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Wind tunnel study of odor impact and air ventilation assessments for relocating sewage treatment works to caverns

Z.R Shu, Y.C He, Q.S. Li *
Department of Architecture and Civil Engineering, City University of Hong Kong, Hong Kong

Abstract

In recent years, the topicality of environment-related issues has been frequently emphasized in terms of sustainability and the better management of development in harmony with the environment. As for Hong Kong, one of the most densely populated cities, the scarcity of land has always been assumed as a major impediment for its long-term development. Therefore, the Hong Kong government actively explores approaches to enhance usable land resources. One viable approach is rock cavern development. This paper presents a feasibility assessment of relocating a sewage treatment works to a cavern, with emphasis on the evaluation of environmental sustainability. Wind tunnel tests were carried out with efforts to estimate the prospective odor impact, as well as the wind availability at pedestrian level. It is noted that the sewage odor concentration depends greatly on the dispersion distance and the surrounding topography. The results indicate that when the sewage treatment works is relocated to the cavern, the predicted odor concentration will not cause damage to human health as long as the ventilation shaft is properly placed. In addition, the air ventilation assessments were conducted for both before/after the planned building development. It shows that the new building development at the current plant site will not significantly influence the wind availability at pedestrian level in the surrounding areas. This paper highlights the importance of sustainable development in connection with the environment, and shows that rock cavern development can be an attractive alternative for strategic urban planning in Hong Kong.

1. Introduction

Sustainable development has gradually become, and certainly will continue to be a prevalent topic that attracts worldwide attention. It was officially defined as “development that meets the demands of the present without compromising the ability of future generations to meet their own needs” (WCED, 1987). Essentially, sustainable development is a broad term that comprises a variety of issues that are pertinently related to the long-term development of society. Over the past few decades, many countries and regions have experienced booming economic development. However, it is unfortunate to observe that environmental conditions sometimes have degraded considerably in parallel with the rapid economic development. Consequently, the 1992 United Nations Conference on Environment and Development officially acknowledged the importance of sustainable development and established a specification that consideration of socioeconomic and environmental issues should be fully integrated into strategic development planning and policy (UN General Assembly, 1992).

As for Hong Kong, the imperativeness to pursue sustainable development is incontestable. Hong Kong is well known as a world-class financial center and renowned tourist attraction, which leads to a rapid augmentation of population in the past few years. The population of Hong Kong has reached 7.15 million in 2012 and it continues to grow at an average annual rate of 0.7% (ISD HKSAR, 2013). Hong Kong has a land mass about 1104 km² and less than 25% of the area is developed due to the complexity of geography and governmental policy (GovHK, 2014). Given the above information, Hong Kong is undoubtedly one of the most densely populated cities in the world. The concentrated distribution of the population has deservedly gained benefits with respect to public transport, efficient land utilization and infrastructure construction, etc. Nevertheless, it concurrently reveals difficulties for urban designers to maximally absorb the advantages of the natural environment, for instance, sunlight and natural air...
ventilation (Ng et al., 2004). These features, in some cases, may diminish the achievability of a favorable living condition.

The Hong Kong government is confronted with a number of environment-related difficulties, one of which is the inadequate land supply. Due to the characteristics of hilly topography, the capacity of usable surface land in Hong Kong is extremely limited and it has been identified as a major impediment that prevents Hong Kong to develop steadily. Under the circumstances, the Government actively explores approaches to minimize the disadvantage and strengthen the land supply. In 2011, a feasibility study titled “Enhanced Use of Underground Space in Hong Kong” was completed by the Government, in which a number of governmental facilities were selected to demonstrate the wide adoptability and viability of cavern development in Hong Kong (CEDD HKSAR, 2011).

Meanwhile, another noticeable environmental problem in many cities such as in Hong Kong, which intensively impacts residents’ daily life, is the unfavorable air quality. The perniciousness of air pollution has been reported constantly and the reduced air quality has gradually become a major menace to the public health in Hong Kong (EB HKSAR, 2013). Regardless of the increasing motor vehicles and local power plants, the inadequate porosity and penetrability in urban fabric are generally considered as the major problem that account for the undesirable air environment. Low speed wind or stagnation is often experienced on the street of Hong Kong, which is partly attributed to the inadequate wind permeability in urban design. The densely distributed high-rise buildings inevitably obstruct the wind from penetrating into deep urban canyons, resulting in accumulation of air pollution. Due to the growing awareness of achieving a favorable living condition, the local government has undertaken a series of initiatives to targetedly ameliorate the current conditions.

2. Review
2.1. Background

To support Hong Kong’s sustainable development, a feasibility study on the relocation of a sewage treatment works to the nearby cavern was suggested, which aims to release the existing site for housing construction. As stated in the feasibility report, the nearby mountain named Nui PO Shan, which has a distance of 2 km to the current plant site, was preliminarily selected as the relocation site. This selection integrates the consideration of various factors, including the geological conditions, the land ownership, as well as the impacts on the surrounding environment, nearby traffic network, and the existing sewerage system. Fig. 1 shows the geographic location of the targeted plant site. This paper presents the environmental impact assessments of the proposed project, with emphasis on evaluating the prospective sewage odor impact to the neighboring communities. Furthermore, the air ventilation performance in the proposed residential area is assessed in accordance with the governmental specifications. Firstly, a brief literature review is addressed to illustrate some key aspects that are considered in this study.

