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# Structural Response to Wind at the Confederation Bridge – Piers 31 and 32

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## ABSTRACT

Ice forces on the piers of the Confederation Bridge are measured indirectly and calculated based on the structural response of the structure. Ice loads can only be determined after the effects of other external forces are known and removed. Previous analyses have concluded that wind is the only external force, other than ice, to cause significant pier tilt.

The influence of wind at two piers of the Confederation Bridge, piers 31 and 32, are analyzed in this paper at times of no ice and no waves for which data and video record is available. Such an analysis is not new to this monitoring program, previous analyses were completed in the program's early years. In 2003 a similar analysis was conducted at piers 23 and 24 for another ice force monitoring program. All have concluded that the pier's tilt due to wind is best described as a parabolic function: wind speed squared, multiplied by a wind speed correction factor. The wind speed correction factor has varied among the previous analyses.

Using all 12 years of data, the analysis discussed within was more comprehensive than earlier analyses, primarily due to the volume of data available. This analysis concluded that the wind correction factor is dependent on pier stiffness and wind heading; heading was taken as 2 directions, both are perpendicular to the bridge axis. Correction factors were found to be independent of data collection years and a changing wind speed. There is a level of error associated with the derived coefficients. The effect of the error on the overall measured ice load is relative to both wind speed and ice load.

## INTRODUCTION

The Confederation Bridge Ice Force Monitoring Program has been in place since 1997. The program measures ice loads at two piers of the 12.9 km bridge that spans the Northumberland Strait and is seasonally ice covered. The program's instrumentation has been extensively described by Brown (2001), Cheung et al. (1997) and others. Tiltmeters in the two piers measure the structural response of the bridge to external forces. Wind, traffic, waves and current all have the potential to cause pier tilt in addition to the ice. Brown (2001) determined that only the effects of wind are significant enough to be considered in the calculation of ice loads. As a result, the pier tilts associated with wind must be removed from the measured tilt. This paper will discuss a study conducted to determine the wind correction tilts at piers 31 and 32, detailing approaches taken, results found and earlier wind analyses completed for piers 31 and 32 and for piers 23 and 24.

## INSTRUMENTATION

Two weather stations along the bridge's length placed on top of street lights, see Figure 1, are used to measure wind speeds and direction and calculate the perpendicular wind speed. A station located between piers 31 and 32 records 1s and 10 min average data. A weather station at pier 21, the bridge's navigational span, records data at 6 min intervals. The perpendicular wind speed ($V_N$) is calculated from the measured wind speed ($V_W$) and direction ($\theta_W$), equation 1. The direction angle for the pier 31/32 instrument is measured as Figure 2 suggests, an angle of $0^o$ means the wind is blowing perpendicular to the pier on its northwest face and the angle increases in a clockwise direction.

a)

b)

Figure 1. Wind sensors at a) Pier 31 – RMYoung and b) Pier 21 - Handar.

$$V_N = V_W * \cos(\theta_W) \quad (1)$$

where:

$V_N$ = wind speed perpendicular to the bridge (m/s),
$V_W$ = measured wind speed (m/s),
$\theta_W$ = direction angle of wind.

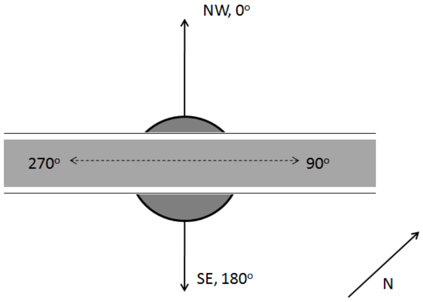



Figure 2. Orientation for wind direction measured between piers 31 and 32.

## BACKGROUND

The process to calculate and remove wind induced tilts, discussed by Brown (2001), has not changed at piers 31 and 32 throughout the monitoring program. The relationship between pier tilts and wind speed is described as a parabolic function, equation 2 and demonstrated in Figure 3, a plot of wind speeds and pier tilts. The wind correction factor, $C_W$, the parameter that determines the contribution of the wind induced tilts, however, has changed.

$$T_W = C_W V_N^2$$



where:

$T_W$ = tilt due to wind (micro radians),
$C_W$ = wind correction factor.

