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ARTICLE

Influence of Waterside Buildings' Layout on Wind Environment and the Relation with Design Based on a Case Study of the She Kou Residential District

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ABSTRACT

It is important to improve residential thermal comfort in the high dense cities, in which wind environment is crucial. Waterside buildings take an advantage of micro-hydrological-climate in summer that should be used to enhance residential thermal comfort especially in the subtropical region. In order to propose design approaches according to the outdoor thermal comfort of the waterside residential, a case study of Shenzhen She Kou residential district has been made. It focused on various factors that could have influence on wind environment for improving thermal comfort. Using wind velocity ratio (ΔRi) criterion, factors of building development volume, building direction and layout pattern, open space arrangement etc. have been broadly explored using FLUENT simulation. To planning parameters, the Floor Area Ratio (FAR) is significantly influence wind environment, the smaller FAR is better. To the vertical layout of the buildings, multi-storey layout and multi-storey & sub high-rise mixed layout would provide better wind environment. To the horizontal layout, the determinant is better than the peripheral. Other factors such as the buildings' direction towards the road, buildings' height, and open space setting, have influence on wind environment yet. In general, the more benefit of design layout for wind breezing, the better wind environment it could get.

1. Introduction

It is well known that wind environment is crucial to community health due to air pollution and heat island [1-4], which are serious problems in the high-dense cities such as the Shenzhen, one of the four top metropolises in China. However, situation could be changed with professional concentrations and broad studies [5-7]. Some studies considered indoor ventilation taking advantages of nature wind [8], some focused on ventilation mechanism by using a proper technique [9], while most concerned on studying relations of spatial variation and nature ventilation for benefiting design in taking water profit is underlined [10-11]. Studies have been done on the use of water body to ease heat effects focusing on water cooling mechanism [12-15]. Song et al. studied the on-shore building distribution on

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the wind environment at a pedestrian level by developing turbulence models taking hydraulic characteristics of water body into account. Their study found that the height of the frontal building and the layout of buildings have influence on the wind environment at a pedestrian level [15]. A study of Yu et al. proved that the buildings distribution and layout of a riverside residential block have influence on outdoor thermal comfort [11]. It can be said that the influence of water body on the waterside residential design should be considered for achieving good ventilation in the hot regions.

Shenzhen is a coastal city located in the southern mainland China adjacent to Hong Kong. The city has been through a fast urbanization process since being pointed as the window of Chinese economic reform and opening up [16]. Currently, the city is fostered as one of the four famous Chinese metropolises with a high dense population. Correspondingly, deterioration of the outdoor environment because of air pollution and heat islands has become a severe problem that spoiling the city's sustainability [17-19]. Recently, from the viewpoint of urban planning and design, the improvement of the inferior outdoor thermal environment has been paid attention in which a quantitative understanding is necessary. The city's north part occupies mountain-terrains while the south part faces ocean. The She Kou residential district situated in the southern part of the city, towards the Shenzhen Bay with a broad great view to the sea. The district has been developed with a high residential value in the time from the 1990s to the 2010s. Most blocks were developed in the last century without considering outdoor thermal comfort. Even to those developed in this century, design attentions have been paid more on the sea views rather than thermal comfort. It is obviously wasting water source for cooling effects on the outdoor thermal comfort. In this paper, efforts have been done on revealing the relation of buildings' layout and the wind environment to the She Kou residential district. The result is supposed to give design approaches of future renovation respecting wind environment for thermal comfort. For doing the study, techniques of wind simulation and criterion of judging the wind environment have been studies and applied.

Wind tunnel experiment is traditionally used in the wind environment study [20], however, computational fluid dynamics (CFD) are frequently used recently due to convenient operation as well as low cost [20-21]. In studying the interaction between buildings and physical spaces with wind environment, authored works have done by using CFD simulations [10-11,14,22-24]. They proved that CFD model simulation is helpful in the initial stage to outline a "qualitative impression" of the wind environment, in which CFD were conducted to analyze the meso/micro wind environment at the urban scale and air polluted outcomes. Ashie et al. used the CFD simulation to explore the effects of building blocks on the thermal environment in Tokyo. Their results noted that air temperatures around the park and river areas are much lower than the bulky building areas and argued that is just the bulky buildings obstructing wind from the sea [24]. Yu et al. study also found that agreeing more winds passing through the residential area would take more advantages from a water body [11].

In this paper: a case study conducted in the Shenzhen She Kou residential district is illustrated. The study used CFD simulation to get ΔR_i, which is a difference of wind velocity ratio of windward and leeward. The study employs the ΔR_i criterion to judge quality of wind environment due to different buildings layouts. It explored the influences of various factors relating to the building and residential design on the wind environment. The results would propose guidelines for waterside buildings' layout to achieve thermal comfort in summer to benefit a waterside residential development.