2.2. Rock cavern development

The topographic characteristics of Hong Kong are generally described as hilly and mountainous, which demonstrates enormous potential for rock cavern development. It was reported that about 64% of Hong Kong’s land is suitable for developing rock cavern (Roberts et al., 1997). Undoubtedly, for most rock cavern developments, the higher capital costs and extra costs for lighting and ventilation will decrease its adoptability comparing with traditional surface ground developments (Zhao et al., 1996). However, on the other hand, the usage of cavern exhibits predominance in

![Fig. 1. Geographic location of the targeted plant site.](image-url)
terms of environmental quality, safety, as well as land use efficiency (Zhao et al., 1996; CEDD HKSAR, 2011). The history of rock cavern development in Hong Kong originated in early 1990s (Roberts et al., 1997; CEDD HKSAR, 2011). Back then, the construction of Stanley Sewage Treatment Works was deadlocked because no suitable surface site was available. Under such circumstance, the Government decided to build the facility inside a rock cavern since it could constitute a natural barrier to shelter the plant and reduce the adverse impacts to the surrounding environment and communities (CEDD HKSAR, 2011). The Stanley Sewage Treatment Works was the first public facility that ever built inside a man-made cavern in Hong Kong, which offered valuable experience for the following cavern developments such as the constructions of Island West Refuse Transfer Station and Kau Shat Wan Explosives Depot, etc. (CEDD HKSAR, 2011). These successful projects have demonstrated the viability of developing rock cavern in Hong Kong. Notwithstanding, the exploration of the possibility of rock cavern development is still rare. Given the significant shortage of land resource in Hong Kong, it is highly suggested that the Government should strategically explore usable cavern resources in order to enhance land supply.

Worldwide, the employment of the rock cavern to house wastewater treatment works has well-developed. It has been extensively applied in the Nordic Countries since 1960s. These wastewater treatment plants were located adjacent to the local communities. It is stated that these plants have been well integrated with the surroundings, without causing significant adverse effects.

2.3. Odor impact assessment

For sewage treatment plant operators, the effective minimization and abatement of the dispersion of unpleasant odors to the neighboring communities are always regarded as the primary task that can affect the environmental sustainability of wastewater treatment works immediately (Gostelow et al., 2001; Lebrero et al., 2011). The odor disturbance generated from wastewater treatment works has been noted for a long time. Sullivan (1969) addressed that the odor was the main public concern with respect to sewage treatment works. More recently, the complaints about sewage odor have increased progressively from surrounding communities (Lebrero et al., 2011), which is mainly due to the increased awareness and expectations of the local environment, etc. (Gostelow et al., 2001). Therefore, it is of great importance to systematically manage the sewage odor diffusion and reduce the possible odor nuisance in the neighborhoods.

As presented by Vincent et al. (1998), Gostelow et al. (2001), Lebrero et al. (2011) and DSD HKSAR (2014), the composition of odor that associated with wastewater treatment is highly heterogeneous and complex. Among them, hydrogen sulfide (H$_2$S) is generally regarded as the major and a representative component (Koe, 1985). H$_2$S is colorless, unpleasant-smelling, and detrimental to the health (Lebrero et al., 2011). It is stated that the health effect of hydrogen sulfide depends mainly on the concentration and duration of exposure (Glass, 1990). Different concentration of H$_2$S may cause different levels of symptom (Guidotti, 1996), and the tolerance ability may somewhat decline once the recipient is exposed repeatedly. Accordingly, odor legislations in many countries take account of the actual odor impact on the environment, which are represented by the level of odor concentration in conjunction with a limit time of percentage. For instance, in New Zealand, the local environmental regulation stipulates that the odor concentration near the facility perimeter should not exceed 2 OU/m$^3$ during the 99.5% time of a year (Lebrero et al., 2011). Otherwise, some regulations take into account of the odor disturbance by means of indirect methods. For example, the regulation in France sets limits based on dispersion modeling; while Switzerland adopts the feedbacks from the local population (Lebrero et al., 2011).

Practically, for the better control of odor dispersion to be implemented, this problem should first be quantified, which allows plant owners and designers to make decision on the selections of process, processes of modification and the scope of the odor control scheme (Hobson, 1995). However, it is quite a challenge to accurately measure the sewage odor. As addressed by Gostelow et al. (2001), odor measurement can be generally classified into two types: sensory measurement and analytical measurement. Sensory measurements employ the human nose as the detector and the effects of odor are obtained based on the observation of the odor assessor. Analytical measurements, on the other hand, characterize odors in terms of their chemical composition (Gostelow et al., 2001). Both of these methods demonstrate advantages and disadvantages. Sensory measurements tend to be costly, time-consuming and overly subjective. Different results may be derived because the characteristics of individual receptor are highly diverse (Lebrero et al., 2011). In contrast, analytical measurements focus on the chemical or physical properties of odor compounds, which is complicated due to the heterogeneity of odor composition. Nevertheless, analytical measurements demonstrate advantages in terms of objectivity, repeatability and accuracy (Brennan, 1993; Gostelow et al., 2001). More importantly, analytical measurements can be directly correlated to theoretical models regarding odor formation or emission (Gostelow et al., 2001).