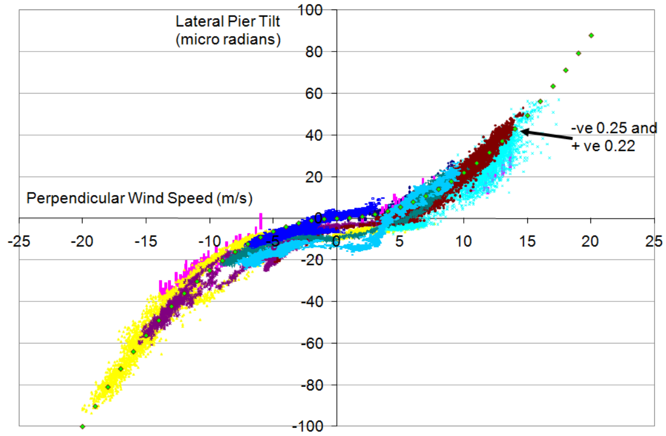
The analysis to determine the correction factor should be completed during the winter months when there is confidence in the wind data, minimal wave action and no ice. Useful data is limited to daylight hours in order to verify ice presence and wave action. Overall data can be difficult to locate, particularly for periods of high wind speeds with minimal wave action. Previous efforts to determine the wind correction factor have included data from outside the ice season due to the unavailability of suitable data.

To determine the correction factor, pier tilts are plotted against the wind speed perpendicular to the pier. Winds originating from the southeast are distinguished from northwest winds by a negative sign. This designation was incorporated early in the monitoring program when it was realized that the wind direction influences the correction factor. This is primarily because the wind anemometers are located on the southeast side of the bridge.

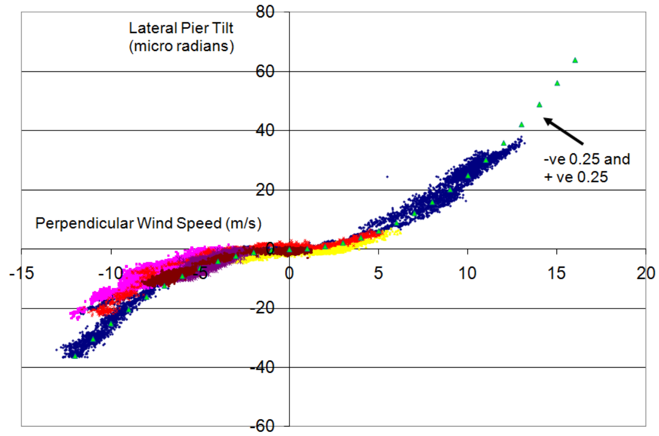
Pier 31 ice forces have been of primary focus in the monitoring program so factors have only been developed for the one pier. The first correction factor, 0.39 was derived from wind tunnel analysis during the design process. After the first season of monitoring it was determined that this factor was too high. As a result, it overemphasized the wind induced tilts. Next, a factor of 0.19 was derived from tilts measured during the summer months and five minute average perpendicular wind. As more data has been collected, other analyses to determine the correction factor have been completed, all concluding that the factor is dependent on wind direction; typically the northwest factor is slightly greater than the southeast factor.

In each study only one year of data has been reviewed. An analysis for every season has not been completed nor has an analysis that incorporates data from all seasons. Figure 3a and b are plots developed from 2002 and 2007 data respectively to determine the wind correction factor(s). Multiple days of data from each season were used in each plot and are indicated by different color data points. Based on the 2002 plot, wind correction factors of 0.22 and -0.25 are suggested for positive and negative wind and for 2007 the factor for positive and negative wind is 0.25.

To minimize error in the measured loads and consequently the assessment of flexural failure models, a comprehensive wind correction factor study for piers 31 and 32 using data from all ice seasons was necessary. With 12 seasons of data, 1998 - 2009, there was enough information available to develop factors based on ice season data only. Work regarding the wind correction factor at piers 23 and 24 of the Confederation Bridge, discussed in the following section, brought insight into the pier's behaviour that were not considered previously at piers 31 and 32. Overall, the objective for the recent wind factor study was to refine and comprehensively document the wind correction factors for piers 31 and 32.




a) 2002 data




b) 2007 data

Figure 3. Relationship between wind speed and lateral pier tilt - based on yearly data.