2. Waterside Residential Area

Layout of waterside buildings usually takes the water into account especially considering view advantages. However, with the crisis of energy and global warming, more attentions have been paid on thermal comfort in which water advantages on wind environment needs to consider. For such reason, the layout of waterside buildings should be particularly designed not only to the view but also on the thermal comfort. In order to figure out design approaches in respect of thermal comfort, this study takes the Shenzhen She Kou residential district as a case to investigate the buildings' layout factors, as such the density scale, the road and building's direction, the height of building, and pattern of buildings' arrangement, influencing the wind environment.

2.1 She Kou Residential District

Figure 1 shows geographic location of the She Kou residential district, it is in the very south part of the Shenzhen Nan Shan administration area, its southern side faces the Shenzhen Bay. The initial development of the district was in 1979, but most residential blocks were built in the late 1990s and the earlier 2000s. With the area industrial vanishing, the district is gradually renewed by the high-value residents. Currently, the She Kou residential district is becoming a big community containing many residential blocks with high properties. The local topography of land-sea contrast in the She Kou causes significant wind variations of the district.

Figure 1. Location of the Shenzhen1She Kou residential district

Figure 2 shows the 3-D model of the district. The district is enclosed by four artery roads that are the R1, R2, R3, R5, the R1 and R3 are the north-south direction road, while the R2 and R5 are the east-west direction road. Besides, there is another artery road with the north-south direction is the R4. Generally, there are twelve east-west direction and nine north-south direction roads including the above five artery roads. This may mostly decide the district wind environment. In the Figure 2, it can also be seen there are thirty-four residential blocks with various urban functions, which are important to define the buildings' layout.

Figure 2. Location of the Shenzhen1She Kou residential district

2.2 Layout of the She Kou Residential District

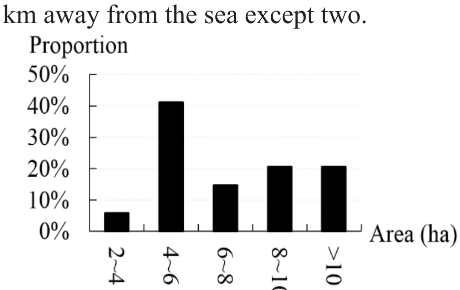
Many design factors related to buildings' layout could influence the wind environment of a residential block, in which the planning parameters and the buildings' vertical and horizontal layout are mostly concerned.

In order to analyze wind environment of the She Kou residential district, factors of planning parameters related to the layout design of all the blocks in the district have been studies and shown in the Table 1. The values of the thirty-four blocks' buildings, floor area ratio (FAR), aspect ratio, and distance to the sea to each block have been got. To the thirty-four blocks, the variation of every factor is rather large.

Table 1. Factors related to the building's layout of each block

No.	Area (ha)	FAR	Aspect ratio	Distance (km)
1	4.90	1.4	0.71	1.88
2	5.66	2.0	0.76	1.97
3	9.24	1.3	1.29	2.02
4	8.02	1.6	1.10	1.62
5	4.56	2.1	1.06	1.70
6	7.03	1.3	1.72	1.81
7	10.4	2.0	0.89	1.35
8	3.27	1.4	1.20	1.45
9	3.93	1.8	1.53	1.54
10	6.00	1.7	2.13	1.62
11	11.10	1.9	1.14	1.37
12	9.70	1.7	0.53	2.08
13	9.31	2.6	0.46	1.9
14	4.80	2.2	0.30	1.64
15	4.87	3.5	1.03	1.62
16	5.55	2.1	1.33	1.41
17	8.57	1.9	1.41	1.14
18	7.92	2.1	1.36	0.97
19	7.60	1.7	0.69	0.74
20	4.81	1.6	0.71	0.83
21	14.00	1.8	1.08	0.95
22	10.61	2.0	0.94	0.63
23	8.19	1.6	1.62	0.56
24	5.28	1.5	1.89	0.48
25	8.21	1.8	3.07	0.3
26	4.09	2.0	1.71	0.36
27	4.36	2.1	4.80	0.17
28	4.91	2.1	2.04	0.22
29	4.40	1.8	0.32	0.41
30	4.90	3.2	0.43	0.07
31	5.08	1.9	2.86	0.05
32	17.28	1.8	1.00	0.28
33	13.23	1.5	1.23	0.71
34	12.87	1.9	0.99	0.59

Based on the Table 1, factors of the area, FAR, aspect ratio, and the distance to the sea of the thirty-four blocks have been compared in the Figure 3. It is found that many residential blocks are 4 ~ 6 ha, few has a small area of 2 ~ 4 ha although others are larger that have an area above 6 ha, some even larger than 10 ha. It is also found that more than 50% blocks have a value of 1.5 ~ 2, 30% ones have 2.0~2.5, however, less is either larger than 2.5 or smaller than 1.5. To the aspect ratio, around 35% blocks have a value of 0.75 ~ 1.25, less than 30% have a 1.25 ~ 2, slightly more than 20% have a 0.3 ~ 0.75, less have a value larger than 2. To distance of the block to the sea, most blocks locate less than 2 km away from the sea except two.



