265: Applying Numerical Simulation for Wind Availability Studies of Complex Topography and Land-Sea Phenomenon – For Urban Planning in Hong Kong

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Abstract

Hong Kong is a high density city both in terms of urban development and population. Owing to its sub-tropical monsoon climate, winds in the dense urban area are crucial to human comfort. The existing urban planning mainly considers "development density" and neglects the healthy environment of the city. The experience of SARS in 2003 compelled the government to improve the current situation and introduce the Air Ventilation Assessment (AVA) [1]. Accordingly, it is important to understand the site wind availability so as to provide a basis for design. Dealing with the complexity of studying the wind pattern in Hong Kong, a mesoscale simulation approach was adopted by introducing the MM5 modeling system to the terrain and urbanscape of Hong Kong. This paper aims to provide a new direction and guidelines for designing the city taking into consideration the wind environment. Wind availability was reviewed in intensity and direction throughout different seasons in a year by using MM5 data. [2] Wind patterns could be observed and their relationship to seasonal change and the complex topography could be illustrated as a tool for understanding wind availability in Hong Kong. The territorial wind map generated by the data was used as a primary study tool for choosing specific sites for further investigation. Different urban areas were selected as a real model for demonstrating the relationship between urban design and the wind environment. A new strategy for urban planning and building design could then be suggested.

Keywords: topography, land-sea phenomenon, MM5, wind availability, urban planning

1. Introduction

According to the latest population projections announced by the Census and Statistics Department (C&SD), Hong Kong's population is projected to increase from 6.72 million in 2001 to 8.72 million in 2031. With a total coverage of only about 1,104 square kilometres, Hong Kong inevitably opts for dense urban development (Figure 1) and, as a result, has a population density of almost 6,280 inhabitants per square kilometres. The availability of wind for thermal comfort in outdoor urban spaces is therefore very important for the inhabitants. [3][4][5] However, owing to the complexity of Hong Kong's topography, its proximity to the sea (sea-breeze condition) [6] and its subtropical monsoon climate, the study of wind availability for comfort is very complicated and difficult to conduct. In 2003, Hong Kong was struck down by Severe Acute Respiratory Syndrome (SARS) and many people died. This urged the Hong Kong Government to critically examine the city for healthy living and to initiate the study titled "Feasibility Study for Establishment of Air Ventilation Assessment (AVA) System", which eventually led to a methodology of Air Ventilation Assessment (AVA). The AVA system has a set of technical guidelines for appropriate use of the measuring tools and wind tunnel for high density urban design. It establishes a methodology for project developers to objectively assess their designs. To further design for wind in Hong Kong, the availability of wind is worth studying so that designers can know how much wind is available and achievable on their sites.

Fig 1. The high dense urban area in Hong Kong

2. Hypothesis

In order to deal with the complexity of studying the wind availability of Hong Kong, a mesoscale simulation approach was adopted. By introducing the Fifth-Generation NCAR / Penn State Mesoscale Model (MM5) to the topography and the urban environment of Hong Kong, together with the climatic information gathered by Hong Kong Observatory, the wind speed and wind direction could be simulated. The data could then be analyzed for land classification and illustrations in design for wind. A similar approach was taken by Kubota, T. and Miura, M. in Tokyo [7], and was successful in studying the wind pattern in the residential areas of Tokyo.

3. Methodology

3.1 A Review of Methodology for Obtaining Site Wind Information

A wind tunnel is an experimental tool for the study of wind and its effects on both building structures and the environment. Generally, a topographical model on the scale of 1 to 2000 is placed into the wind tunnel to simulate the atmosphere. Wind speeds are measured and collected for further analysis. At present, the two common and available standards for wind tunnel tests are A.W.E.S. and A.S.C.E. respectively. The wind tunnel in the Hong Kong University of Science and Technology has been operational since 2000 and the wind tunnel test is a conventional way to collect wind data in Hong Kong. However, deviations of wind tunnel data owing to the neglect of land sea phenomenon and unstable atmosphere lead to the need for the application of the MM5 Modeling System. [8,9]

The Fifth-Generation NCAR / Penn State Mesoscale Model (MM5) was developed from a mesoscale model, which is a terrain-following sigma-coordinate model designed to simulate or predict mesoscale and regional-scale atmospheric circulation. Since MM5 is a regional model, it requires an initial condition as well as a lateral boundary condition to run. To produce the lateral boundary condition for a model to run, girded data is needed to cover the entire time period during which the model is integrated. The MM5 modeling system was used together with the CALMET diagnostic model to provide more accurate simulations. [10]

