Terrain classification and exposure factor in the 2005 National Building Code of Canada

Ted Stathopoulos [a], Ioannis Zisis [a], Kai Wang [b]

[a] *Concordia University, 1515 St. Catherine W., Montreal, Canada*
[b] *formerly Concordia University, 1515 St. Catherine W., Montreal, Canada*

ABSTRACT: The paper indicates the discrepancies between various wind load standards as far as the terrain classification and the exposure factor are concerned. Of special interest is the latest version of the National Building Code of Canada (NBCC 2005) and the changes introduced since the 1995 version. The exposure factors for open, rough and intermediate terrains are discussed and comparisons with recent experimental studies are presented. The results reveal a slightly over-reduced exposure factor for NBCC 2005 and for cases where a patch of rough terrain is located upwind the site.

KEYWORDS: Wind tunnel, wind load, exposure factor, upstream terrain, wind provisions

1 INTRODUCTION

Current wind load standards follow a similar approach on how to derive wind-induced pressures for the design of components and cladding, as well as primary structural systems of rigid buildings. In general, these pressures are the product of a dynamic velocity pressure (q), an exposure factor (Ce) and a gust pressure coefficient (CpCg). For simplicity, gust pressure coefficients used to originate from extreme values obtained in boundary layer wind tunnel experiments under conditions of open country upstream exposure and were reduced by directionality arguments by a factor of 0.80 or 0.85. Regardless of the actual exposure of the low building, the conservative assumption of open upstream exposure warranted very good results, at least in most, if not all, cases.

A renewed interest in a more rigorous definition of upstream exposure and roughness associated with it has dominated more recently the discussions of the Canadian and American Wind Load Code Committees. The objective was to include in the Standard more clear definitions of the exposure including the transition cases by specifying appropriate values for the exposure coefficient [Irwin, 2006]. A detailed elaboration of the exposure effects increases the complexity of the design process but may lead to more adequate and economical wind pressure provisions. Consequently, CpCg provisions are not based anymore on the conservative open country exposure but on the actual upstream roughness. The American standard [ASCE/SEI 7-98, 2000 and its subsequent editions] and the 2005 Canadian Code [NBCC 2005] use the velocity profile of a suburban exposure if the actual building is indeed exposed to a suburban corresponding roughness.

The paper is an extension of a review article presented by Stathopoulos et al. [2009] and is focusing on the recent revisions and developments of NBCC 2005 as far as exposure is concerned.

2 UPSTREAM EXPOSURE PROVISIONS

There are difficulties associated with research aiming at codifying the wind exposure conditions for the evaluation of wind-induced loads on buildings. Traditionally, wind standards or building codes use a rough classification of A, B, C (sometimes also D) to include ranges of cases with upstream conditions being more or less of a similar average roughness. Photos of typical cases (Figure 1) along with generic descriptions proved to be the

Photos of typical cases (Figure 1) along with generic descriptions proved to be the most valuable tool to assist designers to select the exposure resembling better the actual case of the particular building location of interest. However, the level of subjective interpretation is high and disagreements have always been noted in attempting to apply some code provisions. Table 1 provides a comparison of roughness length (z_o) values and minimum upstream fetch length required for the characterization of different exposures in the most recent editions of some well known wind standards /codes, namely the Canadian, American, Australian/New Zealand and British codes of practice. The differences in some cases are quite significant. For instance, for the most common suburban / urban terrain the minimum necessary upstream fetch required for a 5 m high building ranges from 100 to 1000 m depending on the country where the building is located. This is a real problem with a solution requiring a lot of research to address it.