a) Area

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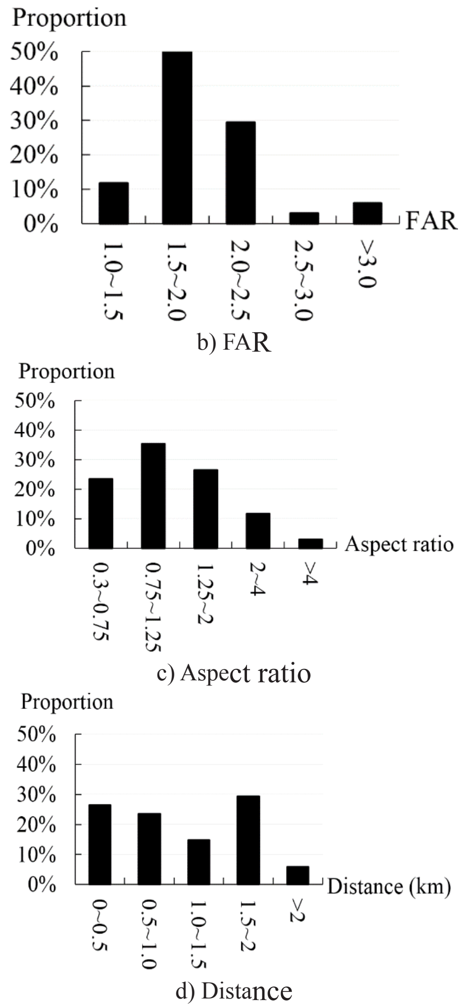


Figure 3. Proportion distributions in terms of various layout factors

In addition, vertical and horizontal layout of the buildings according to each block have been studied. Firstly, classification has been made according to vertical layout in terms of the buildings' height variation of a block. According to the National Standard of the GB 50016 [25], three classifications were defined to the blocks, namely the multi-storey block (most buildings in the block having a height <27m), the high-rise block (most buildings in the block having a height >54m), and the mixed block (most buildings having either above heights). Specific classification to the vertical mixed blocks were further made, which are multi-storey (height <27m) & high-rise (height >54m), multi-storey & sub high-rise (27m < height < 54m) & high-rise, and multi-storey & sub high-rise. Only two blocks can be classified to the high-rise vertical layout. In terms of the horizontal difference, three layouts can be defined, namely the determinant, peripheral, and the comprehensive that has both the determinant and the peripheral. According to horizontal difference, the multi-storey layout can be further classified as the slab and the slab & column point, and then the determinant, peripheral, and the comprehensive. The classification of the vertical and horizontal layout of all the blocks is shown in the Table 2. To the mixed vertical layout, no determinant horizontal pattern exists. The slab multi-storey determinant, the multi-storey & sub high-rise comprehensive are the mainly layouts used in the She Kou residential district. Whereas, the slab multi-storey comprehensive, the slab & column point multi-storey comprehensive, the multi-storey & sub high-rise & high-rise comprehensive, are rare. Only two blocks have the high-rise vertical layout in different two horizontal layout, the determinant and the peripheral.

Table 2. The classification of the layout to the She Kou residentials

Layout				Numbers
Vertical		Horizontal		
Multi-storey		slab	determinant	6
			peripheral	2
			comprehensive	1
		slab & column point	determinant	3
			peripheral	2
			comprehensive	1
Mixed	multi-storey & high-rise	peripheral		2
		comprehensive		3
	multi-storey & sub high-rise & high-rise	peripheral		3
		comprehensive		1
	multi-storey & sub high-rise	peripheral		2
		comprehensive		6
High-rise		determinant		1
		peripheral		1

3. Simulations

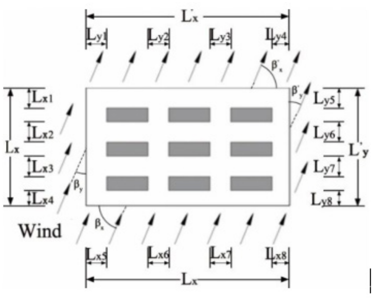
CFD simulation is proven effective in analyzing wind environment [21]. Therefore, this study using the FLUENT software to analyze the influence of the buildings' layouts on wind environment. First, the criterion of assessing the wind effect has been studied, then the simulation model has been present and discussed.

3.1 Assessment

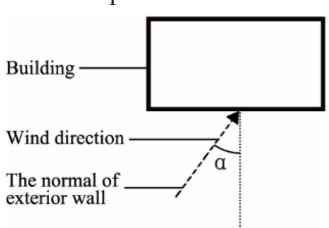
There are many criteria to assess wind environment such as the Beaufort scale, wind speed probability, and wind velocity ratio [26-27]. As the thermal comfort is not emphasized in this study, the wind velocity ratio is employed because of intuitionally reflecting the wind effects. In the study, the wind velocity ratio of the pedestrian height is calculated to each block using the following formula. R means the wind velocity ratio, R_{in} represents the wind velocity ratio of wind entering the block, while R_{out} represents the wind velocity ratio of wind leaving the block, ΔR_i means the deferential of R_{out} and R_{in}. In the formula, V_0 is approaching wind velocity value (usually taking wind value of the pedestrian level without impact of an obstacle), V_{in} is the incoming wind velocity value while V_{out} is the outgoing wind velocity value.