## WIND FACTOR ANALYSIS

*Piers 23 and 24*

Since 1999, the National Research Council of Canada, NRC, have monitored ice forces at two piers, piers 23 and 24, of the Confederation Bridge (Kubat and Frederking, 2001). The equipment set up is very similar to that at piers 31 and 32, measuring the structural response of the pier, as a result the load derivation process between the two sets of piers is comparable. Luu (2003) determined the wind correction factors for piers 23 and 24 are dependent on pier, wind speed, wind behaviour and year. Wind behaviour is described in three ways: increasing speeds (loading), decreasing speeds (unloading) and increasing speeds after decreasing (reloading). For all cases the correction factor is also influenced by wind speed. For loading, there is a correction factor for each wind speed category (0-6 m/s, 6 to 10 m/s, and >10 m/s). For the unloading and reloading situations, the initial unloading speed ($V_U$) dictates the wind factor ($C_i$). The wind correction factors for pier 23 are stated in Table 1. Correction factors for the unloading case are only available for the seven wind speeds listed in Table 1; factors were not developed for all wind speeds because of limited data. The correction factors for pier 24 are not reported in their entirety by Luu (2003). Wind induced tilts at piers 23/24 are determined using equation 1.

Table 1. Wind Correction factors for Pier 23 of Confederation Bridge.

<table>
<tr><th>Loading</th><th colspan="2">Unloading</th><th>Reloading</th></tr>
<tr><td>$T_W = C_L V_W^2$</td><td colspan="2">$T_W = C_U V_W^2$</td><td>$T_W = C_R V_W^2$</td></tr>
<tr><td rowspan="9">$V_W < 6$ m/s: $C_L = 0.23594$<br><br>$6 \leq V_W < 10$ m/s: $C_L = 0.13834$<br><br>10 m/s $\leq V_W$ : $C_L = 0.1042$</td><td colspan="2">$V_U$: wind speed at the beginning of the unloading</td><td rowspan="9">$V_w <= V_U$: $C_R = C_U$<br><br>$V_W > V_U$: $C_R = C_L$</td></tr>
<tr><td>$V_U$ (m/s)</td><td>$C_U$</td></tr>
<tr><td>4.55</td><td>0.30155</td></tr>
<tr><td>4.95</td><td>0.27747</td></tr>
<tr><td>5.67</td><td>0.23747</td></tr>
<tr><td>8.37</td><td>0.1761</td></tr>
<tr><td>10</td><td>0.15339</td></tr>
<tr><td>10.98</td><td>0.14296</td></tr>
<tr><td>11.49</td><td>0.13822</td></tr>
</table>

*Pier 31and Pier 32*

The analysis of interest began with locating wind and tilt data for periods of no ice and minimal wave action, video analysis confirmed sea state. Because the Strait is rarely ice free in January and February, the months of March and April were used. The data collected is summarized in Table 2 where it has been broken down by year, number of days with data and which months the data is from. Data was obtained from all years except 2004 as video was not available at the time of analysis. The database contains significantly more pier 31 data than pier 32, thus there was more pier 31 data available for the analysis.

Table 2. Breakdown of data for wind correction factor study.

| | **Pier 31** | | **Pier 32** | |
|---|---|---|---|---|
| **Year** | **# of Days** | **Months Days are from** | **# of Days** | **Months Days are from** |
| 1998 | 3 | March and April | 0 | No data |
| 1999 | 5 | March and April | 3 | March |
| 2000 | 5 | March | 5 | March |
| 2001 | 10 | March and April | 10 | March and April |
| 2002 | 6 | March | 6 | March |
| 2003 | 5 | March and April | 0 | |
| 2004 | Video not available at time of analysis | | | |
| 2005 | 9 | March and April | 4 | March and April |
| 2006 | 4 | March and April | 1 | March |
| 2007 | 4 | March | 4 | March |
| 2008 | 3 | April | 0 | |
| 2009 | 4 | April | 4 | April |

**FIRST ANALYSIS - YEARLY COEFFICIENTS**

Three different approaches were used to derive the wind correction factors for piers 31 and 32. For the first approach the data was grouped based on wind speed (0-6 m/s, 6-10 m/s and >10 m/s), wind direction, year and pier, the same method as Luu (2003). To find a correction factor each dataset was plotted by its grouping (speed, year, direction and pier) and by date and resulted in a factor and coefficient of determination ($R^2$) for each daily file. This was done due to the manual baseline adjustment that is necessary when deriving ice loads (Brown, 2007). An incorrect baseline of just a few units in a combined dataset increases data scatter. Each dataset was placed into a scatter plot, like Figure 4, with a linear trend line, its equation and $R^2$. The trend line equation provides the correction factor, in Figure 4, the factor would be 0.1818 with $R^2$ equal to 0.3007. A high value for $R^2$ indicates a strong correlation.

