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RISK ANALYSIS OF WIND LOADING INCLUDING FUTURE CHANGES IN SURROUNDING BUILDINGS

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ABSTRACT

Wind tunnel tests of tall buildings are capable of accurately determining the wind loads on a building in its current surroundings, since the surroundings are included in the wind tunnel modelling. The tests may also include some future developments if they are known to be imminent. However, the question of the effects of possible longer term changes in surroundings needs to be considered. In some cases the development of the city may be mature resulting in little likelihood of future changes, but in rapidly developing cities the possible changes may be significant. It is known that buildings very close to the building under test can have significant sheltering effects in some cases and may amplify wind loads in other cases. Cases have been seen where the removal of an important adjacent building more than doubled the wind loads. Wind tunnel testing can readily determine loads in the different scenarios but the question of how to treat the data requires some thought. This paper presents a method called the Combined Risk Method in which the results from the various test scenarios are combined to provide a single risk consistent relationship between load and return period. It does require that the various stakeholders agree on a reasonable probability for each scenario, but once this is done the method makes the path clear to developing appropriate design loads. The paper includes examples of application of the method to several projects.

Keywords: Wind loading, wind tunnel testing, risk, surrounding buildings, unsheltered

1. INTRODUCTION

When using a building code such as the National Building Code of Canada (NBCC, 2010) or a wind standard such as ASCE 7 (ASCE 7, 2010) the analysis methods for establishing wind loads are based on generic shapes and generic surroundings. The building code provisions are intended to envelope the vast majority of possible building shapes and surrounding conditions. However, for tall buildings it is recognized that the wind induced loads and building responses could go outside the envelope of what is covered by the analytical code provisions and it is recommended that wind tunnel tests be undertaken, using appropriate methodology such as described in ASCE 49 (ASCE 49, 2012). In particular the crosswind responses of tall buildings, which can be sensitive to shape and surroundings, and the torsional responses are not adequately covered by the analytical methods, but can be accurately determined through wind tunnel testing.

However, questions arise when undertaking wind tunnel tests as to the possible effects of future changes in surroundings. Wind tunnel tests of tall buildings are capable of accurately determining the wind loads on a building in its current surroundings, since the surroundings are included in the wind tunnel model. The tests may also include some future developments if they are known to be imminent. However, the question of the effects of possible longer term changes in surroundings, not known at the time of the wind tunnel study, needs to be considered. In some cases the development of the city may be mature resulting in little likelihood of future changes, but in rapidly developing cities the possible changes may be significant. In general as a city becomes more built up, which has been the history of most cities, the terrain becomes aerodynamically rougher. Thus the addition of many new buildings to a city will tend to reduce loads through this far field "exposure factor" effect. However, it is known that buildings in the near field, very close to the study building, can be the cause of significant local aerodynamic interference effects, some of which may reduce loads and some of which may cause load increases. Where an adjacent building has a sheltering effect, the probability that it could be removed in future, and the potential load increases if this were to happen, invites some thought. Cases have been studied in the wind tunnel where the removal of an important adjacent building more than doubled the wind loads on the study building.

Wind tunnel testing can readily determine the loads in the different surrounding scenarios but the question of how to treat the data has not received much attention. This paper presents a method called the Combined Risk Method in which the results from the various test scenarios are combined to provide a single risk consistent relationship between load and return period.

2. COMBINED RISK METHOD

The risk of loads being meaningfully increased by some future scenario of surrounding buildings will vary depending on many factors including but not limited to: expectation of future development, design risk and implication to the structure, and relative size and aerodynamic influence of the building relative to surrounding buildings. These risks are difficult to quantify, but, in general, the history of development in major cities (where most buildings are) suggests the risk of future wind increase is relatively low. Most cities are growing, and one does not see too many buildings being demolished with nothing being built to replace them.

