APEC-WW Economy Report 2010: Hong Kong

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ABSTRACT: This report outlines the research and studies carried out in Hong Kong on wind loading guidelines and wind-related environmental problems during the last two years. The progress and discussion of review of the Hong Kong Wind Code 2004 is outlined. For wind environmental problems, research progress on wind-induced ventilation of recessed cavities in tall residential buildings is reported. Other areas of air ventilation assessment and pollutant dispersion in urban environment are described. Most of the studies are based on computational fluid dynamics and wind tunnel tests.

KEYWORDS: Wind loading codes, design wind speed, wind environment, urban pollutant dispersion, urban wind climate

1 REVIEW OF HONG KONG WIND CODE 2004

The current wind code in Hong Kong was in force from 2004 (BD, 2004a). In 2008, a technical committee was formed by the Buildings Department with the primary aim to consider review and development of the code. Up to the time of writing, there have been four meetings of the committee and the following three main issues are under discussion.

The design wind speeds specified in the code are all-direction values and there is no provision for wind directionality. However, wind tunnel testing of many building projects in Hong Kong employ wind climate studies for Hong Kong which enable the use of directional deign wind speeds for different wind directions. Some guidelines from the code may be desirable. The design wind speeds in the code were based on an extreme wind analysis of annual maximum wind speeds recorded at Waglan Island during 1953-1994 (BD, 2004a). On the other hand, the wind climate study in most wind tunnel tests makes use of typhoon simulation by the Monte-Carlo method.

Recently, Lam and To (2009) carried out an analysis of the Waglan Island wind record using the method of independent wind storms. The analysis uses storm hourly mean wind speeds during 1975-2005 and with anemometer correction for the topography of Waglan Island using wind tunnel model (Hitchcock et al., 2001). The resulting all-directions 50-year return wind speed, referred to 250 m above open sea surface, is 52.0 m/s. This compares well with the corresponding value of 52.4 m/s in the code, as well as the values in many typhoon simulations. The number of storm wind data enables a directionality study at sectors of 45^o intervals. It is found that the characteristic product (that is $M\alpha$) in the fitted Type I distribution does not have same values at different wind directions. This means that between two wind directions, the ratio between extreme wind speeds at two different return periods is not the same. This presents difficulties in the usage of the results to derive directional design wind speeds (Cook 1983). Figure 1 shows the ratios of directional wind speeds to the all-directions wind speeds at return periods between R = 10 and 1000 years. It can be observed that the ratios are weakly dependent on R except at low return periods $R \leq 20$.

Applying to 50-year return, the directional wind speeds recommended in the analysis are shown in Fig. 2. These mean wind speeds, at 250 m over sea and at eight wind sectors, They have values between 50% and 90% of the all-directions design wind speed. They are conditioned for wind coming from directions within that sector. For codification purposes, these directional wind speeds need to be adjusted so that its probability of annual exceedence is 1/50 for all possible wind approaching directions (Cook, 1983). The upper curve in Fig. 2 shows the resulting directional 50-year mean wind speeds after adjustment. The strongest winds always come from the east while winds from the northwest have the weakest wind speeds.

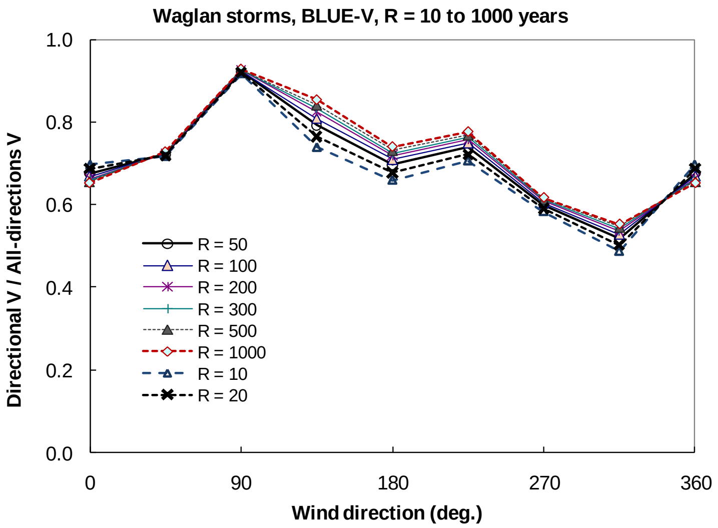


Figure 1. Ratios of directional design wind speeds to all-directions wind speed.

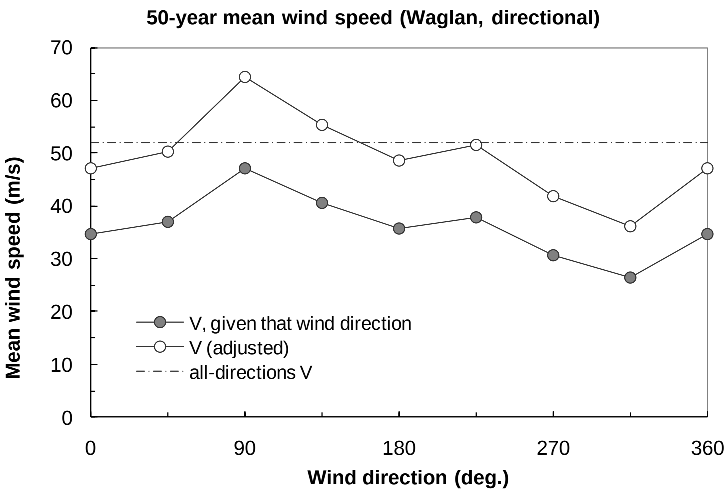


Figure 2. Directional values of 50-year return mean wind speed.

Another issue under discussion in the code meetings is the number of terrain types appropriate for Hong Kong. The 2004 version of the code has only one terrain type and it is the open sea terrain. The early 1973 version allowed two terrain types; the “general” terrain which is close to the open land terrain and the “built-up” or city terrain. The committee is aware of APEC-WW development of unified terrain categories (Choi, 2009) and will consider adopting one or more of the proposed terrain types.