3.2 Method of Study

In order to study the wind patterns in Hong Kong, three sets of data from summer (June to August), winter (December to January) and the annual period (January to December) were obtained. With detailed terrain and land use information obtained from the Planning Department of the Hong Kong SAR government, the system was operated on an hour-to-hour basis. Firstly, a large-scale wind field at 1.5 km resolution was generated by using MM5 as a preliminary estimation. Then, the CALMET model was used to adjust the meteorological fields so as to reflect the high resolution terrain and land use data on an hourly basis. Wind fields were produced at 500 m resolution to draw a detailed wind spectrum for Hong Kong by data simulation from 2004. This approach is particularly important for southern China where the wind variability is considerable. [11] Data obtained from MM5 was compared with data set from Hong Kong Observatory as collation.

Data of wind speed and wind rose at height 60m in 8 directions in 2004 were collected. The collected data of prevailing wind direction and mean speed were then coded to the Hong Kong territory by ArcGIS to generate the Prevailing Wind Direction and Intensity Diagrams and Wind Speed Distribution Graph for the annual, summer and winter periods. However, the simulation was carried out under a few limitations such as the overestimation of wind speed due to rough building geometry and neglect of urban canopy layer and land classification.

As Hong Kong is recognized as a sub-tropical district, summer data were captured for further illustration to better enhance human comfort in urban design for the local climate. Moreover, the mean speed data has been re-interpreted into a graphical chart for analysis of the relative wind strength to geographical aspects. Therefore, clues could be obtained for wind design strategy in urban development with a more scientific environmental approach. [12]

4. Result and Findings

4.1 Site Wind Availability based on MM5

Collected information on wind speed and direction from the HKUST was coded to the Hong Kong territory in ArcGIS. The wind phenomenon in annual and summer periods was studied through analyzing the extracted data. The analysis focused on the seasonal difference, topographical effects and land-sea effects.

The prevailing wind direction and intensity in summer time and annually was coded to the Hong Kong territory [Fig 2 & 3] to implicate the possibility of urban planning design by wind direction and wind speed.

Fig 2. Partial Map of Hong Kong - Prevailing Wind Direction and Intensity (Summer)

Fig 3. Partial Map of Hong Kong - Prevailing Wind Direction and Intensity (Annual)

Hong Kong is under the influence of south and southwesterly monsoons which come from the South China Sea in summer time and generally a north-easterly monsoon from inland according to the annual diagram. The wind intensity is mainly affected by topography and land-sea breeze issues.

The graphical mapping of wind phenomenon was converted into charts as a tool for further analysis. The wind speed distribution and frequency of occurrence of the wind direction in Hong Kong can therefore be compared between summer and winter time.

The wind speed distribution statistics revealed a higher and average distribution of wind speed in winter time while lower wind speeds occur more frequently in summer [Fig.4]. Hence, designing for wind in summer time is more significant for achieving human comfort.

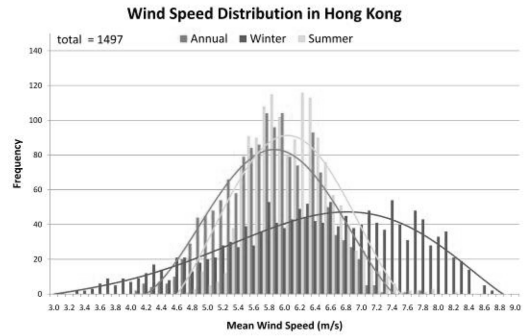

Fig 4. Wind Speed Distribution in Hong Kong

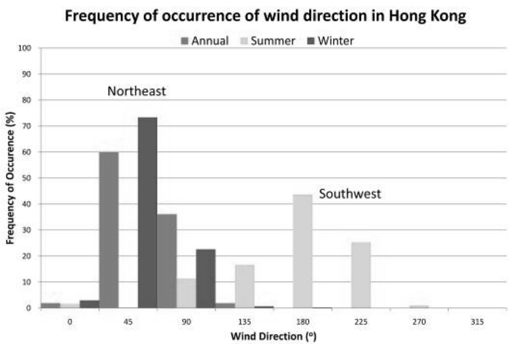

Fig 5. Frequency of occurrence of wind direction in Hong Kong

Another factor in designing for wind could be revealed by comparing the frequency occurrence of wind direction in summer, winter and annually. [Fig.5] As the wind direction occurs at different angles in summer time and annually (southwest in summer; northeast in winter), it becomes an important factor for input into urban planning to enhance better wind penetrability.

