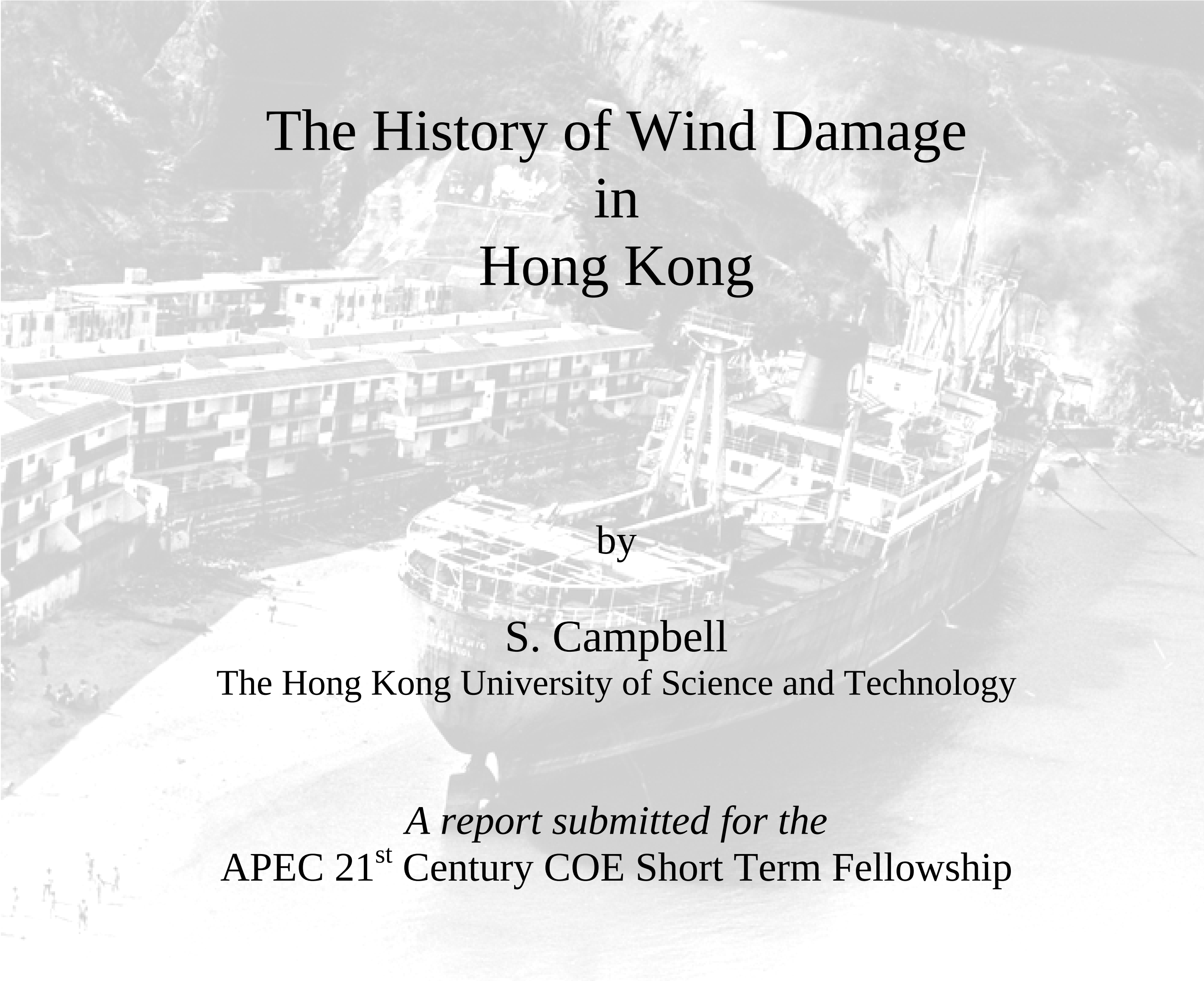

The History of Wind Damage in Hong Kong

by

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A report submitted for the
APEC 21st Century COE Short Term Fellowship

April 2005

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Abstract

This report, entitled “The History of Wind Damage in Hong Kong”, provides a summary of wind and wind-induced damage in Hong Kong. This report is accompanied by another document, called “Typhoons affecting Hong Kong: Case Studies”. For a concise summary of the overall effects of typhoons in Hong Kong, the reader is advised to examine this report. The reader wanting more detail into specific events during typhoons is also recommended to read “Typhoons affecting Hong Kong: Case Studies”.

In this report, a review of the risk of people and buildings to typhoon hazards is discussed. Then, the wind climate of Hong Kong is presented and analyzed with respect to its potential hazards. Next, the design of buildings in Hong Kong is discussed with regards to buildings Codes. It is noteworthy that the “Code of Practice on Wind Effects in Hong Kong 2004” was just released, making 2005 a transition year between the new Code and the “Code of Practice on Wind Effects Hong Kong – 1983”. Finally, a summary of wind-induced damage and its effects on Hong Kong as a whole is presented.

It was observed that the amount of wind-induced damage has generally decreased since the earliest records in Hong Kong. It is reasoned that the most important factor leading to this decrease is better communication. Additional factors responsible for reduced damage are also discussed.

In addition to this report and “Typhoons affecting Hong Kong: Case Studies”, the following is also provided in electronic format for future use *solely* by the staff and students at Tokyo Polytechnic University:

a) A tabulated summary of quantitative typhoon measures and damage categories in the file “COE_WindDamage_HK.xls”. This table contains all relevant typhoon-induced damage data collected between the years 1957 to 2004, inclusive.

b) Wind data of hourly mean, hourly direction and gust wind speeds recorded at Waglan Island collected from the Hong Kong Observatory. These data represent the overall winds affecting Hong Kong during a typhoon. It is important to note that correction factors should be applied to adjust these anemometer measurements at different locations on Waglan Island before a proper comparison can be made. These correction factors and how they should be applied are provided in a technical report from the CLP Power Wind/Wave Tunnel Facility at The Hong Kong University of Science and Technology. This report is entitled “A Study of Anemometer Measurements at Waglan Island, Hong Kong” and is supplied in electronic format, labeled as “tr_wwtf002_2003.pdf”

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The History of Wind Damage in Hong Kong

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1.0 Introduction to Hong Kong

Hong Kong is one of the largest, most-developed cities on the southeast coast of China. From 1842 to 1997 Hong Kong was occupied by the British, who drastically influenced its role in the world. Hong Kong became one of the largest trading, business and financial capitals in the world. In 1997 Hong Kong was peacefully handed back to the Chinese and became known as the Hong Kong Special Administrative Region (HKSAR) of the Peoples' Republic of China (PRC).

In its regional setting, Hong Kong represents a small geographical area as seen in Figure 1. It is a densely populated area accommodating 6,803,000 residents in its 1,103 square kilometres (1). To compensate for the shortage of space, reclamation became a common practice to create more usable land. A significant portion of land is difficult to build upon causing high population densities. Containing a large population in a small space is only possible through the construction of tall buildings both for commercial and residential purposes. As a consequence, Hong Kong has 49 of the tallest 100 residential buildings in the world, most of which were built within the last five years (2).

Figure 1: Hong Kong in its Regional Setting (after Survey and Mapping Office)

Being located on the South China Sea, monsoons and typhoons dominate the wind climate of Hong Kong. Winds generated by typhoons are much stronger than monsoons and are a main design consideration for tall buildings. Many typhoons are observed in the South China Sea every year, only a few of which come close to Hong Kong. In the past, much damage has occurred because of the strong winds and severe rains associated with typhoons. Presently, advances in engineering and construction allow for better management of typhoon hazards. In the future, it is hoped that the target of no loss of life and no damage caused by a typhoon will be met.

In the following, detailed information will be given on the topography of Hong Kong, a brief history of reclamation, demography and the housing situation of the majority of residents. As will be explained, these factors, both independently and in conjunction, are relevant to the vulnerability of Hong Kong to wind hazards.

1.1 Topography

Simply stated, the topography of Hong Kong is complex. A topographical map of Hong Kong can be seen in Appendix A of this report. The HKSAR consists of Hong Kong Island (HKI), Kowloon, and the New Territories (NT), but is commonly referred to in its entirety as Hong Kong, as will be done throughout this report. HKI is complex with respect to its topography starting at sea level with many bays and extends to a maximum height of 552m at Victoria Peak. Other peaks on HKI are: Mount Davis (269m), The Twins (386m) and Mount Parker (532m). It is also noteworthy that there are several elevated reservoirs at Pok Fu Lam, Aberdeen and Tai Tam. HKI is separated from Kowloon to the north by Victoria Harbour, which is about 1 km across.

Kowloon has the largest population density with most of its usable land sandwiched between Victoria Harbour and a ridge of mountains to the north. This ridge runs west to east and consists of Tai Mo Shan (957m), Needle Hill (532m), Grassy Hill (647m), Beacon Hill (457m), Tate's Cairn (577m), Lion Rock (495m), Buffalo Hill (606m), and Ma On Shan (702m). Notable features in Kowloon are the shipping container port terminal on the west and large reclaimed areas including an obsolete airport runway.

The NT encompasses the remainder of the HKSAR and includes part of the mainland and a large number of outlying islands. The mainland part of NT is north of Kowloon and is separated by the west to east ridge of mountains. NT is demarcated on the north by the border with the PRC. The outlying islands are generally small in size and are sparsely populated, except for Lantau Island, which is the largest island in the HKSAR. NT contains many mountains, most notably Lantau Peak (934m) and Sunset Peak (869m) both on Lantau Island. The Chek Lap Kok International Airport lies on the north side of Lantau Island and was created almost entirely of reclaimed land. NT also contains other features such as Tolo Harbour on the east, Ma Po marshes on the northwest, and several large reservoirs.

Based on the description of topography alone, a more-detailed study of wind profiles over complex terrain is warranted. Fok, *et al*. studied wind over Hong Kong topography and concluded that mean wind speed-up multipliers supplied by many wind Codes may underestimate actual winds in Hong Kong, especially for heights below 200m (3).

1.1.1 Land Reclamation in Hong Kong

Since the British first occupied Hong Kong in 1842, a lack of land suitable for development was recognized. The most feasible approach to create more usable land was to reclaim land by moving destroyed hills to the sea. Reclamation started with the lower portion of the Kowloon peninsula and the northern shore of HKI. The first significant area reclaimed for residential and industrial purposes was Kowloon City and San Po Kong, which was completed during the 1920s. After WWII mixed residential and industrial land was created on the west side of Kowloon and in Kowloon Bay. The pace at which reclamation occurred was steady until about the 1970s when the population exploded. Since the late 1970s major efforts to create land for residential construction occurred in Tseung Kwan O, Kowloon Bay, West Kowloon, Ma On Shan, Sha Tin, Tai Po, and Tuen Mun (4). Quantities of reclaimed land from 1887 to 2004 can be seen in Table 1 (5). The total amount of reclaimed land is 67.20 km² while the entire Hong Kong Island is only 78.33 km². A significant portion of this reclaimed land is residential, upon which sizeable high-rise buildings have been constructed. The trend of land reclamation continues and it can only be anticipated that more land for civil infrastructure will be provided in this manner. For further examination a picture of reclamation in Hong Kong is given in Appendix B of this report.

Table 1: Total reclaimed land area in Hong Kong (since 1887)

Regions	Area (km²)
Hong Kong Island and its adjacent islands	6.98
Kowloon	13.64
New Territories – Mainland	28.41
New Territories – Islands	18.17
TOTAL	**67.20**

Land reclamation offers a unique opportunity for engineering buildings. The situation in Hong Kong has older, shorter buildings that were once on the shore, shielded by newer, taller buildings that have just been constructed on newly reclaimed waterfront. In some directions the newer buildings are completely exposed to the approaching wind. This cycle of reclaiming land creates new opportunities and challenges for wind engineering buildings.

1.2 Demography and Housing

Hong Kong has a high population density, accommodating 6,803,000 residents in its 1,103 square kilometres (1). A significant portion of this land is difficult to build upon, however, leading to extreme statistics, such as 50,820 people per square kilometre throughout the Kwun Tong district (6). Maintaining such high population densities is only possible through the construction of tall buildings both for commercial and residential purposes. HKI is the most-inhabited island of the HKSAR with approximately 3 million residents on 7 km². Most of the buildings on HKI are within about 0.5 km of the waterfront.

A large portion of the population in the British territory of Hong Kong in the 1940s lived as squatters on the hilly terrain. However, the presence of civil war in the PRC throughout 1949 caused a large influx of refugees into Hong Kong increasing the squatter population dramatically. Squatter villages had little in terms of water for drinking and cleaning and had difficulty in eliminating sewage. More importantly, shelters were structurally unsafe considering their exposure to strong typhoon winds and impending landslides. Finally in 1953, a fire in Shek Kip Mei left 50,000 people without homes in a single night. In response to this fire, the local government created a resettlement program to house the Shek Kip Mei squatters in two-storey bungalows. One year later, a semi-independent organization called the Hong Kong Housing Authority (HKHA) was given the task to create self-contained flats to resettle the existing squatter population to safer, more hygienic residences. The first of these buildings were completed in 1958 and were six storeys in height. These first series of buildings constructed by the HKHA were taller than other buildings at the time and reflected the beginning of high-rise construction in Hong Kong. By 1965 the HKHA were responsible for housing over one million people and had begun constructing 16 storey buildings. With a burgeoning population concentrated in the Kowloon peninsula, development of "new towns" gained momentum. New towns were designed to ease congestion in Kowloon by creating clusters of high-rise, high-density residential blocks in previously undeveloped areas. Heights of residential blocks rose steadily over the years. In 1992 designs of the Harmony block reached 40 storeys in height (7). The layout of the Harmony block is shown in Figure 2, and has many typical features of buildings in Hong Kong. The convoluted shapes of residential buildings are the result of regulations imposed for reasons of lighting and ventilation. This regulation (8) requires that every room used for habitation must have a window that faces directly into the external air. Additional information regarding the minimum requirements of windows can be found in the Regulations 31 through 34 of the legislation (9).

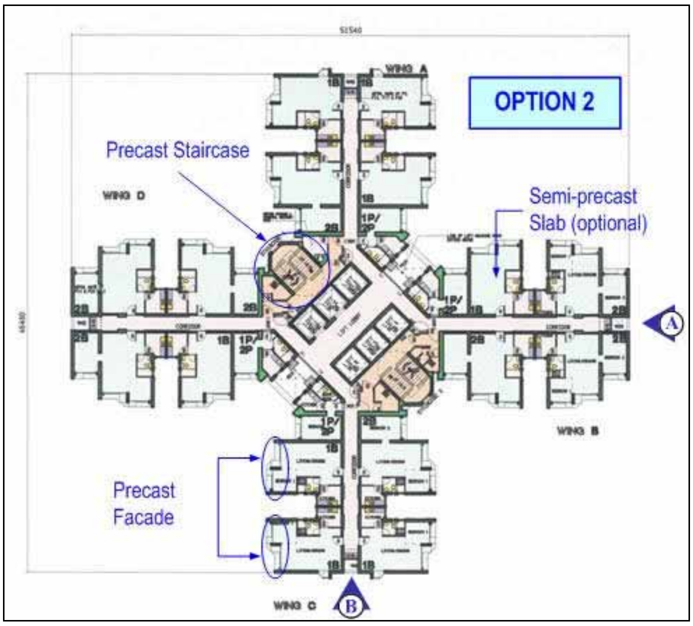


Figure 2: Harmony Block of the Hong Kong Housing Authority (after HKHA)

Today, the HKHA continues to reflect the general trend of high-rise residential construction in Hong Kong. During the 2004-2005 year approximately 22,000 flats will be made available with only a slight decrease in projected production in the next four years (10). Future developments from the HKHA indicate that taller residential buildings will be constructed. It has been observed that newer residential complexes built by private developers are generally taller than those built by HKHA. It can be conclude that tall high-rise residential buildings will continue in Hong Kong.