As a first step we assume that there is a probability, γ, that the adjacent building(s) will be removed and not be replaced during the life of the study building. The probability γ implies that, over the long term, for a fraction γ of the time the building can be considered as unsheltered and for the remaining $(1-\gamma)$ of the time it can be considered as sheltered. We can undertake wind tunnel tests on the sheltered and unsheltered cases and determine the return period of a given load level (e.g. base moment M_x) for each case individually. Denoting the return period in the unsheltered case as T_u and in the sheltered case as T_s, it can be shown (Irwin and Sifton, 1998) that the overall return period, T, for the selected load level, bearing in mind the fractions of time the building is sheltered and unsheltered, is given by

$$[1] \qquad \frac{1}{T} = \frac{\gamma}{T_u} + \frac{1-\gamma}{T_s}$$

In the general case where there are multiple possible configurations of surroundings each with probability γ_i the overall return period relationship is

$$[2] \qquad \frac{1}{T} = \sum \frac{\gamma_i}{T_i}$$

where T_i is the return period for the selected load level in the i^{th} surrounding configuration. However, in this paper we restrict attention to just two surrounding configurations, sheltered and unsheltered.

The question of what value to assign to γ is a difficult one since it requires assessing what might happen or not happen in future. However, many decisions that society has to make involve some similar kind of assessment of probability of future events. Decisions are necessary in order to move forward. The importance of the decision depends on the consequences of being wrong. In the case where a load may be doubled if shelter is removed, then caution is required and even a conservative estimate of γ is better than no decision at all. If one asks about the probability of a large nearby building, currently in full use, being demolished and not replaced with something similar, the usual answer is no more than a few percent. So it is still instructive to see what happens if one conservatively assumes say 10% or 20% probability in the proposed method. In the following examples the sensitivity of the loads to these types of assumption are assessed.

3. APPLICATIONS

In what follows we examine application of the above method to three different projects where removal of adjacent buildings had fairly dramatic effects on the wind loads. The cases considered here were on the extreme end of the scale since not just one adjacent building was removed but large areas of adjacent blocks were cleared of buildings. The results are nonetheless of interest in illustrating what we have called here the Combined Risk Method.

The wind tunnel tests we undertaken in one of RWDI boundary layer wind tunnels, with 2.4 m wide by 2 m high working section. The model scale was 1:400 and the high-frequency-force-balance method was employed to establish wind loads as a function of wind speed at every 10 degree interval of wind azimuth. The wind tunnel data were combined with wind statistics using the up-crossing method described by Irwin et al (2005). The wind statistics were derived from a Monte Carlo simulation of hurricanes for the city in question, which lies in a wind climate where design wind loads are dominated by hurricanes. Essentially the return periods T_s and T_u corresponding to a selection of load levels were determined for the sheltered and unsheltered cases respectively, and then the combined return period for each load level was determined using Equation 1. This provided a table of combined return periods versus load levels from which the load level for any return period could be interpolated.

3.1 Case 1

The wind tunnel tests of Case 1 are illustrated in Figure 1, which shows the sheltered and unsheltered conditions. The unsheltered condition was extreme in that all nearby buildings were completely removed. Figure 2 shows the variation of base moment with return period for the three cases: sheltered, unsheltered and combined or composite. The probability for this example was selected to be $\gamma = 20\%$, which is probably very conservative in view of the large number of buildings that were removed in the unsheltered case. It can be seen in Figure 2 that the 700 year base moment M_x increased by a factor of more than 2.5 in going from sheltered to unsheltered. But even a conservative assumption of $\gamma = 20\%$ resulted in a much reduced factor of about 1.44 for the composite risk case. Much of the jump in base moment M_x in the unsheltered case was due to vortex excitation which had been largely suppressed in the sheltered case. However it is noticeable in the unsheltered case that the increase in M_x between the 700 year and 2500 year return periods was relatively modest. The M_y moment was also increased in the unsheltered case, but not by such a large factor.

