Wind Design of Slender Tall Buildings in Sri Lankan Context

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Abstract

Lateral forces due to wind and earthquake loading are two important phenomenon in design of tall buildings. In the recent decades due to the development of various technologies, tall buildings are becoming more slender, flexible, light weight and irregular in shape. Though flexible and lightweight structures are preferred to minimize the effect of earthquake loading, they becoming more susceptible under wind loading. Wind tunnel testing is adopted as most precise tool to determine the performance of such slender structures under wind loading. Determining the performance of the proposed structural system quite precisely during the preliminary design stage is essential to obtain an efficient, safe and economical design. Due to the associated cost and time performing a wind tunnel test in the preliminary design stages may not be always viable. In such instances preliminary design is carried-out extrapolating the design provisions available. In Sri Lanka BS 6399-2:1997, BS EN 1991-1-4:2005, AS/NZS1170.2:2011 standards are generally adopted in wind design of structures. After withdrawal of British standards, European standards are being adopted as primary design standards internationally including Sri Lanka. Due to the complex nature of the wind and its interaction with the dynamically sensitive slender structures scope of wind design codes to predict the wind effects on slender tall buildings are limited. This study intends to present the importance of selecting suitable wind design approaches to predict dynamic wind effects on tall buildings during the preliminary design stages overcoming the limitations of existing design provisions. A case study authors involved were presented with the validation of wind tunnel testing to elaborate the wind design of slender tall buildings in Sri Lankan context.

Keywords: *Slender tall buildings, Wind design, Wind tunnel test, Sri Lankan context.*

1. Introduction

Tall building construction has been revolved over the time in most of the congested cities around the world to overcome the scarcity for land. Sri Lanka's commercial capital Colombo is one of such very active metropolitan city in tall building development. Figure 1 and Figure 2 illustrate the trend of tall building development around the world and in Colombo.

In the recent past due to the factors such as advancement of construction technology, vertical transportation, adoption of light weight partitions instead of traditional heavy masonry partitions and development of parametric architectural design philosophies; tall buildings are becoming more slender, flexible, light weight and irregular in shape. As a result contemporary tall buildings are more vulnerable for the dynamic wind effects [(Mendis, et al., 2007), (Nakai, et al., 2013)].

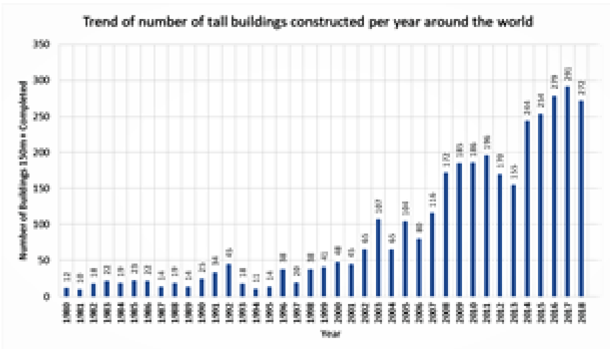

Figure1: Trend of number of Tall buildings constructed per year around the world

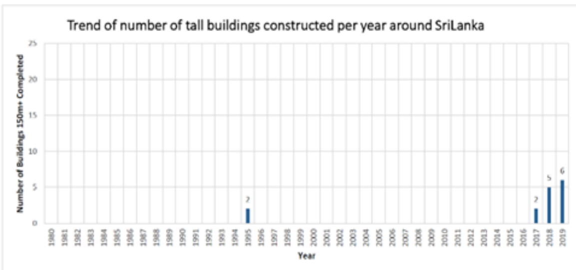

Figure 2: Trend of number of Tall buildings constructed per year in Sri Lanka

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Precise estimation of wind responses of a tall building is vital to arrive at a safe and optimum design since mostly lateral wind loads govern the design of tall buildings. Wind tunnel testing is the most reliable tool to investigate wind effects on slender tall buildings. However, due to the associated cost and time, performing a wind tunnel test in the preliminary design stages may not be always viable. In such instances existing codal provisions of wind design standards are utilized in the preliminary design and verified through the wind tunnel testing during the final design stage.