Traditionally, there are four widely accepted dimensions for odor measurements, namely the concentration, intensity, character (quality), and the hedonic tone (Gostelow et al., 2001; Lebrero et al., 2011). Among them, odor concentration is the most frequently adopted dimension for odor assessment due to its analytical measurability. The techniques for odor measurements have been well documented by Brewer and Cadwallader (2004), while Gostelow et al. (2001) and Lebrero et al. (2011) presented comprehensive reviews that are related to sewage odor quantification, respectively. As stated by Gostelow et al. (2001) and Stuetz and Frechen (2001), hydrogen sulfide (H$_2$S) measurement gains wide acceptance in sewage odor assessment. This is because H$_2$S is usually the dominant component associated with sewage odors. Generally, the concentration of H$_2$S in the ambient atmosphere of the wastewater treatment works can be easily detected by the hand-hold equipment, such as gold film or lead acetate tape type detector, which have been popularly employed for in situ measurements. Moreover, the sensor array, also known as the “electronic nose”, has been increasingly adopted as an alternative approach for odor quantification. Its capability to measure a wide range of concentration and potential to monitor odor emission in relation to wastewater treatment has been reviewed and discussed by Stuetz et al. (1999). Littarru (2007) addressed the advantages of combining the dynamic olfactometry with “electronic noses” for an objective odor assessment from sewage treatment works.

2.4. Air ventilation assessment (AVA)

As indicated hereinabove, due to the limited usable land resources and growing population, Hong Kong is currently jam-packed with high-rise buildings. The condensed arrangement of buildings has shown advantages with respect to several public services. However, in the meantime, it may lead to inadequate wind availability in urban areas. The lack of wind availability not only prevent the air contamination to be removed effectively, but also give rise to decreased pedestrian comfortability, particularly given the fact that Hong Kong has a hot and humid summer climate.
In 2003, Hong Kong was seriously hit by severe acute respiratory syndrome (SARS) which caused many deaths. One of the main factors that was deemed disadvantageous for the disease management is the insufficient air movement in urban areas. Consequently, the Government initiated a feasibility study to targetedly improve the urban conditions. In 2006, the Government officially adopted the methodology of air ventilation assessment (AVA) and required all publicly funded developments to estimate the prospective performance of air ventilation (Ng, 2009).

As illustrated in the feasibility study, the wind velocity ratio expressed in Eq. (1) can be adopted as the indicator of AVA. In Eq. (1), \( V_p \) is the wind velocity at the pedestrian level (2 m above the ground) and \( V_\infty \) is the wind velocity at the top of the atmospheric boundary layer where it is not influenced by the ground surface roughness (Ng et al., 2004). Presently, a velocity ratio of 0.05 – 0.1 is usually observed in deep urban canyons or congested areas, which is certainly not satisfied (Ng, 2009). The effects of a number of urban parameters such as the air path, building dis-position and building permeability on air ventilation were systematically reviewed and discussed (Ng et al., 2004). Meanwhile, some qualitative guidelines were established to facilitate the urban design with emphasis on air movement. For instance, the orientation of the main air path should be parallel to the prevailing wind direction, which is conducive for the penetration of prevailing winds into urban district. Moreover, inhomogeneous building heights appear to benefit the wind environment at ground levels (Ng et al., 2004; Ng, 2009).

\[
VR = \frac{V_p}{V_\infty}
\]

Hunt et al. (1976) proposed the criteria for the wind effects on people based on extensive wind tunnel experiments. Melbourne (1978) used the maximum gust speeds per annum to establish the criteria for environmental wind conditions. Murakami and Deguchi (1981) presented the experiment-based criteria in terms of instantaneous wind speed averaged over 3 s. Lawson (1990) identified the acceptability of wind conditions in urban environment based on threshold values of wind speed and probability of occurrence. The acceptable threshold of wind speed and frequency of occurrence may vary with respect to different pedestrian activities. As for the methodology, wind tunnel test has demonstrated its applicability in wind engineering and has been widely adopted for the ground-level wind environment assessment in various places across the world (Ishumov, 1978; White, 1992; Williams and Wardlaw, 1992). More recently, owing to the advancement of computer technology, numerical simulation method has been increasingly adopted to assess the wind environment at ground level (He and Song, 1999; Tominaga et al., 2008).

Historically, investigations on pedestrian level wind environment have been carried out by many previous researches. Murakami et al. (1979) firstly observed the changes of air flow pattern and increase of wind speed at ground level that resulted from the construction of a high-rise building. Afterwards, the effects of architectural detailing and corner shape of high-rise buildings on pedestrian-level wind environment were individually investigated by Jamieson et al. (1992) and Uematsu et al. (1992). Stathopoulos and Wu (1995) proposed some general models that correlate wind conditions over streets with building configurations including the spatial density of street blocks, building height, etc. The dependence of building height inhomogeneity (Hang et al., 2012), grouping patterns of housing blocks (Asfour, 2010), and the “wall-effect” induced by alignment of high-rise buildings (Yim et al., 2009) on wind movement at ground level have been explored numerically. Tsang et al. (2012) examined the effects of building dimensions and building separations on pedestrian-level wind environment, while Kubota et al. (2008) established the relationship between building density and pedestrian-level wind velocity based on wind tunnel test. Ng et al. (2011) and Yuan and Ng (2012) presented Hong Kong based studies which took into account of the influences of morphology, surface roughness and building porosity on urban ventilation in urban areas.