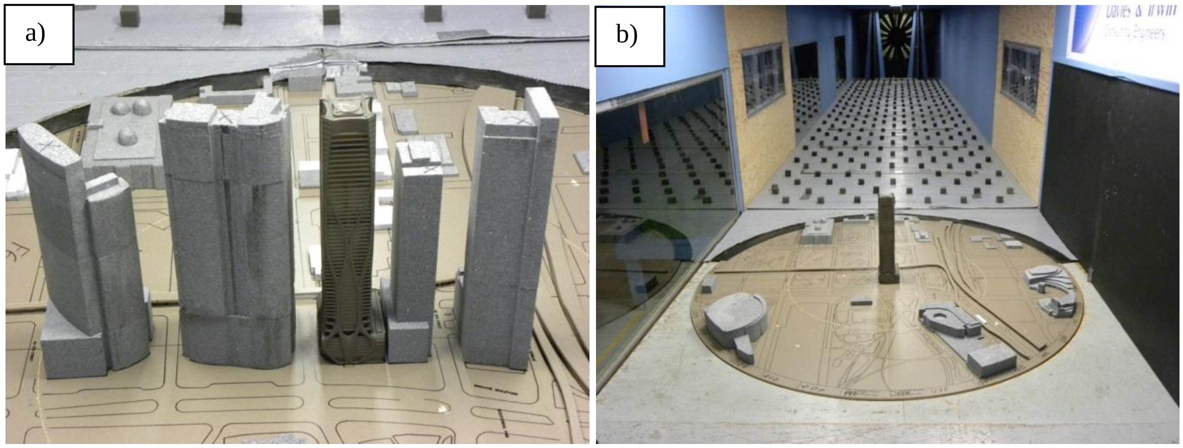

Figure 1: Wind tunnel test of Case 1: a) Sheltered; and b) Unsheltered.

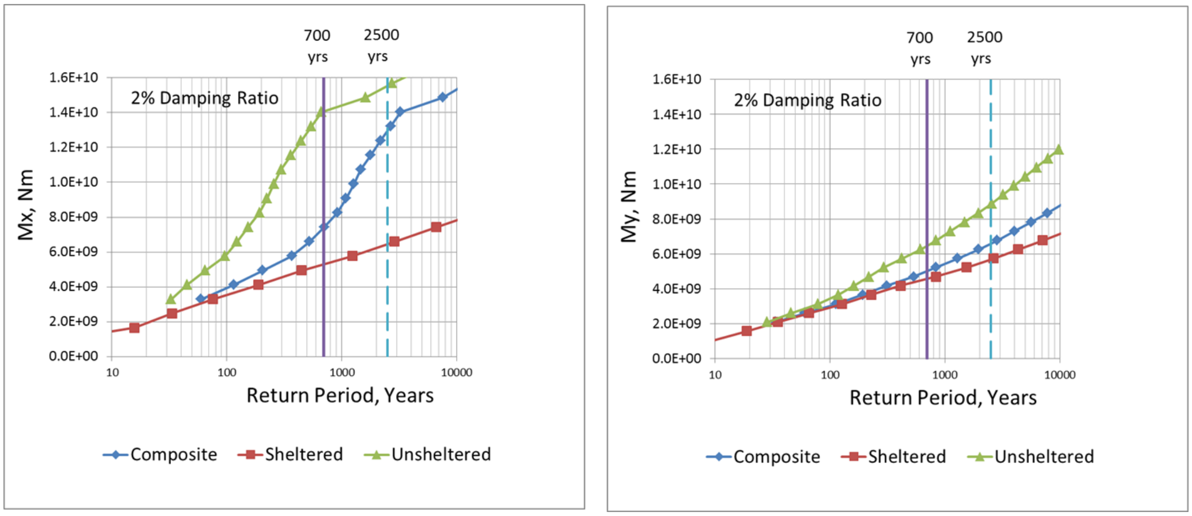

Figure 2: Base moments for Case 1 for the Sheltered, Unsheltered and Combined conditions assuming $\gamma = 20\%$

Figure 3 shows the effect on M_x of different assumptions for γ in Case 1. One could argue that even a 10% assumption for γ is conservative for the complete clearing of nearby surroundings, and at this percentage the increase in 700 year base moment is by a more modest factor of about 1.17.