The third issue attracting attention of the code committee is the serviceability limit of building accelerations and the assessment method. The wind code does not specify a numeric criterion for building acceleration but the concrete code of Hong Kong (BD, 2004b) specifies that the 10-year return peak acceleration should not exceed 0.15 m/s^2 for a residential concrete building or 0.25 m/s^2 for a concrete office or hotel building. These limits are specified for 10-minute events but the Hong Kong wind code gives information on hourly wind speeds only. An appropriate relation between hourly-mean wind speed and 10-minute wind speed is to be decided. For assessment methods, the committee consider those used in other codes including Canadian Code (NBCC, 1995), Australia/New Zealand Code (AS/NZS, 2002) and Japanese Code (AIJ, 2004). It is noted that these three codes uses hourly, 3-second, and 10-minute wind speeds, respectively, for assessment of building accelerations. A desktop study is carried out for the assessment of along-wind building accelerations of a few concrete buildings in Hong Kong for which wind tunnel testing data are available. It is found that NBCC and AIJ provide similar values while AS/NZS gives lower values. The agreements with wind tunnel data are scattered.

2 WIND ENVIRONMENTAL STUDIES

At the University of Hong Kong (HKU), several research projects are being carried out on wind-induced ventilation and pollutant dispersion in the built environment.

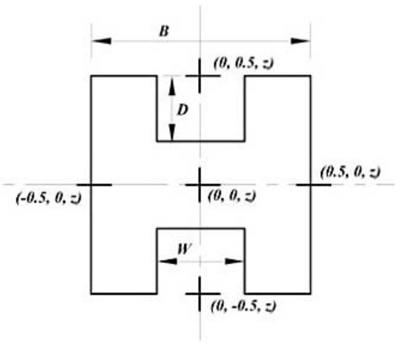
2.1 *Wind-induced ventilation of recessed cavities of tall buildings*

Investigation of wind-induced ventilation of recessed cavities of tall residential building is ongoing. Wind flow past tall buildings with H-shaped cross section and the induced flow inside the recessed cavities are computed with computational fluid dynamics (CFD). Steady flow solutions of the wind field are obtained with RANS (Reynolds Averaged Navier Stokes) using standard k-ε model for turbulence closure. A large number of test cases covering cavities of different widths and depths, buildings of different height-to-breadth ratios, and cavities on the windward, leeward or side building faces have been computed (Fig. 3).

To investigate pollutant dispersion of the recessed cavities, its entire volume is filled with a passive and non-buoyant scalar species at unit level concentration at time zero. The computed solution of wind flow around the building and inside the recessed cavities is then applied and the subsequent concentration field of the pollutant is tracked at successive time steps. The concept of retention or residence time (Lam and Cheng, 2010) is used to measure the overall efficiency of wind-induced flushing of a recessed cavity. It is the time required for the average mean pollutant scalar concentration inside the cavity to decrease to the level of $1/e$ (≈ 0.368).

The dispersion pattern from the recessed cavity on the windward, leeward or side face of the building is shown in Fig. 4. For the first two cases, wind brings fresh air into the cavity mainly through the vertical opening face and removes polluted air out of the cavity through the roof opening face and near the base of the vertical opening face. The side recessed cavity is passively ventilated and needs a much longer time to clear the pollutant. The flow and dispersion of pollutant are governed by two large-scale vortices inside the cavity. The vortex near the ground level brings in fresh air from outside and ejects pollutant-laden air at a short height above. The vortex near the building roof brings in fresh air from outside and thus diluting the pollutant concentration near the top of the cavity.

Figure 5 summarizes the effect of cavity dimensions and building heights on the retention times of pollutant in the recessed cavities. For the windward and leeward cavities, a taller building height always leads to a longer retention time, which means poorer wind-induced ventilation. This is because the outward transport paths are mainly through the roof opening and near the ground so that it takes a longer time to ventilate a taller cavity. For the side cavities in general, the retention time does not depend on the building height. This is because dispersion of pollutant mostly occurs evenly along the building height. In all cases of windward, leeward or side cavities, the retention time increases with the cavity depth.



Case No.	Width (W/B)	Depth (D/B)
1	0.25	0.125
2	0.25	0.250
3	0.25	0.375
4	0.50	0.125
5	0.50	0.250
6	0.50	0.375
7	0.75	0.125
8	0.75	0.250
9	0.75	0.375

Figure 3. Test cases of building sections and dimensions of recessed cavities.

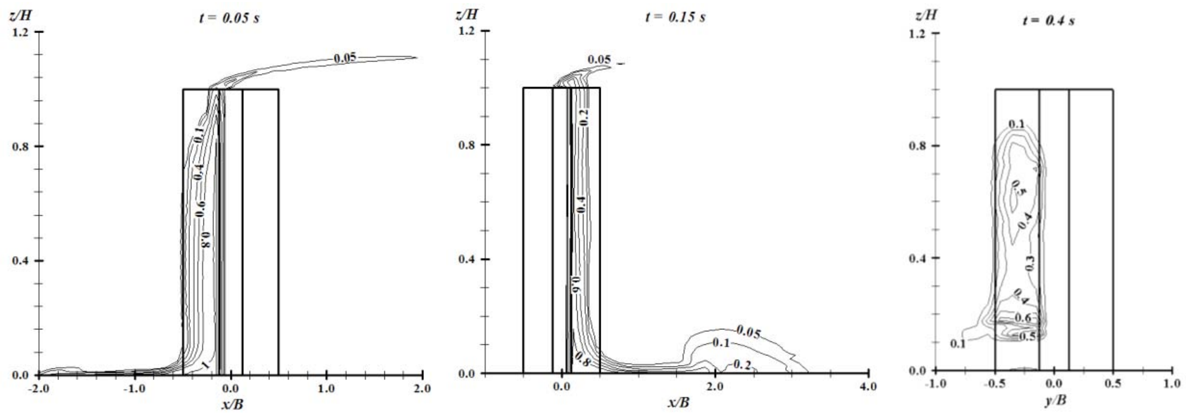


Figure 4. Pollutant dispersion of Case 3 recessed cavities on H/B = 8 building. (a) Windward; (b) leeward; (c) side cavity (vertical scale compressed).