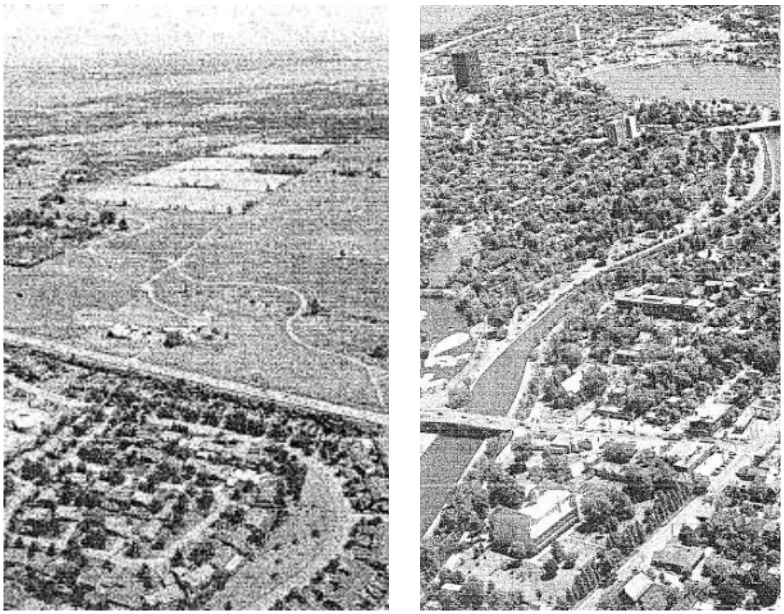
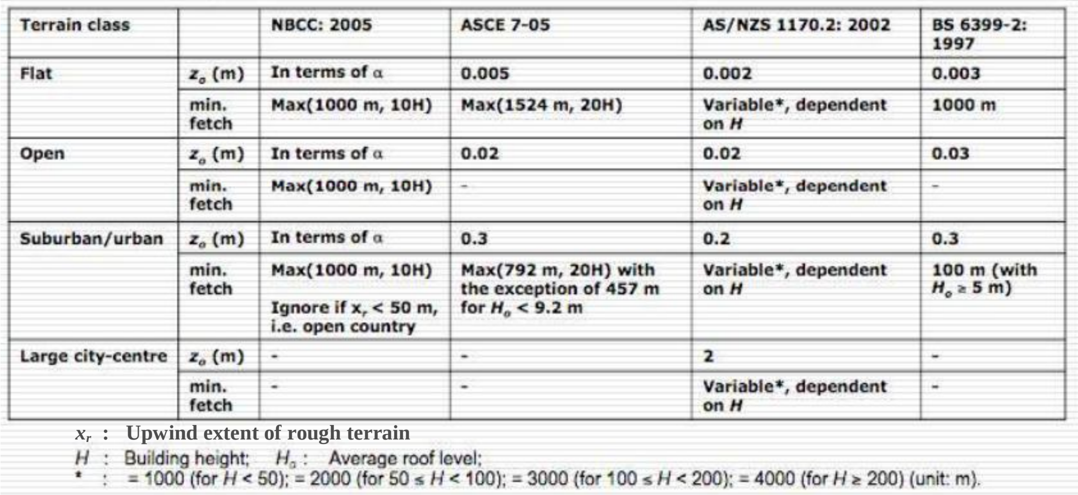


Figure 1. Examples of open and rough terrains used in NBCC 2005.

Table 1. Values of roughness length and minimum fetch of various codes and standards.



Terrain class		NBCC: 2005	ASCE 7-05	AS/NZS 1170.2: 2002	BS 6399-2: 1997
Flat	z_o (m)	In terms of α	0.005	0.002	0.003
	min. fetch	Max(1000 m, 10H)	Max(1524 m, 20H)	Variable*, dependent on *H*	1000 m
Open	z_o (m)	In terms of α	0.02	0.02	0.03
	min. fetch	Max(1000 m, 10H)	-	Variable*, dependent on *H*	-
Suburban/urban	z_o (m)	In terms of α	0.3	0.2	0.3
	min. fetch	Max(1000 m, 10H) Ignore if $x_r < 50$ m, i.e. open country	Max(792 m, 20H) with the exception of 457 m for $H_o < 9.2$ m	Variable*, dependent on *H*	100 m (with $H_o \geq 5$ m)
Large city-centre	z_o (m)	-	-	2	-
	min. fetch	-	-	Variable*, dependent on *H*	-

x_r : **Upwind extent of rough terrain**

H : Building height; H_o : Average roof level;

* : = 1000 (for $H < 50$); = 2000 (for $50 \leq H < 100$); = 3000 (for $100 \leq H < 200$); = 4000 (for $H \geq 200$) (unit: m).

The above alerting indication has been addressed from other studies as well. Indeed, St. Pierre [2002] has compared experimentally measured vertical uplift and horizontal thrust coefficients on an end bay of gabled roof low buildings in suburban terrain roughness with the Canadian [NBCC 1995], American [ASCE/SEI 7-98, 2000] and European [ENV 1995] corresponding provisions. It was shown that the values derived from the examined codes differ significantly. Figure 2 shows typical results from this study.