According to the Government of the Hong Kong SAR, there has been a constant increase in population of about 1% since 1999, discounting 2003 because of the Severe Acute Respiratory Syndrome (SARS) epidemic. This fact suggests that there will be continued demand for high-rise housing and sustained susceptibility to the extreme wind climate of Hong Kong.

1.2.1 Typical Buildings

The shipping, business and financial success of Hong Kong is supported by highly developed infrastructure. The majority of buildings are residential and commercial, with the remaining industrial being few in number. As mentioned above, Hong Kong has almost 50% of the tallest residential buildings in the world, but it also has a large number of tall commercial buildings. Industry was once more important but cheap labour costs have driven many factories out of Hong Kong and into the PRC. Consequently, few industrial buildings are constructed each year.

Regulations pertaining to the construction of buildings in Hong Kong are outlined in the Practice Note for Authorized Persons and Registered Structural Engineers 140 (PNAP 140). This document references Standards that are acceptable to the Building Authority of HKSAR and are grouped in areas of Structures, Building Materials, and Material Tests (11). Referenced Standards include a combination of locally developed codes and British Standards; however, upon consultation and acceptance with the Buildings Department, alternative Standards may be used.

Concrete is the most widely used building material in Hong Kong, especially for residential buildings. The majority of standards concerning the quality and control of materials used in concrete are directly referenced to British Standards. These standards include information regarding acceptable component materials, batching procedures and testing of the concrete to provide confidence in its performance. Locally, there are many additional Practice Notes pertaining to concrete usage. Found below is a list of these additional Practice Notes for Authorized Persons and Registered Structural Engineers that correspond to the use of concrete in Hong Kong:

- PNAP 90 - discusses the inclusion of pulverized fuel ash in concrete and supports this practice so long as its effects are realized;
- PNAP 122 - requires mandatory testing of reinforcement steel for concrete that is delivered on-site;
- PNAP 162 - a recommendation to use concrete from a list of suppliers who have satisfied local quality assurance criteria;
- PNAP 180 - advice to avoid alkali-aggregate reaction in reinforced concrete structures by specifying from the concrete supplier maximum levels of sodium oxide;
- PNAP 221 - provides guidance to prevent the displacement of steel reinforcement during concrete pouring;
- PNAP 224 - suggests safety and public nuisance provisions for maintaining a concrete batching plant on-site;
- PNAP 275 - includes specifications for using recycled aggregates in concrete to improve the environmental impact of construction and demolition materials; and
- PNAP 286 - encourages the adoption of using precast concrete construction methods through the Code of Practice for Precast Concrete Construction 2003.

1.2.1.1 Residential Buildings

Almost all Hong Kong residents live in high-rise dwellings. The majority of high-rise residential dwellings are located throughout the entire Kowloon district and in several large clusters on HKI and in the NT. There are also many shorter buildings throughout the NT that are between 2 to 3 storeys. The HKHA offers residence to almost one third of the population and maintains 381 estates, each comprised of a number of blocks, i.e. individual buildings (12). A good example of a HKHA estate can be seen in Figure 3, where the close proximity and identical design of the buildings appear as a massive wall. The remaining two thirds of the population reside in buildings of similar height and shape and are privately owned.

Residential buildings are commonly designed with reinforced concrete shear walls. Concrete is a relatively cheap material that is suitable for the convoluted planform shape of Hong Kong residential buildings. New residential buildings often have large transfer plate structures that provide large lower-level spaces for atria, parking lots and other amenities.

The roof configuration most commonly found on high-rise residential buildings is flat and resists water penetration through the use of a waterproof membrane. However, residents often use roof areas to supplement their living space and may damage the waterproof membrane in the process. As a precautionary safety measure, parapets are common design features. As most of the residential buildings are high-rise, elevator machinery is found at roof level, enclosed in the elevator shaft. The combination of parapets and the protruding elevator shaft make for complicated flow around and over the top of the building.

Figure 3: HKHA Estate in Tsuen Wan

It is becoming common to have large windows in every room within each apartment. While registered structural engineers and the Buildings Department have approved such design configurations, some concern has been generated due to larger windows resisting large typhoon wind loads. In reaction to this trend, the Buildings Department has issued PNAP 239 (14), which gives additional requirements to ensure habitants safety. Specifically, concern is given to the quality control of the glass manufacture, structural design requirements and international standards that govern the structural glazing of building works.

Another common trend for high-rise residential buildings is the inclusion of a balcony. Balcony area is included in the gross floor area count of the entire apartment. Because apartment floor area is so expensive balcony size is small. The presence of balconies convolutes the outside of the buildings further, disrupting organized flow around the building and potentially alleviates some development of vortex shedding. However, new wind-related risks are introduced when loose objects, such as potted plants, are left on the balcony in a typhoon. These objects may become wind-borne debris that causes damage to other buildings that produces more hazardous debris in a chain-reaction sequence. This problem of wind-borne debris is discussed more thoroughly in the proceeding section.

1.2.1.1.1 Unauthorized Building Works

Apartment sizes in Hong Kong are quite small and it is a common practice for residents to construct Unauthorized Building Works (UBWs) such as roof top awnings and supports for hanging laundry or holding plants outside windows. As its name suggests, residents will not seek authorization for these buildings works and will therefore, not assume any responsibility for its maintenance and safety. Over time the deterioration of these UBWs causes many negative consequences including:

- Creating hazards due to falling objects;
- Increasing vulnerability of structural steel reinforcing to corrosion; and

- Detracting from the overall aesthetics of the building.

A picture of typical deterioration of a building is given in Figure 4, where UBWs are attached to the exterior wall to accommodate room for laundry, plants, storage for other miscellany and possibly to act as a balcony.

Figure 4: Building deterioration caused by Unauthorized Building Works
(after Buildings Department, HKSAR)

Government and building officials have acknowledged the problem of UBWs as promoting decay of the residential building stock in Hong Kong. On 1 May 2001, the Urban Renewal Authority was formed to combat urban decay and create quality and vibrant urban living in Hong Kong. Their priorities with respect to building infrastructure are:

- To accelerate redevelopment by replacing old buildings with new to provide a better living environment and neighbourhood;
- To enable and encourage the rehabilitation of dilapidated buildings to prevent urban decay;
- To preserve by maintaining and restoring buildings of historical and architectural value, and to sustain local characteristics;

This approach of the government marks a concerted effort that spawned because of the current level of urban decay. While UBWs are not the only indicator of urban decay, they deserve particular attention because of their potential to be subjected to, and to induce large amounts of damage in typhoon wind conditions. The proliferation of UBWs throughout Hong Kong is catalogued by the Buildings Department, highlights of which are found below (15):

- There have been anywhere between 9,469 to 54,010 statutory orders for the removal of UBWs between 1999 – 2003;
- Compliance with statutory orders is between 3,684 to 29,370 removal orders of UBWs between 1999 – 2003;
- There were between 4,050 to 43,108 advisory letters regarding unauthorized building works between 1999 – 2003;
- Compliance with these advisory letters constitutes between 487 to 3,913 removals of UBWs between 1999 – 2003; and
- There is an increasing rate of prosecution summonses and convictions for the non-compliance of removal of UBWs, averaging ~400 summonses with a conviction rate of 75% from 1999 – 2003.

The absence of thorough design makes UBWs a potential hazard, especially during typhoon wind conditions. Research conducted on wind-borne debris intended for the

Southeast Asian region indicates that cumulative damage is the major cause for concern to buildings (16). Three features of the Southeast Asian region give particular concern (16):

1. A large fraction of the newest buildings are of all-glass curtainwall construction;
2. Many of these buildings are built in areas where considerable amounts of loose or poorly restrained building or other materials abound that could easily become wind-borne missiles under high wind conditions; and
3. The relatively infrequent nature of typhoon strikes in particular locations leads to a false sense of security amongst both administrators as well as the population at large.

The major missiles identified are cubes, sheets and bamboo poles. These items are easily found in UBWs as well as being prevalent throughout construction sites. UBWs are a major potential risk to the safety of people and health of infrastructure and should be regarded as a persistent threat until their complete elimination.

1.2.1.2 Commercial Buildings

The population of commercial buildings in Hong Kong includes a combination of older low-rise buildings and some of the most recognizable skyscrapers in the world. Commercial and retail space occupies many different locations in Hong Kong. Buildings with mixed commercial and residential spaces are common with ground and lower floors conveniently providing passers-by with amenities and services while upper floors, more distant from the noisy streets, offer housing. This mixed-use configuration is found not just in older buildings but in newer designs as well. Buildings used entirely for commercial purposes often have retail stores at lower floors and office space above. The remaining commercial buildings are almost entirely used as office space.

Commercial buildings do not require many separated spaces like that found in residential buildings and will often have no internal partitions. This allows tenants to have flexibility when designing their office. However, if a breach in the building envelope were to occur, the contents of the entire floor may be damaged. Furthermore, a current trend is to design the buildings with large glass curtain walls to give a more modern feel and maximize the use of natural light. The most practicable means to provide a large open space is through steel, moment-resisting frame structures with columns positioned close to the building envelope. Most often these buildings will have a concrete lift core. Roofs of these buildings are generally flat except for elevator machinery housing. Sometimes support services, such as air conditioning and water tanks, are located on the roof.

The tallest commercial buildings in Hong Kong are office buildings that are steel or steel-concrete hybrid structures. They usually have large atria found at lower levels, enabled through the use of megacolumns. It is becoming common to use advanced structural systems such as outriggers at several heights to mobilize axial stiffness, creating an effectively stiffer structure while maintaining large internal spaces. These buildings often have large concrete cores with a multitude of elevator shafts; with transit lobbies found at intermittent heights and associated machinery found at roof level. The roofs of these skyscrapers usually have elaborate architectural features complicating the wind flow around the upper part of the building.

1.2.1.3 Industrial Buildings

The high-cost of land in Hong Kong has caused the development of multi-storey industrial buildings to wane. Typical industrial buildings are flatted factories and storage structures that contain both small office quarters for business management as well as the actual space for industrial processes.

About 40% of the population of industrial properties was constructed before 1980, and about 80% that were constructed before 1990 (13). The average life span of buildings is smaller in Hong Kong than other parts of the world and the demolition rate of these aging buildings is expected to increase.

Flatted factories are often large concrete structures with function being more important than form. These factories have high inter-storey heights, spacious doorways, massive columns and large, powerful elevators to move products and machinery. There are generally adequate amounts of heating/ventilation/air-conditioning (HVAC) and exhaust in these buildings but have few windows.

Industrial buildings in the form of storage facilities offer expansive spaces to house a variety of goods, with some providing a controlled climate. Windows are rare for such buildings as most of the time the space is not occupied by people. Some storage facilities may be concrete but there are a number that are also steel frame structures. It is common to have an automated storage-and-retrieval system whereby a grid of spaces is accessed by a computer-controlled lift mechanism. Such mechanisms are ideally suited for tall open spaces, these being provided principally by steel frame construction. The walls for typical storage buildings contain the minimum required material to create an effective building envelope. Brick veneer and aluminum siding are common materials used for the building envelope. HVAC and refrigeration machinery are usually located on the roofs, which are flat, and may sometimes offer further protection to these vital systems through the use of hoardings.

2.0 Wind climate of Hong Kong

2.1 Wind measurement in Hong Kong

The complex topography of Hong Kong has caused much uncertainty in wind measurements. Chen (1975) performed one of the earliest, most comprehensive studies of wind measurements in Hong Kong (17). Relationships between anemometers (dines and propeller) at different locations throughout the region were analyzed. It was recognized that Waglan Island with its ideal exposure best represented the overall wind conditions affecting Hong Kong. Waglan Island was therefore used as a reference for other wind readings from other sites for purposes of obtaining relational factors between wind measurement sites. It was noted that wind speeds at certain stations depend very much on wind direction because of the complex and dynamic terrain surrounding the anemometers. Chen (1975) concluded "(that) because of rugged and hilly land, surface winds in Hong Kong would not be expected to be uniform. … It is therefore not possible to derive a definite and exact one-to-one relationship between winds experienced at different stations. On one occasion, winds experienced at one station may be higher than at the other, but on another (occasion), they may be lower.". Wind measurements by other researchers have also come to this same conclusion.

The overall assessment of winds on a day-to-day basis is the responsibility of the Hong Kong Observatory, which is discussed below.

2.1.1 The Hong Kong Observatory

The Hong Kong Observatory (HKO), formerly the Royal Observatory, Hong Kong, is responsible for collecting meteorological information in Hong Kong. The HKO is part of the Government of the HKSAR, and as such it is responsible to the public. One of the main channels used by the HKO to disseminate meteorological information is through the website, www.hko.gov.hk. Information collected by the HKO is generally available to the public for free or at a minimal cost.

Figure 5 illustrates positions of anemometers and tide-gauges around the Hong Kong region. Generally, the oldest anemometer positions are located in areas that have become densely populated and are at heights close to, or shorter than, those of nearby buildings. Locations such as King's Park and Star Ferry (Kowloon) are examples of anemometer locations that are potentially influenced by their surroundings. Probably the best and most extensive wind records have been maintained at Waglan Island, which has been operational since December 1952.

