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Monitoring of wind-induced building motion and comparison with wind tunnel measurements

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Abstract

This paper describes the results of monitoring the wind-induced building motion of five tall buildings in New Zealand between 2009 and 2012. The measured accelerations were compared with acceptability criteria from ISO Standard 10137:2007. The accelerations were within the acceptability criteria for four of the buildings, and exceeded the criteria by about 20% for the fifth building. The measured wind-induced accelerations are approximately proportional to the cube of the wind speed, demonstrating that accurate estimation of the wind speed is critical for accurate design predictions of wind-induced building motion. An existing predictive equation has been modified based on the results from the building monitoring. A wind tunnel study was done for one of the buildings, and demonstrated reasonable agreement with the building monitoring results.

Introduction

This paper describes the results of monitoring the wind-induced motion of five tall buildings in New Zealand between 2009 and 2012. Four of the buildings are in Wellington and one is in Auckland. The monitoring has been undertaken as part of a research programme to develop an improved methodology for the design of tall buildings, to ensure that wind-induced motion of new tall buildings remains within acceptable limits. Our study is intended to add to the available data on full-scale monitoring of wind-induced motion of tall buildings. In this paper, we focus on Building D, which is the only Auckland building in the study. The measured motion of the building is compared with the results from a wind tunnel study. The research has been previously described in papers including Carpenter et al (2011) and (2012).

Description of the buildings

The five buildings which have been analysed are referred to as Buildings A, B, C, D and E, which are listed in the order that monitoring commenced. As part of our agreement with the building owners, these buildings have not been named.

- Building A is a residential building in Wellington. It is 10 storeys high, with a rectangular planform, and a steel frame structure. Monitoring as part of the New Zealand GeoNet project has been ongoing since early 2009.
- Building B is an office building in Wellington. It is 25 storeys high, with an approximately square planform, and has a structure consisting of concrete perimeter columns with a central core. It was monitored by Opus from 21 August 2009 to 15 October 2009.
- Building C is an office building in Wellington. It is 17 storeys high, with an approximately square planform, and has a concrete structure including a wall on one side, and an offset core adjacent to the concrete wall. It was monitored by Opus from 21 October 2009 to 22 February 2010.
- Building D is a residential building in Auckland. It is 25 storeys high, with a rectangular planform, and has a concrete structure. It was monitored by Opus from 20 October 2010 to 27 May 2011.
- Building E is an office building in Wellington. It is 28 storeys high, and has a concrete structure. Monitoring as part of the New Zealand GeoNet project has been ongoing since early 2012.

Multiple modes of vibration have been identified for each building through analysis of the motion time histories. The measured X, Y and Torsion frequencies for each building are listed in Table 1.

Building	X direction	Y direction	Torsion
A	1.56 Hz (~EW)	1.42 Hz (~NS)	2.10 Hz
B	0.55 Hz (~NS)	0.54 Hz (~EW)	0.84 Hz
C	0.63 Hz (~NS)	0.65 Hz (~EW)	0.65 Hz
D	1.09 Hz (~NS)	0.79 Hz (~EW)	1.41 Hz
E	0.44 Hz (~NS)	0.46 Hz (~EW)	0.68 Hz

Table 1. Measured X, Y and Torsion frequencies for the five buildings

	Building				
Measured	A	B	C	D	E
X direction at centre of building (milli-g)	2.1	1.1	1.8	0.6	3.2
Y direction at centre of building (milli-g)	3.2	2.9	3.0	1.3	4.3
Combined XY at centre of building (milli-g)	3.3	2.9	3.6	1.3	4.4
Acceleration at the corners due to torsion (milli-g)	2.3	0.7	3.6	0.5	2.9
Corner (max acceleration at either corner) (milli-g)	3.6	3.2	5.8	1.7	6.2
Amplitude at centre of building (mm)		5.4	3.8	1.2	10.5
Date	23 May 2009	26 Aug 2009	08 Jan 2010	18 Apr 2011	8 Sept 2012
Airport mean wind speed (m/s)	23	16	14	14	18
Airport wind direction	210	300	340	240	340

Table 2. Summary of accelerations measured during the single biggest building-motion event for each building.

Building motion measurements

A summary of accelerations measured during the single biggest building-motion event for each building is listed in Table 2.