3. Methodology and results

The studies presented in this paper are based on the project of relocating Sha Tin sewage treatment works to a cavern. The prospective sewage odor impact to the surrounding areas, as well as the air ventilation performance in the potential developing area (PDA), were experimentally evaluated through wind tunnel tests. This investigation aims to give a predictive assessment of the proposed project in terms of environmental sustainability.

3.1. Validity of wind tunnel modeling

Before the implementation of wind tunnel tests, it is important to validate the applicability of wind tunnel testing for odor dispersion and air ventilation modeling. As addressed in the Environmental Protection Agency (EPA) (Snyder, 1981), “A well-designed and carefully executed fluid modeling study will yield valid and useful information—information that can be applied to real environmental problems – with just as much and generally more credibility than any current mathematical models”. Wind tunnel modeling has demonstrated the potential to be a useful tool to evaluate odor dispersion in the atmosphere. Wind tunnel testing is simulating wind flow at a reduced scale, which has been widely used for air pollution and wind environment studies. The “atmospheric dispersion comparability tests” (EPA, 1985) have shown that wind tunnel velocity profiles match the profile shapes as observed in the atmosphere, and the horizontal and vertical dispersion coefficients are in good agreement with the default dispersion coefficients used in AERMOD/PRIME model (Cimorelli et al., 2005). In addition, the capability of wind tunnel modeling to simulate flow dispersion was further testified by the comparisons with field measurements, which indicated a high level of consistency (Weil et al., 1982; Meroney, 1987; Petersen, 2008). More information on the validity of wind tunnel simulation have been documented by Snyder (1981) and Cermak (1984). Likewise, Durgin (1987) highlighted that wind tunnel testing can provide reliable estimates of pedestrian level wind conditions. The suitability of wind tunnel testing was experimentally validated by Vickery (1992) who carried out a 1:400 scale model study to investigate the pedestrian level wind environment in a small park. The experimentally predicted results were compared to field measurements. The comparison was qualitatively good, with two sets of results showing simultaneous peaks and valleys of gusts. The discrepancy between the experiment-based and field-measured wind speeds over a three month period was only 4% (Vickery, 1992; ASCE, 2011).

3.2. Odor impact assessment

Due to the increasing complaints of odor in the area surrounding sewage treatment works, the plant operators are subject to legal responsibility to mitigate the odor nuisance. Since the assessment work is required at the initial design stage, wind tunnel testing was performed to give a predictive evaluation of the odor impact. In the preliminary study, three premeditated locations (i.e., P1, P2 and P3) were considered for the placement of the ventilation shaft (as shown in Fig. 2). Meanwhile, 20 predetermined measurement locations (T1 through T20) were
carefully selected, which takes account of the influence of topography and meteorology, as well as the local demographic characteristics. Fig. 3 shows the physical model for odor dispersion modeling in the wind tunnel.

Table 1 reveals the information on the discharged gas from the ventilation shaft in reality. Since odor dispersion in the atmosphere depends greatly on the ambient topography, this study adopted a small-scale physical model (1:4000) with a purpose to fully capture all the pronounced topographic characteristics in the surrounding area. Once the geometric scale was settled, the parameters of the discharged gas in the wind tunnel test can be determined accordingly, as tabulated in Table 2.

The experiments were conducted in the boundary layer wind tunnel laboratory at City University of Hong Kong, as shown in Fig. 4. The wind tunnel is a re-circulating flow tunnel with an overall working section length of 20 m. The test section is about 4.2 m in width and 2.0 m in height. The wind tunnel is well constructed with all standard features, such as the expansion, contraction etc. Beyond these, there are some advanced features to enhance the operation of the wind tunnel. For example, a blockage-tolerance roof is incorporated into the wind tunnel with a purpose to minimize the undesirable blockage effect. A number of remote contolled roughness elements are located upstream of the test section, which are convenient for the simulation of boundary layer wind flows.

Due to the inherent requirement of the measurement instrument, the tracer gas for physical modeling in the wind tunnel test

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Table 1 Information on the exhaust gas in reality.

| Components of odor | Dominated by H₂S |
|--------------------|------------------|
| Emission rate     | \( R_e = 596 \text{m}^3/\text{s} \) |
| Exhaust velocity (at the outlet) | \( V_e = 3 \text{m/s} \) |
| Emission area (shaft) | \( A_e = 198.67 \text{m}^2 \) |
| Concentration (at the outlet) | \( C_e = 2.4722 \text{ppm} \) |

Table 2 Information on the exhaust gas in the wind tunnel test.