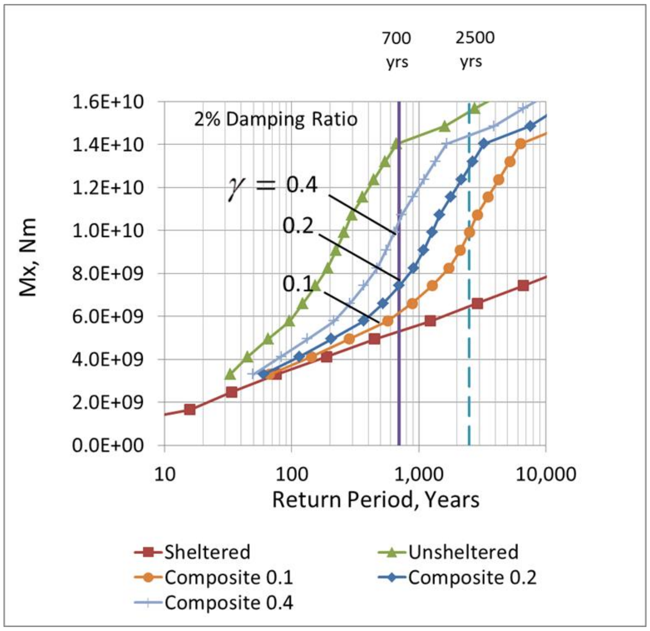

Figure 3: Sensitivity of base moment M_x for Case 1 to assumption of probability γ

3.2 Case 2

The wind tunnel tests for Case 2 are illustrated in Figure 4. Several surrounding buildings were removed for the unsheltered case and the results for base moments are shown in Figure 5 with the assumption of $\gamma = 20\%$ again for the composite case. It can be seen that in this case the M_y moment was the most affected response by the removal of surrounding buildings. In the unsheltered case the building tended to experience vortex excitation at about the 200 year return period, as indicated by flattening of the M_x for return period between 200 and 700 years. In the composite case the flattening was moved to higher return periods. The 700 year M_y value was increased by a factor of about 1.72 in the unsheltered case and by 1.34 in the composite case. A less conservative assumption for γ would probably be appropriate in view of how many buildings were removed. At $\gamma = 10\%$ the increase factor drops to about 1.15.

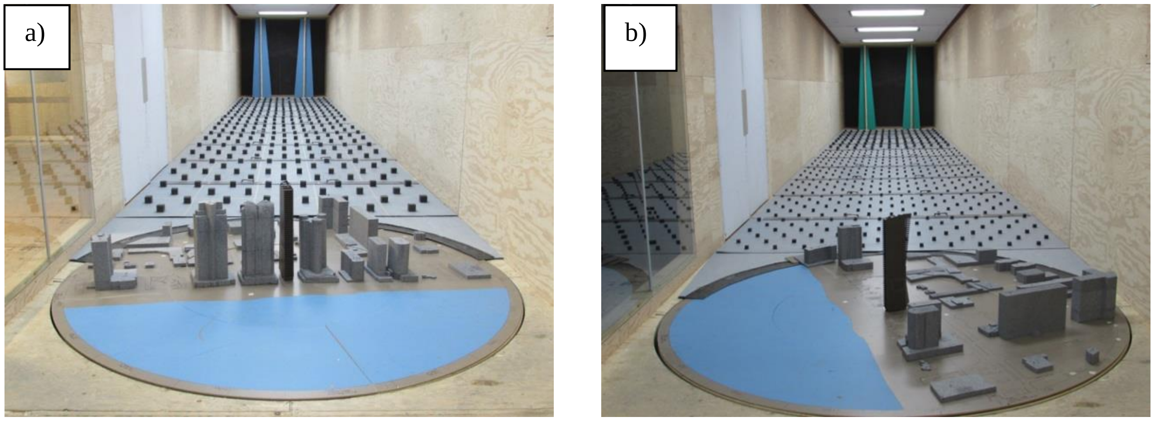

Figure 4: Wind tunnel tests for Case 2: a) Sheltered; b) Unsheltered.