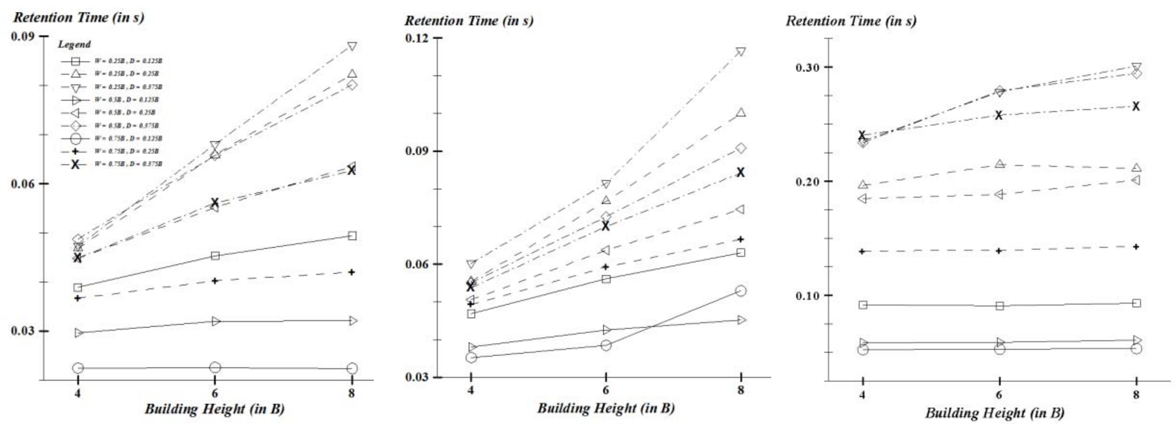


Figure 5. Retention times of recessed cavities: (a) Windward; (b) leeward; (c) side cavities.

2.2 *Comparison study of pedestrian-level wind environment*

Wind tunnel tests have been conducted at HKU to measure pedestrian-level wind speeds for the target buildings defined in the APEC-WW 2007 meeting for the WG of "Pedestrian Wind Environment" (Fig. 6). Model of the two buildings were constructed at scale 1:250 and tested in the wind tunnel with simulated wind of the suburban terrain type. The measured mean wind speed profile, in the region $0 < z < 150$ m (full-scale), was found to best match the power law with power exponent $\alpha = 0.18$. The longitudinal turbulence intensity at building roof height was 0.085.

Three components of turbulent wind speeds were measured with a 7-hole probe on two horizontal planes, at 1.5 m and 10 m height, full-scale. The 7-hole probe (Aeroprobe) was connected to a pressure scanner (PSI) so that mean and fluctuating velocities were measured at the designed points (Fig. 6) and other points in the building wake. Figure 7 shows the mean horizontal wind vectors on the two measurement planes. It should be noted that the 7-hole probe pointed towards the approaching wind direction and thus could not accurately measure reverse flow velocities in recirculating wake region directly behind the building. Table 1 summarizes the results of mean and peak wind speeds at the designated points, normalized by the upstream mean wind speed at building roof height, U_H. These are horizontal wind speed values which were computed as follows. At each measurement time, the instantaneous horizontal wind speed was calculated from the two horizontal velocity components. Mean and standard deviation values were then computed from the history of horizontal wind speed. The peak wind speed was computed as the mean value plus 3 times the standard deviation value.

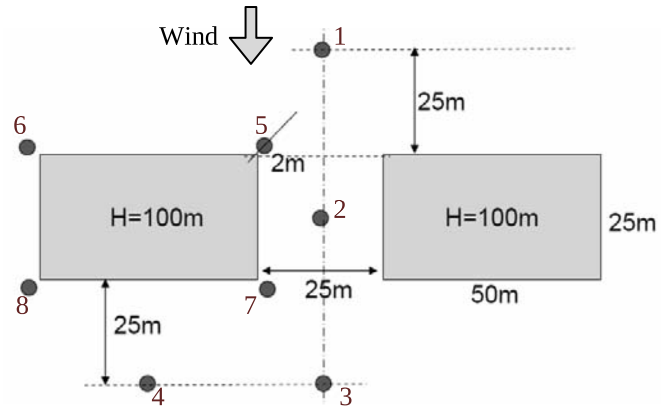


Figure 6. Building arrangement and reference locations for pedestrian wind environment study.

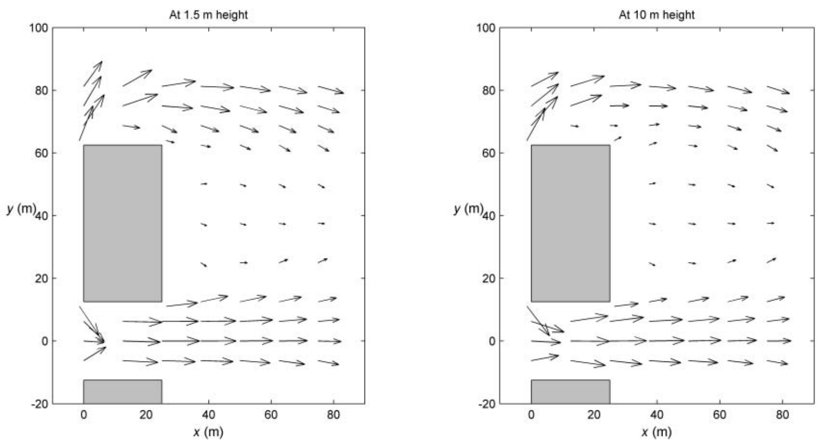


Figure 7. Mean horizontal wind vectors measured in wind tunnel.

Measurement point (Fig. 6)	z = 1.5 m		z = 10 m	
	Mean: $\overline{U}/U_H$	Peak: $\hat{U}/U_H$	Mean: $\overline{U}/U_H$	Peak: $\hat{U}/U_H$
1	0.25	0.57	0.34	0.74
2	1.06	1.43	1.07	1.56
3	0.91	1.49	0.90	1.47
4	0.41	1.15	0.34	0.94
5	0.94	1.38	1.00	1.38
6	1.01	1.36	1.01	1.33
7	0.85	1.51	0.67	1.55
8	0.31	0.87	0.28	0.66

Table 1. Local mean and peak wind speeds measured in wind tunnel.

2.3 *Pollutant removal mechanism from urban street canyons*

Another research project at HKU aims at the mechanism of pollutant removal from urban street canyons as a result of wind and buoyancy. The meteorological process in urban canopy layer (UCL) exhibits a distinct neighbourhood-scale climate consisting of wakes and recirculations and a street canyon is an ideal generic unit for urban climate studies (Britter and Hanna, 2003). Depending on the building-height-to-street-width ratio, flows over idealized two-dimensional (2D) street canyons could be grouped into 3 characteristic flow regimes, namely, isolated roughness, wake interference, and skimming flow (Oke, 1988). Similarly, in fluid mechanics, the flows over a rough wall with 2D ribs are classified into *d*-type and *k*-type flows depending on the separation between the ribs (Jiménez, 2004). At HKU, large-eddy simulation (LES) is used to examine the pollutant transport in 2D street canyons. The focus is on the pedestrian level inside the street canyons and the UCL over the street canyon in order to address the pollutant removal mechanism in urban environment.