| Geometrical Scale | 1:4000 |
|-------------------|--------|
| Components of odor | \( C_3H_8 \) diluted by N₂ |
| Emission rate     | \( R_{model} = 2.2 \text{L/min} \) |
| Exhaust velocity (at the outlet) | \( V_{model} = 3 \text{m/s} \) |
| Emission area (shaft) | \( A_{model} = 12.417 \text{mm}^2 \) |
| Concentration (at the outlet) | \( C_{model} = 5300 \text{ppm} \) |
was represented by the mixture of Propane ($\text{C}_3\text{H}_8$) and Nitrogen ($\text{N}_2$). The well-mixed tracer gas is assumed to have a similar density as the ambient air. The density ratio of exhaust gas to the ambient air in the model testing and real condition was 0.968 and 1.000, respectively. The tracer gas in the exhaust outlet was released ascendingly with an angular deviation of 45° to the vertical, which is in accordance with that in reality. The exhaust velocity of the tracer gas in the wind tunnel test was set consistent to the velocity of exhaust gas in real condition. A flow gauge (NGX-PLATON), with a rate resolution of 0.2 L/min, was employed to stabilize the output. For the concentration measurement of tracer gas, the Cambustion HFR 400 fast response flame ionization detector (FID) was utilized, which consists of two major parts: the probe sensor and the data acquisition system. The probe sensor was mounted on a 3-dimension traversing system that allows the sensor to move longitudinally, horizontally and vertically. The data acquisition system is functionally used to covert the measurement information into voltage signals with precision of $\pm 2\%$. Before the test, the measurement system was calibrated and proved to be applicable for the odor dispersion modeling. The approaching wind profiles adopted here were adjusted according to the provisions stipulated in the national design code of China (GB 50009, 2012), the wind code of Hong Kong (BD HKSAR, 2004), and the Japanese wind load code (AIJ, 2004). Fig. 5 shows the vertical wind speed profile, turbulence intensity profile and turbulence spectrum in the longitudinal direction. The vertical wind speed profile in the boundary layer was represented by the power law:

$$U(z) = U_{\text{ref}} \left(\frac{z}{z_{\text{ref}}}\right)^{0.15}$$

where $U(z)$ and $U_{\text{ref}}$ denote the mean wind speed at height $z$ and $z_{\text{ref}}$, respectively. The power law exponent was 0.15. The vertical distribution of turbulence intensity was as follows (AIJ, 2004):

$$I(z) = 0.1 \left(\frac{z}{Z_{\text{C}}}\right)^{-0.05}$$

where $I(z)$ denotes the turbulence intensity at height $z$. $Z_{\text{C}}$ is the gradient height. $\alpha$ is taken to be 0.15. The Karman-type spectrum is used to illustrate the characteristics of turbulence spectrum. (Fig. 5). The simulated boundary layer is about 125 mm thick over the test section in the wind tunnel, which corresponds to 500 m in reality. The atmospheric condition in the wind tunnel was modeled as neutral stratification. It is noteworthy that in real condition, the exhaust gas is not heated or cooled before discharging from the ventilation outlet. Meanwhile, the computed density ratio of exhaust gas to the ambient air is close to unity (ASHRAE, 2001). Given the above information, the buoyancy of the exhaust gas is not fully modeled, which allows using a small-scale model to achieve a high enough Reynolds number (ASHRAE, 2001).

For the physical modeling of odor dispersion, some key experimental parameters, such as the approaching wind speed and measurement heights, need to be determined properly. Hence, a series of tentative tests were conducted in order to resolve the uncertainties of these parameters. As shown in Fig. 6 and Table 3, tracer gas concentrations were measured at test locations T1 and T6, with varied wind speed and measurement height. Clearly, the results of tracer gas concentration were variant with different measurement heights and approaching wind speeds. Higher wind speed was conducive for the dissipation of exhaust gas, which resulted in a lower concentration level. It was found that when wind speed exceeded a certain value (5 m/s), the measured tracer concentration at some locations were close to the background concentration. Meanwhile, due to the consideration of the operability of the wind tunnel facilities, a wind speed above 2 m/s is suggested. The dependence of gas concentration on measurement height is also noticeable, particularly under a low wind speed condition. Therefore, in the following wind tunnel tests, the wind speed was fixed at 3 m/s based on these observations in conjunction with the statistic information of wind in Hong Kong, and all the gas concentrations were obtained at a height level of 5 mm
Cf and ⎟⎟, and the emission rate ratio can be derived accordingly. Substituting all Qm, the C are the characteristic length H, Um are the emission rate in are the approaching wind speed in and model study, the geometric scale was

\[ \text{Geometric scale} = 4000 \]

Fig. 6. Measurement results of pretests.

Table 3

| Wind speed (m/s) | Tracer gas concentration (ppm) |
|-----------------|-------------------------------|
|                 | T6                            | T1                           |
| 1               | 49.1                          | 16.7                         |
| 2               | 11.5                          | 6.89                         |
| 3               | 6.2                           | 4.43                         |
| 5               | 3.61                          | 2.49                         |
| 7               | 2.16                          | 1.57                         |
| 10              | 1.53                          | 0.992                        |

All the tracer gas concentrations were measured at 5 mm above the roofs of the concerned buildings.

above the roofs of the concerned buildings under steady-state conditions.

