Effect of Morphological Indicators on the Pedestrian Level Wind of the Existing Workers Villages in Shanghai

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Abstract. The workers villages are typical residential type during Shanghai's urbanization built from the 1950s to the 1980s. Due to changes in the urban environment and climatic circumstances, the workers villages have inadequate natural ventilation and difficulty in dispersing pollutants, putting residents' health at risk. In the context of urban renewal, it is necessary to clarify the effect of building morphological indicators on pedestrian level wind, especially in such old residential communities. In this paper, 100 workers villages representatives were gathered by GIS. Their summer ventilation conditions were simulated using the CFD solving the LES turbulence equation. The correlation between 9 morphological indicators and 2 pedestrian level wind indicators was obtained quantitatively by Pearson analysis and regression analysis. The result shows increasing the building coverage of 0.94% in the workers villages, the ratio of the area of the static wind in summer will increase subsequently by 10%. The results highlight the importance of considering morphological indicators to enhance the wind environment, and provide suggestions for the environmental transformation of communities with similar characteristic in the high-density city.

Keywords: The workers villages · Pedestrian level wind · Morphological indicators · Static wind · Linear regression

1 Introduction

The rising density and height of buildings within cities, along with the rapid development of urbanization, has had an impact on the original natural climate. The concentrated expansion of urban centers in coastal parts of China has exhibited a high degree of saturation, and dense building clusters in cities can decrease air flow and have a direct impact on urban wind speed [1]. Excessive wind speed and inadequate ventilation can both cause changes in the thermal environment, which can impair human comfort in outdoor settings and population health [2]. Uneven wind speed distribution also contributes to the accumulation of dangerous gases and air pollutants like sulfur dioxide [3], as well as major air pollution concerns like haze, which can cause respiratory ailments and reduce daily visibility [4].

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Because of the dense population of Shanghai's core city, convective winds are severely impeded, and significant sections of the building complex are windless [5]. Due to changes in construction requirements and changes in the surrounding environment, which is poorly ventilated and prone to heat and pollutant buildup, some old neighborhoods built in the last century have wind speeds of less than 1 m/s in parts of the interior of residential areas, causing problems for pedestrians. By the end of 2011, the existing workers villages in Shanghai had a total housing area of around 170 million square meters, accounting for 31% of the total area [6]. Workers villages have also been an important objective of Shanghai's urban renewal plan, which is focusing on urban regeneration and traditional old district renovation. In order to mitigate the heat island effect and promote sustainable urban growth, the rehabilitation of ventilation conditions in old neighborhoods in high-density cities has become a critical issue.

The goal of this research is to improve the outdoor wind environment in old communities, which are represented by the workers villages. Building coverage and height, for example, have been demonstrated to have a considerable impact on regional ventilation performance in studies [7], which will affect to some extent the comfort and safety of wind environment in outdoor pedestrian spaces [8]. The outdoor wind environment of the old communities represented by the workers villages are studied, quantitative indexes are introduced, and the relationship between building form and outdoor wind environment is presented qualitatively and quantitatively through the calculation of an idealized geometric form model and multiple regression analysis, and applied to the optimization of existing buildings.

2 Methodology

In the present study, a total of 100 neighborhood models of workers villages in different regions of Shanghai were collected via GIS and Rhino. The morphological indicators of the neighborhood models were calculated by the plug-in Grasshopper. Then, wind environment simulation of 100 workers villages and their surroundings were calculated, and the data obtained were filtered and processed by the plugin ladybug and eddy3D. It is an interactive interface on rhino/grasshopper platform based on openFOAM open source computational fluid dynamics (CFD) library. Solving LES equation has the advantages of fast and accurate. It has been proved to be adaptive in complex urban environment [9]. Eventually, correlation analysis and regression analysis were carried out between morphological and environmental factors to eliminate loosely related factors and clarify their correlations. Scatter diagrams were also created to verify the correlation. The overall process is shown in Fig. 1.