$$\Delta R_i = R_{out} - R_{in} = \frac{V_{out}}{V_0} - \frac{V_{in}}{V_0} \quad (1)$$

Although ΔR_i can be used to assess the wind effects of a block, it is difficult to use for designers. Therefore, a spatial ratio of wind velocity (SRW) is developed to measure the differential of incoming wind and outgoing wind of a residential block. As the study is going to provide good wind environment in summer to subtropic area, it is supposed that the more the wind blows the better effect it brings, which means a higher spatial ration of wind velocity needs. Figure 4a presents the measurement of spatial ratio of wind velocity according to the incoming and outgoing wind speed. The result of wind environment is relied on the differential of the $L_{out} = L_{y1} + L_{y2} + L_{y3} + L_{y4} + L_{y5} + L_{y6} + L_{y7} + L_{y8}$ divided by the whole L_{out} and the $L_{in} = L_{x1} + L_{x2} + L_{x3} + L_{x4} + L_{x5} + L_{x6} + L_{x7} + L_{x8}$ divided by the whole L_{in}. The Figure 4b shows how to calculate an angle α to present relation of the wind direction and building.



a) Calculation of spatial ratio of wind velocity



b) Angle of wind projection and building

Figure 4. Measurement of spatial ratio of wind velocity

3.2 Simulation

The study used the FLUENT software to simulate wind environment. Song et al. has found that the RNG *k-ε* and the Realizable *k-ε* model integrated in the FLUENT is more precise to simulate a waterbody's wind environment. However, the result made by a Realizable *k-ε* model is closer to the wind tunnel experiment if considering the variation of spatial tendency as shown in the Figure 6 [15]. Therefore, this study used the Realizable *k-ε* model to do the simulation.

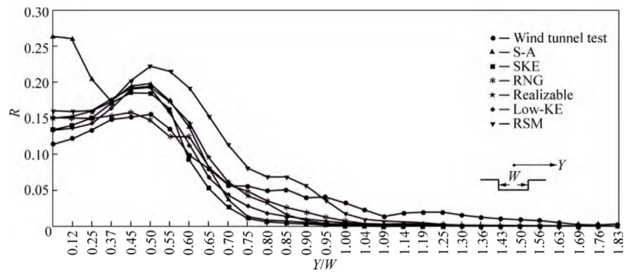


Figure 5. Simulation results of different CFD models vs tunnel experiment [15]

Figure 6 shows the 3-D model of the She Kou residential district including the nearby mountain. Correspondingly, the computational domain size was set including a rather larger area than the 3-D model based on the Franke suggestion for avoiding the airflow disturbance at the model boundary [28].

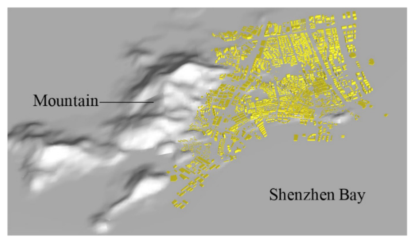
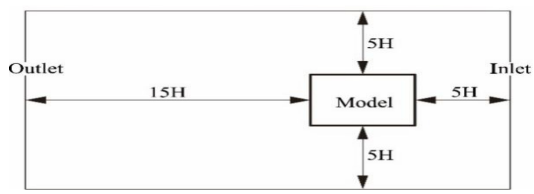
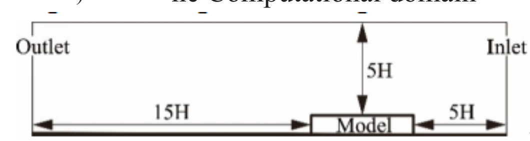


Figure 6. Simulation model of the She Kou residential district

Figure 7 shows the computational domain size to the simulation. H is the highest building's height of the simulation site. According to the Frank, five times H was set to the inlet boundary and fifteen times H was set to the outlet boundary, in which H is the height of the highest building in the model.



a) Plan of the Computational domain



b) Section of the Computational domain

Figure 7. The computational domain

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For simulation, the wind speed and direction to the She Kou residential district have studied. The site-specific wind roses of annual year have been explored using the fine climatic grid data of the point 1 and 2 nearby the She Kou district as shown in the Figure 8. According to the data of the point 1 and 2, the non-typhoon winds in 16 directions of an annual summer were calculated. The approaching wind velocity is 3.25m/s with a south-west to south direction. A high-resolution was set to the She Kou residential district that is 5 m x 5 m of the plan and 0.03 m of the elevation dimension, a three-dimensional mesh with a resolution of 30m was set to the nearby mountain.