Examples of the plots which were produced for each hour of recorded data for Building D are shown in Figures 1, 2 and 3. Figure 1 shows the X, Y and torsion accelerations measured on the roof for a 100 s period, including the biggest building-motion event that was measured for Building D. The torsion acceleration is the acceleration measured at the corners of the roof, relative to the centre of the roof. The corresponding wind speed and direction, measured at a height of 2.5 m above southwest corner of the roof, is also shown. Figure 2 shows an XY plot of 10 seconds of the building displacement, using the same data as Figure 1. Figure 3 shows the frequency spectra for X, Y and torsion, with clearly separated frequencies for each mode.

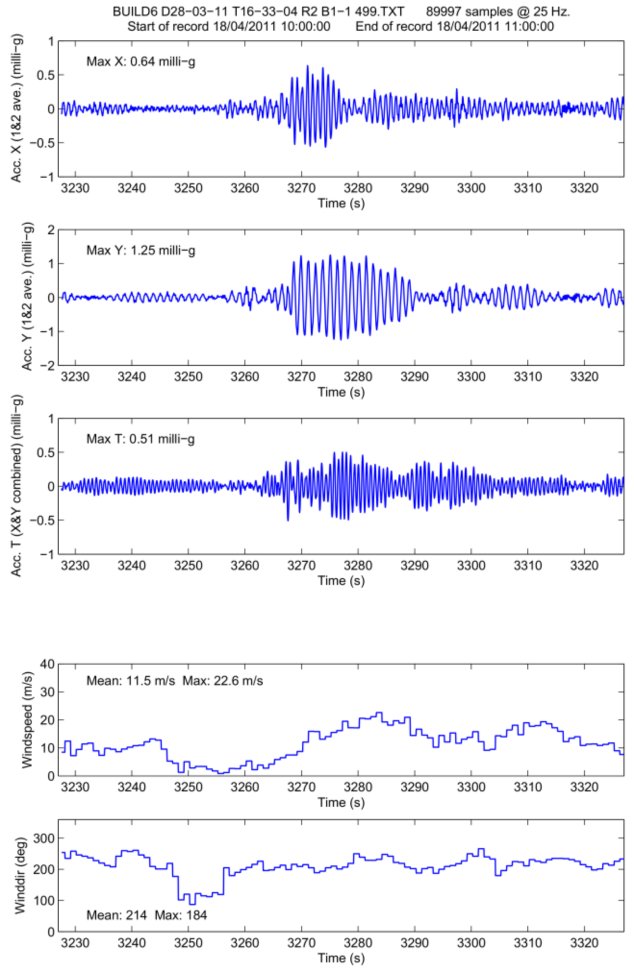

Figure 1. Measured accelerations during the biggest building-motion event for Building D.

Three buildings (B, C and D) provided sufficient data to analyse the relationship between wind speed and resulting acceleration. Figure 4 shows the maximum acceleration measured at the centre of the roof during 589 hours, for all wind directions with a westerly component, when the mean wind speed on the roof exceeded 4 m/s. Figure 5 shows the same data averaged into acceleration bands, which considerably improves the fit of an exponential curve. The wind speed exponent calculated in Figure 5 is 3.43. However it can be seen that the highest point in Figure 5, corresponding to the five measurements greater than 0.9 milli-g in Figure 4, is a less good fit to the exponent line and perhaps suggests an increase in the slope of the line at higher wind speeds. If the five measurements above 0.9 milli-g are excluded, the exponent reduces to 3.18, and this value has been used in subsequent analysis.

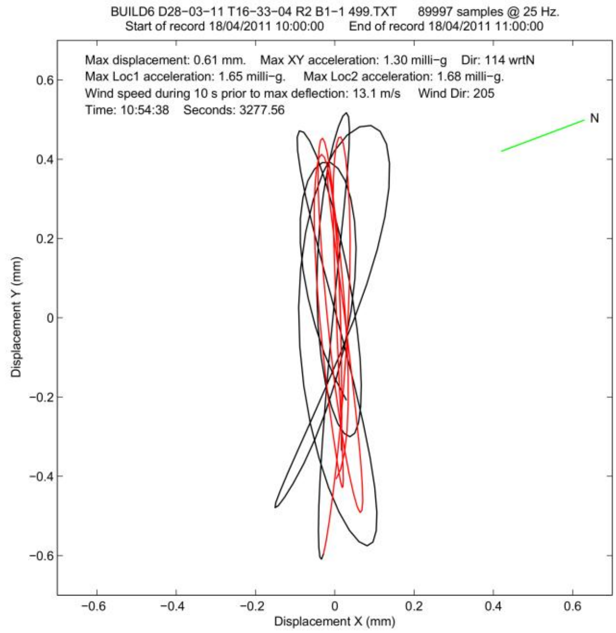

Figure 2. Measured displacements during the biggest building-motion event for Building D. (10 seconds of data: 5 s black followed by 5 s red).