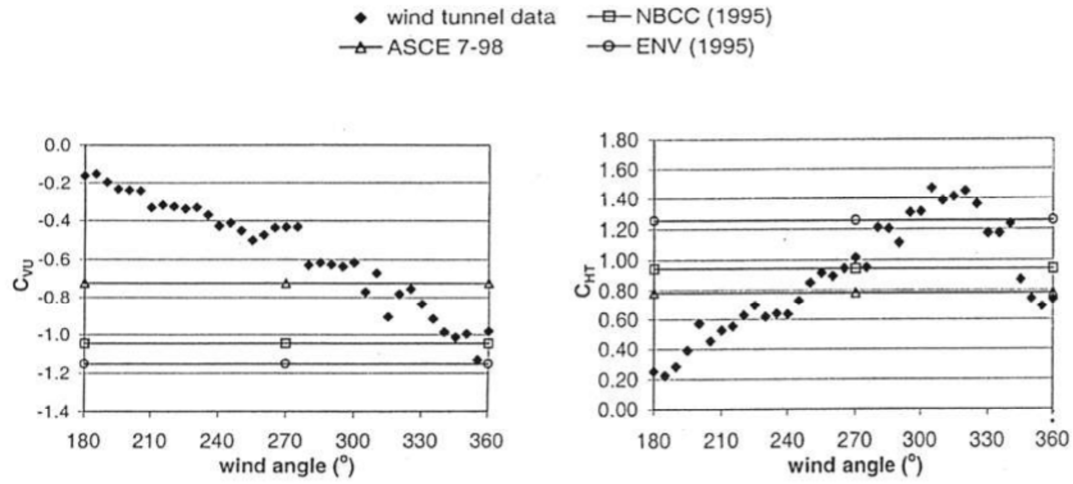


Figure 2. Minimum vertical uplift and maximum horizontal thrust coefficients for the end bay of a gabled roof building in suburban terrain exposure, (a) eave height: 9.75 m; roof slope: 3:12 (b) eave height: 7.32 m; roof slope: 1:12 (after St. Pierre, 2002).

3 EXPERIMENTAL EVALUATION OF EXPOSURE EFFECTS

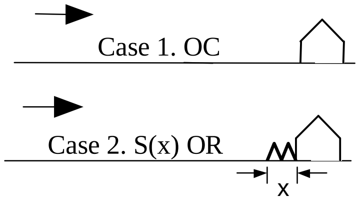
A recent experimental study by Wang and Stathopoulos (2006) has revealed a number of interesting characteristics regarding the effect of upstream exposure on the wind loading of low buildings. In short, the study found that the peak wind loads are dominated by the upstream terrain configuration only in a short distance upwind the site.

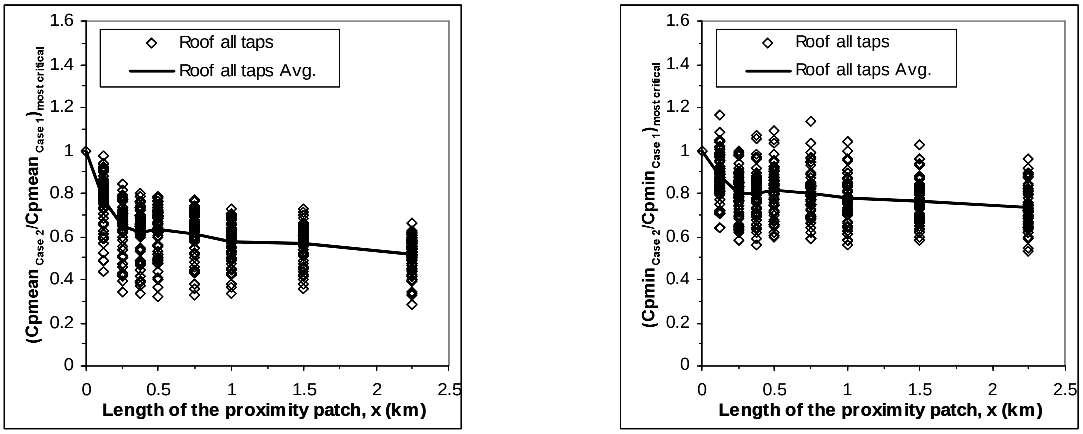
A low building model with 4:12 gable roof slope (typical residential construction) was employed for this study. For each of the 66 fetch cases used in this study, the pressure were scanned with 13 wind angles of attack (θ), namely 0^{o}, 35^{o}, 40^{o}, 45^{o}, 50^{o}, 55^{o}, 90^{o}, 125^{o}, 130^{o}, 135^{o}, 140^{o}, 145^{o} and 180^{o}.