In Sri Lanka BS 6399-2, BS EN 1991-1-4:2005 and AS/NZS1170.2:2011 standards are generally adopted in wind design of structures. After withdrawal of British standards, European standards are being adopted as primary design standards internationally including Sri Lanka. Due to the complex nature of the wind and its interaction with the structure significant discrepancies are found between the international standards in prediction of wind effects on slender tall buildings [(Holmes, et al., 2008), (Ge, et al.), (Holmes, 2009)].

Thus selection of most suitable wind design standard, with understanding of its capabilities and limitations is utmost important to obtain the most sustainable structural scheme during the conceptual design stage, for which predicted responses are expected to correlate well during the wind tunnel testing [(Mendis, et al., 2014)]. Various critical aspects to be considered in the wind design of slender tall buildings, capabilities and limitations of different international standards, selection of suitable wind design procedures during the preliminary design are discussed in following sections.

2. Characteristics of Wind

Wind is a complicated phenomenon due to the gusts and lulls which have a random distribution over a wide range of frequencies and amplitudes in both time and space [(Mendis, et al., 2007), (Boggs & Dragovich, 2006)].

Among the three major types of wind, both prevailing and seasonal winds are considered separately compared to local winds because those are fluctuated over a period of several months. While the variation in the mean velocity of prevailing and seasonal winds are referred to as fluctuations, it is mentioned as gusts for variations in local winds due to occurrence over a very short period of time. Statistical distributions of speeds and directions are considered in wind design of buildings rather than simple averages due to its random nature of wind loading [(Boggs & Dragovich, 2006)]. Generally mean wind velocities fluctuate with three types of averaging times (3-seconds, 10-minutes and 1-hour) are adopted in different international wind codes.

In practice, each code provides only one out of above three kinds of averaging time as summarized in Table 1. A return period of 50 years and 100 years are considered for the basic wind speeds among different international standards.

Table 1: Basic wind speed consideration

Standard	Reference Height (m)	Averaging Time	Return Period (Years)	No. of Terrain
BS 6399-2	10	1-h	50	2
BS EN 1991-1-4:2005	10	10-m	50	5
AS/NZS 1170.2:2011	10	3-s	50	4
AIJ-RLB-2004	10	10-m	100	5

Basic wind speeds for Colombo derived for different return periods based on the climatic study conducted by wind tunnel testing laboratories are tabulated in Table 2.

Table 2: Basic wind speed adopted for Colombo (Source: wind climacteric study reports)

Design Criteria	Return Period (Year)	Wind Speed (m/s)		
		3-s gust	10-min avg	Hourly mean
Acceleration	1	20	12	11
	5	28	16.5	15.5
	10	30	17.5	16.5
Deflection	20	33	19.5	18
Ultimate	50	38	22	21

Dominant wind direction and relative orientation of the building is an important factor which influences the wind loading on tall buildings. Wind rose plot of wind climate observed at Bandaranaike International Airport presented in Figure 3 is referred in the wind analysis of tall buildings in Colombo.

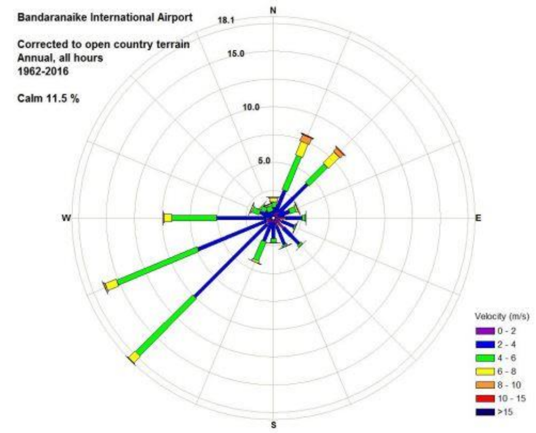

Figure 3: Wind rose plot of wind climate observed at Bandaranaike International Airport

3. Wind Effect on Tall Buildings

Large wind pressure fluctuations can occur on the surface of a building due to distortion of mean flow, flow separation, formation of vortices, and development of the wake. As a result, large aerodynamic loads are imposed on the structural system and intense localised fluctuating forces act on the facade of such structures. Due to these fluctuating forces, a building tends to vibrate in three modes as shown in Figure 4.