2.1 Geography and Climate of the Research Object

The rapid urbanization process is currently a big issue all over the planet. With such a large population, there is a great demand for natural resources, which stimulates city development at a high density. The high-density built-up area in Shanghai causes the wind speed to drop year after year, reducing the comfort of pedestrian wind environments

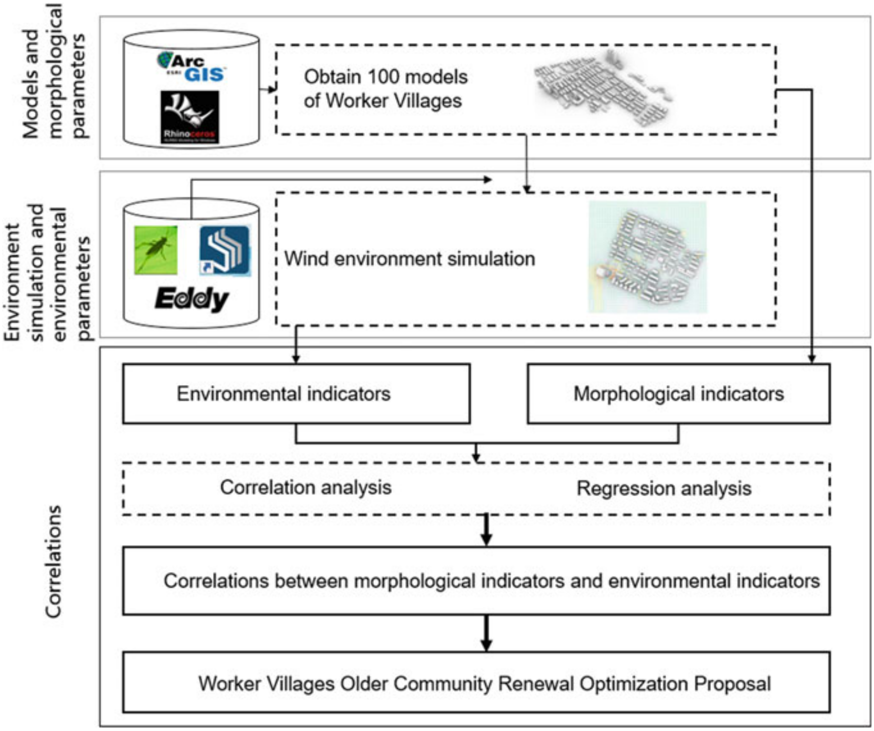

Fig. 1. Overall process

[10]. The workers villages were constructed earlier, and the wind environment was not taken into account during building, resulting in poor overall comfort.

In this study, about 100 existing old workers villages in Shanghai were selected as samples. The models were obtained and processed through software such as ArcGIS and Rhino to obtain a model library of the research objects.

2.2 Morphological Indicators

Eight morphological indicators were used in the study to quantitatively describe the varied spatial characteristics of workers villages: building coverage ratio, building volume density, floor area ratio, average building height, roughness length, height dispersion, frontal area index, and sky view factor.

Among these eight morphological indicators, the significant impact of average building height has been proven in numerical experiments [11], and its increment led to larger air change rates at roof and targeted canyon monotonously [12]. A study took place in Hong Kong [13] emphasis that frontal area index is to be a better morphological factor in depicting the wind environment at the pedestrian level. Illustration and equation of various indicators are showed in Fig. 2 and Table 1. Each indicator's abbreviations are included in the table and will be used later in the text.

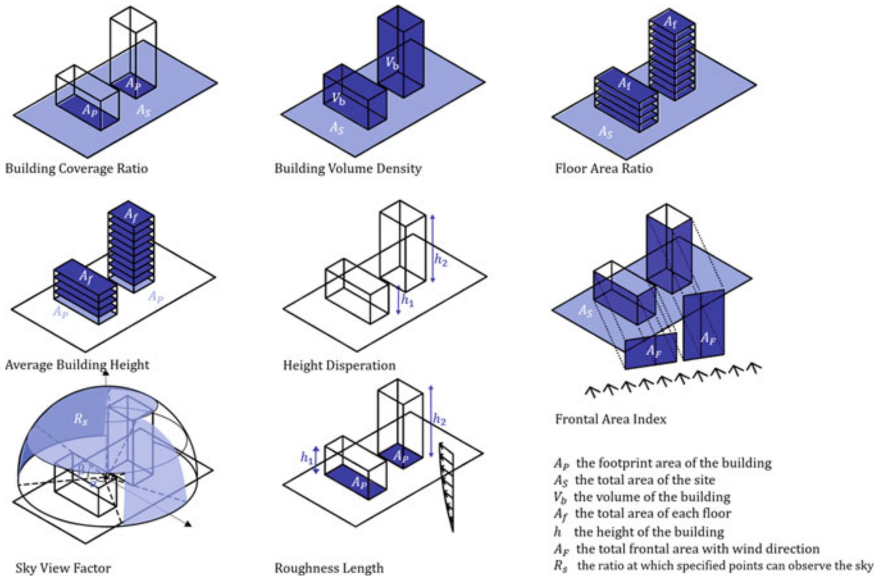

Fig. 2. Illustration of morphological indicators

2.3 Pedestrian Level Wind Indicators

In consideration of the characteristics of wind environment in the community, the geographical features of its location in high-density urban areas, where wind speeds greater than five meters rarely occur, and comfort under different pedestrian behavior, this paper puts forward an approximate division threshold for Shanghai workers villages. Static wind area is classified as areas where wind speed is smaller than 1 m/s, and areas with wind in 1–5 m/s and >5 m/s are defined as comfort wind area and strong wind area relatively. The area ratio of static wind area is used to describe the proportion of uncomfortable pedestrian areas in the community in the total area, especially in summer.