Figure 3 shows the wind load variation above terrain with a single roughness change from smooth-to-rough as it approaches the building. More specifically this figure shows the variation of *Cp* ratios for an upstream terrain configuration of "*A SUBURBAN patch of variable length directly upwind of the building with the OC terrain as remainder*" over those of OC as a function of the upstream suburban patch length. The configuration of '*a SUBURBAN patch on otherwise OC terrain*' is considered the critical one in comparison to that of '*an URBAN patch on otherwise OC terrain*' for the smooth-to-rough terrain configurations. Data show that the peak loads decrease rapidly for a length of the upwind patch about 250 m and then stabilize. Clearly, it takes a longer distance for the mean loads to stabilize than the peak loads.

In reality, there may be open gaps existing in the nearest upwind suburban fetch section. A number of such cases are shown in Figure 4. These cases commonly have a suburban patch of 125 m long directly upwind the site, and they are compared with the homogeneous suburban case. The solid lines in Figure 4 are the overall averages of all of the data points of one fetch case, or of several fetch cases that have the same total length of the open gaps. When the total length of the open patches reaches somewhat between 250 and 500 m, the wind loads stabilize or may increase by ~10% from those above suburban. Once again, data in this figure imply that the high variation of terrain roughness not directly upwind the building does not have a significant impact on the peak loads.

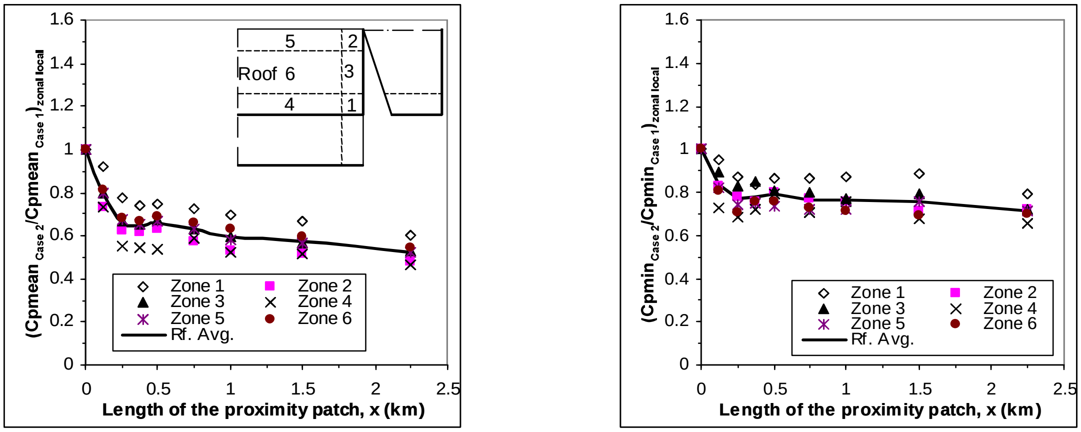
Generally speaking, low building peak loads can be determined by a fetch as short as 300 – 400 m, irrespective of the configurations of the further upwind terrain. It should be recalled that the British Code [BS 6399-2, 1997] has specified that it takes only 100 m of a suburban patch to characterize the entire exposure for the evaluation of design loads as suburban – see Table 1. Therefore, the present finding falls into the middle of the range of current standard provisions. This finding encourages proposing a new approach for low building design load, i.e. designers need to pay attention just to terrain configurations close to the site and neglect further upwind terrain configurations with the exception of large topographic features, e.g. hills.