Inside the street canyon, flow and pollutant distribution and the associated transport behaviors are investigated in different flow regimes (Chung and Liu, 2010). Figure 8 compares the instantaneous snapshots of pollutant transport in street canyons of different aspect ratios. The pollutant plume dispersion is illustrated by the iso-surface of pollutant concentration (at 5% of the source concentration). Figure 8(a) clearly shows that, in the isolated roughness regime of street canyon (at aspect ratio 1:15), the pollutant plume from the upwind building covers the leeward roof level and then entrains down to the ground level on the leeward side. Right before the downwind building, a fast updraft takes pollutant away from the street canyon. When the street width is reduced to unity, the characteristic flow falls into skimming flow regime. The pollutant plume cannot entrain into the street canyon anymore but covers the roof of the two buildings (Fig. 8(b)). The isolated nature of the recirculating flows inside the street canyon suggests that the pollutant removal for this canyon is governed by intermittency.

In the region above the street canyon, the building geometry (aspect ratio for 2D idealized buildings) is found to affect the cross-wind pollutant dispersion and the associated plume development (Wong and Liu, 2010). Figure 9 compares the instantaneous snapshot of pollutant transport over a flat plate and street canyons of aspect ratio 1 and 1:4. The pollutant plume development is illustrated by the iso-surface of pollutant concentration (0.1% of the source concentration). Figure 9(a) shows that the pollutant plume development over a flat plat is rather shallow. Once street canyons of aspect ratio 1 are introduced at the bottom of the ABL, updrafts and downdrafts of larger scales are clearly depicted in Fig. 9(b) that help promotes the upward transport of pollutants resulting in higher pollutant plume development. When the aspect ratio of the street canyons are decreased to 1:4 (wider street), more massive updrafts and downdrafts are observed in Fig. 9(c) so the plume development further rises up into the UCL.

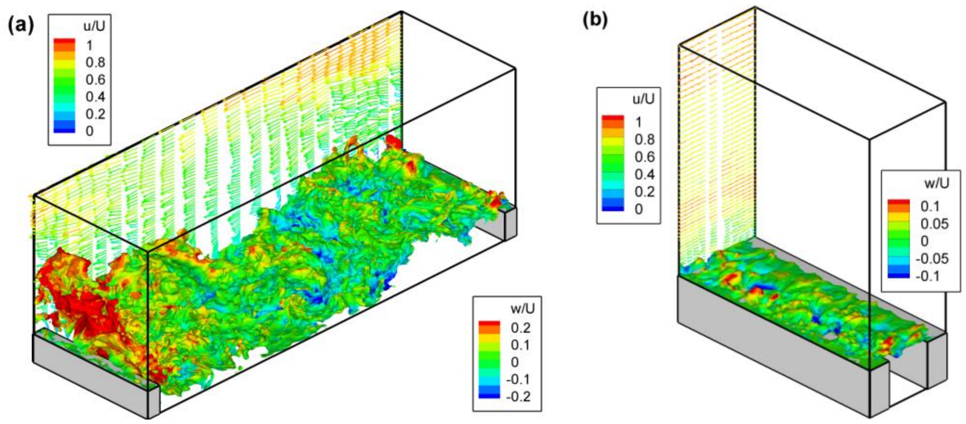


Figure 8. LES snapshot of iso-surface of pollutant concentration (at 5% of source concentration) inside street canyons of aspect ratio: (a) 1:15 (isolated roughness regime or *k*-type) and (b) 1 (skimming flow regime or *d*-type). Also shown are flow vectors on vertical *x*-*z* plane and contours of vertical velocity on pollutant iso-surface.

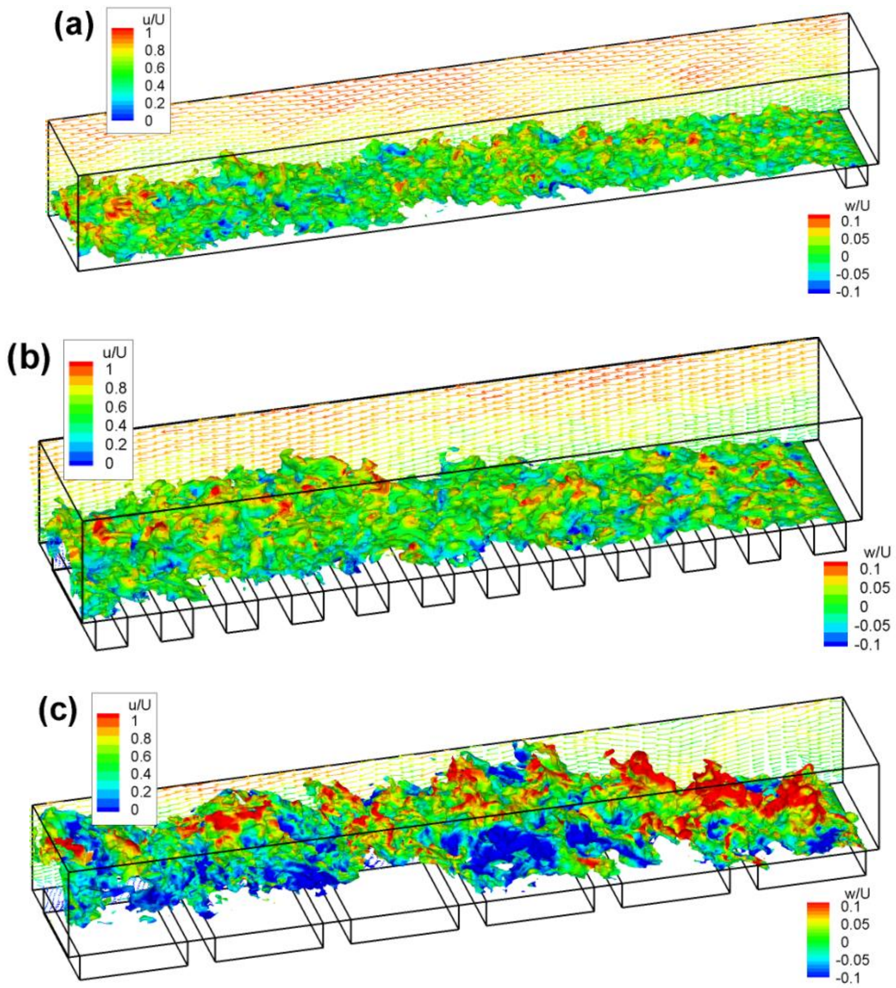


Figure 9. LES snapshot of iso-surface of pollutant concentration (0.1% of source concentration) over: (a) flat plat; (b) street canyons of aspect ratio 1 and street canyons of aspect ratio 1:4 (skimming flow regime or *d*-type). Also shown are flow vectors on vertical *x*-*z* plane and contours of vertical speed on pollutant iso-surface.