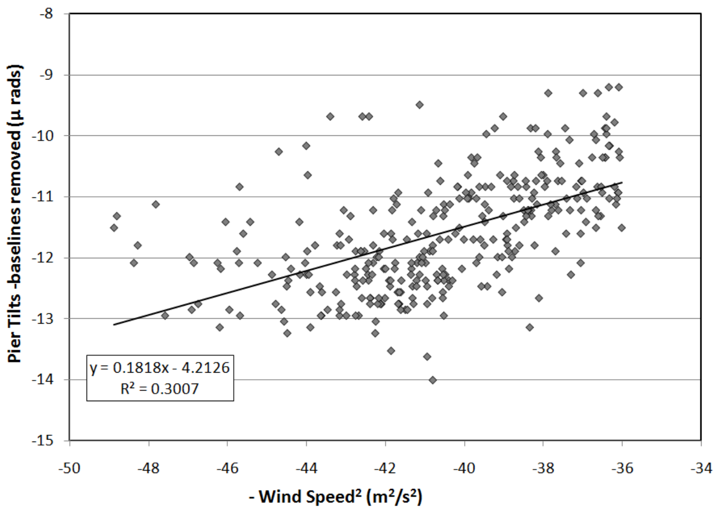



Figure 4. Example of a correction factor scatter plot – P31 wind speeds -6 to -10 m/s.

Common factors based on year or among all seasons for specific wind speed intervals were expected because of Luu's findings but did not result. The data within each group was very scattered resulting in a poor coefficient of determination. Half of pier 31's data had coefficients of determination greater than 40% and such factors were quite varied (ie for -6 to 0 m/s winds factors ranged from 0.118 to 0.525). Significant ranges in correction factors were noted for all wind speed categories. Upon reviewing all data, regardless of correlation between factor and data, the range increased.

Contributing to the poor correlation was the small datasets. A daily file had a maximum of 2500 suitable data points but after grouping each file by wind speeds the number of data points per file ranged from 100 to 2000. Even with data from 12 years, if each day of data in Table 2 was a full day of data, less than 5% of the available data was suitable for this analysis. This first analysis indicated that a factor for all years rather than one for each year, is possible and might be achieved with more confidence than a single factor for each year based on a small dataset.

**SECOND ANALYSIS - WIND DIRECTION**

The next approach analyzed the data based on wind heading. The influence of wind direction on the correction factor had never been considered, nor suspected but was considered in this analysis because the perpendicular wind speed is based on the direction angle. Pier 31 data was organized in two ways, split into groups based on both wind speeds (0-5 m/s, 5-10 m/s and >10 m/s) and direction headings and by solely direction headings. The eight direction heading groups were: $0^{o} \pm 22.5^{o}$, $45^{o} \pm 22.5^{o}$, $90^{o} \pm 22.5^{o}$, $135^{o} \pm 22.5^{o}$, $180^{o} \pm 22.5^{o}$, $225^{o} \pm 22.5^{o}$, $270^{o} \pm 22.5^{o}$ and $315^{o} \pm 22.5^{o}$.

Similar to the first analysis, the perpendicular wind speed squared was plotted against pier tilts and coefficients with a $R^2$ value greater than 0.4 were averaged to determine the mean coefficients, which are reported in Table 3. A common trend existed when the data was organized by speed and heading, factors decreased with an increasing wind speed for all headings except the $0^{o} \pm 22.5^{o}$. For the results that do not consider the wind speed categories (all wind), similar coefficients are reported among the angles which give positive wind and then likewise for the negative direction, as identified in Table 3. The average coefficient for positive wind speed directions was 0.241 and for negative wind speed directions was 0.21. The positive/northwest wind coefficient is greater than the negative/southeast wind coefficient and this is consistent with earlier work. Of the three coefficients for positive wind and the three for negative wind, for each group two coefficients were very similar to each other. The third coefficient in either group came from wind directions that were $180^{o}$ apart, $135^{o}$ heading and $315^{o}$ heading.