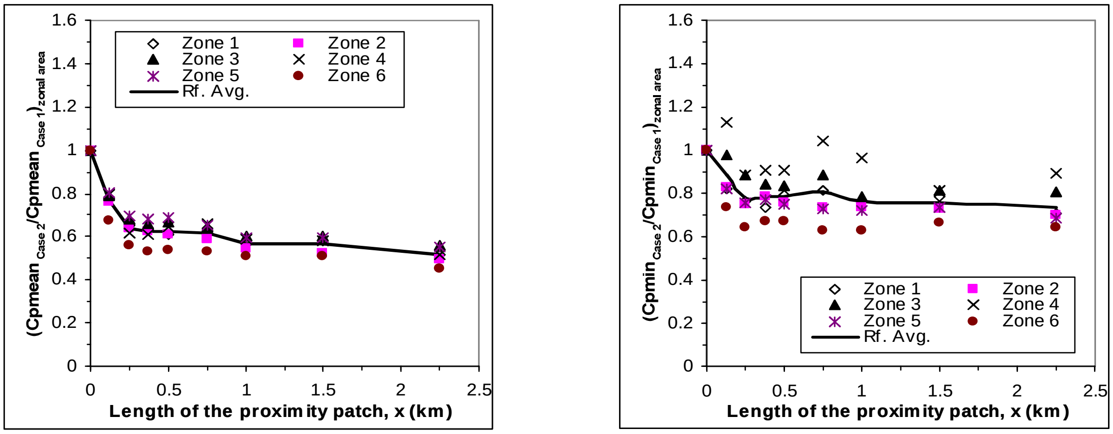
(a) Roof all taps, ratio of *Cp* mean

(b) Roof all taps, ratio of *Cp* min



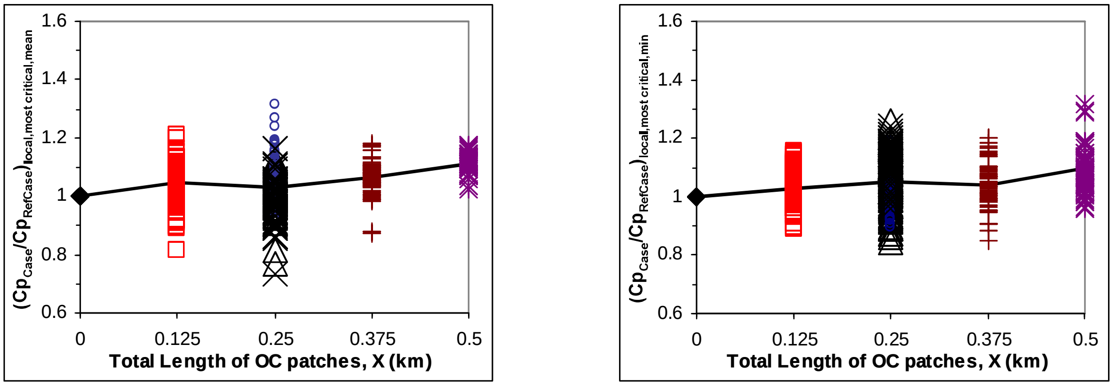
(c) Roof zonal worst local, ratio of *Cp* mean