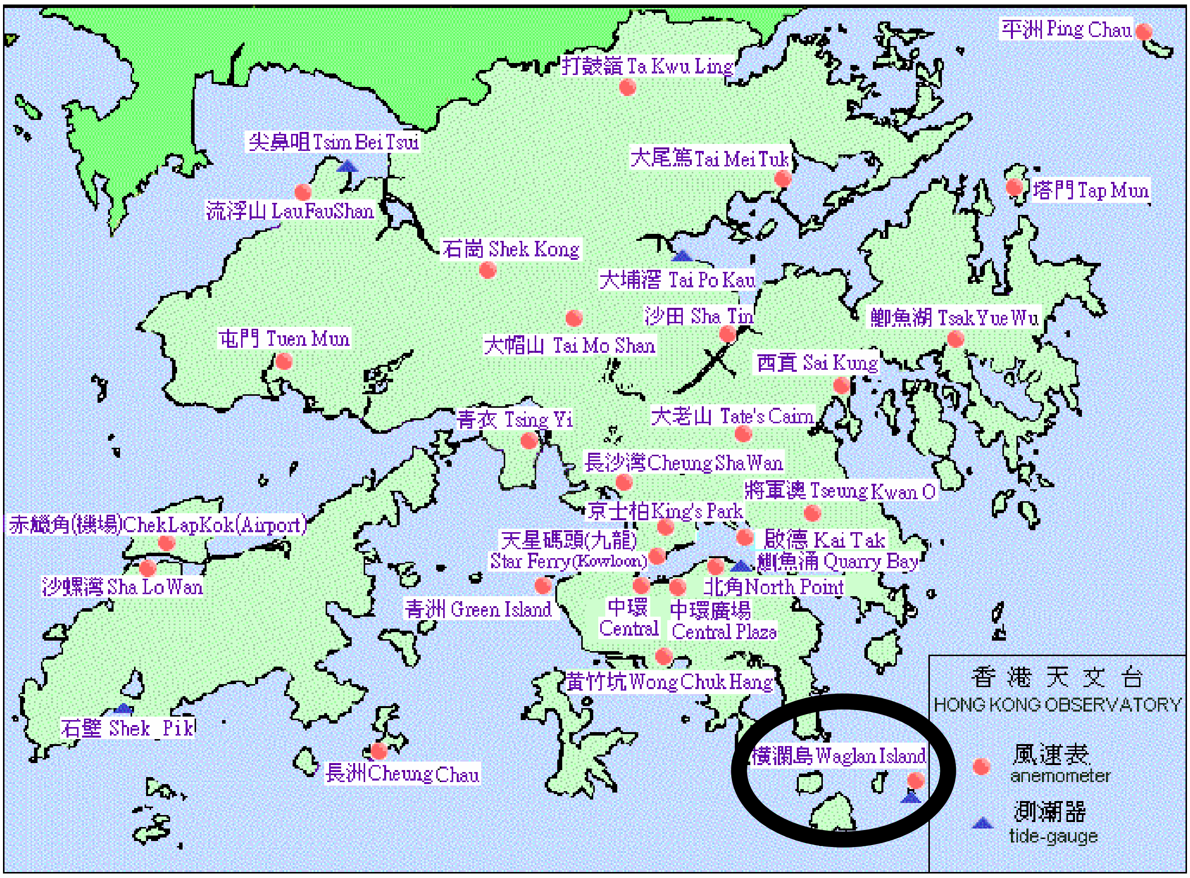


Figure 5: Anemometer and Tide-Gauge Monitoring Stations operated by the Hong Kong Observatory (after HKO)

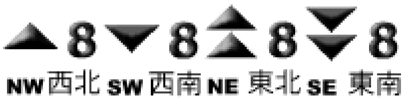
The classification of warning signals used by the HKO since 1973 can be found below in Table 2 (18). Previous classification systems used the same wind speeds to define the warning signals but were simply named differently. The warning signals reflect the overall wind conditions measured, or predicted, in Hong Kong. In other words, a tropical storm that comes close to Hong Kong may incur a higher warning signal than a typhoon that is more distant. The HKO tries to provide information about typhoon conditions in a timely manner without causing unnecessary panic. Signals are usually given incrementally as the conditions in Hong Kong get worse or ease up. Therefore, one will most likely never find a Signal 9 without Signals 1 and 3 before and after. However, there are many exceptions where Signal 1 is skipped leading up to, and coming down from, Signal 3.

For convenience in the following sections reference to Signal 8 implies Signals 8NW, 8SW, 8NE and 8SE.

Wind speed and wind direction data can be obtained through the HKO at a nominal price. Various measurement durations are available but for most wind engineering purposes a 10-minute duration suffices. The HKO provides measurements of mean wind speed, gust wind speed and wind direction for 1-minute, 10-minute and hourly durations. The definition of the 10-minute mean wind speed measured by the HKO is (19):

> “The 10-minute mean wind speed is the scalar mean of the ten latest 1-minute mean wind speed values… The 1-minute mean wind speed is the scalar mean… of the sixty wind speed readings taken within the minute.”

Table 2: Warning Signals in use by the Hong Kong Observatory (since 1973)

Warning Signals	Description
	This is a stand-by signal, indicating that a typhoon is centred within 800 km of Hong Kong and may later affect the territory.
	Strong winds are expected or blowing in Victoria Harbour, with a sustained speed of 41-62 km/h (kilometres per hour). Gusts may exceed 110 km/h. Winds are normally expected to become generally stronger in the harbour areas within 12 hours after the issuing of this signal.
	Gale or storm force winds are expected or blowing in Victoria Harbour, with a sustained wind speed of 63-117 km/h from the quarter indicated. Gusts may exceed 180 km/h.
	Gale or storm force winds are increasing or expected to increase significantly in strength.
	Typhoon force winds are expected or blowing. Sustained wind speeds are reaching upwards from 118 km/h. Gusts may exceed 220 km/h.

The definition of the 10-minute maximum gust wind speed measured by the HKO is:

> “The 10-minute maximum gust is taken to be the largest of the 1-minute maximum gusts in the past ten minutes… The 1-minute maximum gust is the largest of the sixty wind speed readings taken within the minute.”

The definition of the 10-minute wind direction measured by the HKO is:

> “The 10-minute mean wind direction is calculated from the ten latest 1-minute mean wind direction values… (there are) sixty wind direction readings taken within the minute…”

The definition of the hourly mean wind speed measured by the HKO is defined as (19):

> “The (hourly) mean wind speed is the scalar mean of the sixty latest 1-minute mean speed values… The 1-minute mean wind speed is the scalar mean… of the sixty wind speed readings taken within the minute.”

The definition of the hourly gust wind speed measured by the HKO is defined as:

> “The (hourly) maximum gust is taken to be the largest of the 1-minute maximum gusts in the past sixty minutes… The 1-minute maximum gust is the largest of the sixty wind speed readings taken within the minute.”

The definition of the hourly wind direction measured by the HKO is defined as:

“The (hourly) mean wind direction is calculated from the sixty latest 1-minute mean wind direction values… (there are) sixty wind direction readings taken within the minute…”

For more information regarding the calculation procedures used by the HKO, the reader is referred to Appendix 3 of the document “A Solar-Powered Automatic Weather Station”.

Waglan Island is considered to be representative of the overall winds affecting Hong Kong. However, several times since becoming operational in 1952, the anemometer has been relocated. Its present position since 26 April 1993 is at the top of a mast 82.1m above Mean Sea Level, or 26m above ground, which can be seen in Figure 6 (20). To determine the topographical effects on the wind measurements at these various positions, staff at the CLP Power Wind/Wave Tunnel Facility at The Hong Kong University of Science and Technology conducted a 1:400 wind tunnel study. Measurements were made at the 16 cardinal directions for the entire azimuth at the various anemometer positions and were then referenced to the freestream flow at a height of 200m. Adjustment factors have been determined for these 16 cardinal directions that should be applied to data that has been procured from the HKO to obtain a better estimate of the freestream wind at Waglan Island (20).

Figure 6: The HKO Anemometer stationed at Waglan Island
(courtesy of JD Holmes after HKO)

2.2 Winds affecting Hong Kong

Surveys of the wind climate affecting Hong Kong have been performed by Choi (1978, 1983), Davenport, *et al.* (1984), Melbourne (1984), Jeary (1995), Kwok & Hitchcock (2003) (21,22,23,24,25,26). These surveys all identify that Hong Kong is dominated by the occurrence of two types of wind events: monsoons and typhoons.

2.2.1. Monsoons

Summer monsoon winds from the Indian Ocean and South China Sea affect Hong Kong due to a persistent low-pressure centre over the heart of Mainland China. Intense solar heating leads to scorching temperatures over the Asian landmass. As a result, the overlying air heats up, expands and rises upwards. This leads to the formation of a semi-permanent low-pressure area near the heart of the continent. Warm and moist air from the Indian Ocean and the South China Sea flowing into this low-pressure area is experienced as the summer monsoon in Hong Kong and the surrounding region. The summer monsoon is experienced as southwesterlies in Hong Kong (27). The large-scale circulation generating the summer monsoon conditions in East Asia are pictured in Figure 7, with the low pressure centre located in the southeastern part of China.

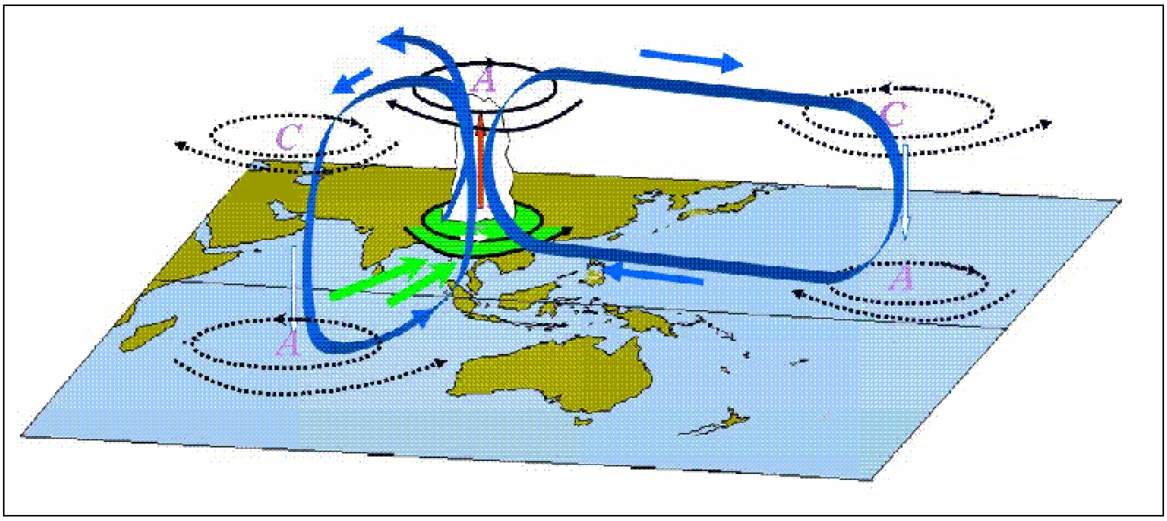


Figure 7: Summer monsoon activity drawing warm air from Indian Ocean and Western Pacific to the low-pressure centre (after HKO)

Winter monsoon winds arise from the presence of a large-scale anticyclone over Mainland China that allows cold wind to flow from the northeast (28). In winter, the continental land mass cools off rapidly, resulting in very low temperatures over central Asia. As cold air accumulates, pressure rises and a continental anticyclone develops over Siberia with the Tibetan Plateau forming an effective barrier blocking the southward spread of cold air. Depending on the time of the season and the juxtaposition of various weather systems, these surges will arrive in Hong Kong as northerlies, northeasterlies or easterlies (28). Figure 8 depicts the large-scale circulation that generates the winter monsoon, with the large low-pressure centre located towards Indonesia and Australia.

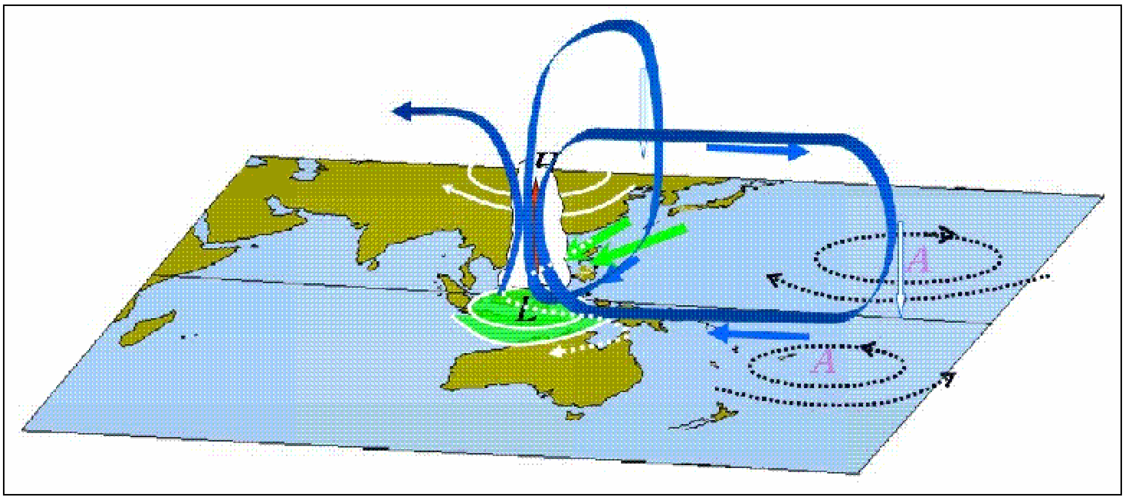


Figure 8: Winter monsoon activity drawing cold air from the Asian landmass and East China Sea to the low-pressure centre (after HKO)

Winds associated with the monsoons are generally more persistent than those brought by typhoons and may last for days. Generally winter monsoon winds affecting Hong Kong are stronger than summer. In intense surges of the winter monsoon, northeasterlies of up to gale force (Beaufort force 8, approximately 18m/s) are not uncommon over the south China coastal waters.

It may be necessary that the HKO issue a strong monsoon winds warning signal. The Strong Monsoon Signal warns people that winds associated with the summer or winter monsoon are currently blowing in excess of, or are expected to exceed 40 km/h (11 m/s) near sea level anywhere in Hong Kong. The warning signal given by HKO is seen in Figure 9.

Figure 9: The Hong Kong Strong Monsoon Wind Signal (after HKO)

2.2.2. Typhoons

Hong Kong is affected by about 6 typhoons per year on average, based on records maintained by the HKO. The typhoon season in Hong Kong runs from about May to December, with the majority occurring between June to September.

Typhoons that affect Hong Kong rotate counter-clockwise towards a low-pressure centre, this being typical in the northern hemisphere. Spiral rainbands are associated with typhoons, and extend from the core to diameters of up to several hundred kilometres (29). Meteorologists define a typhoon as composed of three components: storm-scale structure, inner-core structure and spiral rainbands (30). The storm-scale structure includes the entire cyclonic circulation, defined by having sustained tangential winds greater than 15 m/s and can be hundreds to thousands of kilometers across and as tall as the entire troposphere. The inner-core structure is a low-pressure region that includes the eye and eyewall clouds that are seen to span distances of 8 to 80 km (29).

Generally, typhoons will recurve as they translate; a process by which a rapid change in direction occurs, caused by a combination of trade winds and ocean currents. Typhoons that affect the southeast coast of China have tracks that vary over the course of the season. Different typhoon tracks can be seen in Figure 10. Typhoons can recurve at any time but those occurring in the early and late part of the season generally recurve at lower latitudes.

The strongest winds associated with a typhoon are found just outside the eye where there is the highest rate of rotation. Depending on the counter-clockwise rotation of the typhoon and the position of an observer, an additional velocity vector is added or subtracted because of the translational velocity of the storm. Therefore, if the eye of a typhoon passes on the west of Hong Kong, winds will likely be stronger than if the eye had passed on the east, due to the vector addition of wind velocity and translational velocity. Despite recognizing the importance of typhoons with respect to design wind speeds, knowledge about their mean wind speed profiles, turbulence intensity profiles and gust factors is relatively poor.