Table 3. Mean correction factor dependent on wind heading – P31.

| Wind Range | Mean | Count | Comments | Wind Range | Mean | Count | Comments |
|---|---|---|---|---|---|---|---|
| *$0^{o} \pm 22.5^{o}$* | | | Perpendicular to pier<br><br>Positive Speeds | *$180^{o} \pm 22.5^{o}$* | | | Perpendicular to pier<br><br>Negative Speeds |
| 0-5 | 0.285 | 5 | | 0-5 | 0.249 | 4 | |
| 5-10 | 0.216 | 8 | | 5-10 | 0.175 | 8 | |
| >10 | 0.257 | 4 | | >10 | 0.163 | 5 | |
| All wind | 0.226 | 14 | | All wind | 0.199 | 10 | |
| *$45^{o} \pm 22.5^{o}$* | | | Positive Wind Speeds | *$135^{o} \pm 22.5^{o}$* | | | Negative Wind Speeds |
| 0-5 | 0.415 | 1 | | 0-5 | 0.36 | 1 | |
| 5-10 | 0.248 | 4 | | 5-10 | 0.332 | 6 | |
| >10 | 0.204 | 2 | | >10 | 0.259 | 2 | |
| All wind | 0.232 | 10 | | All wind | 0.264 | 16 | |
| *$315^{o} \pm 22.5^{o}$* | | | | *$225^{o} \pm 22.5^{o}$* | | | |
| 0-5 | 0.360 | 1 | | -5 to -10 | 0.366 | 3 | |
| 5-10 | 0.332 | 6 | | -10- -20 | 0.200 | 3 | |
| >10 | 0.259 | 2 | | < - 20 | 0.130 | 1 | |
| All wind | 0.264 | 16 | | All wind | 0.250 | 7 | |
| *$90^{o} \pm 22.5^{o}$* | | | Parallel to Bridge Axis | *$270^{o} \pm 22.5^{o}$* | | | Parallel to Bridge Axis |
| All wind | 0.322 | 1 | | 0-5 | 0.197 | 1 | |
| | | | | 5-10 | 0.176 | 1 | |
| | | | | All wind | 0.239 | 2 | |

Wind originating at a $90^{o}$ or $270^{o}$ angle to the pier (parallel to the bridge axis) was found to have minimal influence on the pier tilts. Three coefficients with a suitable $R^2$ value were used to determine the average coefficients for wind parallel to the bridge despite multiple data files for these categories. There was significant variation in the factors and most had a low $R^2$ value. This finding is logical, small changes in direction for the $90^o$ and $270^o$ heading causes significant changes in the perpendicular wind speed, and if wind originating from these directions does not influence the lateral pier tilt, then the results should be scattered.

In conclusion to this second approach, there was variability among the coefficients, many of which were derived from a few data files. Nine correction factors were developed from two or less data files, see the count column in Table 3. Overall, the correction factor decreases with an increasing wind speed (absolute) for all wind directions with the exception of the >10 m/s category with a $0^o$ angle. The correction factors derived by Luu (2003) also decreased with an increasing wind speed.

**THIRD ANALYSIS - A COMMON COEFFICIENT AMONG ALL YEARS, P31**

The third analysis considered a single factor for all ice seasons, deriving coefficients from a single ice season. The logic in focusing on one year was to first find coefficients that fit a season and then apply the same factors to data from other ice seasons. The 2009 ice season was selected because the wind sensors had undergone maintenance prior to the start of the season and data was expanded to include January and February data. Wind speed categories used were: 0-5 m/s, 5-10 m/s and >10 m/s.

Correction factors for each dataset were determined using the same process as the first and second analysis. The only exception to using coefficients with $R^2$ greater than 0.4 was for the -5 to 0 m/s range because this dataset had only $R^2$ values less than 40%. The final coefficients reported in Table 4 are averages of the suitable factors. Coefficients were also determined based on positive and negative wind, they are labelled positive, all wind and negative, all wind.