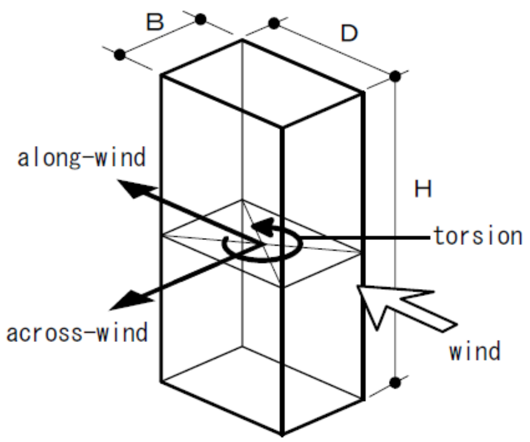

Figure 4: Wind effect on tall buildings

4. Wind Design Codal Provisions

Many international design standards/ guidelines are developed for the prediction of wind response of tall buildings. Scope of most of the wind design codes are limited to regular-shaped structures and due to the governance of dynamic responses again limitations are imposed either based on building height or natural period. Nevertheless, for the buildings fall in the scope of the design codes inconsistences are found in the results obtained from different design codes although they are developed based on the common theoretical basis [(Holmes, et al., 2008), (Ge, et al.), (Holmes, 2009)].

Hence, the wind design codes should be used with considerations regarding the constraints. To understand the key limitations behind the wind standards, four major international codes were analysed: British Standard (BS 6399-2:1997), Australian Standard (AS/NZS1170.2:2011), Euro Code (EN1991-1-4:2005), and Japanese Code (AIJ 2004). Nine important aspects, where the codes have limitations were identified and summarised in Table 3.

All four standards considered set out provisions for the prediction of along wind and cross wind loading except BS 6399-2:1997, which only consist provisions for along wind loading calculations. Due to the complex nature of torsional wind loading it is specified as nominal eccentricities in few of the international standards and most of other international codes are silent about torsional loads [(Nakai, et al., 2013)].

The nominal eccentricities specified in different standards are tabulated in Table 4 below. Only AIJ code provides a detailed estimation for calculation of torsional moments. The importance of further development of these simplified provisions are well noted in many literature.

BS 6399-2:1997 does not provide any guide-lines for the calculation of wind induced acceleration whereas only along wind acceleration calculations are presented in EN1991-1-4:2005. In most of the cases cross wind vibrations induced due to the vortex shedding is more critical than the along wind vibration. AS/NZS 1170.2:2011 provides guidelines for the calculation of both along wind and cross wind accelerations. Torsional vibration is even critical and more sensible in asymmetric structures. Guidance for calculation of torsional acceleration is only given in AIJ, 2004. Nevertheless, for the buildings fall in the scope of the design codes inconsistences are found in the results obtained from different design code

Table 3: Applicability of different design codes

<table>
<tr><th>Criteria</th><th>BS 6399</th><th>EN1991-1-4:2005</th><th>AS/NZS 1170.2:2011</th><th>AIJ2004</th></tr>
<tr><td>Height</td><td>No provisions for h>300 m</td><td>No provisions for h>200 m</td><td>No provisions for h>200 m</td><td>No explicit limit specified</td></tr>
<tr><td>Frequency</td><td></td><td>No provisions for f<0.2s</td><td>No provisions for f<0.2s</td><td>No explicit limit specified</td></tr>
<tr><td>Geometry</td><td colspan="4">No provisions for buildings with complicated shapes</td></tr>
<tr><td>Along wind loading</td><td colspan="4">Geometrical and height restrictions in along wind load calculations Geometrical</td></tr>
<tr><td>Across wind loading</td><td>No provisions are given</td><td colspan="3">Geometrical and height restrictions in across wind load calculations</td></tr>
<tr><td>Torsional loading</td><td>No provisions are given</td><td colspan="2">Nominal eccentricities specified</td><td>Detailed provision</td></tr>
<tr><td>Along wind accelerations</td><td>No provisions are given</td><td colspan="3">Provisions are given</td></tr>
<tr><td>Across wind accelerations</td><td>No provisions are given</td><td>No provisions are given</td><td colspan="2">Provisions are given</td></tr>
<tr><td>Torsional accelerations</td><td colspan="3">No provisions are given</td><td>Provisions given</td></tr>
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5. Case Study

In this section various important points in designing of high-rise buildings against wind loading is discussed through authors' experience. Different considerations to be made from the preliminary design to the construction level detailing are discussed. Importance of determining the wind loading to acceptable level of accuracy during the preliminary design and subsequent verification through wind tunnel testing are emphasized.