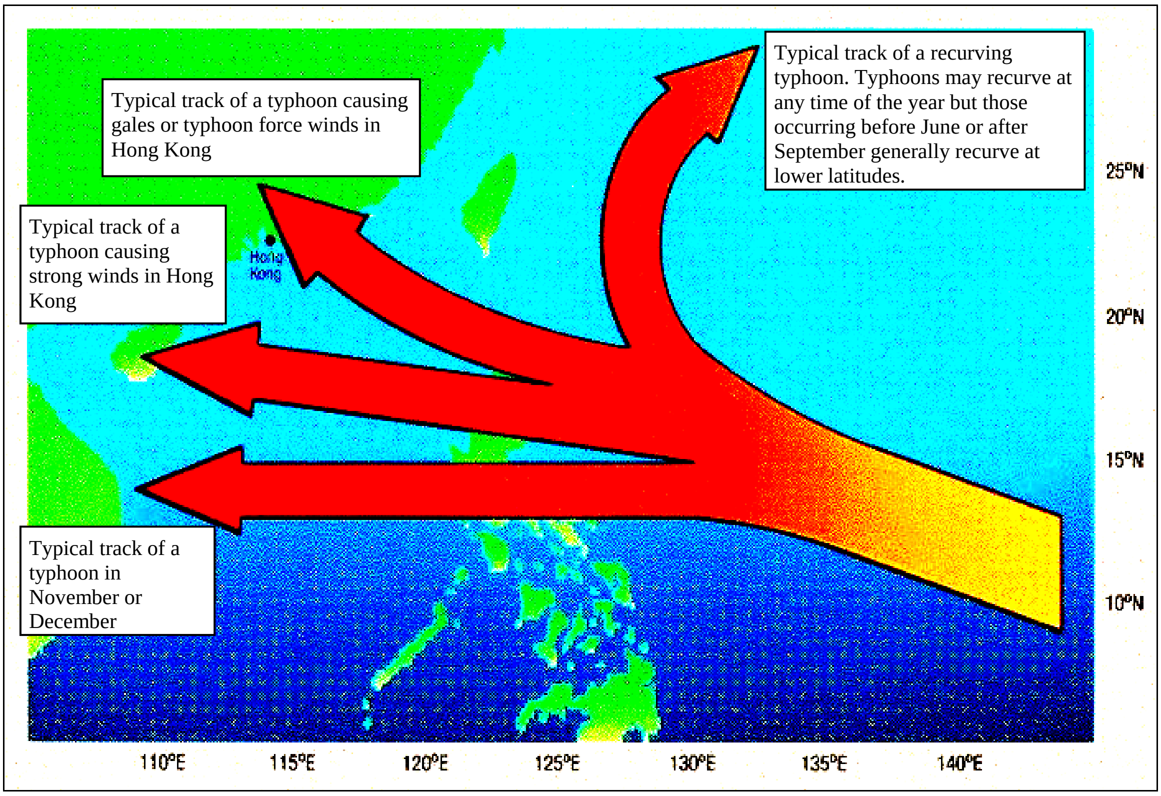


Figure 10: Typical Typhoon Tracks towards Hong Kong (after HKO)

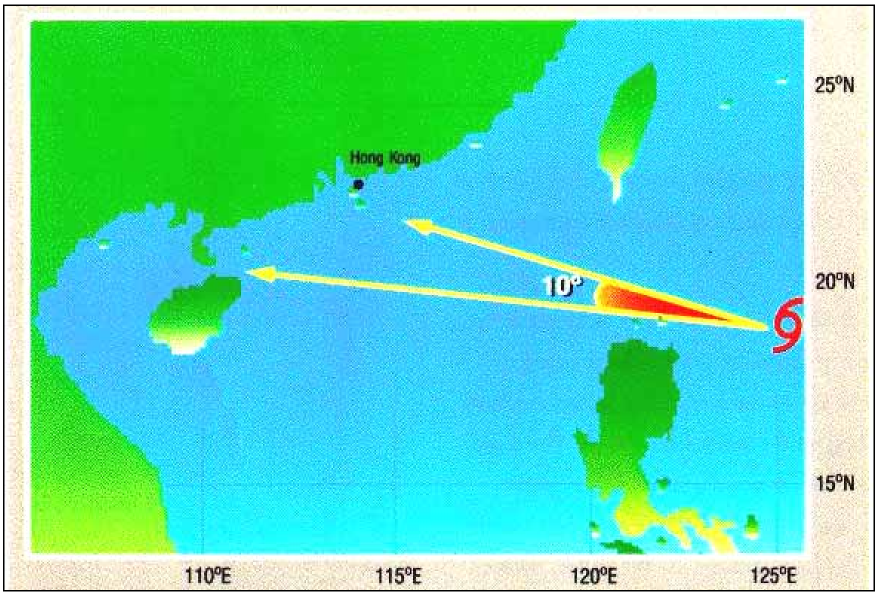


Figure 11: Effects of a Small Change in Typhoon Approach Angle (after HKO)

Because of its small geographical area, Hong Kong is seldom hit directly by a typhoon. As in illustration, Figure 11 shows the effect of a change of 10° on typhoon tracks in the South China Sea with respect to Hong Kong. Nevertheless, a summary of typhoon tracks passing through the western Pacific and South China Sea from 1972 to 2002, presented in Figure 12, indicates that Hong Kong is in a highly active region. As can be seen, the average annual number of typhoons, of any intensity, that will pass within approximately 500 km of Hong Kong is greater than unity. Such a common occurrence of typhoons emphasizes the necessity of building design to resist large wind loads in Hong Kong.

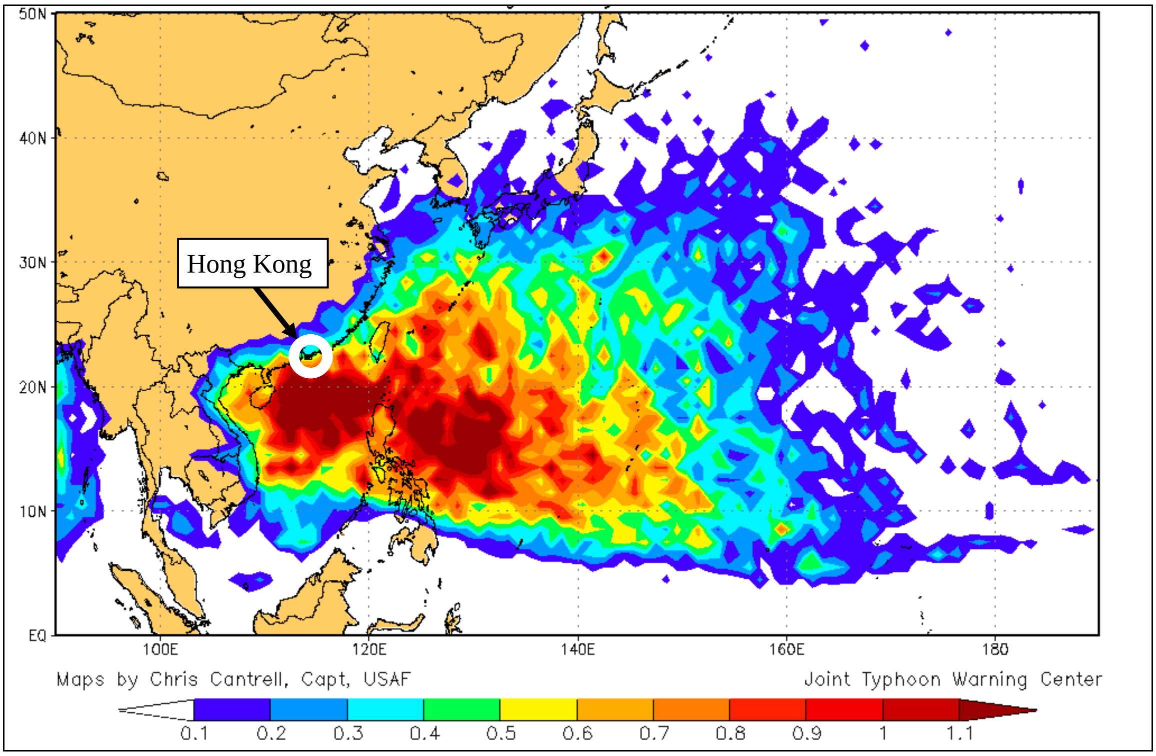


Figure 12: Average Annual Typhoon Occurrences in the Western North Pacific passing through 1x1 degree bins: 1972-2002 (after Joint Typhoon Warning Center)

The monthly distribution of all typhoon warning signals issued by the HKO between 1946 and 2004 can be seen in Figure 13. There is a noticeable drop in number but an increase in strength of typhoons affecting Hong Kong in August. To this date, the reason for this drop is not fully understood.

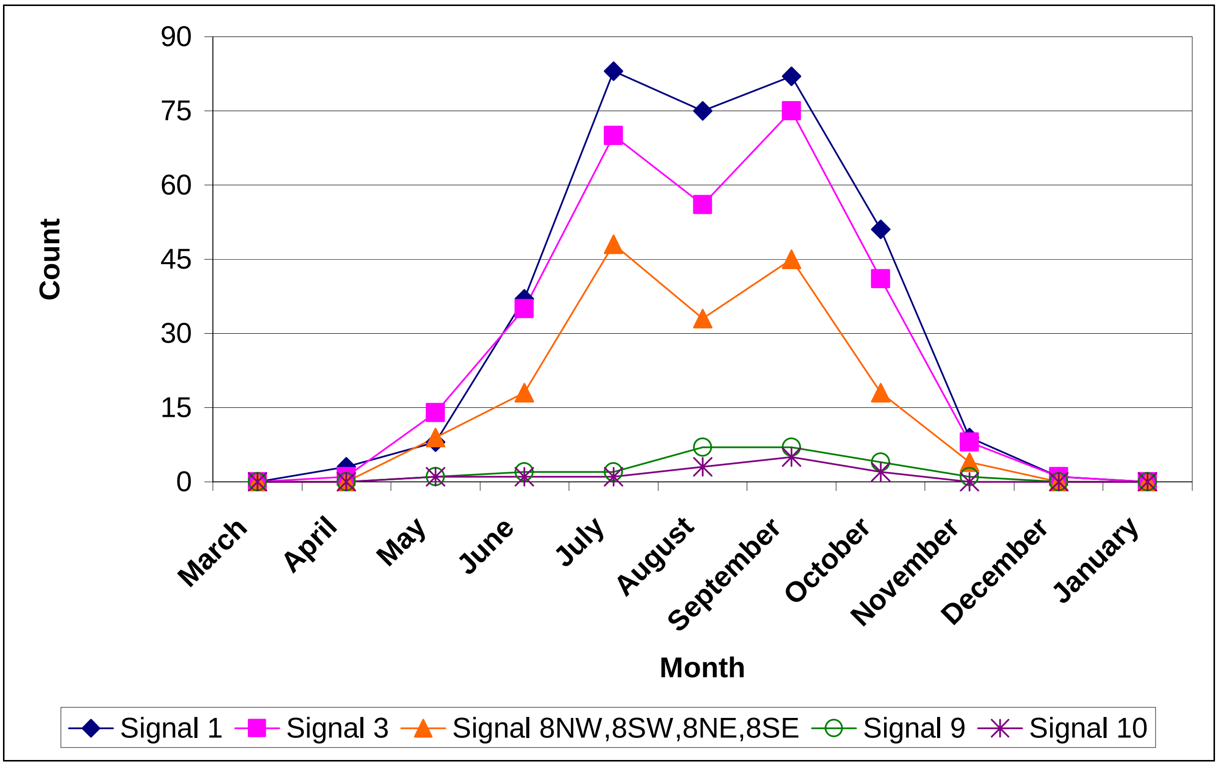


Figure 13: Monthly Occurrence of Typhoon Warning Signals issued by the Hong Kong Observatory: 1946-2004

Figures 14, 15, 16, 17 and 18 depict the normalized probability of the occurrence of Signals 1, 3, 8, 9 and 10, respectively. The data in these Figures has been distributed into months and normalized with respect to the total number of signals from 1946 to 2004 for their respective Signal level. For example, in Figure 18, if there is a Signal 10 in any season, the normalized probability that it will occur in September is 0.38. It can be seen that the peak probabilities for all Signals occur between July and September. There is a distinct shift of the strongest storms to occur later in the season, especially in September.

Figure 19 gives the number of typhoons affecting Hong Kong based on warning signals from 1946 to 2004. This figure uses only the highest signal of a typhoon as it affects Hong Kong. Labeled data correspond to notable years, such as low or high counts of warning signals, or denote that significant physical damage occurred. Information on the extent of damage caused by typhoons is provided in Section 3.2 and in the accompanying spreadsheet "COE_WindDamage_HK.xls". There is considerable fluctuation of the number of warning signals from a low of 2 in 1969 and 1997 to a high of 11 in 1974.

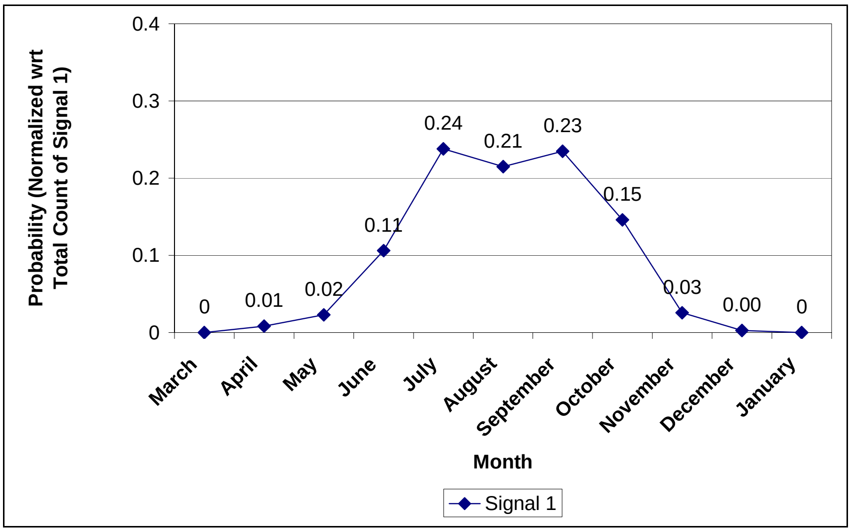


Figure 14: Probability Distribution of Monthly Typhoons requiring Signal 1 in Hong Kong: 1946-2004

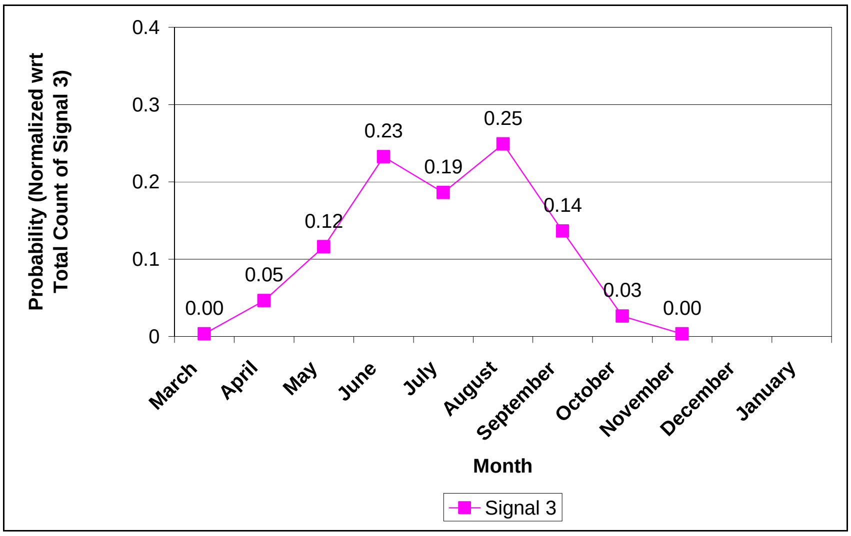


Figure 15: Probability Distribution of Monthly Typhoons requiring Signal 3 in Hong Kong: 1946-2004