Other than static wind ratio, this paper also uses standard deviation to express the overall dispersion degree of each calculation point of wind speed in the whole test model site. Due to the construction of high density, the uniformity of air flow will be affected. The lower the wind speed dispersion, the more stable the overall wind speed distribution and the weaker the wind turbulence, resulting in a better wind environment. The unreasonable layout of building corners and building spacing will lead to a sudden increase in wind speed, leading to higher wind speed dispersion, resulting in unsafe or comfortable circumstances. Equation of various indicators are shown in Table 2.

2.4 Pearson Correlation Coefficient and Linear Regression

Pearson correlation coefficient is used to expose the correlation of indicators, whose output range from −1 to 1, and 0 means no correlation. Negative value means negative correlation and positive value means positive correlation. The larger the value to

Table 1. The equations used in the calculation of building morphological indicators

Morphological indicators	Unit	Calculation equation		Theoretical meaning
Building Coverage Ratio	%	$BCR = \frac{\sum_{i=1}^{n} A_p}{A_s}$	[14]	Building intensity in an area
Building Volume Density	m	$BVD = \frac{\sum_{i=1}^{n} V_b}{A_s}$	[15]	BVD indicates total volume of buildings divided by the total area
Floor Area Ratio		$FAR = \frac{\sum_{i=1}^{n} A_f}{A_s}$	[16]	Use intensity of construction land
Average Building Height		$\overline{h} = \frac{1}{n}\sum_{i=1}^{n}(\frac{A_f}{A_s})$	[17]	Vertical building intensity
Roughness Length	m	$z_0 = \overline{h} \cdot \frac{C_d}{0.74} \cdot (1 - \frac{z_d}{\overline{h}}) \cdot \frac{FAI}{BCR}$ $z_d = \overline{h} \cdot (1 + A^{-BCR} \cdot (\mathrm{BCR} - 1))$	[18]	the efficiency of transforming the energy of average wind speed into turbulent motion in the boundary layer [19]
Height Dispersion	m	$\sigma = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(h_i - \overline{h})^2}$	[20]	discrepancy of building height in the site
Frontal Area Index		$FAI = \frac{A_F}{A_s}$	[21]	a building's frontal area over a site's area
Sky View Factor	[0–1]	$SVF = 1 - \sum_{i=1}^{n} sin^2 \beta_i (\frac{\alpha_i}{360^o})$	[14]	the ratio at which specified points can observe the sky

Table 2. The equations used in the calculation of building environmental indicators

Environmental indicators	Representative/calculation equation	References	Theoretical meaning
Static wind ratio	Ratio of areas with wind speed less than 1 m/s to the total area	[22]	Proportion of static wind accumulation area
Wind-speed standard deviation	$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \mu)^2}$	[16]	Variation of wind speed

both sides, the stronger the correlation is. Pearson correlation coefficient's capability of achieving this is accomplished through centralization and cosine calculation.

Furthermore, linear regression explains the higher correlation and is able to generate the results of linear regression equation. Correlation analysis is the basis and premise of regression analysis, and regression analysis is the deepening and continuation of correlation analysis. Due to the existence of some samples with wide orders of magnitude, directly processing ignores some independent variables with extremely small value level may cause an inaccurate fitting result, normalization is introduced to avoid dimensional effects. Normal distribution of data is kept and zoomed to the range of 0 to 1.

3 Results and Analysis

After completing the wind environment simulation of 100 real models, this paper firstly makes a qualitative description of the overall and individual workers villages, along with description of data distribution, and then makes a quantitative analysis using Pearson correlation and linear regression.

3.1 Geographical Distribution and Analysis of Individual Cases

Figure 3 shows the geographical distribution of selected models, which display a circular distribution centered on urban area. It is obvious that most of the tested workers villages in Shanghai don't display an optimistic performance in comfortable wind area—in the figure, a large number of points is biased to orange and red.