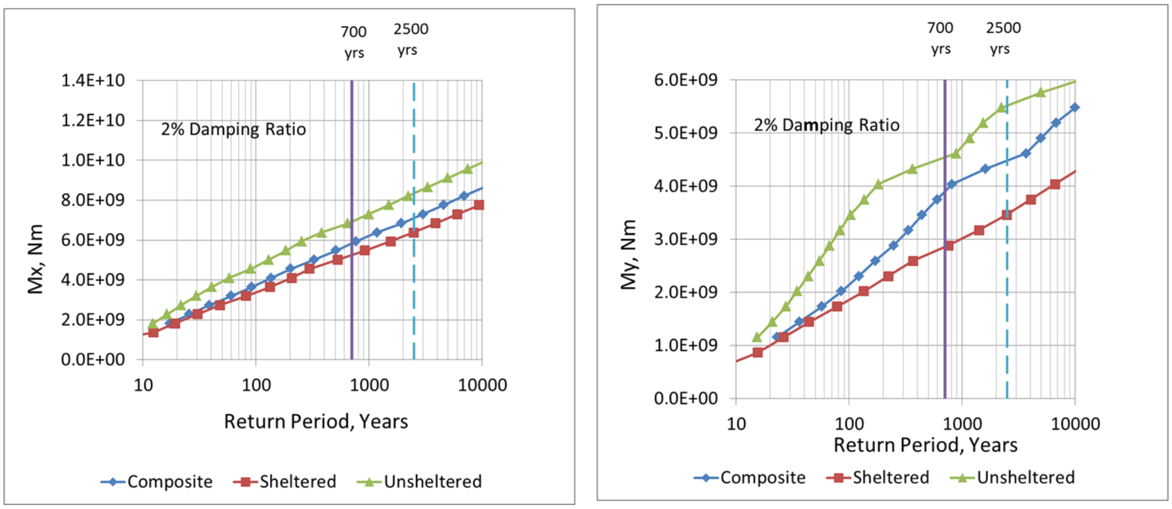

Figure 5: Base moments for Case 2 for the Sheltered, Unsheltered and Combined conditions assuming $\gamma = 20\%$

3.3 Case 3

The wind tunnel tests for Case 3 are illustrated in Figure 6. Many buildings were removed for the unsheltered case and the results for base moments are shown in Figure 7 with the assumption of $\gamma = 20\%$ again for the composite case. The removal of the sheltering buildings allowed vortex excitation to come to the fore dominating wind loads for M_x at about the 400 to 600 year return period but having almost no effect on M_y. Above 400 years the response in M_x did not increase much further as the return period increased. In the sheltered case there was little sign of vortex excitation. In the composite case the results for M_y are hardly changed from the sheltered case and the results for M_x at 700 year return period are increased by a factor of about 1.13.

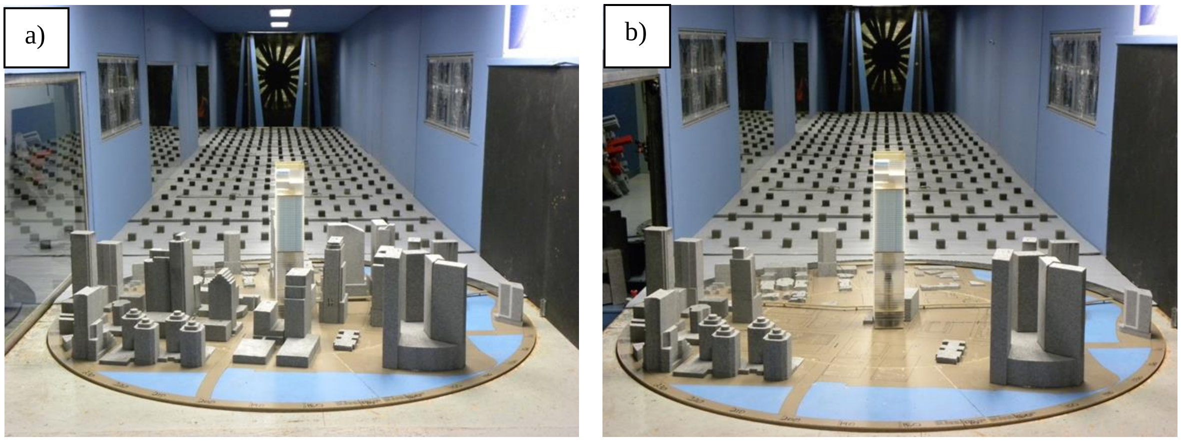

Figure 6: Wind tunnel tests for Case 3: a) Sheltered; b) Unsheltered.