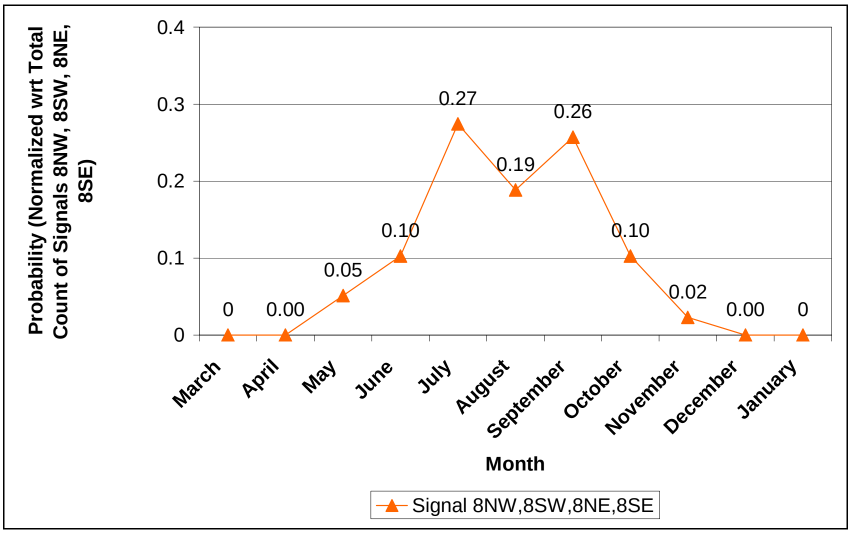


Figure 16: Probability Distribution of Monthly Typhoons requiring Signal 8NW, 8SW, 8NE or 8SE in Hong Kong: 1946-2004

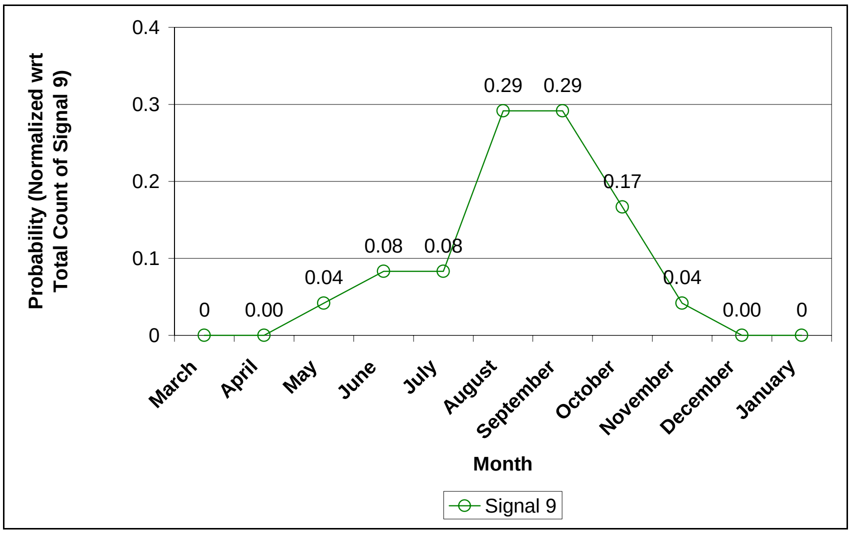


Figure 17: Probability Distribution of Monthly Typhoons requiring Signal 9 in Hong Kong: 1946-2004

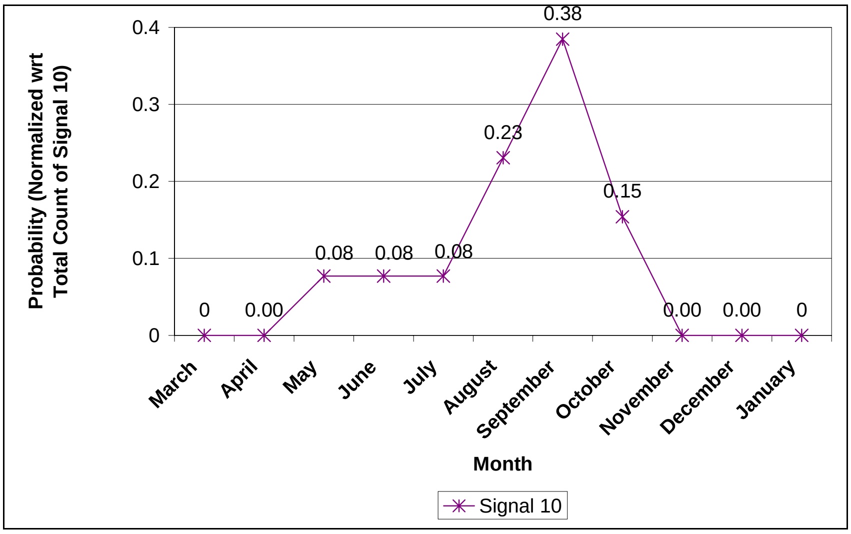


Figure 18: Probability Distribution of Monthly Typhoons requiring Signal 10 in Hong Kong: 1946-2004

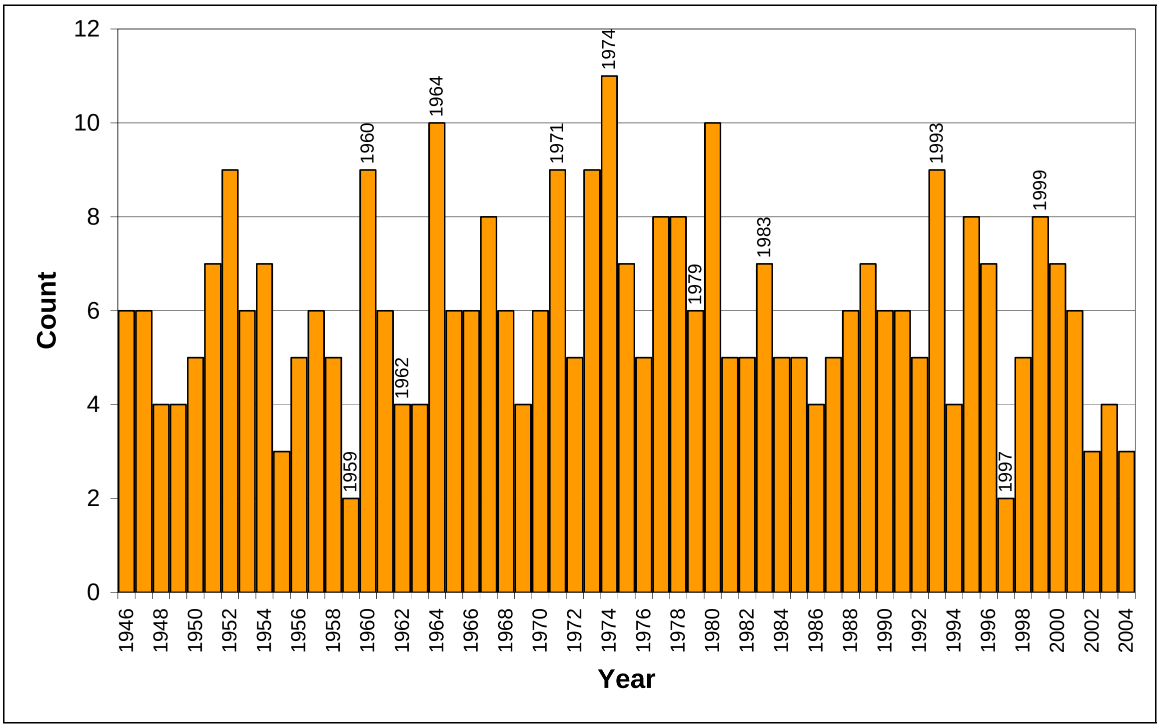


Figure 19: Number of Typhoons affecting Hong Kong based on Warning Signals: 1946-2004

Figure 20 presents the normalized distribution of all typhoon warning signals that have been issued by the HKO from 1946 to 2004. As expected the distribution indicates that as Signal number increases, prevalence decreases.

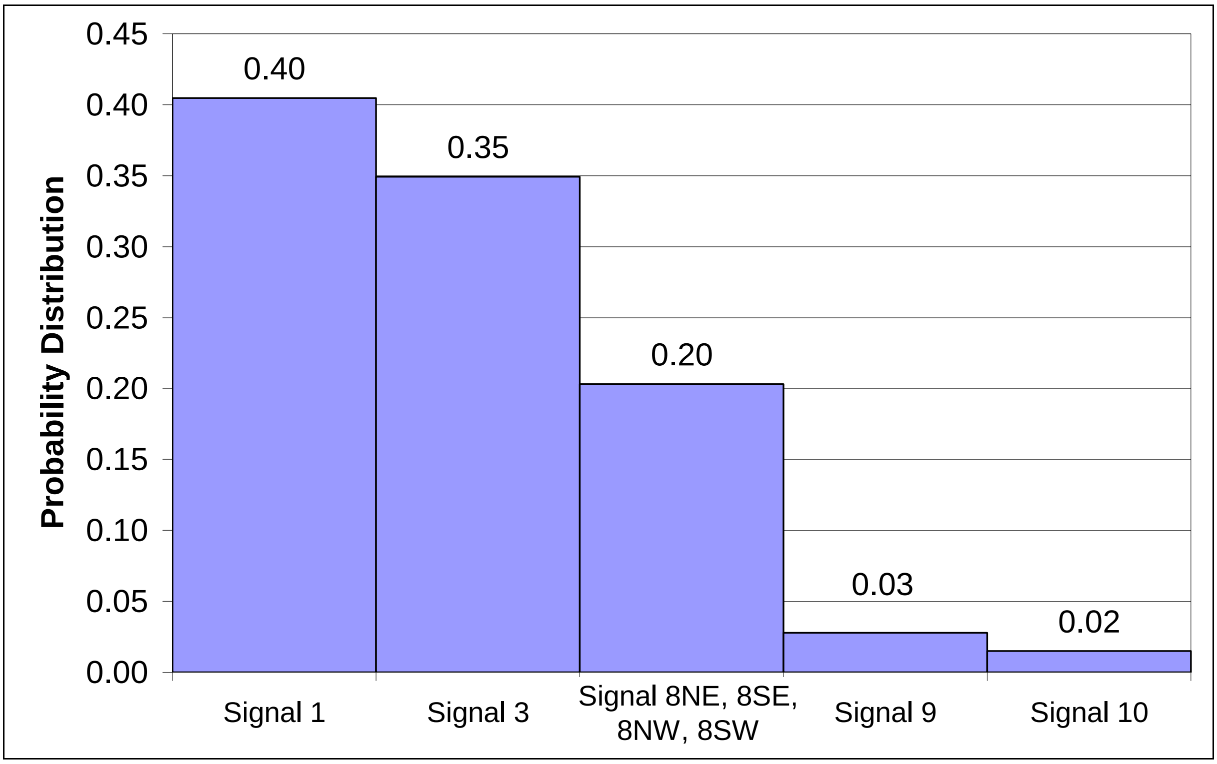


Figure 20: Normalized distribution of Typhoon Warning Signals used in Hong Kong: 1946-2004

2.2.3 Other Winds affecting Hong Kong

Hong Kong is also exposed to other types of wind phenomena such as waterspouts/tornados and downbursts/microbursts. These phenomena affect Hong Kong to a lesser extent than monsoons and typhoons but are nevertheless the source of sudden and potentially damaging winds.

The HKO, with its advanced weather monitoring equipment, is (sometimes) capable of identifying extreme winds from waterspouts, tornados, and downbursts. Forecasting these small-scale, transient events on the other hand, is not within the current capabilities of any meteorological station in the world, let alone the HKO. The necessary conditions, however, that may result in these phenomena are known and are well recognized. These are described in more detail below.

2.2.3.1 Waterspouts and Tornados

Waterspouts and tornados manifest themselves as a small, quickly rotating funnel of winds that start from the base of thunderstorm clouds and extend downwards, sometimes touching the earth below it. A rotating column of air (made visible by cloud droplets) that does not touch the water surface is called a funnel cloud. Waterspouts are similar to tornados except that the former occurs over water and the latter over land. The genesis of these intense winds results from a warm front being trapped below a cold front, which induces circulation. Along with the help of Coriolis forces, the rotation stabilizes and develops into a concentrated funnel. These phenomena are almost always associated with thunderstorms. Legend has it that some mariners report fish falling from the sky after a waterspout has passed.

In Hong Kong, the most recent sighting of waterspouts occurred on 31 July 2003. On this day, three waterspouts were sighted to the west of Hong Kong in the Pearl River estuary, each lasted about 10 minutes and headed in the northeast direction. Waterspouts are most commonly seen in June and July. Since 1959, there were a total of 29 cases of waterspout and 12 cases of funnel cloud sighted within 460 kilometres of Hong Kong (31). A funnel cloud alongside a waterspout can be seen in Figure 21.

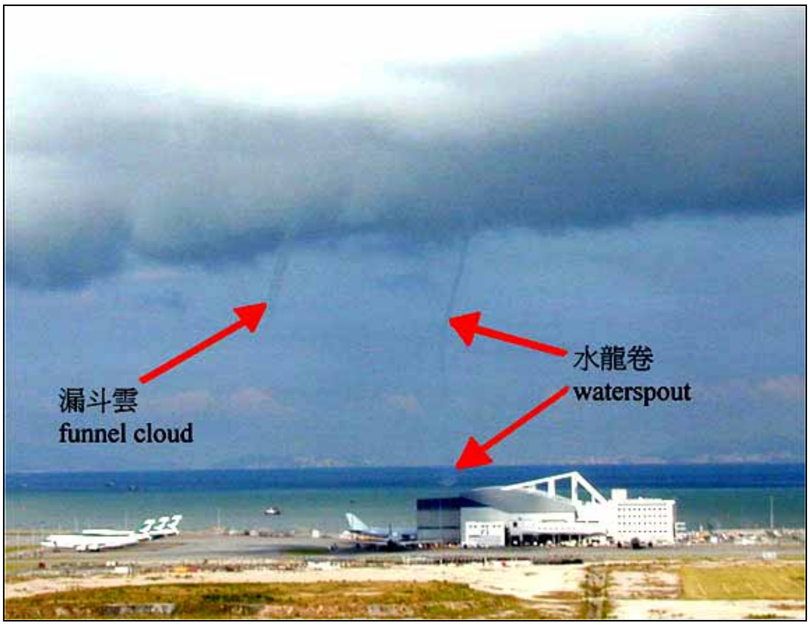


Figure 21: Observation of Funnel Clouds and a Waterspout in Hong Kong (31 July 2003)

A tornado is a fast rotating column of air extending from thunderclouds to the ground. In Hong Kong, tornados are mostly associated with unstable weather during the rain season from May to September. On record, there are a total of 6 cases of tornadoes in Hong Kong (32).

Tornados occur more often in Hong Kong than what the general public perceives. According to an HKO meteorologist, tornados occur once in about 3 years, on average (33). Because of their rarity, meteorologists and pedestrian observers are quite surprised at their occurrence. Besides being a nuisance by blowing dust and small light objects about, no evidence has been found indicating damage to structures or injury to people.

An experienced meteorologist observed the most recent tornado in Hong Kong on 6 September 2004. A picture from the Doppler radar that spotted the symptomatic wind conditions is given in Figure 22. The phenomenon started as a thunderstorm and then quickly developed into a tornado. There was only a single tornado that lasted for about 5 minutes. Previous to this one, the last two reported tornados in Hong Kong occurred on 20 May 2002 and 17 May 1994 (32,33).