The ultimate goal of this LES study of pollutant transport inside and over idealized street canyons is to provide a fundamental understanding of environmental fluid mechanics in urban scale and to develop more sophisticated urban model for city parameterization for meso-scale meteorology applications.

3 AIR VENTILATION STUDIES

Air ventilation (or the lack of air ventilation) at the pedestrian level is presently a major concern in Hong Kong. With the ever growing population, cities around the world are fast expanding. Hong Kong has one of the world's densest urban environments. In order to accommodate more and more occupants, the issue of quality and sustainable built environment has often been overlooked. There are many cases of continuous lines of closely packed high-rise buildings creating the so call "Wall" effect blocking wind and sunlight. Areas inside densely-built developments suffered from poor air ventilation, bad air quality and higher temperature in summer months. Since the SARS outbreak in 2003, the Hong Kong Government is setting up measures to improve the quality of the built-environment of Hong Kong. The final report of Team Clean, "Measures to Improve Environmental Hygiene in Hong Kong", was released on 9 August 2003. The report pointed out that the Government was examining the practicality of stipulating air ventilation assessment as one of the considerations for all major future developments or redevelopments.

To study the air ventilation in areas inside a city development it is important to understand the wind flow pattern in the city and around building blocks. The problem can be studied in two levels; the first is the wind blowing around and over the city, which gives information on the wind available to the inner areas of the city. The second is the wind characteristics and flow pattern in streets and around building complexes.

3.1 *Topographic effect*

Wind, before reaching the city area, usually blows over landscapes with certain topographic features, for example, hills, mountain ranges, valleys and etc. The topography of these features will modify significantly the wind characteristics of the approaching wind. Wind tunnel studies to investigate the effect of topography on wind flow pattern are carried out at the City University of Hong Kong. Some of the results are presented as follows. Figure 10(a) shows the effect of mountain and hills on wind speed. The wind speed profile at the downstream of a mountain range is presented. The terrain profile is also given in the figure. As can be seen the first kilometre of the site is flat and with mild slope and over the second kilometre with elevation rising to about 100 m. The highest peak is about 410 m high at a distance 2.7 km away. Beyond which the level oscillates about the 200 m height. It is noted that the highest Peak (552 m) of the range is not direct on the wind (WSW) path, but deviates by about 8° to the north of the path. The wind speed profile (normalized by the wind speed at 1000 m height) is shown on the left hand side of the figure. It can be seen that the wind speed drops significantly at around 500-600 m. This is the height range of the mountain peaks showing the wake at the shadow of the mountains. Wind speed ratio at the lower levels is around 0.25 - 0.30. This means that the available wind over the specific site is much weaker than the unobstructed wind upstream. Two other cases showing the topographic effect on the downstream wind of mountain range are shown in Fig. 10(b-c). It can be seen that wind speed is much reduced downstream of mountain ranges.

Topographic effects on wind direction are also studied. Figure 11 shows the change in wind direction as the wind blows into a valley. It can be seen that winds are observed to funnel into a valley aligning in the NE-SW direction.

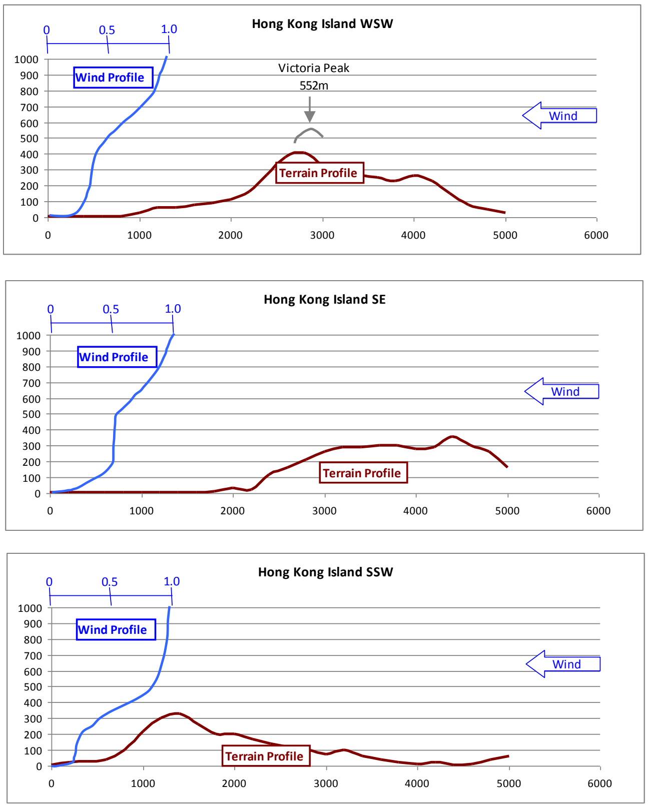


Figure 10. Wind speed profiles downstream of mountain ranges for wind directions: (a) WSW; (b) SE; (c) SSW.

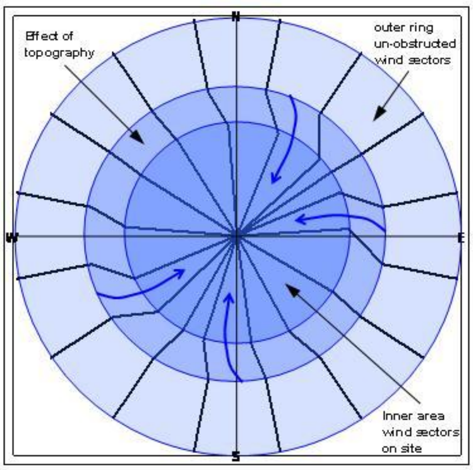


Figure 11. Changes in wind direction as wind blows into a NE-SW lying valley.

3.2 *Effect of urban development on wind flow*

Given the available wind blowing onto the outskirt of a city, its speed and direction will further be affected by buildings forming the fabric of the city. Wind flow is affected by the city fabric in different levels. First, as wind blows through an area, it tries to take the path of the least resistance to penetrate the area. That is, the wind will converge and blow along the major express ways, river channels and multi-lane roads forming a continuous path; these are the “breeze way” as sometimes are termed. Second, buildings of the area contribute towards the terrain roughness of the area. A rougher terrain, that is, taller buildings, will slow the wind down. This effect will start at low level and progresses upwards. Therefore, the general height of buildings of the area will have an effect on the lower level wind speed. Third, layout of buildings in a building complex will have strong effects on the local wind. Furthermore geometry of individual building and podium will also play an important role in defining the local wind condition.