(d) Roof zonal worst local, ratio of *Cp* min

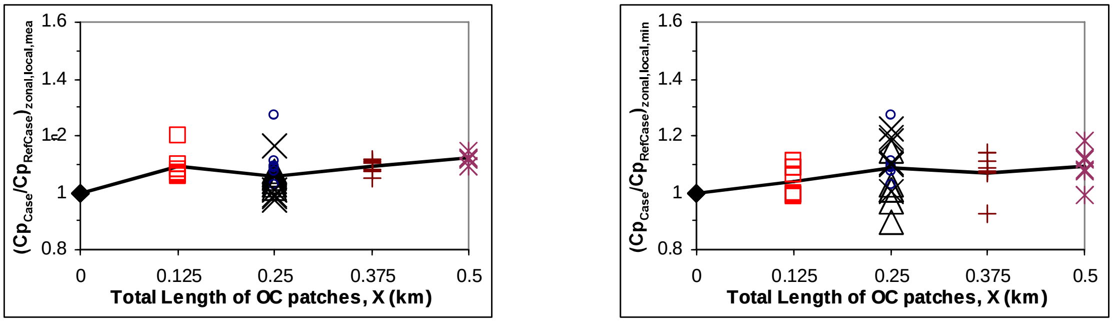


(e) Roof zonal area, ratio of *Cp* mean (f) Roof zonal area, ratio of *Cp* min

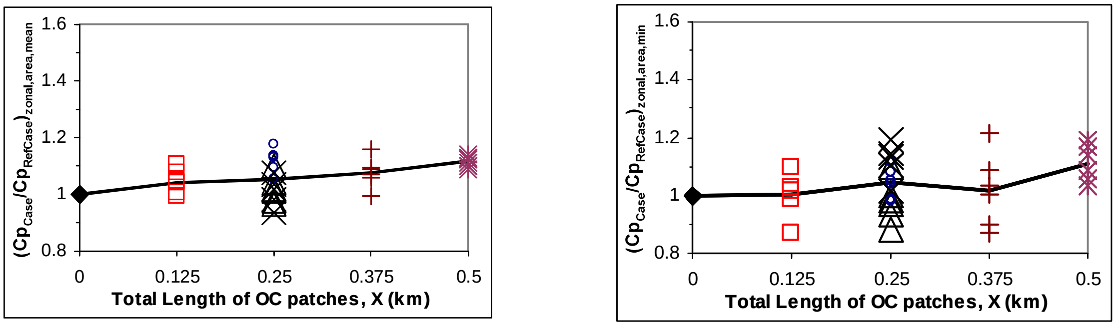
Figure 3. Most critical C_P ratios for the cases in the test group "Suburban patch of variable length directly upwind to the building with oc as remainder".



(a) Roof all taps *Cp* mean (b) Roof all taps *Cp* min



(c) Roof zonal worst local *Cp* mean (d) Roof zonal worst local *Cp* min



(e) Roof zonal area *Cp* mean (f) Roof zonal area *Cp* min

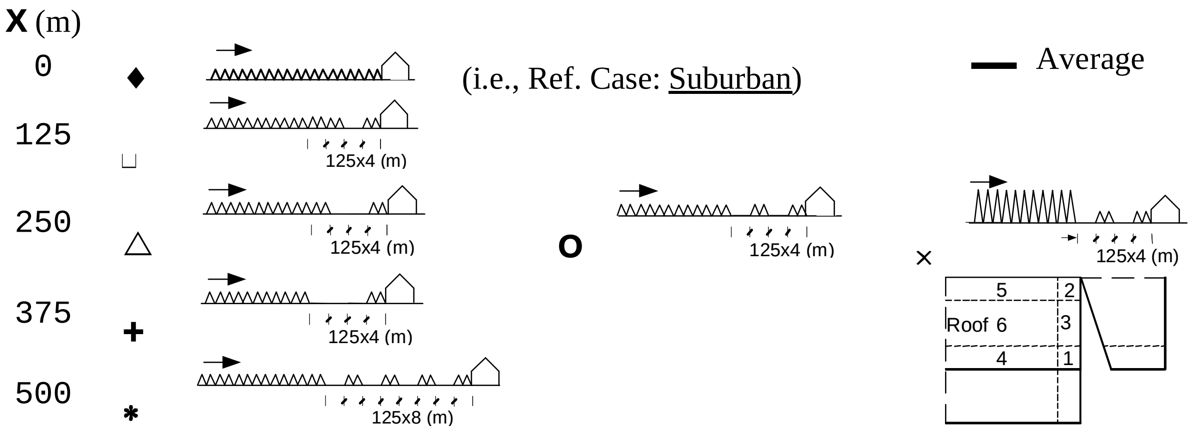


Figure 4. Most-critical C_p ratio of cases that have a 125 m long Suburban patch directly upwind to the building.

4 NBCC 2005 EXPOSURE ISSUES

The NBCC 2005 followed a similar analysis procedure with that of the 1995 version, as far as the wind load calculation is concerned. Terrain classification was still grouped under three separate wind load calculation procedures: static, appropriate for the majority of low- and medium-rise buildings; dynamic, appropriate for taller and slender structures; and the experimental, recommended for more complex cases. One of the changes introduced in the 2005 version was the consideration of a rough terrain class under the static procedure along with a new equation for the calculation of the exposure factor (C_e):

$$C_{er} = 0.7\left(\frac{h}{12}\right)^{0.3} \geq 0.7 \qquad (1)$$

where:
C_{er}: rough terrain exposure factor
h: reference height above grade (m)
It should be noted, that NBCC 1995 suggested exposure factor values for the static procedure, were based only on open terrain assumption regardless of the actual exposure. Moreover, NBCC 2005 took into consideration cases where transition from smooth to rough terrain occurs, presenting a new intermediate exposure factor based on the following equation:

$$C_e = C_{er}\left(0.816 + 0.184\log_{10}\left(\frac{10}{x_r - 0.05}\right)\right) \leq C_{eo} \qquad (2)$$

where:
C_{eo}: open terrain exposure factor
x_r: upwind extent of rough terrain ($0.05 < x_r < 1.00$ km)
The intermediate values were suggested for those cases where a terrain was not clearly defined for a distance of 1 km or 10 times the building height (whichever is greater). The ratios of the intermediate over the rough exposure factor with the respect to the varying length of the upwind extent of rough terrain are presented in Figure 5. As the plot indicates the intermediate exposure factor is 1.37 times higher than the rough exposure factor when the upwind extent of rough terrain takes its minimum value of 0.05 km. The different terrain categories were accompanied by figures that tried to clarify the –not so discrete- variations of upstream terrain. A summary of the changes related to exposure effects between the two versions of the NBCC is presented in Table 2.

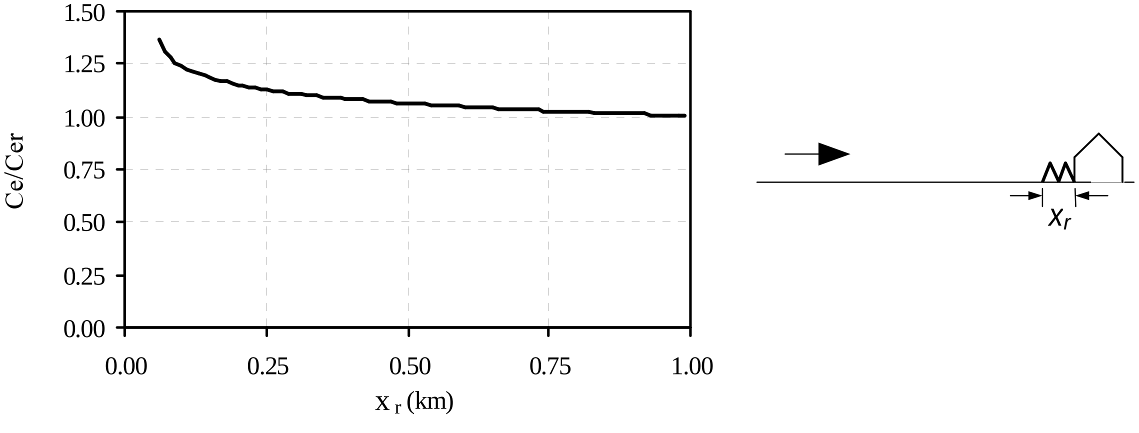


Figure 5. Ratios of intermediate over rough exposure factor for variable length of upwind extent of rough terrain.

Table 2. Exposure effect related changes between NBCC 1995 and 2005.

	NBCC 1995	NBCC 2005
Terrain Classes (Static Procedure)	1 (Open)	2 (Open, Rough)
Ce,open	$(h/10)^{0.2}$	$(h/10)^{0.2}$
Ce,rough	-	$0.7(h/12)^{0.3}$
Ce,intermediate	-	see Equation (2)
Minimum Fetch	-	max(1000 m, 10H)
where h:reference height, H:building height		

Specifically for the static procedure in NBCC 2005, which is of greater interest due to its broad applicability, terrain was classified as open and rough and two different formulas were designated for each one (4.1.7.1 Sentence 5 – see Table 2). The two formulas are function of the reference height above grade (h in meters) and are plotted in Figure 6. Their ratio ($C_{e,r}$ / $C_{e,o}$) has also been included and shows that for low-rise buildings (h<10 m) its minimum value is approximately 0.70, i.e. wind load calculated for rough terrain is 30% lower than that of open terrain.

Two issues were addressed previously by Wang and Stathopoulos (2006): what should be the appropriate exposure factor value and what is the minimum design fetch length. Figure 7 compares the results from the Wang and Stathopoulos study and those derived by the formulas provided in NBCC 2005 (see Table 2). For the latter, only heights from 0 to 10 m were considered and interpolation was carried out for upwind extent of rough terrain (x_r) up to 1 km. The comparison indicates that NBCC 2005 slightly overestimates the alleviating effect of a rough terrain patch especially for patch lengths over 400 m. As Stathopoulos et al. (2009) previously have indicated, a value of 0.8 should be the minimum ratio of the interpolated exposure factor over its open terrain counterpart.