4.2 A Summary Evaluation of Wind Characteristics of Urban Areas in Hong Kong

Urban areas and towns in Hong Kong are our focus in the study. Due to the changing direction of seasonal monsoons and the complex topography, wind direction in different periods of a year in particular areas of Hong Kong varies. By reviewing the results, based on the understanding of the direction of prevailing winds and intensity in summer time and the annual base in that particular area as shown in Fig.2 & Fig.3., we have classified different areas of Hong Kong into five types according to the direction of prevailing winds in summer time and the annual base in that particular area [Fig.6].

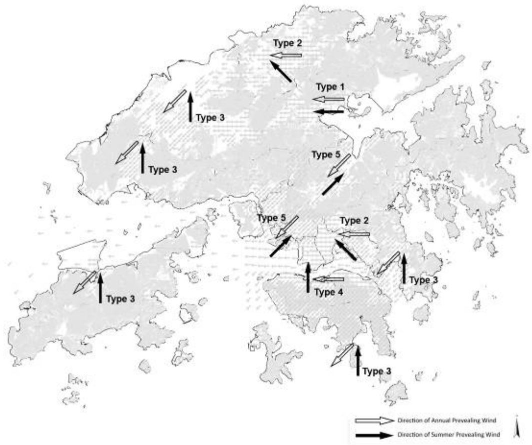

Fig 6. Prevailing wind direction zoning of urban areas

Type 1

Prevailing winds in summer time and annually in an area of this type are in the same direction [Fig. 7].

Tai Po in the New territories is a town of this type where both the annual and summer prevailing wind come from the east.

Tai Po, the town, has developed along the Lam Tseun River which runs from west to east. Tolo Harbour is at the eastern end of Tai Po. The given geographic conditions facilitate the possibility of an urban design which favors wind direction.

Building blocks in this area should be distributed in rows in the direction of the prevailing wind. A variety of building heights will facilitate the washing down of wind to the street level.

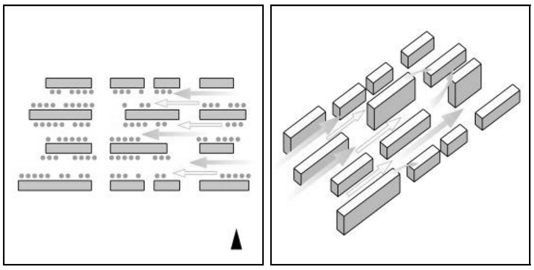

Fig 7. Design implication for 'type 1' sites

Type 2

Prevailing winds in summer time come from the southeast and annually from the east. The two wind directions are roughly 45° to each other [Fig. 8].

East Kowloon faces the eastern entrance of Victoria Harbour where new development will soon commence and northern areas such as Fanling and Sheung Shui can be classified as this type. The latter two areas are flatlands in the northern part of Hong Kong with a continuous ridge on the southern side.

The main streets follow the direction of the summer prevailing winds to favour the penetration of summer breezes. Widening of streets on the south east side of the road would lead to a better acceptance of wind. Ascending building heights in the direction of the summer prevailing winds would ensure the acceptance of wind to building behind.

Secondary streets could be arranged in the direction of the annual prevailing winds for receiving wind for dispersal. The angle could be varied by 30° for minor wind deflection. A variety of building heights would aim for more down wash to enhance the street environment.

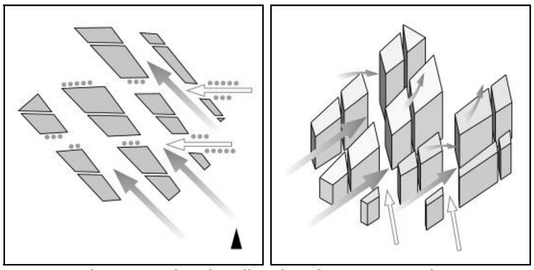

Fig 8. Design implication for 'type 2' sites

Type 3

Prevailing winds in summer time come from the south and annually from the northeast. The two wind directions are roughly 45° to each other [Fig. 9 & 10].

Most of the new towns including Tuen Mun, Yuen Long, Tung Chung and Tseung Kwan O fall into this category.

The building blocks and street arrangements are similar to that of type 2 except for a different angle of penetration.