Studies on the effect of building geometry and building layout on air ventilation are carried out in the City University of Hong Kong. CFD and wind tunnel studies on the effect of building geometry are carried out. For instance, Fig. 12 shows a study of air ventilation behind two buildings with a gap between them. Figure 13 shows the flow pattern behind a building where the building height is varied. Study on the air ventilation of a whole town with over 60 high-rise buildings is also carried out using wind tunnel technique. Figure 14(a) shows the layout of the building complexes and Fig. 14(b) shows the air ventilation pattern.

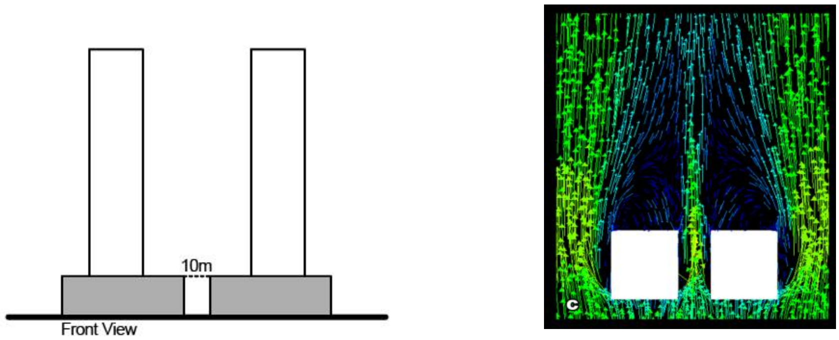


Figure 12. Study on the effect of building gap on air ventilation.

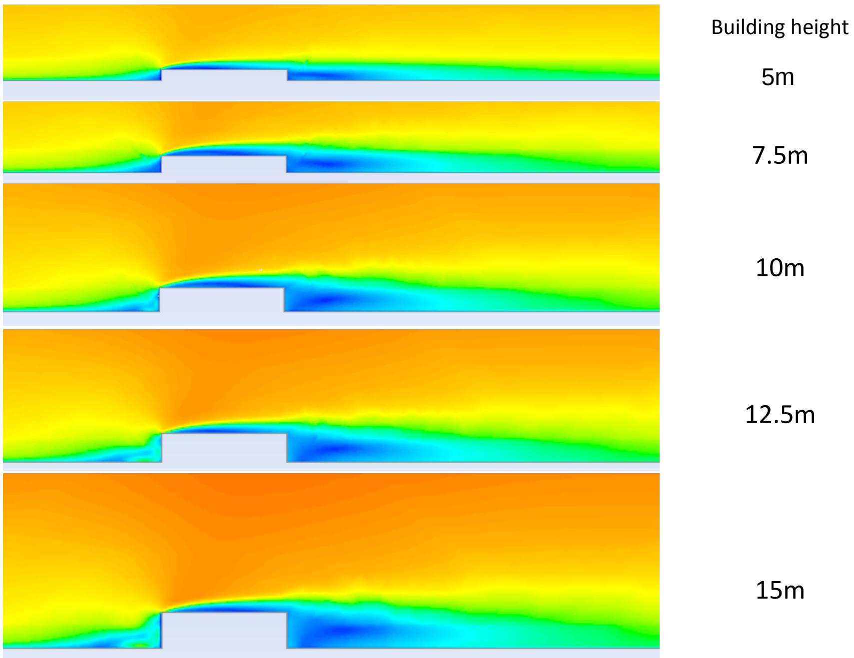


Figure 13. Study on the effect of building height on air ventilation.

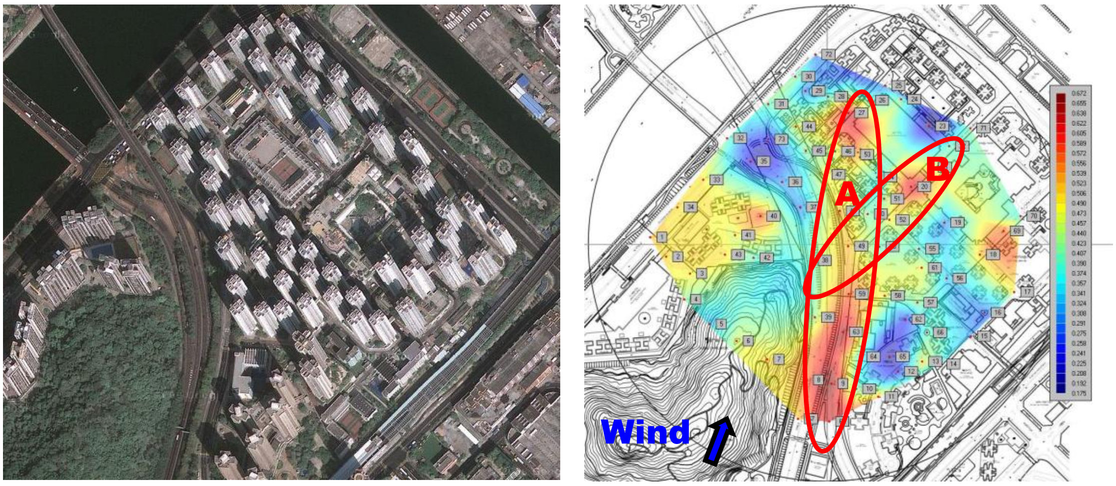


Figure 14. Air ventilation study of whole town: (a) region under study; (b) ventilation for summer prevailing wind.

3.3 *Air ventilation assessment system and urban climate mapping for Hong Kong*

To tackle building-induced “wall” effect and weak urban air ventilation related problems, Hong Kong Government started in 2006 to call for “Air Ventilation Assessment System” (AVAS) as one of the considerations for all new major development projects in Hong Kong. The AVAS is implemented through two policy mechanisms. First, a high level Joint Bureau Technical Circular (Housing, Planning and Lands Bureau, and Environment, Transport and Works Bureau) was issued. Second, a new chapter on urban air ventilation has been added to the Hong Kong Planning Standards and Guidelines (Ng, 2009). A register for all AVA studies conducted by government departments and quasi-government organizations has also been placed online for the general public to refer to.