5.1 Case study -1

Wind design of a fifty storied twin tower development located in Colombo is discussed in this section. Geometric details, dynamic characteristics of the towers and the orientations are shown in Table 4 and Figure 6 respectively. Due to the higher aspect ratio (>6) and a first mode period exceeding 5 s these slender towers are falling out of the scope of wind de-sign codes such as BS EN 1991-1-4:2005 and AS/NZS 1170.2:2011. As these standards are to be adopted as primary design standards for the proposed project applicability of extrapolating the provisions of these standards are evaluated during the preliminary design. As a result, a comparative study on prediction of wind effects are determined using four international standards namely BS 6399-2:1997, BS EN 1991-1-4:2005, AS/NZS 1170.2:2011 and AIJ: 2004. After finalization of conceptual design with optimum structural arrangement based on this comprehensive desk study, a wind tunnel testing was carried-out for the final design validation.

Table 3: Geometric details and dynamic characteristics of the towers

<table>
<tr><th rowspan="2">Dimensions (bxdxh) /m</th><th rowspan="2">Frequency (Hz)</th><th colspan="3">Directional Factors</th></tr>
<tr><th>U_x</th><th>U_y</th><th>R_z</th></tr>
<tr><td rowspan="3">Tower 1 (27x30x172)</td><td>0.180</td><td>0.819</td><td>0.166</td><td>0.016</td></tr>
<tr><td>0.197</td><td>0.178</td><td>0.803</td><td>0.019</td></tr>
<tr><td>0.263</td><td>0.004</td><td>0.033</td><td>0.963</td></tr>
<tr><td rowspan="3">Tower 2 (29x26x172)</td><td>0.188</td><td>0.123</td><td>0.867</td><td>0.016</td></tr>
<tr><td>0.205</td><td>0.868</td><td>0.128</td><td>0.004</td></tr>
<tr><td>0.280</td><td>0.019</td><td>0.006</td><td>0.975</td></tr>
</table>

Figure 5 shows the physical model of proposed building at a scale of 1:350 in CPP's wind tunnel with surrounding buildings located within 500 m radius. Aerodynamic loads are measured in the form of moments on a rigid model mounted on an instrumented balance known as High-frequency balance (HFB). Dynamic response of the structure was then computed analytically.

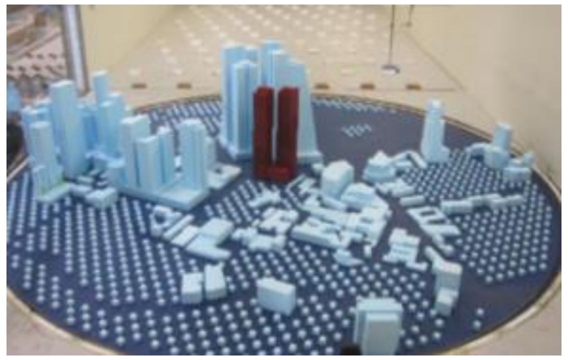

Figure 5: Wind tunnel model viewed from north

Wind induced base reactions for both towers for selected cases are presented in Table 5 for comparison. Along wind predictions are observed to be well matching with the code predictions whereas significant variation can be noted in the prediction of cross wind and torsional moments. Further wind directionality, shielding and interference effects due to adjacent buildings highly influenced the wind loading on these towers. Considering all these factors, standard critical load cases were identified as shown in Figure 7 in order to determine the most suitable combinations of along wind, across wind and torsional effects. Base reactions derived for critical combinations and relevant wind directions are shown in Table 5 and Figure 6 respectively. Peak base shear and over turning moments determined for majority of these critical cases are found to be within the code prediction as shown in Figure 8 and 9.

Predicted peak top story resultant accelerations using the AS/NZS 1170.2:2011 and that obtained from wind tunnel test for different damping ratios are presented in Figure 10 along with the different perception criteria. It was noted that code predictions well related with the wind tunnel results and optimization carried-out based on the codal provisions during the preliminary design stages was validated.