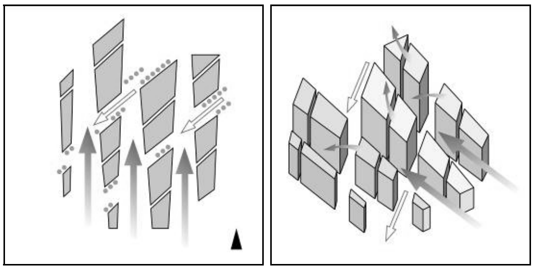

Fig 9. Design implication for 'type 3' sites

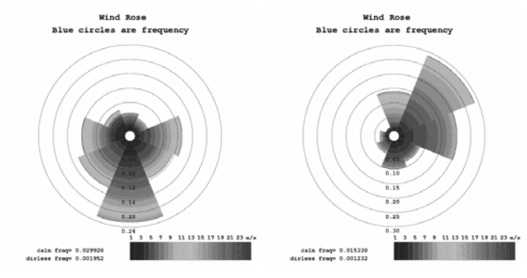

Fig 10. Wind rose of summer, 01 June to 31 Aug 2004 (left), and annual, 01 Jan to 31 Dec 2004 (right) of Tseung Kwan O area (Type 3)

Type 4

Prevailing winds in summer time come from the south and annually from the east. The two wind directions are roughly perpendicular to each other [Fig.11].

Areas along the northern part of Hong Kong Island alongside Victoria Harbour including Central, Wan Chai and Causeway Bay are classified as this type.

Due to the complex wind environment, point type buildings favour the perpendicular wind penetration at different times of the year. Density of buildings may change according to the directions of summer and annual prevailing winds. A larger distance between rows of buildings in the direction of the summer prevailing winds will ensure better penetration of summer breezes.

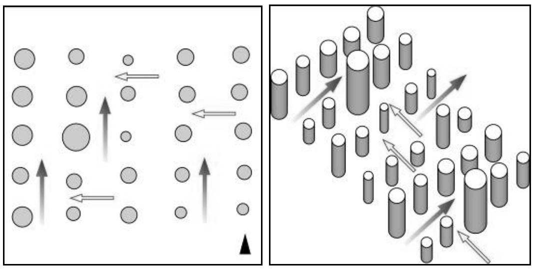

Fig 11. Design implication for 'type 4' sites

Type 5

Prevailing winds in summer time and annually in areas of this type come from opposite directions [Fig.12].

Summer southwesterly and annual northeasterly prevailing winds affect areas of this type.

West Kowloon and Shatin can be classified in this type. The annual prevailing wind comes from the northeast and summer's prevailing winds come from the southwest in both areas.

The arrangement of buildings and streets is similar to that of type 1 but is further differentiated for the acceptance of wind in the different seasons.

The overall arrangement of buildings is in rows. The widening of streets or the introduction of open spaces at the entrance for summer breezes would enhance the acceptance of the breezes and the street conditions. Together with ascending building heights, a better wind distribution in summer time could also be achieved. The ascending building heights would also lower the strength of the wind in winter which comes from the opposite direction. Winds in winter are generally stronger and are sometimes unfavorable for human comfort. Planting trees at the end of the street where the street receives the winter wind would further improve street conditions. The proposed layout for the above five types are qualitative and subject to further detailed studies and tests.

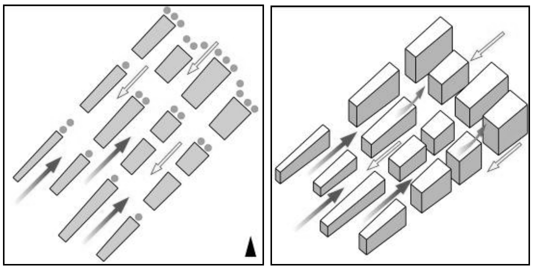

Fig 12. Design implication for 'type 5' sites

Topography and land-sea breezes are the two major causes which have significant effects on wind direction and wind speed. Topography can refer to the channeling effect which dominates the wind direction while land-sea breezes have a greater effect on wind speed during the summer time.

Shatin and West Kowloon are two districts with the same prevailing wind direction in both summer and annually (Type 5). Shatin is sandwiched between two ridges along the wind path while West Kowloon is located on the shore of Kowloon Peninsula facing the western entrance of Victoria Harbour. These two areas were selected to demonstrate the effects of topography and land-sea breezes by analyzing their wind rose diagram in summer time.

During the summer time, the prevailing wind comes from the South China Sea entering Victoria Harbour from the south. The wind direction is deflected into Victoria Harbour from the east and west entrances. The land-sea breezes then reach West Kowloon and continue to the Shatin area by passing over a ridge.

Comparing the two wind rose diagrams [Fig.13], it can be seen they both have a southwesterly prevailing wind. However, Shatin shows a higher intensity of southwesterly winds (more than 30%) compared with the West Kowloon diagram, which has a more even wind direction distribution ranging from east to southwesterly (15-20%). The differences result from the enhanced channeling effect of the Shatin topography.