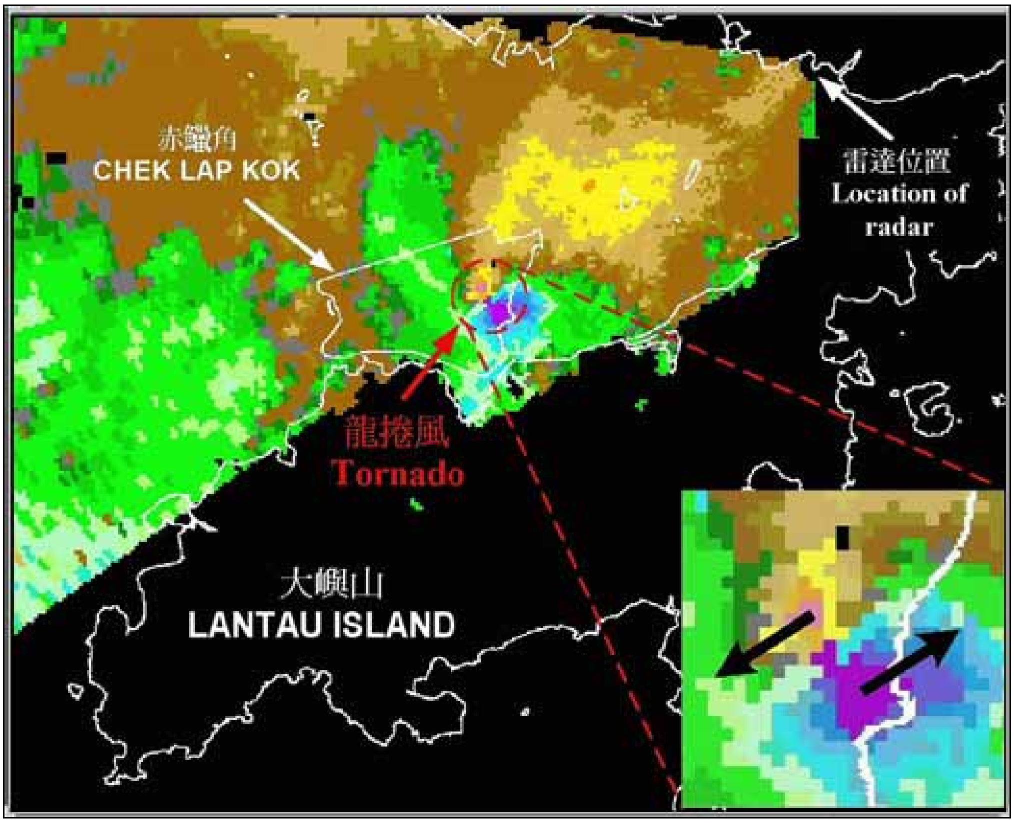


Figure 22: Doppler Radar Image of a Tornado taken on 20 May 2002. Arrows indicate contra rotating winds in the northeast and southwest directions (after HKO)

2.2.3.2 Downbursts and Microbursts

A downburst is a strong downdraft of wind that is also usually associated with thunderstorms. Downbursts are caused by the rapid descent of air associated with the thunderstorm that is cooler and denser than the surrounding air. Hong Kong has, on average, 37 days where thunderstorms occur, which may bring downburst winds (34). A microburst, as its name suggests, is a smaller version of the downburst and is classified as being less than 4 km in horizontal extent. Microbursts are typically associated with extra-tropical or temperate climates, particularly where these occur over large land masses. What is less expected is the presence of microburst type conditions in the tropical, maritime air mass that is typical in Hong Kong (35).

Winds caused by downbursts and microbursts have been the attention of the HKO for sometime, especially at the Hong Kong International Airport where adverse wind conditions can severely affect aircraft flight. Because of the size and transient nature of downbursts, and even more so, microbursts, records of wind speed are scarce if available at all. In summary, downbursts and microbursts do occur in Hong Kong and while no significant damage has been recorded to date, their sudden strong winds remain potentially hazardous.

2.3 Prediction of Extreme Winds

Extreme value analyses of wind speeds in Hong Kong have been previously performed by Bell (1961), Davenport, *et al*. (1984), Melbourne (1984) and Holmes, *et al*. (2001) (36,23,24,37). Preempting any application of their chosen statistical method, it was acknowledged that wind data obtained from the HKO require some amount of correction due to terrain effects. HKO recognized that readings may be influenced by terrain and have moved some anemometers several times to address this issue. Nevertheless, wind tunnel studies performed by Davenport (1984), Melbourne (1984) and Hitchcock, *et al*. (2003) for purposes of assessing terrain effects have found that corrections to wind speed are required for previous and current anemometer locations (23,24,20). Indeed, Hong Kong terrain is complex and changes dramatically with time indicating that site-specific studies for new buildings would be beneficial.

2.3.1 Peaks-over-threshold Analysis of Extreme Winds

One method of calculating extreme wind speeds from historical data uses the peaks-over threshold (p-o-t) approach. This approach uses historical wind data that has been separated with respect to a dominant source mechanism, which, in Hong Kong arises from typhoons. The p-o-t approach can be considered an approach with which to fit data to the Generalized Extreme Value distribution, and has an advantage of including all relevant data in the analysis. Holmes, *et al*. (2001) performed such an analysis of typhoon hourly mean and 1-second gust wind speeds in Hong Kong, the results of which are outlined below (37).

Hourly mean and 1-second gust wind speeds associated with typhoons in Hong Kong were procured from HKO. As mentioned above, an anemometer based at Waglan Island measures winds that best represent the overall winds affecting Hong Kong. The hourly mean wind data have been corrected to 200m to account for topographical effects on the anemometer location according to the factors determined by Hitchcock, *et al*. (2003). The 1-second gust wind data was also affected by the various anemometer locations and were corrected to 50m using a combination of corrections previously used by Melbourne (1984) for years before 1993, and corrections derived from Hitchcock, *et al*. after 1993. The procedure by which the p-o-t approach can determine return period wind speeds is as follows (37):

i. Several threshold levels of wind speed are set: u_0, u_1, u_2, etc. (e.g. 20, 21, 22 … m/s). For this analysis the lowest threshold was set at 18 m/s, with all data being greater.
ii. The exceedences of the lowest level u_0 by the maximum storm wind are identified, and the rate of crossing of this level (number/year, λ), is calculated
iii. The differences ($U- u_0$) between each storm wind and the threshold level u_0 are calculated and averaged (only positive excesses are counted)
iv. (iii) is repeated for each level, u_1, u_2, etc., in turn
v. The mean excess is plotted against the threshold level and a straight line fitted
vi. A scale factor, s, and a shape factor, k, are determined from the slope and intercept of the line by the following equations:

$$\text{Slope} = \frac{-k}{(1+k)} \qquad \text{Intercept} = \frac{\sigma}{(1+k)}$$

Once this procedure has been followed, predictions of the return period wind speeds can be done using the following formula:

$$U_R = u_0 + \sigma\left[1-(\lambda R)^{-k}\right]/k$$

where U_R is the R-year return period wind speed. For extreme wind data the shape factor, k, is usually in the range of +0.1 to +0.3.

Table 3 presents a summary of the parameters and results of the p-o-t analysis. The return mean wind speeds whose values are at 200m can be compared to the values used in the design codes in Hong Kong. The Code of Practice on Wind Effects - Hong Kong 1983 and the Code of Practice on Wind Effects in Hong Kong 2004, have design 50-year return mean hourly gradient wind speeds of 64 m/s and 59.5 m/s, respectively. It is worthy to note that the 2004 value of 59.5 m/s suggests that gradient height is reached at 500m. The value calculated from the p-o-t approach is significantly smaller than those values used in either edition of the Hong Kong Code, being 74% of the 1983 value and 79% of the 2004 value. These differences are accentuated even further when one converts wind speed to force, knowing that the drag force of an object in wind is proportional to the square of the velocity. Some difference between values may be attributed to the conservative nature of the Codes and uncertainty of the nature of typhoon winds. However, it was considered for quite some time that the 64 m/s value was excessively conservative. Consequently, the 2004 value of 59.5 m/s is regarded as being more representative of typhoon winds in Hong Kong.

Table 3: Results of peaks-over-threshold analysis of winds in Hong Kong (reproduced from Holmes, *et al.*, 2001)

	Waglan Island: means (200m)	Waglan Island: gusts (50m)
Lowest threshold, u_0 (m/s)	20	24
Rate (number/year), λ	1.44	1.42
Scale, σ (m/s)	9.2	11.8
Shape, k	0.18	0.14
20 year Return Period (m/s)	43.1	55.5
50 year Return Period (m/s)	47.3	61.8
200 year Return Period (m/s)	52.5	69.9
1000 year Return Period (m/s)	57.1	77.6

2.4 The Hong Kong Code of Practice on Wind Effects

The Buildings Department of the Government the HKSAR (formerly the Building Authority of Hong Kong) regulates how structures should be designed according to wind effects through the publication of a Code of Practice on Wind Effects. Revised versions of the Codes of Practice on Wind Effects were published in 1976, 1983 and 2004 and are hereafter referred to as the "1976 Edition", "1983 Edition" and "2004 Edition", respectively (38,39,40).

Published along with the Code is a Practice Note for Authorized Persons and Registered Structural Engineers (PNAP 150) entitled "Wind Tunnel Testing of Buildings" (41). PNAP 150 was first published in 1991, with a revised version coming out in 1994. Outlined in PNAP 150 are general guidelines for wind tunnel testing static and dynamic structures including recommended values for wind tunnel modelling in Hong Kong. Parameters specifying the variation of mean wind velocity and turbulence intensity for the simulation of natural wind are given for two types of terrain: General and Built-up. The

General and Built-up terrain profiles will be discussed in more detail below. Section (d) of Appendix A of PNAP 150 states that "The 50-year return mean hourly gradient velocity implied in the Code (of Practice on Wind Effects 1983) is 64 m/s." In Appendix C of this report the 1983 Edition, the 2004 Edition, and other supporting documents are provided.

2.4.1 1983 Edition

The 1983 Edition of supersedes the 1976 Edition. The 1983 Edition is similar to the BS CP 3: Chapter V: Part 2:1972. Selected highlights are presented here since the 2004 Edition has recently come into effect. The major revisions from the 1976 Edition include:

- Adoption of gust velocity as the basis for design;
- Reanalysis of probabilistic wind speeds on a statistical basis from records obtained from the Hong Kong Observatory; and
- Wind data that has been measured since 1976.

The 1983 Edition does not apply to buildings of an unusual shape or buildings situated at locations where the local topography significantly influences the wind conditions.

The design wind pressures have been derived from the peak gust velocities for a mean return period of 50 years.

PNAP 150 recommends undertaking a site-specific study if topographic effects are important in deviating from that associated with General and Built-up terrain. The parameters describing the General and Built-up terrain classifications are presented in Table 4, found below. Beyond this statement no other information regarding topographic effects has been accounted for either by PNAP 150 or the 1983 Edition.

Table 4: Code of Practice on Wind Effects Hong Kong – 1983 Terrain Parameters

General Terrain	
Power exponent for mean wind velocity	0.19
Power exponent for turbulence intensity	-0.26
Gradient Height	200m
Reference turbulence intensity at 75m height	0.10
Built-up Terrain	
Power exponent for mean wind velocity	0.33
Power exponent for turbulence intensity	-0.40
Gradient Height	300m
Zero plane displacement	25m
Reference turbulence intensity at 75m height	0.18

2.4.2 2004 Edition

The 2004 Edition supersedes the 1983 Edition. A recently published document entitled "Explanatory Materials to the Code of Practice on Wind Effects in Hong Kong 2004" (EM) provides background information and the rationale used in creating the 2004 Edition (42). A Practice Note for Authorized Persons and Registered Structural Engineers (PNAP 291) has also been published providing an overview to the usage and applicability of the 2004 Edition. PNAP 291 highlights the major changes to the 2004 Edition from the 1983 Edition as being (43):

- Adoption of a single terrain wind velocity profile from the two categories in the 1983 Edition;
- A new approach to address site topographic effects;

- A more comprehensive assessment of resonant dynamic effects of sensitive buildings; and
- New guidance on wind tunnel testing.

The PNAP 291 also states that the EM should not be construed as part of the 2004 Edition of the Code. This fact is reiterated in the EM document itself.

Found below are more detailed accounts of the major changes or inclusions seen in the 2004 Edition.

Design Wind Speed and Pressure

Records of wind data from Waglan Island from 1953 to the present have been used to estimate the mean return period wind speeds, referenced to a height of 90m. Although there have been changes in the height of the anemometer at Waglan Island since 1953, it has been deemed that correction factors to relate the measurements to 90m only make a small difference in the absolute estimate of mean return period wind speeds and, therefore, have not been applied. The reference 50-year hourly mean return period wind speed and 3-second gust wind speed at 90m is estimated as 46.9 m/s and 56.9 m/s, respectively. Furthermore, the reference turbulence intensity measured at Waglan Island at 90m is 0.1055. These base values are used in determining the design values, which are extrapolated to gradient height once the mean wind velocity profile has been determined.

The hourly-mean wind velocity profile is approximated by a power law relationship with a gradient height of 500m and an exponent of 0.11. This suggested profile is the same that was proposed by Kwok & Hitchcock (2003). This relationship reflects the hourly-mean wind velocity profile found over open sea terrain, which shall be applied to Hong Kong in its entirety. Therefore, the hourly-mean wind speed and 3-second gust wind speed at gradient height are 56.6 m/s and 74.9 m/s, respectively. Kwok & Hitchcock (2003) suggest a value of 57 m/s as the 50-year return period hourly-mean 500m gradient wind speed. However, there is still some uncertainty about the nature of typhoon winds because of difficulties in obtaining quality full-scale measurements in such conditions. Furthermore, it has been reported in the 2004 Edition that some wind tunnel tests have measured localized pressures that are in excess of code values. Consequently, a safety factor of 5% has been added to the gradient wind speeds, which is ultimately reflected in the design values. A summary of equations to be used with the design values in the 2004 Edition is presented in Table 5.

Topography Factor

Topographic effects in the 2004 Edition are treated similarly to the BS6399-Part 2. Whereas BS6399-Part 2 applies topographic factors to gust wind speeds, the 2004 Edition applies topographic factors to the gust wind pressures. The 2004 Edition also warns that in very complex terrain the given factors may underestimate actual speed-up, and recommends that specialist advice be sought. The inclusion of this section marks a significant step beyond that of the 1983 Edition, which does not include any means of calculating topographic effects on wind flow.

Forces on Buildings and Building Elements

The total force or pressure on a building calculated in the 2004 Edition is the same in the 1983 Edition. Reduction to the force coefficients may be applied to structures with large frontal surface areas or are composed of framework. These reductions in the 2004 Edition are the same as the 1983 Edition. Values used for internal pressures when assessing the worst pressures acting on a building are +0.2 or –0.3. A note in the 2004 Edition is included for a building composed of contiguous structures identifying that even if the structures are structurally independent, the force coefficient should be applied to the entire building.

Table 5: Code of Practice on Wind Effects in Hong Kong 2004 Design Equations

Design Equations and Values in the Explanatory Materials to the Code of Practice on Wind Effects in Hong Kong 2004

$$\bar{v}_z = \bar{v}_g \left(\frac{z}{z_g} \right)^{\alpha}$$

$$\frac{I_z}{I_g} = \left(\frac{v_z}{v_g} \right)^{-1} = \left(\frac{z}{z_g} \right)^{-\alpha}$$

$$v_z = \bar{v}_z \left(1 + 3.7 I_z\right) = \bar{v}_g \left(\frac{z}{z_g} \right)^{\alpha} \left[1 + 3.7 I_g \left(\frac{z}{z_g} \right)^{-\alpha} \right]$$

$$q_z = \frac{1}{2} \rho v_z^2$$

where:
- z = Elevation less than or equal to gradient wind;
- z_g = Elevation of gradient wind;
- $\bar{v}_z$ = Hourly mean wind velocity at elevation, z;
- $\bar{v}_g$ = Hourly mean wind velocity at gradient;
- α = Power law exponent on mean wind velocity and turbulence intensity profiles;
- v_z = 3-second gust wind velocity at elevation, z;
- v_g = 3-second gust wind velocity at gradient;
- I_z = Turbulence intensity at elevation, z;
- I_g = Turbulence intensity at gradient;
- q_z = pressure at elevation, z; and
- ρ = density of air = 1.2 kg/m³.