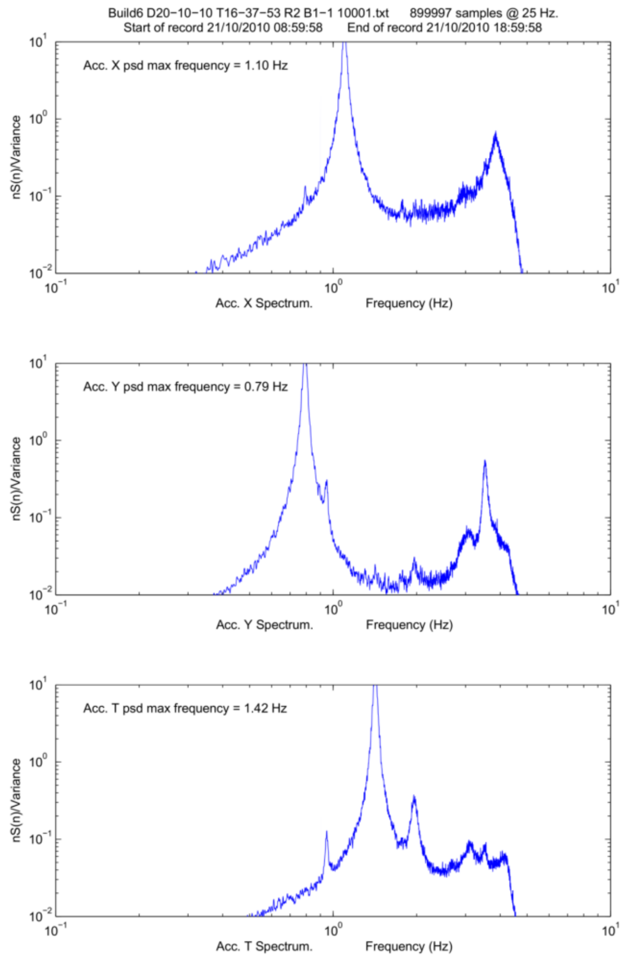

Figure 3. Building D frequency spectra.

The wind speed measure used in this analysis is the effective wind speed Veff, which is the average of the mean wind speed and the maximum wind speed (1 s) during the whole hour. Some measures of the wind speeds closer to the building motion event were also included in the analysis, including the 100 s mean wind speed, the 10 s mean wind speed, and the maximum wind during the 100s. The correlation with the measured accelerations was examined for all these wind speed measures. It was notable that the two wind speed measures for the whole hour (the mean and the maximum) produced substantially better correlations than the other measures, and the best correlation of all was achieved using the average of the 1-hour mean and the 1-hour maximum.

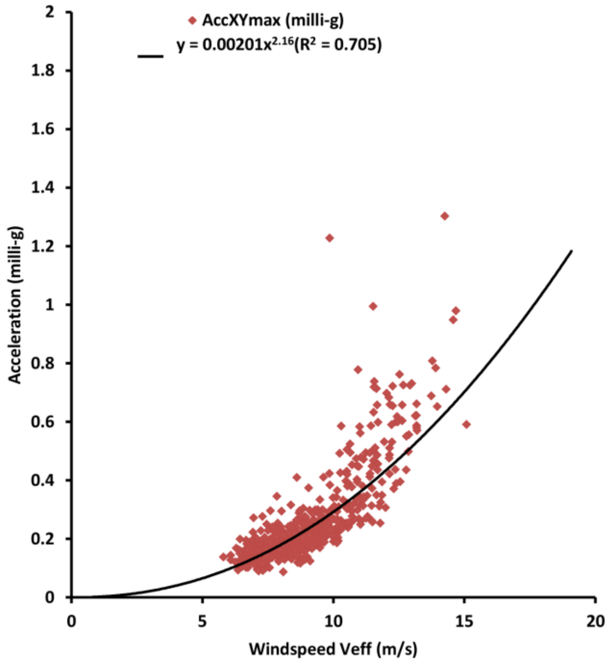

Figure 4. Building D. Relationship between wind speed and acceleration. Westerly winds, Vmean > 4 m/s