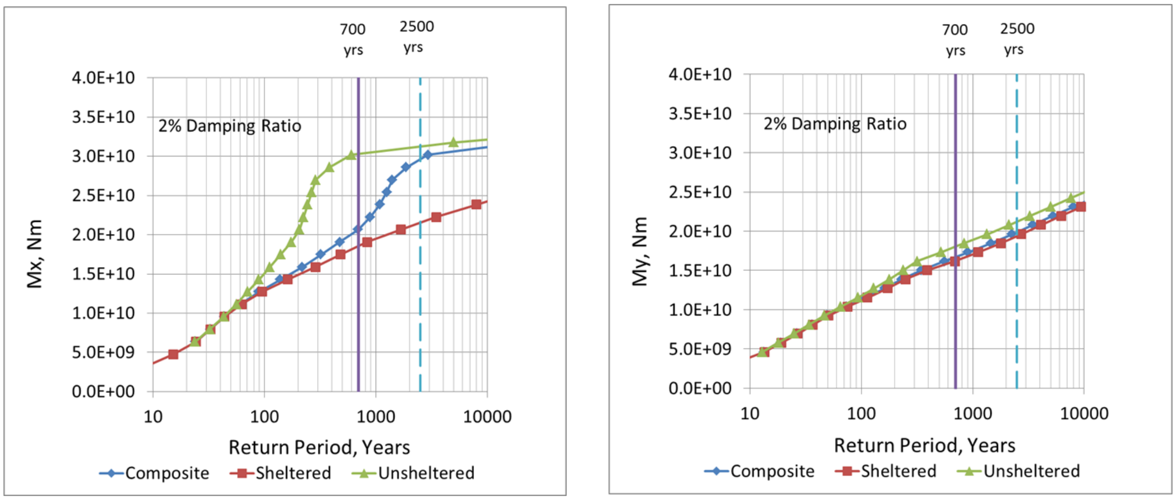

Figure 7: Base moments for Case 3 for the Sheltered, Unsheltered and Combined conditions assuming $\gamma = 20\%$

4. DISCUSSION AND CONCLUSIONS

The proposed Combined Risk Method is a relatively simple approach for formulating the overall risk of various load levels being exceeded that includes the probability of varying future surroundings. It has been applied to three case studies where removal of surrounding buildings caused a substantial increase in the wind loads in at least one direction. By assuming a probability of the future surrounding condition actually occurring, a rational procedure for assessing overall risk is possible. The selection of the appropriate probability is a matter where consensus must be reached by the various stakeholders and it will be affected by the how many surrounding buildings it is felt reasonable to remove. In the cases shown in this paper the removal of surroundings was somewhat extreme but the results have nonetheless illustrated several outcomes. First, even a relatively conservative assumption on the probability of the future condition leads to very significant drops in wind load compared with the raw unsheltered result. Second, the amount of reduction obtained relative to the raw unsheltered result does depend on at what return period in the unsheltered case vortex shedding reaches its peak. In Case 2 this occurred at a return period of about 200 years and the combined risk calculation moved it to close to the design return period of 700 years. In this case the reduction obtained in the combined case was not as dramatic as in the other cases. In Case 3 the vortex shedding peak in the unsheltered case was at about the 400 to 600 year range and in the combined risk calculation moved it to well above the design return period of 700 years. In this case there was a dramatic reduction in load even assuming a fairly high 20% probability of the unsheltered case occurring.

The combined risk approach has been used for other applications in wind engineering such as the combination of exterior cladding pressures with the probability of openings in the envelope (Irwin and Sifton, 1998). It has also been used at RWDI to assess the risk of aerodynamic instability on long span bridge decks under the combination of strong winds with severe icing accumulations of safety screens at the deck edges. In this last case the probability of the future occurrence does not have to be arrived at by consensus since it can be based on past statistical data.

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