More than 30 projects and studies have gone through the AVAS since 2006. Some of their study reports can be accessed at the website of the Planning Department (PlanD) of Hong Kong Government. One of the first important government projects that have gone through the AVAS is the new Hong Kong Government Headquarters building on the Tamar site in the central business district. Four design proposals, each utilized its own wind engineer and wind tunnel test results, were submitted. Finally the design by a local architect Rocco Design Ltd. and their wind engineer RWDI was selected (Fig. 15). The site wind availability data were provided by CLP Power Wind/Wave Tunnel Facility (WWTF) at The Hong Kong University of Science and Technology (HKUST) using a 1:2000 scale topography model. CFD was used for the initial option studies. The buildings on site are designed to be positioned based on an understanding of the prevailing wind of the site. The resultant design has a very large hole in it so as to allow sufficient ventilation through it to the public transport interchange and the city to the site’s wind wakes (Fig. 16).

In 2006, further to the study that had resulted in the AVAS, the Hong Kong Government commissioned a study to produce an Urban Climatic Map of Hong Kong. The map evaluated the thermal load and dynamic potential of the Hong Kong territory so that the bio-meteorological characteristics of urban Hong Kong can be better understood for planning decision making purpose. In 2009, the first draft of the urban climatic map was completed. Within the map, there is a layer specifically on Wind Information. It gives planners an understanding of the various wind characteristics in different part of Hong Kong. The Chinese University of Hong Kong (CUHK) has been an active player in the study (Ng, 2007).

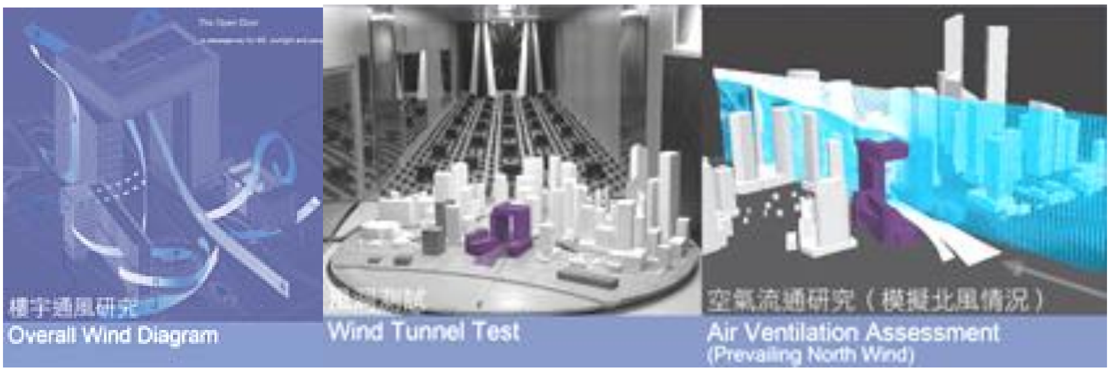


Figure 15. The Tamar design undergoing wind tunnel tests.

Figure 16. The Tamar design with the whole hole in it for better air ventilation.

The Wind Information Layer of the Urban Climatic Map took into account input data from the Hong Kong Observatory and the MM5-CALMET model simulated wind data of Hong Kong (Fig. 17). The data was then expertly evaluated together with PlanD and Hong Kong Observatory colleagues, and simplified for planning purpose to denote the prevailing wind directions in the summer months of Hong Kong, as well as the localized channeling, katabatic air mass exchange and land-sea wind movements that are important to urban planners.

Under the Urban Climatic Map study, thermal comfort surveys and benchmarking studies using wind tunnels had been conducted. The data had been instrumental development of a Wind Performance Criterion of Hong Kong. Based on the user thermal comfort survey study, it had been established that the neutral Physiological Equivalent Temperature (PET) of Hong Kong inhabitant in the summer months is in the order of 28^{o}C (Cheng et. al., 2010). It was then calculated that under normal shaded urban conditions, light air of 1 to 1.3 m/s over the pedestrian area is conducive to human thermal comfort. On the other hand, based on wind tunnel benchmarking tests, it was established that in most part of urban Hong Kong, getting the desirable light air is difficult. A practical approach based on performance/prescriptive measures may be necessary. CUHK is still actively working towards the Wind Performance Criterion of Hong Kong to be finalized and endorsed by Hong Kong Government. This may become version 2 of the AVAS.

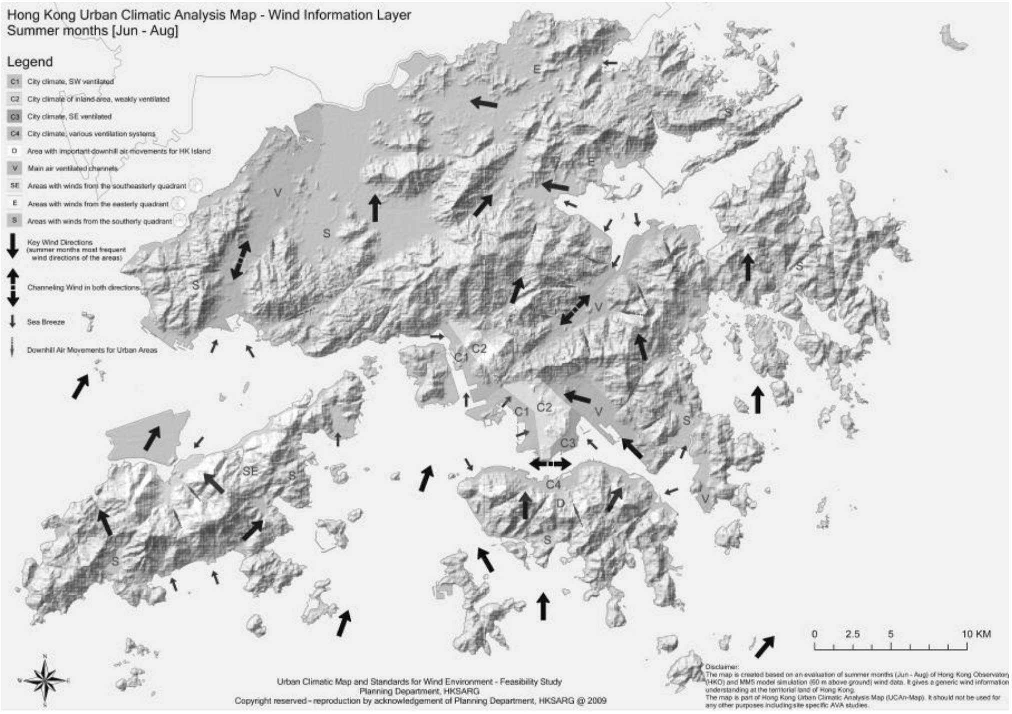


Figure 17. Wind Information Layer of Hong Kong Urban Climatic Map.