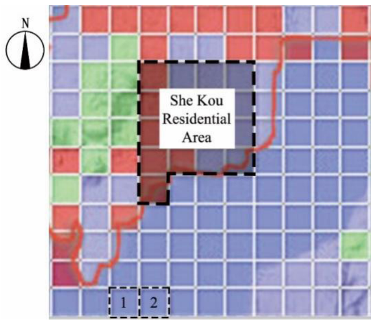

Figure 8. The fine climatic grid of the Shenzhen She Kou

3.3 Results

Figure 9 presents the simulation result of the She Kou residential district. The wind environment is not good as plenty calm wind areas exist. However, the south-north direction roads have better wind environment, which provides more wind permeability to the district. The wider the road is the better the wind effect it provides. The further an east-west road away from the sea, the worse wind effect it gives. Moreover, the two parks inside the district also provide good wind effect to the district.

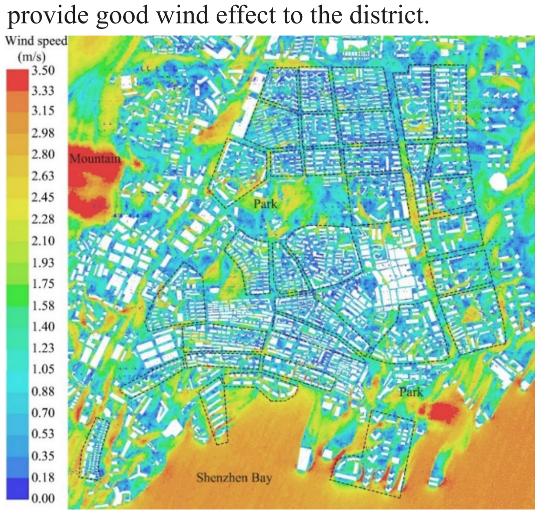

Figure 9. The wind velocity map of the She Kou residential district

4. Analyses

Based on the Figure 9, data of wind velocity collected for analyses of buildings' layout factors influencing the wind environment have been made. Firstly, relations of the wind environment and the factors of planning parameters, such as the block area, FAR, aspect ratio, and the distance of the block to the sea have been discussed; then, the influence of vertical and horizontal layout of a block on the wind environment has been studied, following by the study of buildings' arrangement influence.

4.1 Influence of Planning Parameters

The block area, FAR, aspect ratio, and the distance of the block to the sea are essential factor to determine a building's layout. Therefore, Person correlations of these factors and ΔR_i (differentia of wind velocity ratio of the outgoing wind and the incoming wind) have been firstly analyzed. Barely significant correlation has been found except FAR, which is significantly correlated to ΔR_i with a negative correlation value of 0.43 ($p<0.05$). It indicates a dense residential block has worse wind environment.

Table 3 illustrates the Person correlations of ΔR_i and the FAR, aspect ratio, and distance of a block to the sea in terms of the area difference. It found that only FAR has significant influence on ΔR_i. However, it is worth noting that a higher negative correlation value exists to all indicating a dense block has worse wind environment. It is also interesting to note that only the large area blocks have a negative correlation of the distance to ΔR_i, indicating the farther the large block away the sea, the better wind environment it could get, but not to the small and the medium blocks. Table 4 illustrates the Person correlations of ΔR_i and the Area, FAR, and distance of a block to the sea in terms of the aspect ratio difference. No significant influence exists. Unlike the area and FAR, the tendency of the distance with ΔR_i in terms of aspect ratio is changed.

Table 3. Person correlations of the factors and ΔR_i in terms of the area

Factors	Small (S< 5 ha)	Medium (5 ha <S <10 ha)	Large (S >10 ha)
FAR	-0.61*	-0.21	-0.75
Aspect ratio	0.06	0.01	0.07
Distance	0.19	0.27	-0.55

*. Correlation is significant at the 0.05 level.

Table 4. Person correlations of the factors and ΔR_i in terms of the aspect ratio

Factors	E-W long (the east-west length/the south-north length > 1.25)	Approx. square (0.75 < the east-west length/ the south-north length < 1.25)	S-N long (the east-west length/the south-north length < 0.75)
Area	0.25	0.25	0.05
FAR	-0.58	-0.33	-0.31
Dis-tance	0.42	-0.21	0.51

Table 5 illustrates the Person correlations of ΔRi and the area, FAR, and aspect ratio in terms of difference of the block distance to the sea. Except the FAR, no significant correlation exists. A higher significant correlation exists of the FAR to ΔR_i but only to the blocks far away from the sea. The tendency of the area, FAR, aspect ratio influencing ΔR_i is not the same due to the different distance, sometimes is positive sometimes is negative.

Table 5. Person correlations of the factors and ΔR_i in terms of the distance

Factors	Close (D < 0.5 km)	Middle (0.5 km <D < 1.5 km)	Far (D > 1.5 km)
Area	0.20	-0.09	0.17
FAR	-0.62	0.13	-0.64*
Aspect ratio	0.29	-0.03	0.29

*. Correlation is significant at the 0.05 level.