The proposed project is located in the vicinity of several other land mark tall buildings and surrounded by an important road network. Thus a Computational Fluid Dynamics (CFD) analysis was carried-out to study the alteration on wind flow pattern and pedestrian comfort around the building. Intended wind speeds in vulnerable areas such as ground floor entrances, podium area around the pool, sky lounge and public road network in the vicinity were predicted from the CFD simulation and probable comfort level is evaluated. The areas identified as critical locations were recommended to perform real time measurements and further improvement.

6. Conclusions

Important design considerations related to wind design of slender tall buildings were discussed. Limitations of current design codes in terms of applying them to design for wind induced motion of slender tall buildings were also discussed. Four international wind design codes were studied and the comparisons are given. Selection of suitable wind design procedure for slender tall buildings during preliminary design stage to obtain an efficient, safe and economical structural design was emphasized. Importance of wind induced dynamic effects such as across wind and torsional effects were highlighted.

Requirement of wind tunnel testing to address important factors such as interference effect, shielding, wind directionality and aerodynamic effects are addressed.

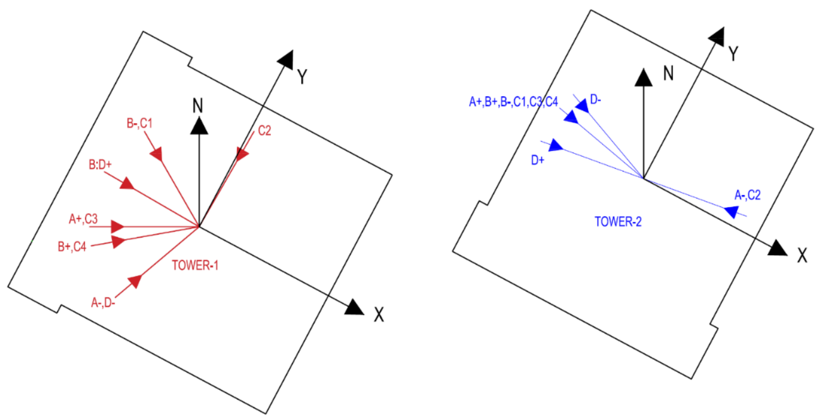

Figure 6: Orientations of towers and different governing wind

Table 4: Base reactions for critical load cases for Tower 2 – Code prediction

Tower	Code/Method	Fx (kN)	Fy (kN)	Mx (GNm)	My (GNm)	Mz (GNm)
Tower - 1	BS 6399-2	5.62	-	-	0.689	-
	BS EN 1991-1-4:2005	6.85	4.28	0.422	0.920	0.020
	AS/NZS1170.2:2002	6.22	3.35	0.345	0.835	0.037
	AIJ:2004	5.84	2.95	0.285	0.721	0.032
	Wind tunnel	6.64	3.02	0.415	0.873	0.035
Tower - 2	BS 6399-2	5.84	-	-	0.748	-
	BS EN 1991-1-4:2005	6.55	4.84	0.683	0.921	0.034
	AS/NZS1170.2:2002	5.60	3.95	0.438	0.764	0.029
	AIJ:2004	5.45	2.85	0.425	0.725	0.031
	Wind tunnel	6.42	4.80	0.624	0.805	0.030

Table 5: Base reactions for critical load cases for Tower 2 – Wind tunnel

Load Definition			Wind	Base moment (GN-m)				Base Shear (MN)	
Case	Comb.	Significance	Dir. (deg)	Mx	My	Mz	XYresultant	Vx	Vy
1	A+	Max My, Vx	310	0.107	0.805	-0.014	0.812	6.42	-0.78
2	A-	Min My, Vx	110	-0.039	-0.608	0.004	0.609	-4.88	0.26
3	B+	Min Mx, Max Vy	310	-0.723	0.173	-0.007	0.743	1.46	5.52
4	B-	Max Mx, Min Vy	310	0.601	0.430	-0.008	0.739	3.47	-4.52
5	C1	Max res. M w/ V in Q1	310	0.413	0.733	-0.013	0.842	5.85	-3.10
6	C2	Max res. M w/ V in Q2	110	0.000	-0.607	0.003	0.607	-4.87	-0.03
7	C3	Max res. M w/ V in Q3	310	0.000	0.798	-0.014	0.798	6.37	0.04
8	C4	Max res. M w/ V in Q4	310	-0.674	0.000	-0.008	0.674	0.10	5.15
9	D+	Max Mz	290	-0.114	-0.215	0.019	0.243	-1.68	0.93
10	D-	Min Mz	320	-0.039	0.499	-0.030	0.501	4.02	0.31