Table 4. Mean coefficients for pier 31 based on 2009 data.

| Wind Range | P31 | | Wind Range | P31 | |
|---|---|---|---|---|---|
| | Coefficient | Count | | Coefficient | Count |
| -5 to 0* | 0.319 | 4 | 0-5 | 0.339 | 3 |
| -5 to -10 | 0.270 | 7 | 5-10 | 0.270 | 14 |
| < -10 | 0.166 | 11 | >10 | 0.235 | 5 |
| negative, all wind | 0.211 | 15 | positive, all wind | 0.240 | 37 |

*$R^2$ for this data category is less than 0.4

The coefficients are all higher for the positive wind direction than the negative direction, this is consistent with the second analysis. Trends were observed amongst coefficients in different categories. Coefficients for the 5 to 10 m/s wind group for both positive and negative wind were the same, 0.27. The positive and negative all wind category's coefficients are the same as the second analysis, 0.24 for positive wind and 0.21 for negative wind even though different datasets are used in the two analyses.

To study the significance of wind speed categories, the number of wind speed categories was reduced from 3 to 2, combining the 0-5 m/s and 5-10 m/s groups. The factor from the 5-10 m/s group was selected if 2 categories were considered. In doing this the difference in ice load, shown in Table 5, for a 5 m/s perpendicular wind, is minimal. Decreasing the number of wind speed categories simplifies the wind induced tilts calculation with minimal effect on the loads.

Table 5. Change in ice load for 5 m/s winds due to different factors and considering different wind range categories.

| Wind Speed (m/s) | Wind Coefficient – Using 3 Speed Categories | | Wind Coefficient – Using 2 Speed Categories | | Difference in Loads (MN) |
|---|---|---|---|---|---|
| | Net Pier Tilt (μ rads) | Ice Load (MN) | Net Pier Tilt (μ rads) | Ice Load (MN) | |
| 5 | 8.47 | 0.292 | 6.74 | 0.232 | 0.0596 |
| -5 | 7.98 | 0.275 | 6.76 | 0.233 | 0.0422 |

The next part of this analysis was application of the 2009 factors with data from other years but prior to this a measure of error was incorporated into the correction factors. The variability among factors in the first two analysis suggested that a single wind correction factor may not be able to describe all data. Rather it indicated the potential error associated with assigning a single factor to all data and this error needed to be considered. A 10% error factor was considered because the suitable 2009 correction factors were all within 10% of the average factors reported in Table 4.

This analysis also revealed that at low wind speeds pier tilts were not at the expected zero tilt. Theoretically when there is no wind and no ice tiltmeters should record zero tilts instead the tilts were within 5 micro radians of zero. Although initially observed with the 2009 data, this was consistently apparent in all data and explains the offset of -4.2 in the trendline of Figure 4. This is demonstrated again in Figure 5, pier tilts are within 5 μrads at 0 m/s wind.

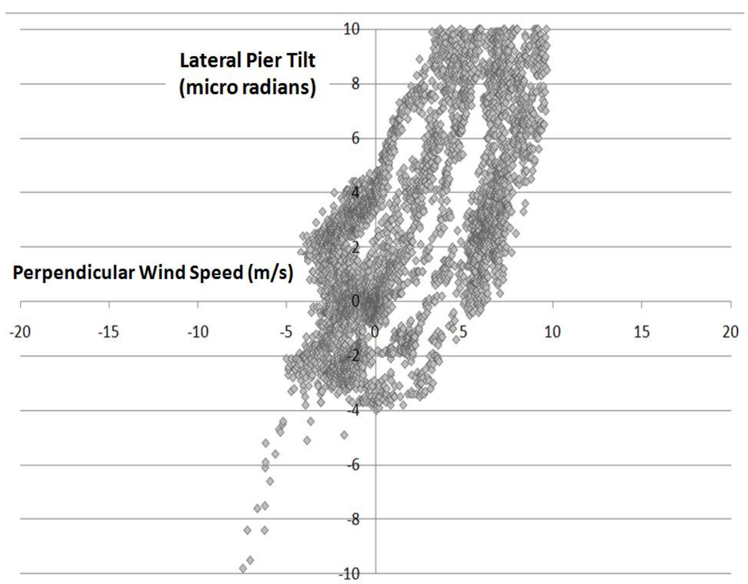



Figure 5. Pier tilt at low winds, 2006 data.