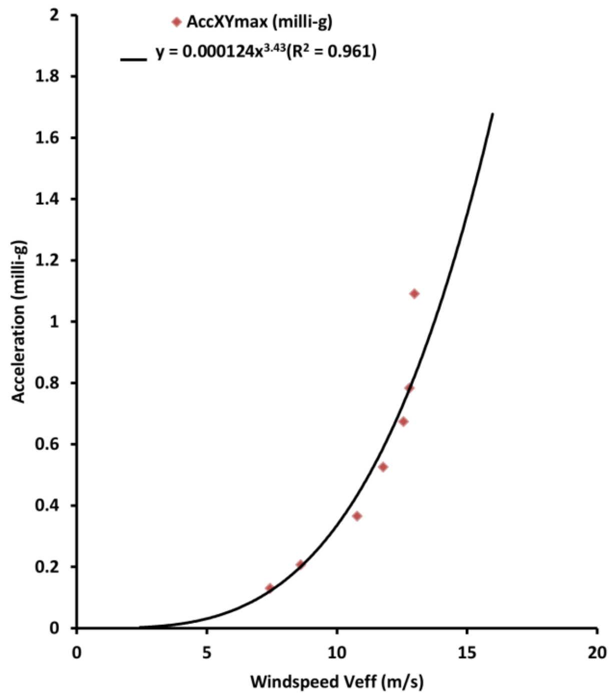

Figure 5. Building D. Same data as Figure 4, but averaged into acceleration bands.

The exponent of the power-law fit calculated for the band-averaged data is as follows for the three buildings for which we have sufficient data to do this analysis:

Building B	2.89
Building C	3.10
Building D	3.18

For the three buildings combined, the average exponent of the power-law fit is 3.06.

Annual maximum building motion

A statistical analysis of the largest building motion events has been applied to estimate the building motions with a 1-year return period. These are listed in Table 3. Also listed here are the ISO 10137 limits for each building, and the predicted accelerations calculated using Equation (1).

	Building				
Estimated annual maximum accelerations	A	B	C	D	E
Combined XY at centre of building (milli-g)	3.2	5.4	9.0	3.0	4.4
Torsion (milli-g)	2.1	1.9	8.2	1.3	2.2
Corner (maximum acceleration at either corner) (milli-g)	4.4	6.5	15.4	3.6	5.7
ISO 10137 limit (milli-g)	4.1	8.0	7.5	4.6	8.8
Predicted accelerations calculated using Eqn(1) (milli-g)	4.2	4.4	6.0	5.5	5.6

Table 3: Estimated annual maximum accelerations for the five monitored buildings.

We apply the ISO criteria to both the combined XY acceleration at the building centre, and also separately to the torsion acceleration. Buildings A and D are residential; Buildings B, C and E are offices. Using these criteria, Building C exceeds the limits by about 20%. The other four buildings are within the limits.

A study by Cenek and Wood (1990) led to the derivation of a simplified empirical equation for prediction of building motion. We have applied this equation to the buildings in the current study. We have found a small average under prediction of the measured accelerations of 12%, and so it seems prudent to revise the constant in the equation to correct for this under prediction. The modified prediction equation is:

$$a = \frac{0.113 V^3{}_{des,1-year}}{f m_0} \qquad (\mathrm{m/s^2}) \qquad (1)$$

where

$V_{des,1\text{-}year}$ may be calculated using AS/NZS 1170.2.
f = fundamental frequency (Hz).
$m_0 = \rho_b A$ = mass per unit length over the top one third of the structure (kg/m).
a = peak resultant acceleration (m/s^2).
ρ_b = building density (kg/m^3).
A = building plan area (m^2).

The equation provides a simple indication of likely levels of building response, and does not include the effects of variables including building shape, damping, mode shapes, or building interactions. Figure 6 shows a comparison of the estimated annual maximum accelerations from the building monitoring, and the predicted accelerations using Equation (1), for the 5 buildings in the monitoring program as listed in Table 3. Figure 6 also includes previously unpublished data for an additional building (Building F) measured in 2004, which has been included here to indicate the applicability of Equation (1) over a wide range of accelerations.