Summarily, the above factors of planning parameters have less influence on the wind environment except FAR. A higher FAR could bring worse wind environment. An interesting note is that the tendency of the distance with ΔR_i is not same unlike the other factors with ΔR_i. If not considering the distance influence, the area and aspect ratio is usually positively correlated with ΔR_i whereas the FAR is negatively correlated. Significant negative influence has been found to the blocks having a rather smaller area also to those far away from the sea. A positive correlation of FAR and ΔR_i has been found only to the blocks having a middle distance to the sea but not reaching significant. But, significant negative correlation of FAR and ΔR_i has been found to the blocks closer or far away from the sea. The results show that a larger area and higher aspect ratio is better to wind environment, but a smaller FAR is better, however, this could change if taking the distance into account.

4.2 Vertical Layout Influence

As building height has influence on wind distribution [29], the vertical layout on wind environment is studied. Figure 10 shows the ΔR_i changes in terms of different vertical layouts as presented in the Table 2.

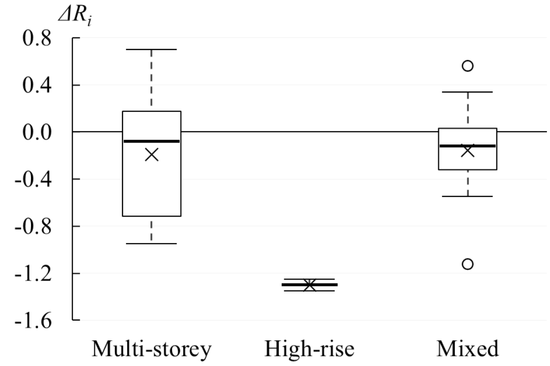

Figure 10. ΔR_i in terms of vertical layout difference

It is found that the high-rise layout is worse to wind environment as having the lowest ΔR_i although only have two cases. To the multi-storey and the vertical mixed layout, it is hard to say which one is better as the difference is small. Therefore, further analyses were made to the mixed vertical layout. Three types of the mixed vertical layout were analyzed in the Figure 11. The Type A stands for the blocks of multi-storey & high-rise mixed, the Type B for the blocks of multi-storey & sub high-rise & high-rise mixed, Type C for the blocks of multi-storey & sub high-rise mixed. The Type C (blocks of multi-storey & sub high-rise mixed) has better wind environment as having a higher ΔR_i whereas the Type A (blocks of the sub high-rise & high-rise mixed) has worse. The Figure 11 also compared the different mixed types with the multi-storeys. The wind environment of multi-storey is better than that of the Type A and the Type B but worse than that of the Type C. A possible reason is that the sub high-rise buildings are usually having column-point horizontal layout to benefit wind permeability.

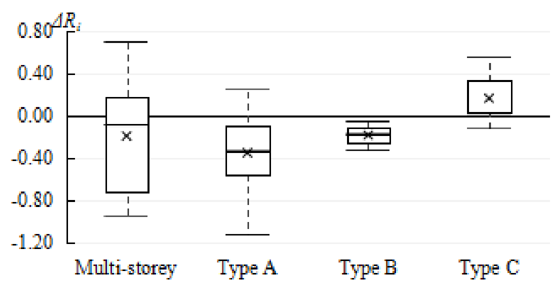

Figure 11. ΔR_i in terms of mixed vertical layouts and the multi-storey

4.3 Horizontal Layout Influence

Apart from the vertical layout influence on wind environment, variation of the horizontal layout is also influence on wind environment yet. In order to avoid interference of the vertical layout, the horizontal layout influence

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was analyzed in terms of vertical layout. The Figure 12 shows the influence of the horizontal layout due to the multi-storey ones.

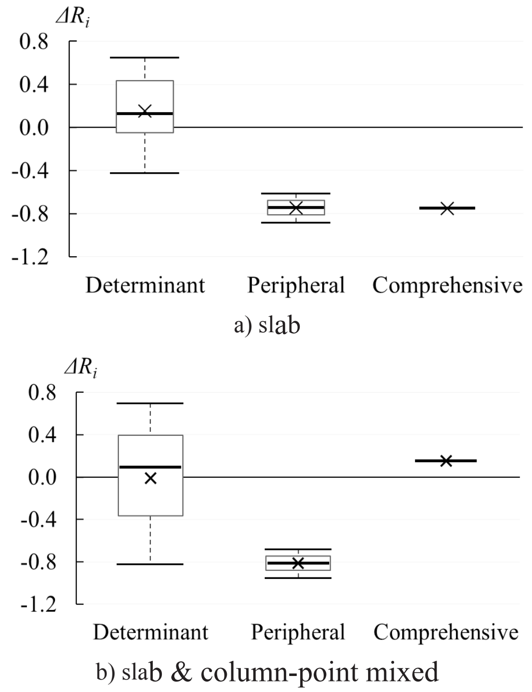

Figure 12. ΔR_i of the variation horizontal layout according to the multi-storey

To the slab buildings, the determinant layout has better wind environment than the peripheral and the comprehensive, however, this is not correct to the slab and column-point mixed. To the slab mixed with the column-point buildings, the comprehensive layout has better wind environment but only having one case. It must point out that the result to the comprehensive layout is not supported by enough cases, only one case exists no matter to the slab or the slab mixed with the column-point. In general, the residential blocks having a determinant layout have better wind environment than those having a peripheral layout.