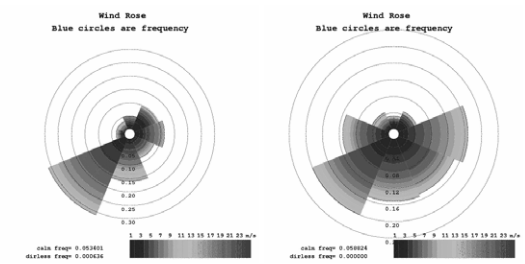

Fig 13. Wind Rose Diagram of Shatin, Summer, 01 June to 31 August 2004 (left); Wind Rose Diagram of West Kowloon, Summer 01 June to 31 August 2004 (right)

These observations revealed the various wind environments in different areas of Hong Kong which cover both developed and some newly developing areas. The classification could become a useful tool to prompt new ideas and enable new thinking on urban planning especially for a densely populated city. Urban design, especially the orientation of building volume and building height, of different areas may be varied according to the different wind environment type for better human comfort and living.

The above 5 types do not suggest a uniform urban pattern in the city, but can provide suggestions for the planners and designers. They can also be adopted together with other features, such as open green spaces, or a wide wind channel. As there are other aspects to consider when planning the city, the above 5 types may serve as initial ideas when designing for wind. Elevated open space, roof garden, and other devices that enhance natural ventilation can be adopted on a case by case basis, in order to cater for the uniqueness of the extended design.

4.3 Wind Availability and Achievable Wind

From the results of the Prevailing Wind Direction and Intensity (Annual/Summer), the dominant wind speed in Hong Kong is about 5-6 m/s at 60m above ground. Due to the terrain follow nature of wind and the urban roughness of the urban environment, the wind speed of achievable wind at the pedestrian level is less than the wind speed at 60m above ground [Fig.14].

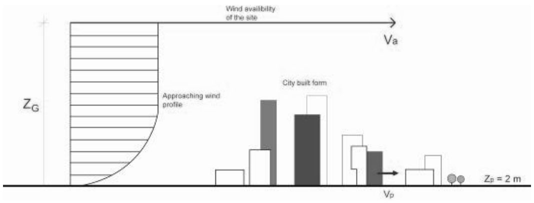

Fig 14. Effects of urban environment on the wind profile.

As the areas in this study in Hong Kong have a high degree of urbanization, the urban roughness plays a more important role than the 'terrain follow' nature of wind. The urban environment creates friction for the air flow, which reduces the wind speed and changes the profile of the wind in a logarithmic way. Such a phenomenon, which is generally limited to the lowest 100m of the atmosphere (the surface layer), can be numerically expressed in equation (1) and urban roughness is one of the factors for estimating the wind speed at the desired height from the ground. The equation to estimate the wind speed (u) at height z (metres) above the ground is:

$$u_z = \frac{u_*}{\kappa}\left[\ln\left(\frac{z-d}{z_0}\right) + \varphi(z, z_0, L)\right] \qquad \text{......................(1)}$$

where u * is the friction (or shear) velocity (m/s), κ is von Karman's constant (~0.41), d is the zero plane displacement, z0 is the urban roughness (in metres), and □ is a stability term where L is the Monin-Obukhov stability parameter. Under neutral stability conditions, z / L = 0 and drops out. The value of the displacement 'd' is approximated to 1.2 times the urban canopy layer height. [13]

According to some preliminary studies of effects of urban roughness on the wind speed, it is estimated that VRw (Wind Velocity Ratio) in Hong Kong is 30% for open space, 15% for areas of low buildings, and 10% for the city centre.

Taking into consideration urban roughness, the achievable wind at the pedestrian level is about 1.5m/s in summer and 1.8m/s in winter for open space, 0.75 and 0.9m/s for low buildings, and 0.5 and 0.6m/s for the city centre respectively, which barely satisfies the wind speed required for human comfort. Therefore in order to optimize natural ventilation for human comfort, wind direction plays an important role in urban planning when designing for wind.

5. Conclusion

The Town Planning Board has recently approved a low-density proposal to redevelop the former North Point Estate and has requested the Planning Department for the first time in Hong Kong to conduct an Air Ventilation Assessment of the site. Under this development plan, a separate residential and commercial area will be built, with a height restriction of 80 meters. The plot ratios for the two sites are to be reduced from 10 to 4.12 and 3.05.[14]

This suggests there might be a new consideration for the wind environment in town planning in the future. Prevailing wind directions will therefore affect decision-making about design in different types of areas. For this reason different approaches and strategies should be applied according to the wind environment. This paper has examined types of area for pilot design guidelines for use by planners. The types can be tested parametrically to establish quantitative contribution to the wind environment in the city. The use of numerical simulation provides an instant tool for planners to obtain the basic information needed to design for wind in order to enhance the living environment.

6. Acknowledgements

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