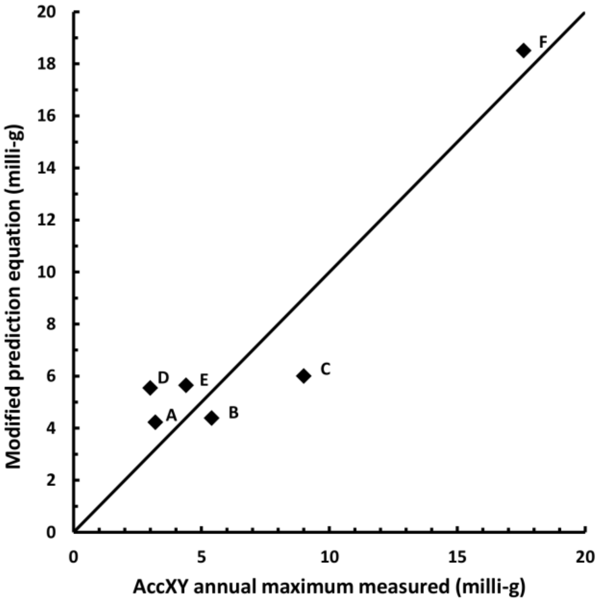

Figure 6. Comparison of estimated annual maximum accelerations from the building monitoring, and predicted accelerations from Eqn(1).

Some points to note from Figure 6 are:

- The measured acceleration for Building C exceeds the predicted value by 50%. The main reason for this is believed to be that the X, Y and torsion frequencies are all very similar for the building, resulting in coupled mode response.
- The measured acceleration for Building D is over predicted by Equation (1). However the predicted acceleration is more consistent with the results from the wind tunnel study for Building D which is discussed below.

Wind tunnel study for Building D

A wind tunnel study for Building D was done in the Opus wind tunnel at a scale of 1:300, and included the surrounding city. The high frequency base balance spectrum method was used, using a 6-axis high frequency balance. Only the X and Y moments have been used in the analysis. The signals from the balance were recorded at a rate of 1000 samples/second/channel, for 30 minutes for each wind direction.

Figure 7 shows a plot of the wind tunnel measurements of the annual maximum accelerations at the centre of the top floor of Building D. Some features to note in the wind tunnel data, compared to the building monitoring data are:

1) The biggest acceleration in the wind tunnel data occurs for direction 080. This was not apparent in the building monitoring data. This could perhaps be because there were few periods of strong easterly winds during the monitoring period, and consequently there was insufficient data to achieve an adequate statistical analysis for easterly winds.

2) The estimated annual maximum acceleration in westerly winds from the building monitoring was 3.0 milli-g. This is a little less than the wind tunnel measurement of 4.0 milli-g for a wind direction of 300. The biggest single building-motion event occurred for a wind direction of about 250, but the data was insufficient to be able to readily determine the detail of the variation with wind direction.

The average value of the wind speed exponent measured in the wind tunnel study was 2.95, ranging between 2.7 and 3.2 for different wind directions.

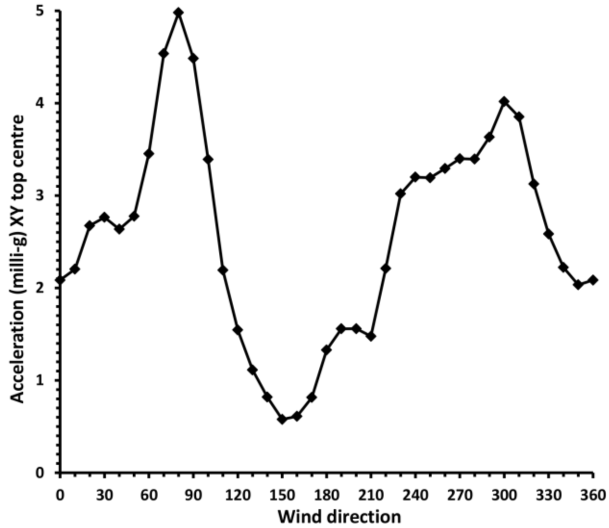

Figure 7. Building D wind tunnel results – annual maximum accelerations at the centre of the top floor.

Conclusions

The study has provided a considerable quantity of information to help to ensure that wind-induced motion of new tall buildings remains within acceptable limits. The measured accelerations are approximately proportional to the cube of the wind speed, demonstrating that accurate estimation of the wind speed is critical for accurate design predictions of wind-induced building motion. A simple predictive equation has been found to give reasonable estimates. The results from a wind tunnel study were consistent with the building monitoring data.

Acknowledgments

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