To the vertical mixed layout, Figure 13 shows the ΔR_i of the peripheral and comprehensive horizontal layout. There is not much difference in terms of the different vertical layout. The comprehensive horizontal layout has better wind environment than the peripheral, nevertheless, the study cases are rather limited. In terms of the high-rise vertical layout, only two cases exist. One has the determinant horizontal layout but the other has the peripheral horizontal layout. According to ΔR_i, the peripheral layout has better wind environment. Although the study case is quite limited, the result is an agreement with the previous study [10].

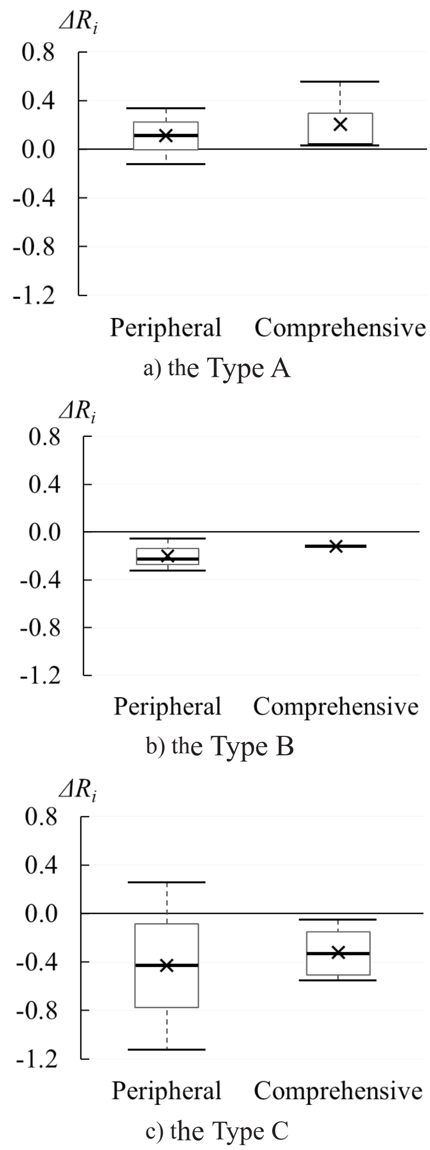

Figure 13. ΔR_i of the various horizontal layout according to the vertical mixed layouts

4.4 Building Arrangement

In addition to the above factors, other factors also related with the buildings' layout such as buildings arrangement along the block boundary, the buildings' height, and the arrangement of open spaces, likely have influence on the wind environment.

4.4.1 Buildings along the Boundary

According to the section 3.1, the spatial ratio of wind velocity (L_{out} - L_{in}) related with the buildings' arrangement along the block boundary may decide the wind effect. Person correlations have been made to the L_{out} - L_{in} and ΔR_i, a significant positive correlation of 0.78 has been found, indicating the higher the spatial ratio (L_{out} - L_{in}), the better the wind environment is achieved. Enhancing the difference of the L_{out} and L_{in} would provide a better wind environment.

In addition the spatial ratio, the wind projection angle to the block is also another determinant on the wind environment. Figure 14 shows the influence of the wind projection angle on the ΔR_i. The wind projection angle is the angle of the windward and building exterior wall normal. It can be seen the best wind projection angle of the windward and building exterior wall normal is 45° as it has the highest average ΔR_i, which indicates a good wind environment could be got. Whereas, the worst wind projection angle is 67.5°.

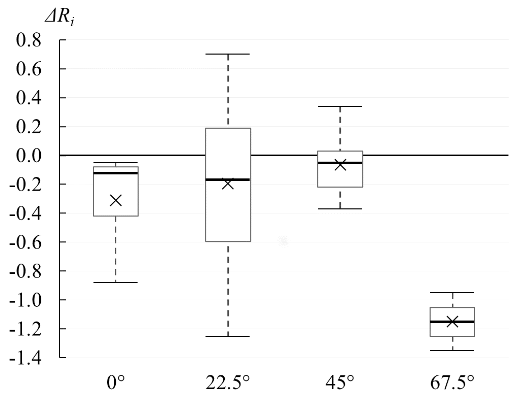

Figure 14. ΔR_i due to the wind projection angle to the block

According to the wind projection angle, the angle of the boundary along building with the road must be analyzed. From the Figure 2, it found that most roads in the She Kou residential district are in either an east-west or a south-north direction. Then in the Figure 15, two kinds road situation are included. To the east-west road, the best angle of the boundary along building with the road is 22.5°as it has a 45°wind projection angle, however, the worst is the building perpendicular to the road as it has a 67.5°wind projection angle. To the south- north road, the worst is the building parallel to the road as it is a 67.5°wind projection angle, but, the best angle of the boundary along building with the road is still 22.5°. Summarily, to the east-west road, the building is better set parallel to the road rather than perpendicular, and when the angle is in 0° to 22.5°, the bigger it has a better wind environment could achieve, but when the angle is over 22.5° in a range of 22.5° to 90°, it is just opposite. However, to the south-north road, the situation is reverse to the east-west road. No matter how, the best angle of the boundary along building to the road is 22.5° as it has a 45°wind projection angle.