In order to examine effects of nearby topography on odor dispersion, a 1:4000 physical model, with all significant topography features being properly scaled and reproduced, was installed on the remote-controlled turntable. The measurements in the wind tunnel tests were made for 16 wind directions with an interval of 22.5°. Within each wind direction, the tracer gas concentrations were measured at the test locations where positioned on the downwind region, which is based on the observations that the gas concentration levels on the upwind side of the ventilation shaft were negligibly small.

For the assessment of sewage odor impact, the tracer gas concentrations measured in the model test should be transformed into those in reality. This study adopted the methodology proposed by Snyder (1981) who suggested that the relation of concentration between prototype and model test can be represented as

\[ C_f = C_m \left( \frac{U_m}{U_f} \right) \left( \frac{H_m}{H_f} \right)^2 \left( \frac{Q_f}{Q_m} \right) \]  

(4)

where C_f and C_m denote the normalized concentration in the field and model study, U_f and U_m are the approaching wind speed in the field and model study, H_f and H_m are the characteristic length in the field and model study, Q_f and Q_m are the emission rate in the field and model study. In this study, the approaching wind speed was set identical in the field and model study \( \left( \frac{U_m}{U_f} = 1 \right) \), the geometric scale was \( \frac{H_m}{H_f} = 4000 \), and the emission rate ratio \( \left( \frac{Q_f}{Q_m} = \frac{W_f A_f}{W_m A_m} = \left( \frac{4000}{1} \right)^2 \right) \) can be derived accordingly. Substituting all the obtained values into Eq. (4), it turns out that the normalized concentration in the model test equals to that in the field. Therefore, the normalized gas concentration was derived by dividing the measured gas concentration with that at the emission outlet (i.e., Eq. (5)). Then, the prospective H2S concentration at each measurement location can be determined by multiplying the normalized concentration with source concentration of H2S in reality (i.e., Eq. (6)).

\[ C_{\text{norm}} = \frac{C_{\text{tracer}}}{C_{\text{emission}}} \]

(5)

\[ C_{H2S} = C_{\text{norm}} \times C_{\text{source}} \]

(6)

where \( C_{\text{norm}} \) denotes the normalized tracer gas concentration, \( C_{\text{tracer}} \) and \( C_{\text{emission}} \) denote the tracer gas concentration at measurement location and emission outlet, respectively. \( C_{\text{source}} \) is the source concentration of H2S in reality and \( C_{H2S} \) is the calculated value of H2S concentration at measurement location.

Several previous studies have suggested different threshold values to assess the H2S effect (Leonardos et al., 1969; Ruth, 1986; AIHA, 2013; Guidotti et al., 1996). In this study, the threshold value of H2S was set at 0.005 ppm. Meanwhile, the toxicity of hydrogen sulfide to human health has been addressed by many researchers (Evans, 1967; Beauchamp et al., 1984; Reiffenstein et al., 1992; Guidotti, 1996). It is known that the health effect of hydrogen sulfide depends greatly on the concentration level. Evans (1967) stated that most organ systems are susceptible to the effect of hydrogen sulfide. Low level of concentration (0.15–10 ppm) may cause sensorial offensiveness, while high level of concentration (above 50 ppm) can lead to irritation or even paralysis (Beauchamp et al., 1984; Reiffenstein et al., 1992; Guidotti, 1996).

Fig. 7 illustrates the tracer gas concentrations at T17 and T18 which were identified as the most hazardous locations. It can be observed that when the ventilation shaft was placed at P3, the results at T17 and T18 were markedly larger than those for the locations at P1 and P2. The most critical cases were found at T17 when wind originated from 45°, 67.5° and 90°, resulting in H2S concentration of 0.043 ppm, 0.032 ppm and 0.027 ppm, respectively. These results have overly surpassed the threshold value of H2S concentration. In such circumstances, the existence of hydrogen sulfide may be easily recognized (Beauchamp et al., 1984). Hence, P3 was not recommended for the placement of the ventilation shaft.

Examples of measurements from other test locations are shown in Fig. 8. As it indicates, the obtained H2S concentrations are generally small. Mostly, H2S concentration was derived with a value under 0.008 ppm. At measurement location T1, the highest value of H2S concentration was found around 0.002, which is below the H2S threshold. Under such circumstances, the odorous H2S is hardly detectable. As Fig. 8 shows, in most cases, the H2S concentrations for the placement of the ventilation shaft at P2 are somewhat lower than the H2S concentrations for the placement of the ventilation shaft at P1, which suggests that P2 is more preferable for the placement of the ventilation shaft.

3.3. Air ventilation assessment (AVA)

According to the statement in the governmental specifications, any publicly-funded projects should undertake an air ventilation assessment. In this study, since directly usable wind field information in the potential developing area was not available, a site wind availability study was required to determine the local wind field. The local wind characteristics can be obtained through a small-scale (1:4000) wind tunnel test. Subsequently, for the evaluation of wind environment at pedestrian-level, a detailed air
ventilation assessment study with larger length scale (1:800) model test was carried out, in which the velocity ratio that demonstrates the proportion of wind speed at pedestrian level to that at the boundary layer height was selected as the indicator.

