_{pk_g} = 10$ min to $t_{pk_g} = 60$ min, the majority of the larger-magnitude peaks are within ±15% when $n_{pk_g} = 30$ and within

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±20% when $n_{pk_g} = 15$. Considering the other uncertainties in developing design wind loads, a 95% probability range covering ±10% for larger-magnitude peaks should be acceptable in practice, given that the overall expected coefficient of variation for wind loads on structures is about 35% (Ellingwood 1999). Thus, if T is required to be 60 min, the total minimum sampling duration is approximately $t_{\text{total}} = 150$ min (with $t_{pk_g} = 5$ min and $n_{pk_g} = 30$). If T is required to be only 10 min, then, holding the same extrapolation ratio, the total minimum sampling duration is approximately $t_{\text{total}} = 30$ min (with $t_{pk_g} = 1$ min and $n_{pk_g} = 30$). The analysis of area-averaged coefficients leads to a similar conclusion but with a slight improvement in estimation accuracy and precision for large n_{pk_g}. Thus, current wind tunnel studies that acquire data for approximately 30 min in equivalent full scale, have sufficient accuracy for 10-min statistics if 30 peaks of 1-min duration are used.

Finally, the peak estimation procedure in ISO 4354 was compared with the Gumbel-fitting approach using equivalent input (common t_{pk_g} and n_{pk_g}). No advantage was identified between methods with regard to the resultant uncertainties in the estimated Cp_{pk_g}.

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Notation

The following symbols are used in this paper:

Cp = pressure coefficient;
Cp_{emp} = peak pressure coefficient calculated from empirical cumulative distribution function of F_{emp} with $n_{pk_g} = 60$ and a fractile level (F_{pk_frac}) of 80% for a certain t_{pk_g};
Cp_{pk} = peak pressure coefficient;
Cp_{pk_g} = peak pressure coefficient estimated from Gumbel-modeled cumulative distribution function (F_g);
$Cp_{pk_g_60}$ = estimated peak pressure coefficient with peak evaluation time (t_{pk_g}) of 60 min (full scale) without use of Cook-Mayne conversion;
$Cp_{pk_g_t}$ = estimated peak pressure coefficient calculated using peaks whose peak evaluation time (t_{pk_g}) of t min (full scale) is converted to its 60-min equivalent using Cook-Mayne conversion;
$\bar{C}p_{pk_g}$ = average of Cp_{pk_g};
e = difference between U_{pk_g} and U_{emp};
F_{emp} = empirical cumulative distribution function;
F_g = Gumbel-modeled cumulative distribution function;
F_{pk_frac} = peak fractile level set for the estimated peak pressure coefficient;
MSE = mean square error between individual estimated peaks (Cp_{pk_g}) and empirically estimated peak (Cp_{emp});
n_{pk_g} = number of observed peaks from Cp times series used in the calculation of Cp_{pk_g};
n_{peak} = number of Cp_{pk_g} estimated from 30-h (full-scale) Cp time series for a certain combination of t_{pk_g} and n_{pk_g};
t_{pk_g} = peak evaluation time;
t_{total} = total testing time required to estimate Cp_{pk_g}, which is ($t_{pk_g} \times n_{pk_g}$);
U_{emp} = $Cp_{\text{emp}} \pm 3$ standard error (SE) range; and
U_{pk_g} = 95% probability range of all Cp_{pk_g} estimated for a certain combination of t_{pk_g} and n_{pk_g}.

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