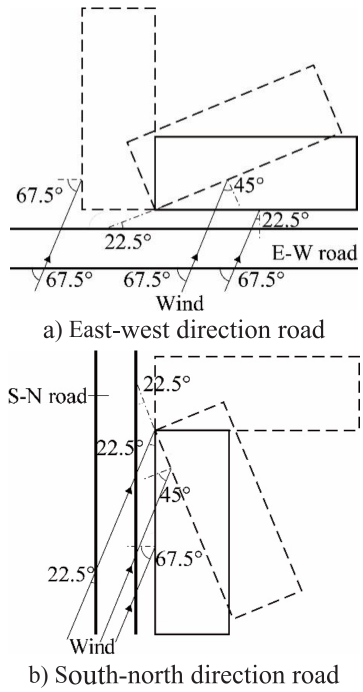

Figure 15. ΔR_i due to the angle of the boundary along building with the road

4.4.2 Buildings' Height

Buildings' height could influence wind environment too [30]. Therefore, the buildings' height influence has been discussed in the study. Figure 16 shows ΔR_i due to four different buildings' height arrangement, which are A' – frontal building low & back high, B' – frontal building high & back low, C' – middle building lower & frontal and back similar high, D' – middle building higher & front and back similar low. Here, the frontal means the building closer to the sea while the back means the building far away the sea, the middle means the building is between the frontal and the back. It can be seen that the best one is the A' whereas the worst is the D', while the B' is slight better than the C'. The result indicates that the buildings' height with the frontal low & back high is better to wind environment, but the difference is not too much.

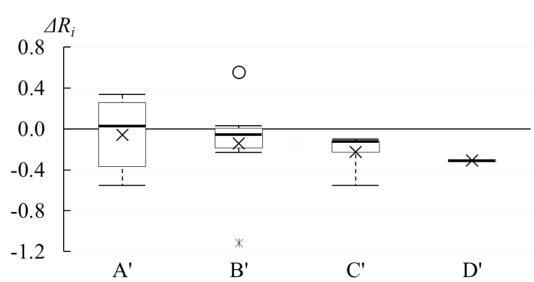

Figure 16. ΔR_i in terms of the arrangement of buildings' height of a block

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4.4.3 Open Spaces

Open spaces usually have benefits on the physical environment without exception of wind [10-11]. Figure 17 shows the ΔR_i according to three setting locations of an open space in a block based on their location to the sea, which are the close, the middle, and the far. A rather good wind environment could achieve when the open space is far away from the sea except few cases. The close open space has lower ΔR_i indicating it is bad to wind environment although the difference is not much with the middle.

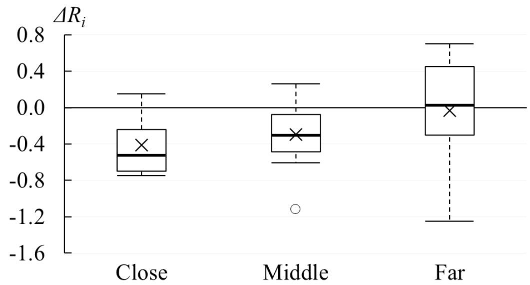

Figure 17. ΔR_i due to the distance of an open space to the water

5. Discussion and Conclusions

In order to provide residential outdoor thermal comfort in the subtropical region, this paper illustrated the influencing factors correlated with the buildings' layout design to a residential block on wind environment through case study on the Shenzhen She Kou residential district.

The result showed 1) Road design is important as can attract waterside wind passing through the residential blocks, the south-north direction roads are better in the Shenzhen She Kou residential district as the roads direction coincident with wind breezing; 2) Generally, FAR has significant negative correlation with ΔR_i, especially to the smaller blocks and the blocks closer to the sea. A smaller FAR block usually has better wind environment; 3) Comparing different vertical layouts, the mixed block of multi-storey & sub high-rise provides a better wind environment; 4) Comparing different horizontal layouts, the determinant layout has best wind environment except to the high-rise blocks; 5) According to the buildings' arrangement, the best wind environment is achieved by the frontal low & back high blocks that means the closer buildings to the sea should be lower than those farther away. The best wind projection angle is 45°as having a higher ΔRi, which needs the boundary along buildings have a 22.5° to the either E-W or S- N road. To the E-W road, it is better for buildings parallel to the road, however, it is opposite to the S-N road; 6) It is better to set an open space farther away from the sea to get a better wind environment. A reason might be the farther away from the sea part is the leeward side of the block, which has been proven to benefit wind spreading [10].

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