In the site wind availability study, a 1:4000 scale physical model was adopted, which aims to fully reproduce all the significant topographic features in the concerned area. The long-term field measurements (from 01/2005 to 11/2010) from Waglan Island weather station (WGL) were used as the reference wind information. The wind field at the center of the potential developing area (PDA) was measured as a function of wind direction, with an increment of 22.5° (16 wind directions in total). Within each test direction, mean wind speed and turbulence intensity were obtained at 9 height levels corresponding to 15 m, 50 m, 100 m, 150 m, 200 m, 250 m, 300 m, 400 m and 500 m in full scale. Fig. 9 compares the wind rose diagrams corresponding to Waglan Island weather station and the potential developing area, respectively. It can be clearly observed that the wind speed and direction distributions at these two locations are distinctly different, which is due mostly to the pronounced topographic effects in the vicinity. The wind speed measurements from the potential developing area are somewhat smaller than those from Waglan.
Island weather station, particularly in summer season. It is possibly attributed to the existence of hilly terrain in the southern part of Hong Kong that coincidentally blocks the prevailing southerly-originated summer wind from penetrating into the urban areas. As revealed in Fig. 1, the alignments of valleys on both sides of the potential development area are shifted with an included angle about 45° to the geographic north direction, which demonstrates inevitable influence on the local wind characteristics. Fig. 9(c) and (d) indicates that the privileged wind directions in the potential development area are parallel to the alignment of nearby valleys.

It is said that for any wind-related problem, the well-established wind profiles are of considerable importance. In the 1:4000 scale model test, the obtained 16 wind speed profiles were separated into three types according to the shapes of the profiles. Therefore, for the 1:800 scale detailed test, the approaching wind profiles were adjusted accordingly to maintain the shapes of the profiles and fit the similarity theory (as shown in Fig. 10). Since two different scale models were used in this study, wind speed scaling factors were introduced to ensure the consistency of wind speed between these two wind speed profiles. The wind speed scaling factor was derived as

\[ F = \left( \frac{u_z}{u_{\text{ref}1}} \right)_{1:4000} \cdot \left( \frac{u_{\text{ref}2}}{u_z} \right)_{1:800} \]

Fig. 9. Wind roses obtained at (a) (b) Waglan Island weather station; (c) (d) center of the Potential Developing Area (PDA).

Fig. 10. Adjustments of approaching wind speed profiles for 1:800 scale model test.

where \( F \) denotes the wind speed scaling factor, \( u_z \) is the mean wind speed measured at height \( z \) (i.e., where \( z \) is equivalent to 15 m, 50 m, 100 m, 150 m, 200 m, 250 m, 300 m, 400 m and 500 m in full scale). \( u_{\text{ref}1} \) and \( u_{\text{ref}2} \) denote the reference wind speed measured in the 1:4000 and 1:800 scale model test, respectively. The reference wind speed was determined as the averaged mean wind speed measured at 9 heights in the two scale model tests. Hence, in order to maintain a constant mean wind speed value at each height (\( u_z \)), the scaling factor was derived as
the ratio of \( \frac{u}{u_{\text{ref}}} \). Directional wind speed scaling factors are illustrated in Table 4.

Fig. 11 shows the arrangement of all the test points in the 1:800 scale detailed study. The circle represents the assessment area where structures and topographic features were reproduced with a length scale of 1:800. For the convenience of data analysis and results discussion, the assessment area was subdivided into 7 zones (as confined by the dotted line). As stated in the “Technical Guide for Air Ventilation Assessment for Developments in Hong Kong” (PD HKSAR, 2006), the test points are generally classified into two types: the perimeter test points and the overall test points. The perimeter test points (with capital letter P in Fig. 11), as its name indicates, are mainly positioned at the boundary of the potential development area, particularly at junctions of roads leading to the potential developing area, main entrances, as well as the boundary corners. The results from these points can be used to determine the “Site spatial average velocity ratio (SVR)”, which reflects how the newly-constructed project would impact the wind environment in the immediate vicinities. The overall test points are principally placed in open spaces, streets, and locations where pedestrians frequently assess. All the test points were separated into 7 groups based on their geographic locations. For the discussion of air movement behavior, this study adopted the velocity ratio as the indicator which denotes the ratio of wind speeds at pedestrian level to that at boundary layer height. Subsequently, the concept of velocity ratio was upgraded by associating with the direction probability distribution and the wind speed scaling factor. It is then represented by

\[
VR_w = \sum_{i=1}^{16} F_i \times VR_i
\]

where \( F_i \) is the occurrence probability of wind originating from direction \( i \); \( VR_i \) is the velocity ratio of wind from direction \( i \), which can be calculated by multiplying the directly measured velocity ratio by the speed scaling factor. According to its definition, it is shown that the higher the velocity ratio, the less likely would be the impact of the proposed development on the wind availability (DB HKSAR, 2006). It is noted that due to the complexity of topographic and meteorological characteristics in Hong Kong,
quantitative benchmarks are not provided by the Government in the current framework of air ventilation assessment. Nevertheless, the results offer an indication of potential wind conditions that are likely to occur on a relatively frequent basis.