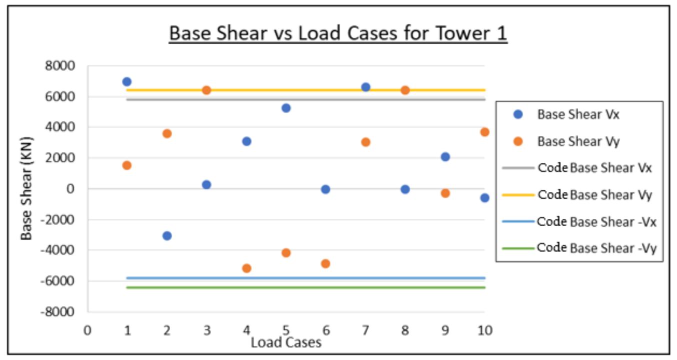

Figure 7: Comparison of base shear – Tower 1

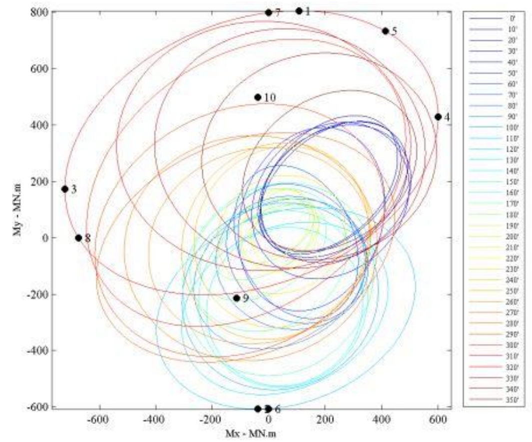

Figure 8: Locations of the standard load cases (black dots) within the Mx and My plane for Tower 2

Verification of pedestrian comfort within the site and in the vicinity is outlined. Finally, a case study summarizing the important design consideration of slender tall buildings in Sri Lankan context is presented.

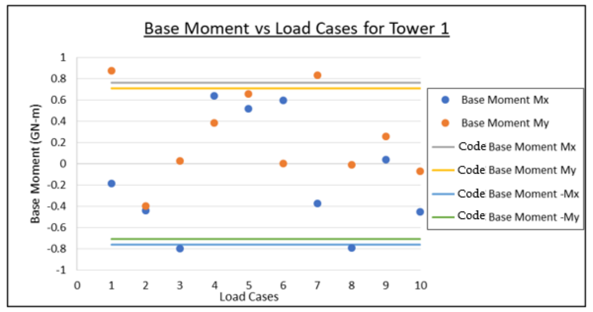

Figure 9: Comparison of base moments – Tower 1

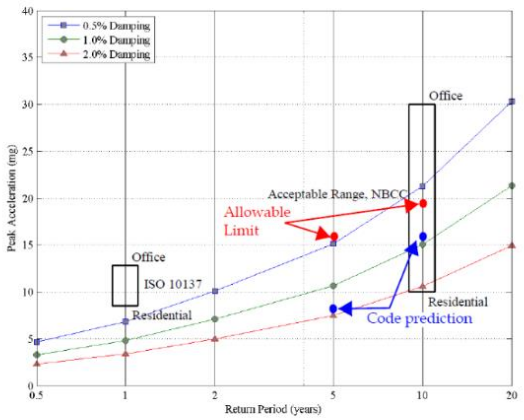

Figure 10: Peak top story accelerations for Tower 2

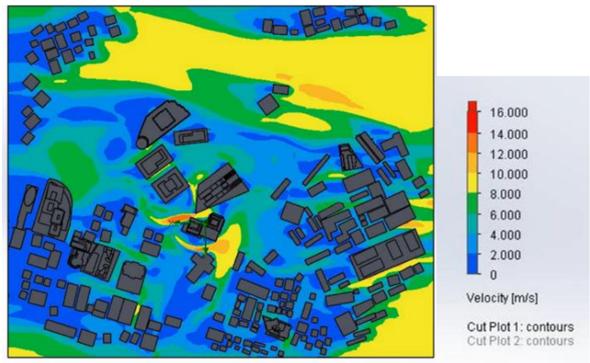

Figure 11: CFD prediction of wind flow in the vicinity

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