Factor uncertainty and baseline correction were both considered in determining the effectiveness of the 2009 factors with data from other years. The effectiveness of the 2009 coefficients, is shown in Table 6 by year for the two sets of coefficients, wind speed categories and positive and negative wind speed, and considers the combined uncertainty of the pier tilts and correction factor (factor/baseline). The first set of results in each category (row 1, group) consider the correction factor dependent on wind speed (0-10 m/s and >10 m/s) and the second set of results (row 2, +ve/-ve) is based on the use of a coefficient for all positive wind and another for all negative wind. The overall average is stated for both types of coefficients, on average over 70% of the data is within the tilt range. If the baseline variation of ±5 micro radians was not considered (Factor only), the results are drastically different. Less than 12% of the data would be within the tilt range defined, thus both measures of error, factor and baselines need to be considered.

Table 6. Effectiveness of 2009 factors - considering factor and baseline uncertainty.

| | Year | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2005 | 2006 | 2007 | 2008 | 2009 | Avg |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Factor and Baseline | Group | 56% | 96% | 71% | 70% | 67% | 77% | 85% | 76% | 88% | 65% | 69% | 75% |
| | +ve /-ve | 57% | 97% | 70% | 67% | 63% | 83% | 87% | 71% | 90% | 67% | 70% | 75% |
| Factor Only | Group | 2% | 21% | 6% | 7% | 9% | 17% | 10% | 18% | 17% | 11% | 9% | 12% |
| | +ve /-ve | 2% | 18% | 4% | 4% | 8% | 22% | 12% | 19% | 18% | 11% | 9% | 11% |

Whether the uncertainty in baselines is or is not considered, the average results listed in Table 6 indicate that there is no advantage to have correction factors specific to wind speed categories. When only the factor uncertainty is considered the average differences between wind speed categories and the all wind categories are always less than 0.3%, these differences are higher in some cases when comparing ice seasons. The wind speed categories are slightly more effective. Meanwhile, in accounting for both baseline and correction factor uncertainty the opposite results, a single coefficient for positive wind and another for negative wind was most effective, the maximum average difference between the different categories was 1.7%.

Results of the third analysis concluded that there is variability surrounding quantifying wind induced tilts. Variability was observed in all three analyses so it cannot be ignored and was subsequently considered in the third analysis through factor error. Factor error can be up to 10%. In summary, a single factor for the positive wind direction and another for the negative wind direction that is common for all years is recommended. This is the most simplistic approach to implement of all those suggested, yet it is the most effective at including data.

**PIER 32 WIND CORRECTION FACTORS**

Data from pier 32 was also analyzed for the first analysis in an attempt to determine its wind correction factor. Like pier 31, the resulting coefficients from this first analysis were significantly scattered. Because full pier 32 data was not available for every ice season it was most appropriate to determine the approach for calculating wind factors with pier 31. After a suitable approach to deriving wind correction coefficients was established, the factors for pier 32 were computed, and are listed in Table 7. This was the first comprehensive study into a wind correction factor for pier 32 for the Confederation Bridge Ice Force Monitoring Program.

Table 7. Wind correction factors for Piers 31 and 32.

| Pier Number | Wind Correction Factor, $C_W$ | |
|---|---|---|
| | Positive Wind | Negative Wind |
| 31 | 0.24 | -0.21 |
| 32 | 0.17 | -0.13 |

## QUANTIFYING ICE LOAD ERROR FROM WIND TILTS

Wind induced tilts are calculated using the mean coefficient that corresponds to the pier and wind origin. The 10% error provides a range of coefficients that are plausible and as a result can be used to determine the error associated with the measured ice load. The error associated with the factor is relative. For a 5 m/s and 10 m/s wind in the positive direction the overall difference in loads is 0.02 MN and 0.08 MN respectively for a 1 MN load. If the ice load is 2 MN the error due to the 5 m/s wind is 1% and if the load is 5 MN the error is only 0.4%.

## CONCLUDING REMARKS

The ability to accurately calculate wind induced tilts is critical to the measurement of ice loads at the Confederation Bridge. Data has indicated a parabolic relationship exists between wind speed and pier tilt. Much effort has been placed in quantifying the wind induced pier tilts for pier 31 as well as piers 23 and 24, which are part of another ice load monitoring project, however limited available data has restricted the scope of those studies. From 12 years of data multiple wind correction factors are recommended for both piers 31 and 32 because of its dependence on pier and wind origin. The correction factor is described best as a range rather than a single value and the range is based on a 10% variation in the correction factor and a baseline offset. The factors derived in this analysis are specific to the bridge piers of interest and instrumentation used. The methodology of the analysis however may be applicable to another structure with a similar set up.

## ACKNOWLEDGEMENTS

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