The results of dimensional velocity ratio for each zone for both with/without development scenarios are illustrated in Fig. 12. For zone A, it is evident that the newly-proposed development will inevitably affect the local air movement. As shown in Fig. 12(a), a majority of the scatter points are distributed on the left-upper side of the reference line, which implies a reduction of velocity ratio after the development. At some locations, an increase of velocity ratio is observed, which is possibly attributed to the “channeling effect” that is generated by the alignment of new buildings. However, since zone A is the potential developing area where the proposed constructions are mainly concentrated, the influence on velocity ratio is considered unavoidable. As for zone B, the results indicate that the influence is noticeable at some test locations, particularly where are located adjacently to the potential developing area. With the increase of distance, such influence gradually diminishes. Fig. 12(c) comprises the results generated from zones C, D, E, F, G which are located in the surrounding areas. It is noteworthy that the developed communities are mainly occupying within these regions which are of considerable importance. It can be observed that the results in Fig. 12(c) can be desirably fitted by the reference line \( y = x \), which indicates the proposed development will not significantly affect the wind environment at these neighboring regions.

Fig. 13 exhibits the distribution of weighted velocity ratio \( (\text{VR}_w) \) in each zone for both annual and summer cases and the statistic analysis results are illustrated in Table 5. As shown in Fig. 13 and Table 5, the velocity ratios for summer are generally lower than those for the whole year. This is possibly due to the shelter effect that demonstrated by the continuously distributed mountains in the southern part of the Hong Kong island. The results of \( \text{VR}_w \) show a high level of consistent with the results of directional velocity ratio. For zones A and B, the proposed development may lead to a reduction of velocity ratio, whereas for the rest of the zones, the deviation of velocity ratios between before and after the development are hardly distinguishable.

According to the results presented in Table 5, the annual mean velocity ratio \( (\text{VR}_w) \) in each subzone was determined as 0.26 for zone A, 0.32 for zone B, 0.29 for zone C, 0.23 for zone D, 0.29 for zone E, 0.30 for zone F and 0.21 for zone G; whereas for summer, the mean velocity ratio \( (\text{VR}_w) \) was derived as 0.22 for zone A, 0.27 for zone B, 0.22 for zone C, 0.23 for zone D, 0.24 for zone E, 0.24 for zone F and 0.19 for zone G, respectively. The site spatial average velocity ratio was obtained as 0.29 for annual and 0.24 for summer.

It is noted that low velocity ratios are mostly obtained on the streets that are perpendicular to the main wind direction, which can be ascribed to the inadequate air permeability in urban design. In this case, several suggestions are provided to achieve a better wind environment at pedestrian level.

1. Staggered arrangement of buildings is deemed conducive for air ventilation so that the streets behind the buildings could be able to receive the wind penetrating from the gaps in the front row.
2. The building height should be inhomogeneous and stepped down towards the orientation of the prevailing wind, which allows more wind to travel down to the ground level.
3. Open spaces should be created and organized appropriately, which can benefit the circulation of wind in the built areas.
Fig. 13. Comparison of results $VR_w$ with/without the development.
### Table 5

| Zone | No. | Velocity ratio (VR<sub>∞</sub>) | Annual |        |        |
|------|-----|-------------------------------|--------|--------|--------|
|      |     | mean | max | min | mean | max | min |
| A    | 94  | 0.26 | 0.40 | 0.14 | 0.22 | 0.33 | 0.10 |
| B    | 35  | 0.32 | 0.51 | 0.18 | 0.27 | 0.42 | 0.13 |
| C    | 22  | 0.29 | 0.48 | 0.14 | 0.22 | 0.34 | 0.11 |
| D    | 17  | 0.23 | 0.32 | 0.17 | 0.23 | 0.30 | 0.13 |
| E    | 18  | 0.29 | 0.42 | 0.19 | 0.24 | 0.30 | 0.17 |
| F    | 8   | 0.30 | 0.47 | 0.12 | 0.24 | 0.32 | 0.11 |
| G    | 9   | 0.21 | 0.27 | 0.15 | 0.19 | 0.23 | 0.14 |

### 4. Conclusion

Given the sparsity of land resource in Hong Kong, the local government actively explores approaches to enhance the land supply in order to support Hong Kong’s sustainable development. Among which, the suggestion of relocating public facilities into caverns is widely accepted.

This study examined the feasibility of relocating a sewage treatment works into caverns, with emphasis on experimentally assess the prospective sewage odor impact, as well as the wind availability at pedestrian level. It was found that the odor concentration depends greatly on the dispersion distance, measurement height and approaching wind speed. Also, the existence of pronounced topographic effects in the vicinity may influence the measurements. The results indicate that the hydrogen sulfide associated with sewage treatment works will not adversely affect the wellbeing of residents in the areas surrounding the site of the new plant. When the ventilation shaft is placed at P2, the predicted concentration of hydrogen sulfide at receptor locations is generally below the threshold concentration value, which implies that the presence of odorous hydrogen sulfide is negligible.

For the air ventilation assessment, the wind velocity ratios in the tests before/after the planned building development were investigated, respectively. It is noted that in the areas surrounding the potential development site, the new building constructions will not significantly affect the wind availability at the pedestrian level.

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