Suggested design values:
- z_g **= 500m;**
- $\bar{v}_g$ **= 59.5 m/s;**
- v_g **= 78.7 m/s;**
- I_g **= 0.087; and**
- α **= 0.11.**

Height Aspect Factors for enclosed rectangular plan shaped buildings in the 2004 Edition correspond to a maximum height/breadth (h/b) ratio of 20.0, up from 10.0 in the 1983 Edition. Including a h/b value of 20.0 raises the maximum Height Aspect Factor from 1.2 in the 1983 Edition to 1.4 in the 2004 Edition. The Shape Factors for enclosed buildings in the 2004 Edition have been narrowed to a range of breadth/depth (b/d) values of <1.0 to >3.0 corresponding to Shape Factors of 1.0 to 1.3, where the 1983 Edition Shape Factors were for a b/d range of <0.5 to >4, corresponding to values of 0.8 to 1.45. Reduction factors for enclosed buildings in the 2004 Edition are identical to those found in the 1983 Edition. The force coefficients for open framework buildings are also identical to those found in the 1983 Edition.

In the 1983 Edition values for force coefficients, if not selected from the given Tables, may be substituted by values from the British Code. This is similar to the 2004 Edition, however, values are acceptable not just from the British Code, but from other International Codes as well.

Dynamic Effects

The 2004 Edition offers an additional component in the evaluation of the dynamic response of structures. Specifically, it offers a signpost similar to that of the AS/NZS 1170.2-1989 and states that a structure may be dynamically sensitive if:

a) The height exceeds 5 times the least horizontal direction; or
b) The height of the building is greater than 100m,

unless it can be justified that the fundamental natural frequency is greater than 1Hz.

The alongwind dynamic response is calculated using the gust factor method based on the earlier work of Davenport. There is some mention of crosswind and torsional response of buildings but no formulaic approach to predicting these responses is given. It is advised that in the occurrence of crosswind and/or torsion response, procedures following the literature should be employed, or specialist advice should be sought.

Values of damping for steel and reinforced concrete structures are provided in the 2004 Edition. The damping for steel structures is 1.5% of critical, while that for reinforced concrete structures is 2.0% of critical. Specialist advice is suggested, however, for particularly slender buildings. No criteria are offered for what constitutes a slender building, leaving that judgement to the practitioner.

Necessary Provisions for Wind Tunnel Testing

The content of Appendix A of the 2004 Edition contains much the same information that is contained in PNAP 150. The major exception is that the mean wind speed and turbulence intensity profiles suggested in PNAP 150 have been replaced with a single profile in the 2004 Edition. This single profile should be matched in the wind tunnel in terms of gust pressures instead of mean wind speed. The EM highlights that the structure of typhoon winds are still not fully understood, especially with regards to building design. Some of the rationale of choosing a single terrain is due to Hong Kong lying close to the sea. The change of gust wind speeds is slower than mean wind speeds as wind flows from the sea to land.

Other Changes or Inclusions

Appendix B of the 2004 Edition provides a method to calculate design wind pressures for return periods greater than 50 years. This method uses a factor by which to multiply the given design wind pressures. This factor is presented below.

$$\left(\frac{5+ln(R)}{5+ln(50)}\right)^2$$

where R is the period of exposure to wind in years.

3.0 Typhoon Damage in Hong Kong

Typhoons have always affected Hong Kong but it was not until larger populations and major infrastructure appeared that their destructive potential was realized. Building development in Hong Kong occurred first in low-lying areas, with settlements located on or near the waterfront. Once these low-lying areas were established, many squatter settlements appeared on the hills. When typhoons came damage occurred both in the ‘properly’ developed areas and the squatter settlements. Typhoons caused an array of damage that can be classified as direct or indirect. Direct damage could be attributed to strong winds, heavy rain and flooding. Indirect sources of damage could be from flying debris (possibly caused from damaged infrastructure) and fires. Squatter settlements generally suffered the most damage, with landslides due to heavy rain being particularly the most destructive. The effects of typhoons were not limited to land, as the sea faring livelihood of the Hong Kong people was also at peril. Small boats used for private residences and large shipping container vessels were known to be at high risk and it was not too long before boat shelters were constructed. However, no matter how well shelters were constructed, the fact is that the boats were still relatively open to the effects of typhoons. A good example of typical typhoon damage in Hong Kong can be seen in Figure 23, where a large boat was washed aground on the island of Cheung Chau. In addition to boat damage, infrastructure damage may have also occurred indicated by billowing smoke in the background.

Figure 23: Ship Aground on Cheung Chau Island, Hong Kong caused by Typhoon Ellen - 1983 (after HKO)

Case studies of past typhoons provide an excellent means to understand the problem of typhoon damage. In the proceeding section a summary of damage resulting from typhoons is discussed, while a more detailed account of individual case studies is given in the report “Typhoons affecting Hong Kong: Case Studies”. The list of typhoon case studies within the aforementioned report and summarized here, is as follows:

- Typhoon York (1999);
- Typhoon Sam (1999);
- Typhoon Dot (1993);
- Typhoon Ellen (1983);
- Typhoon Hope (1979);
- Typhoon Rose (1971);

- Typhoon Wanda (1962);
- Typhoon Mary (1960);
- The Typhoon of 1937;
- The Typhoon of 1906;
- The Typhoon of 1874; and
- The Typhoon of 1847.

3.1 Typhoon Damage in Hong Kong: A Qualitative Perspective

Some effects of a typhoon are obvious such as physical damage to people, environment and buildings. Economic loss is another obvious effect such as businesses not operating and the time required for clean up. Additionally, complaints about building motion being misconstrued as being unsafe may cause tenants to move out, causing economic loss.

A good example of obvious damage came during Typhoon York which hit Hong Kong in 1999. Most notably, windows were shattered from several skyscrapers in a prominent business district on Hong Kong Island, pictures of which are given in Figure 24. The damage that was caused during this storm highlighted the vulnerability that all types of buildings are susceptible to damage.

Figure 24: Cladding damage in the Wan Chai district of Hong Kong during Typhoon York (left), and a close-up of the damage (after van der Woning)

To this day, Hong Kong remains closely tied to its maritime ancestry. The ports and bays around Hong Kong are always filled with a combination of personal and commercial watercraft. For many decades many local people lived on junks, which were especially vulnerable to typhoon damage. Large shipping and military boats were less vulnerable but not immune to the effects of typhoons. When a large typhoon hit Hong Kong, the combination of increased strength of waves and wind caused some boats to drag anchor, leading to their destruction. In combination with boats, moorings and docks were often also damaged. The destruction of larger boats has been catalogued much better than small junks. In many reports of typhoons, especially those dating to the 19th century, the damage to military boats is well documented. Figure 23 shows what may happen with a larger boat caught in a typhoon as it has washed ashore Cheung Chau Island. In what was one of the worst disasters in world history, an estimated 11,000 people lost their lives when a typhoon hit Hong Kong in 1937.

The livelihood of many people in Hong Kong depend upon agricultural and fish farming. The susceptibility of these farms to typhoon damage from wind, flooding and storm surge is great and may potentially ruin crops for an entire season. There is no adequate way to protect fruit trees, field crops or fish from the effects of a typhoon and often their survival and health is left to luck. During every major typhoon that has passed close to Hong Kong damage has affected farmers significantly. Furthermore, damage occurring to the natural environment can also be substantial. Typhoons have knocked down trees and damaged the flora throughout the entire Hong Kong. It is possible that trees injure people and damage property when they fall. If they fall over roadways they also may cause confusion and panic amongst drivers who damage their vehicles while trying to avoid the trees. Trees that fall over roadways also require resources for their removal, adding to the monetary cost of the typhoon. An example of damaged trees can be seen in Figure 25.

Figure 25: Damaged trees due to Typhoon York (after HKO)

The loose soil found in Hong Kong is especially susceptible to landslides. A typhoon that does not have strong winds may still bring large amounts of rain triggering landslides. Unfortunately these incidents are sudden in nature and depending on its location and the surrounding demography, loss of life may occur. Several cases are recorded where dangerous slopes forced the evacuation of nearby buildings as a precautionary measure.

Some effects caused by typhoons may not be so obvious. For example, once typhoon warning signals are issued, confusion may arise from their misinterpretation. Confusion often occurs with the Heavy Rain warning that is sometimes associated with typhoons. If the Heavy Rain warning is issued, employees do not need to go to, or remain at, work. Although technically illegal, unscrupulous employers have fired employees who have missed work when they have abided to Heavy Rain warnings.

Damage from typhoons may provide positive or constructive information to engineers through identifying weakness in design. This is another unobvious effect from typhoons. Although immediate damage is undesirable, it is possible to learn from past mistakes and improve future designs and Codes.

Political debate may also arise from damage caused by typhoons. A perfect example is from Typhoon Dot, which occurred in 1993. Typhoon Dot was not a particularly strong typhoon in terms of wind speed but it brought heavy rains that caused a tremendous amount of flooding. Particularly, many people lost their homes and much agricultural land was destroyed when the Shenzhen River overflowed its banks. The Shenzhen River defines a large section of the border between the HKSAR and the Mainland China border. To prevent future flooding, change to the land on either side of its course was proposed. Debate arose from the local governments and the individual property owners regarding how to balance public safety and landholder compensation within the best engineering solution. Situations of this nature require much time to resolve and implement. A suitable solution arose in a three stage engineering project that involved straightening large portions of the Shenzhen River. Funding came from both local governments and the project team comprised of engineers from both sides of the border. The first and second stages of the project were completed in 1997 and 2002, respectively. The last stage of the project will finish in 2006; thirteen years after Typhoon Dot caused the flooding (44). Before and after pictures are given for the Shenzhen River in Figure 26.

Figure 26: The Shenzhen River in 1993 (left) and in 2002, after flood control prevention (after Drainage Services Department, Government of HKSAR)

Not all effects from a typhoon are serious. It is evident from the numerous newspaper clippings that most people do not worry about damage or injury from typhoons. For example, a common concern is with taxi drivers charging increased rates during a typhoon. Insurance companies do not cover taxis that drive during a typhoon, but some drivers choose to risk the storm to make more money. Since buses do not operate during typhoons, the only choice for transportation is taxi. The concern with higher fares during a typhoon reflects that people are cavalier towards the possible damage or injury from a typhoon because they are willing to travel. This complacent attitude, however, usually occurs only after a long period of time without significant typhoon damage. Unfortunately it seems that the only way for people to remain cautious during a typhoon is through intermittent damage from typhoons.

3.2 Typhoon Damage in Hong Kong: A Quantitative Perspective

To observe trends in damage it is important to be able to quantify a number of parameters associated with a typhoon. Firstly, values concerning the intensity of the typhoon are defined. Secondly, values concerning the extent of damage caused by typhoon are defined. In the following section an attempt has been made to observe trends and comment on why they are occurring.

Different values associated with typhoons were measured or estimated to indicate its intensity or strength. The major intensity values are divided into the following:

- Classification, i.e. typhoon, severe tropical storm, or tropical storm;
- Hourly mean wind speed at Waglan Island;
- 1-second gust wind speed at Waglan Island;
- Measured mean hourly pressure in Hong Kong;
- Closest approach to Hong Kong; and
- Maximum storm surge at Quarry Bay and Waglan Island.

As previously stated, Waglan Island wind records provide the best indication of the overall winds affecting Hong Kong, therefore, only this site was used for wind records.

Similarly, the effects of the typhoon were organized into 8 damage categories as follows:

- Persons dead;
- Persons missing;
- Persons injured;
- Ocean-going vessels in trouble;
- Small water craft sunk or wrecked;
- Small water craft damaged;
- Number of landslides; and
- Total monetary value of damage.

There is an emphasis on effects that typhoons have on the marine environment because of the large potential for damage and death on the water.

A tabulated summary of the intensity values and damage categories are given in a spreadsheet entitled “COE_WindDamage_HK.xls”. This table contains all relevant typhoon data collected between the years 1957 to 2004. A summary of typhoon-related damage is presented in Table 6.

The correlation between each intensity value of a typhoon (e.g. hourly mean wind speed or 1-second gust wind speed) and each damage category (e.g. persons dead, persons injured) was calculated. There were generally small, positive correlation values relating the hourly mean wind speed and 1-second gust wind speed to the damage category. However, for the number of persons injured compared to the hourly mean wind speed and the number of persons injured compared to the 1-second gust wind speed there were higher correlation coefficients of 0.73 in both cases. This relationship can be seen in Figures 27 and 28. For measured pressure and storm surge, the correlation coefficients indicated little relation between all damage categories.

Figures 29 through 34 provide information on the damage statistics with respect to year. These graphs are plotted with a logarithmic ordinate to emphasize lower levels of damage and hence, do not include zero damage. All statistics indicate that the amount of damage is decreasing with time, except for the number of persons injured. Reasons for this decrease are presented below.

Causes for decreasing damage can mainly be attributed to better practices of information management and the building of safer structures. The recognition of the hazards and risks of typhoons affecting Hong Kong buildings has also promoted the development of disaster plans. These reasons for damage reduction are discussed further below.

The avoidance of damage to people depends on information regarding the hazard. Firstly, information about the hazard including its location and movement must be accurate. Without accurate information it is uncertain whether subsequent human actions will increase or decrease risk. Attaining accurate information is quite difficult, however, as the random nature of typhoons is considered in a probabilistic manner. The HKO can only give their best estimates of the track and intensity of a typhoon when it spawns in the western Pacific Ocean or South China Sea. If a typhoon warning signal is given too late, there may be a catastrophe because people are not prepared. If the warning signal is too early or false then the population will be annoyed and sometimes outraged. The political ramifications of early or false signals are unfortunately sometimes worse than the typhoon itself. Recently there has been more collaboration between meteorological agencies around the world. It is now possible to identify typhoon genesis because of the plethora of satellites constantly observing the surface of the earth. A Severe Weather Information Centre (SWIC) has been established by the World Meteorological Organization that focuses on severe weather across the globe. The website for SWIC is maintained by the HKO. From collaborations like this the chances of obtaining accurate information are higher.