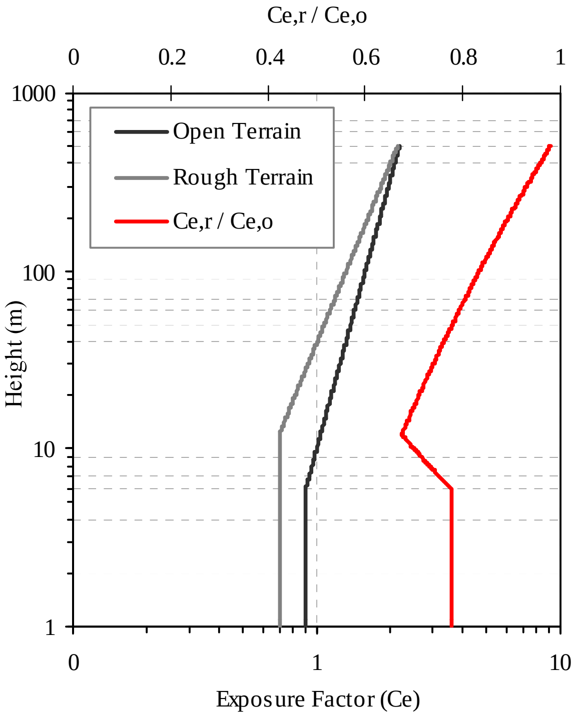


Figure 6.Exposure factor values for open and rough terrains (NBCC 2005).

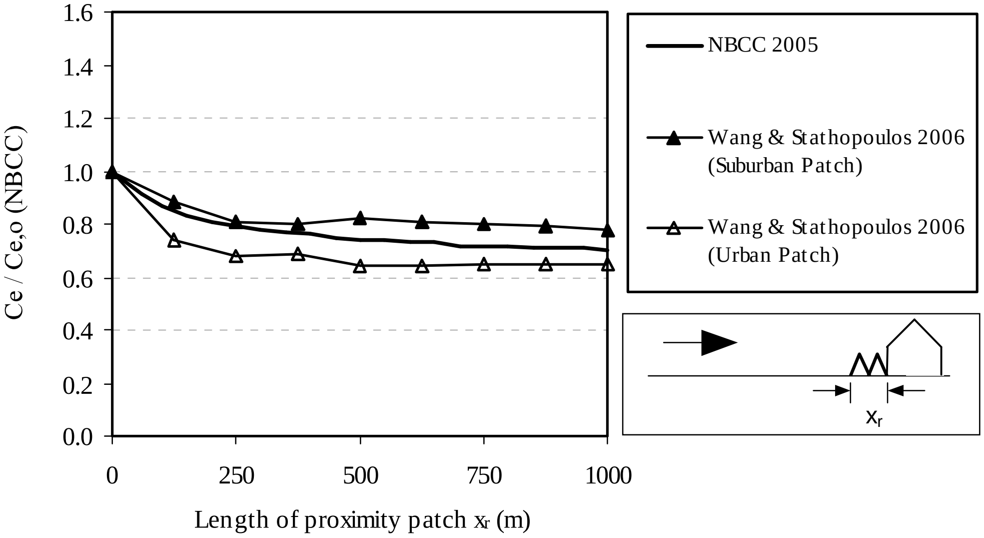


Figure 7.Exposure factor ratios based on $C_{p,min}$ measured for varying upwind rough terrain patches.

5 CONCLUSIONS

The paper identifies the changes related to wind load and upstream exposure characterization introduced to the latest version of the NBCC. The recommendations extracted by NBCC 2005 are compared to other wind load standard provisions and significant discrepancies are revealed. In addition, the results of a wind tunnel study dealing with the low building wind load variation for upstream fetch with roughness changes are presented and discussed. This study indicates that the exposure factor should be closer to 0.8 rather than the 0.7 mark suggested by NBCC 2005. The same study has taken into account the load variability that comes from roughness variation indirectly upwind the site within the first 300 – 400 m fetch section, to which peak loads are indeed sensitive.

6 ACKNOWLEDGEMENT

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