For conducting AVA studies, wind at the boundary layer, typically at 500 m above the site is needed for calculating the wind velocity ratio and the wind availability on ground. In the past, 1:2000 wind tunnel models have been used extensively to obtain this information. However, it is known that normal wind tunnel tests cannot model localized thermal induced land sea breezes and wind circulation system (Ng and Fung, 2008). PlanD, its consultants, and the Hong Kong Observatory has come together and may propose a set of standardised site wind availability data for AVA studies based on model simulations. It is likely that MM5 is to be used. The results will then be nest into another model to downscale the data's spatial resolution to 100 or 200 m interval. Wind probability tables at various heights above ground, wind profiles as well as wind turbulence profiles at 16 wind directions will be produced. A new method using the data to calculated wind velocity ratio and wind speed on ground is being developed. The work, in which CUHK is involved, is still on-going.

Another issue of AVAS concerns the use of CFD. Although a lot of progresses have been made recently using CFD for urban wind studies, it is also known that careful quality control procedures are not normally followed in many consultancy studies (Yau et. al., 2009). Steps are now taken by PlanD and their consultants to establish guidelines and best practice for using CFD on AVA studies. The work is still on-going.

4 WIND LOADING OF NOISE BARRIERS AND NOISE ENCLOSURES

The rapid development of infrastructure in Hong Kong is beneficial to the city's economy but at the same time it also raises the public's concern about vehicular noise generated on highways and other major roads that are often located in quite close proximity to residential estates and public areas. Noise barriers/enclosures can be an effective means of alleviating the noise impact of a highway on the surroundings. There are currently no specific provisions in design codes and/or standards in Hong Kong for the assessment of wind loads and drag coefficients for different forms of noise barriers/enclosures, which has led to the use of a variety of different design approaches that may or may not be applicable to noise mitigation structures employed in Hong Kong.

The CLP Power Wind/Wave Tunnel Facility (WWTF) at The Hong Kong University of Science and Technology (HKUST) is conducting a collaborative study with the Bridges and Structures Division of the Highways Department (HyD), Hong Kong Government, to study wind drag coefficients on noise barriers/enclosures erected locally at roadsides or on highway structures. The objectives are to determine and develop pressure/force coefficient data that are applicable for the design of noise barriers and noise enclosures to resist wind-induced loads in Hong Kong.

The study commenced with a desk-top study reviewing wind loading provisions specified in prominent national design standards and codes of practice and other data available in the public domain. A detailed summary and statistical database of noise mitigation structures (NMS), including barriers and enclosures, commonly employed in Hong Kong was established from HyD's records and archives. Based on the statistics for Hong Kong, a number of NMS configurations are being studied by CFD (Fig. 18) and wind tunnel model studies (Fig. 19).

A parametric study was conducted using CFD for a number of NMS configurations to give generic guidance and further information to facilitate the design and methodology to be used in subsequent detailed wind tunnel model tests. The parameters investigated include the ratio of length to height, angle of attack, and geometric parameters for various NMS configurations. Detailed wind tunnel tests are currently ongoing.

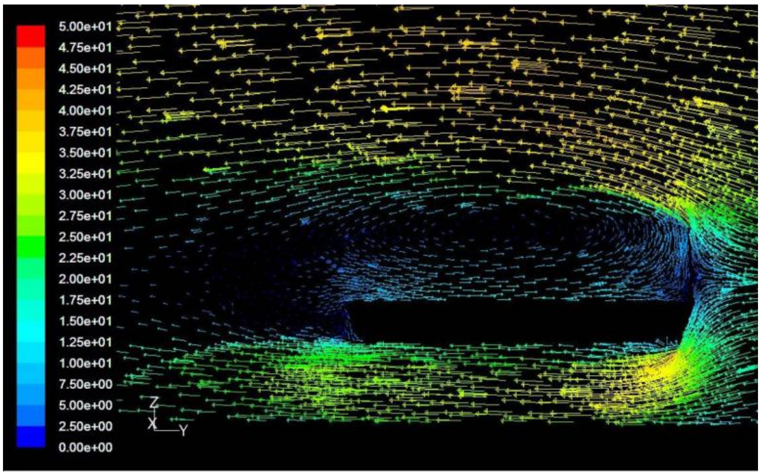


Figure 18. Example of CFD study: velocity vectors (m/s) around a vertical noise barrier on a bridge.

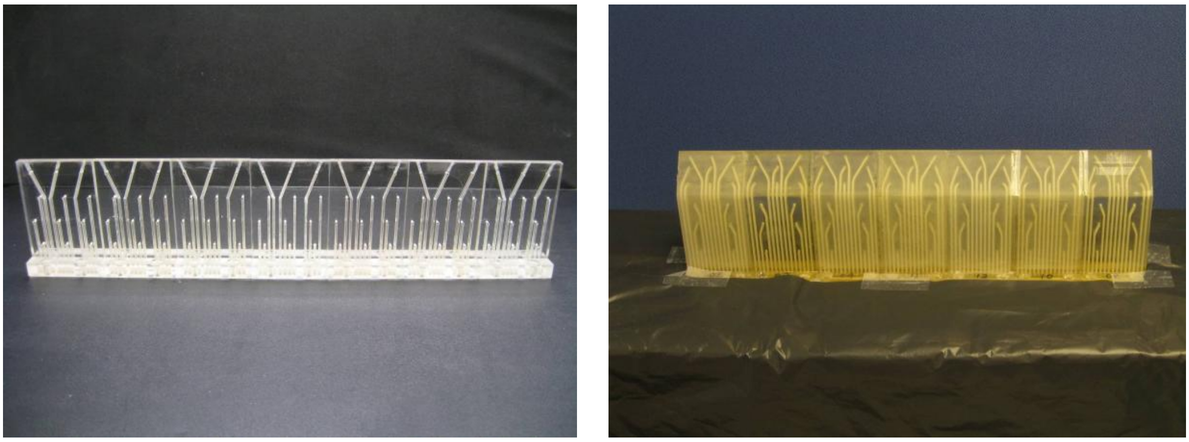


Figure 19. 1:75 scale pressure-tapped wind tunnel models of a vertical noise barrier (left) and an inverted-L shaped (right) noise barrier.

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