Table 6: Summary of Typhoon Damage in Hong Kong: 1957-2004

TOTALS	133	513	129	4401	292	1149	2257	808	463.724
Year	Number of Significant Storms	Persons dead	Persons missing	Persons injured	Ocean-going vessels in trouble	Small craft sunk or wrecked	Small craft damaged	Number of Landslides	Total Value of Damage $HK million
1957	1	8	*	111	*	*	*	*	*
1960	1	45	11	127	6	352	462	*	*
1961	2	11	0	20	*	1	*	*	*
1962	1	130	53	*	36	0	756	*	*
1963	1	3	0	51	0	2	0	*	*
1964	5	78	20	506	30	88	419	*	*
1965	2	7	0	19	0	1	0	*	*
1966	1	1	0	6	0	*	6	*	*
1967	1	0	0	3	3	1	0	*	*
1968	1	0	0	4	1	*	3	*	*
1969	1	0	0	0	0	3	0	*	*
1970	2	2	0	0	2	0	0	*	*
1971	3	112	5	354	52	305	13	*	*
1972	1	1	0	8	3	0	0	*	*
1973	1	1	0	38	14	*	*	*	*
1974	4	1	0	0	10	*	*	*	*
1975	3	2	1	46	11	3	1	*	*
1976	5	32	6	99	6	4	8	*	*
1977	3	1	0	40	3	0	0	*	*
1978	6	4	7	190	11	36	50	*	*
1979	5	13	0	327	31	186	207	*	*
1980	4	2	1	59	5	2	4	*	*
1981	1	0	0	32	0	0	3	*	*
1982	3	0	0	16	0	1	3	*	*
1983	4	10	12	391	46	136	229	*	*
1984	1	0	0	1	0	0	0	0	*
1985	3	2	1	26	6	5	5	31	*
1986	4	4	1	48	4	6	9	55	*
1987	1	0	0	1	0	0	0	0	*
1988	4	2	1	17	1	2	2	22	14.2
1989	3	8	1	150	2	3	14	103	10.746
1990	6	6	2	3	1	1	3	3	0
1991	3	0	0	18	2	2	15	14	1.209
1992	4	2	0	65	3	0	4	40	15.1
1993	6	4	1	426	0	2	19	196	158.825
1994	2	1	0	7	0	1	3	0	1
1995	3	3	0	54	0	0	0	73	39.01
1996	2	2	1	4	0	0	0	0	0
1997	2	1	0	61	0	0	0	36	4.99
1998	3	1	0	25	0	0	0	0	0
1999	6	7	0	888	3	2	0	204	215.99
2000	3	2	1	7	0	0	1	23	0
2001	4	3	0	12	0	1	0	6	1.03
2002	3	0	0	34	0	0	4	2	0.6
2003	4	1	4	95	0	3	14	0	1.024
2004	3	0	0	12	0	0	0	0	0

* Data unavailable.

The dissemination of this accurate information is the next important link in the chain. A number of ways now exist whereby information can reach the general population. People can be reached through television, radio, newspaper, internet and in the near future through mobile devices. Sea-faring vessels as well as the population on land can now take the necessary actions to minimize their risk and therefore, reduce the potential for damage. However, it is also important to receive the information in a timely manner. This problem leads back to the proper analysis and assessment of the typhoon itself and rests in the hands of the HKO. Timely delivery of information and accurate assessment of a typhoon are competing quantities and it is up to the officials who issue the warning signals to aid in the safety of the population without minimizing their disturbance.

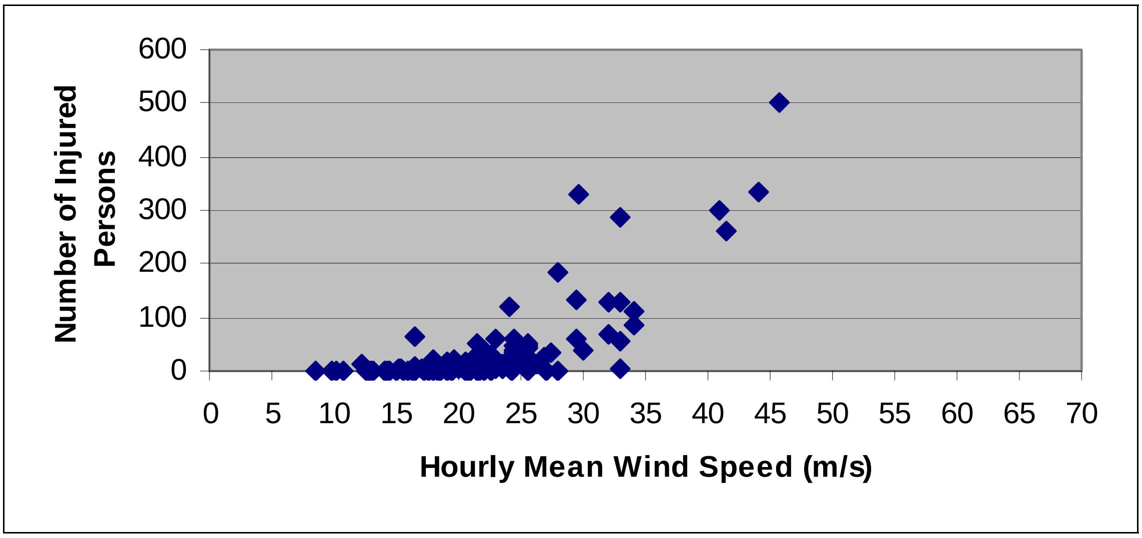


Figure 27: Number of Persons Injured vs. Hourly Mean Wind Speed

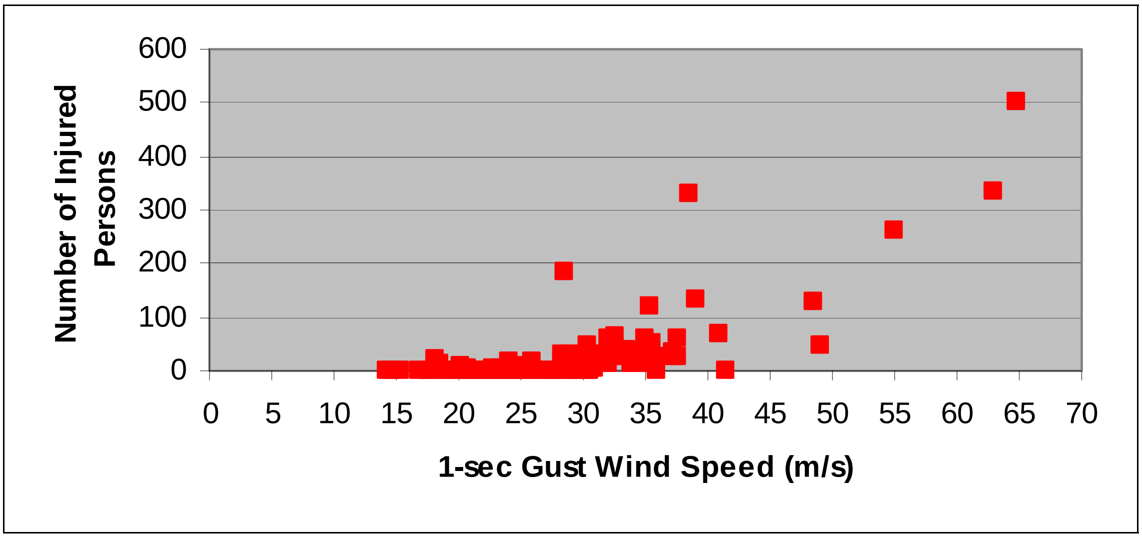


Figure 28: Number of Persons Injured vs. 1-second Gust Wind Speed

Information is not just important when a typhoon is threatening. Education of the general public during non-typhoon conditions is just as vital to preventing damage. Education offers a means by which people can learn how to protect themselves and their homes from unnecessary damage. Outreach programs have been set up by the HKO through "open houses", a website and occasionally over the radio. Education can prepare and equip people with the proper approach to minimizing the risk of themselves, their family and their environment to damage.

In the case that damage occurs to buildings rendering them uninhabitable, the government of Hong Kong has set up shelters for people. These shelters are designed to withstand more severe conditions than regular buildings. These shelters are not intended for large numbers of people, but can generally support enough people in the case of emergencies. Shelters for boats have also been constructed along parts of the waterfront at harbours and marinas across Hong Kong. These shelters are simply a small area offering protection from waves through the use of breakwaters. Similar to human shelters they often cannot accommodate every boat. What is different from human shelters is that boat shelters are always used when a typhoon hits Hong Kong as there is no other place for boats to go.

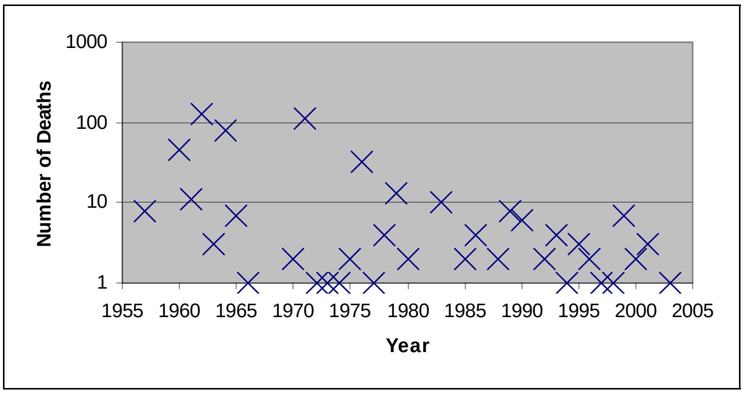


Figure 29: Number of Deaths caused by Typhoons per year

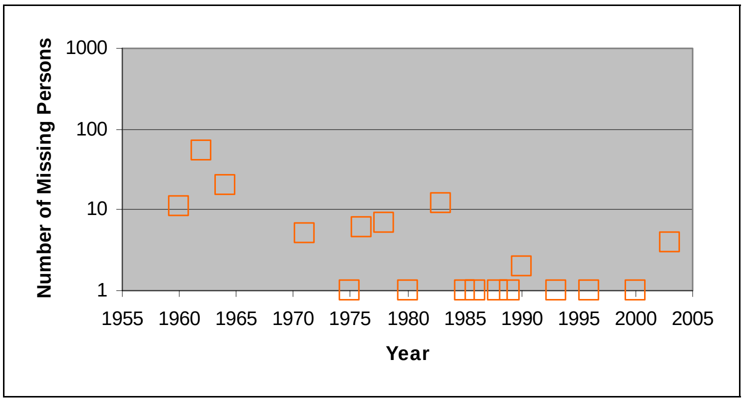


Figure 30: Number of Missing Persons caused by Typhoons per year

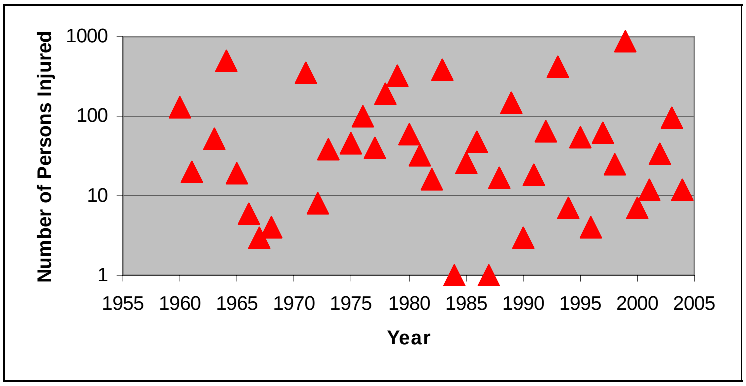


Figure 31: Number of Persons Injured caused by Typhoons per year

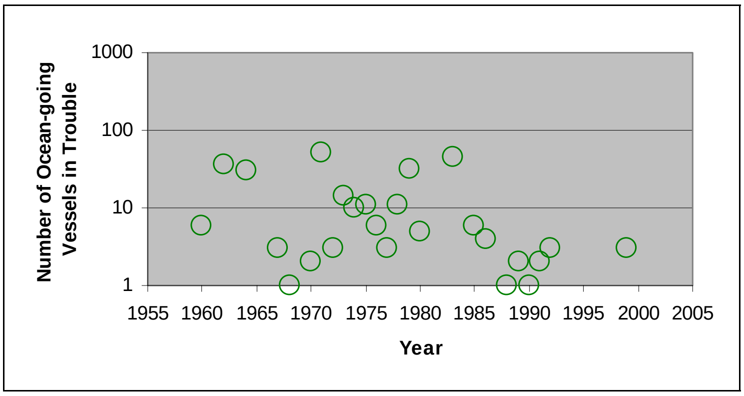


Figure 32: Number of Ocean-going Vessels in trouble from Typhoons per year

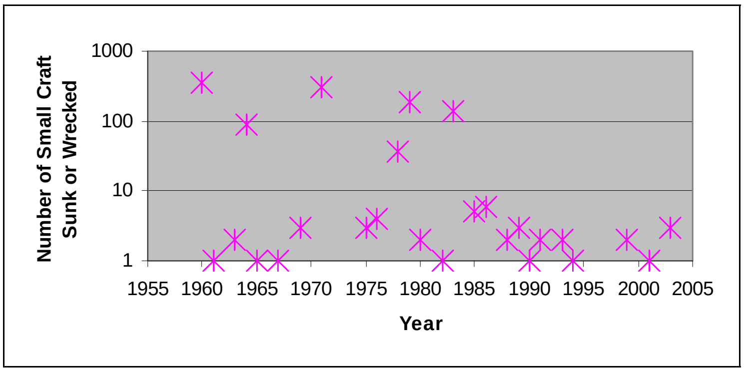


Figure 33: Number of Small Craft Sunk or Wrecked by Typhoons per year

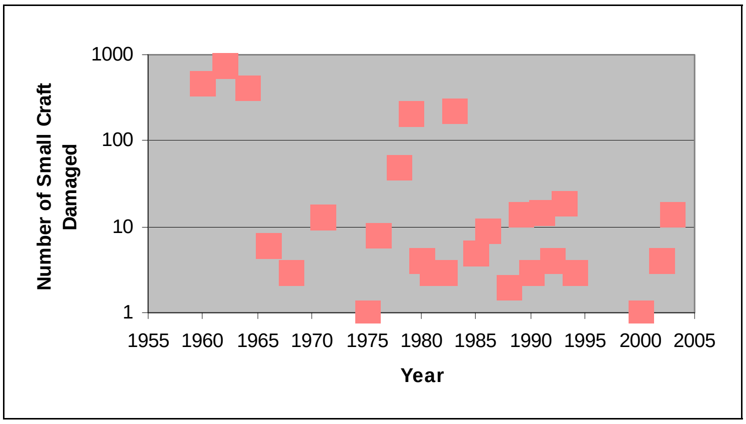


Figure 34: Number of Small Crafts Damaged by Typhoons per year

4.0 Conclusions

Hong Kong has a high density of tall buildings that are highly susceptible to typhoon-induced damage. Because of high population density localized damage to a building may affect a large number of people. The use of Unauthorized Building Works increases the potential for damage to people and buildings during a typhoon because of wind-borne debris.

The wind climate of Hong Kong is complex as a result of its susceptibility to typhoons. Many areas around Hong Kong encounter wind flow that is highly modified by terrain. Winds over this terrain accelerate and may cause large amounts of damage in terms of people, buildings and the natural environment.

Typical damage may occur from high winds, heavy rains or storm surge. Common types of damage occur to people, boats, farms, trees and buildings. For example, in 1937 a typhoon hit Hong Kong killing an estimated 11,000 people. In 1999 Typhoon York damaged the glass curtainwalls of several tall buildings. Buildings situated near slopes may be affected by landslides, which, in the past, occurred often during typhoons. Many buildings may also be affected by flooding, which is often the case in the northern parts of Hong Kong, and was observed with the Shenzhen River during Typhoon Dot in 1993.

The principal reason that damage has decreased over the years is because of better practices of acquiring and communicating typhoon information. The work of the Hong Kong Observatory, in conjunction with meteorological stations around the world, has made the genesis and tracking of typhoons observable, allowing people to react appropriately. Furthermore, advanced understanding of typhoons has lead to better methods to design buildings to withstand the associated forces of a typhoon and has lead to the latest “Code of Practice on Wind Effects in Hong Kong 2004”.

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APPENDIX A

Topographic Map of the Hong Kong Special Administrative Region

APPENDIX B

Map of Reclamation & Development in Hong Kong

APPENDIX C

- Code of Practice on Wind Effects Hong Kong – 1983;
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- Explanatory Materials to the Code of Practice on Wind Effects in Hong Kong 2004;
- Practice Note for Authorized Persons and Registered Structural Engineers 150: Wind Tunnel Testing of Buildings; and
- Practice Note for Authorized Persons and Registered Structural Engineers 291: Code of Practice on Wind Effects in Hong Kong 2004.