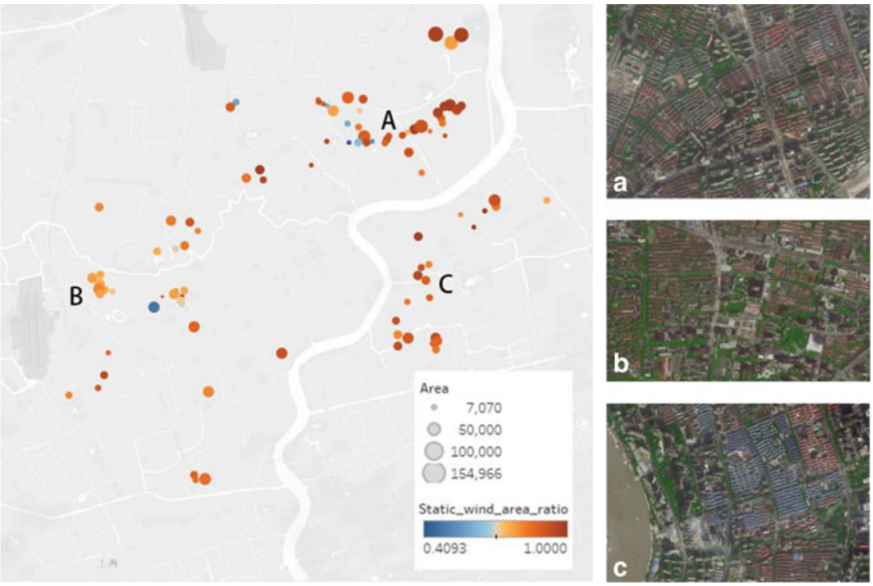

Fig. 3. Distribution of tested new workers villages and corresponding static wind area ratio and site area sizes, **a**–**c**, three typical areas with concentrated points are concerned.

The static wind ratio of the 3 areas (Fig. 4), on a mesoscale, is different from the overall condition. Lighter colored points are gathered in Area B than A and C, also showing the characteristics of homogenization, which means it has a better pedestrian level wind environment than area A and C in summer. Different geographical locations, preliminarily assumed, will alter specific morphological aspects, hence influencing the wind environment. Specifically, three areas have a varied overall tendency in terms of construction orientation. A and C are oriented primarily southeast, whereas B is oriented north–south. Besides, FAI and other morphological indicators will be affected by different orientations, which alter the wind environment. As the satellite image display, BD of surrounding sites of area B (Fig. 3b) is lower than which of the other plots (Fig. 3a, c), indicating that the overall building density of the two plots B is also much lower than that of the other plots.

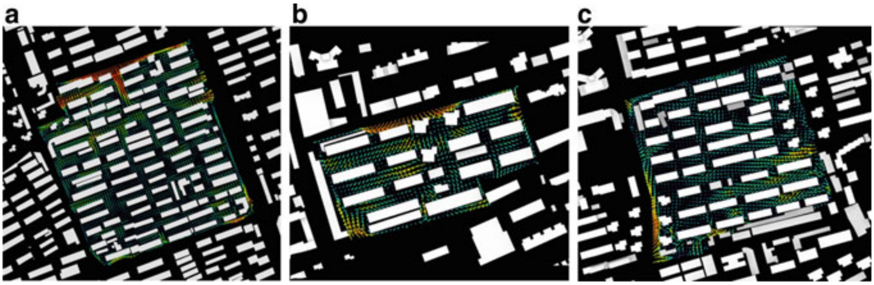

Fig. 4. Wind simulation of 3 typical cases corresponding 3 areas mentioned in Fig. 3

Some preliminary conclusions can also be obtained from the micro scale. In addition to the variances in morphological aspects induced by different geographical locations, the layout of workers villages has an impact on the wind environment. The determinant dominates most workers villages, although there are other combinations of determinant and point group or enclosed organization. Because the point group and determinant combination in area B (Fig. 4b) is more extensive, the area of static wind is comparatively small. As a result, it is clear that this arrangement is worthy of note and can be used as a component in the optimization and reconstruction of future workers villages.

3.2 Descriptive Analysis of Data

The morphological characteristics, BCR, and SVF have a more concentrated distribution with fewer outliers, as seen in Fig. 5. BVD, z_0, σ, and FAR are all right skewed, with more outliers. The distribution of static wind area ratio is more concentrated than the distribution of wind speed standard deviation among the environmental performance indexes, and the distribution of wind speed standard deviation is more scattered.

From the box-and Whisker plot for all indicator result distribution of wind simulated models (Fig. 5), it can be seen that the median of the static wind area ratio of the workers villages is about 0.87, and the vast majority of the values fall between 0.6 and 1, which means that the vast majority of the workers villages' summer static wind area ratios is above 60%. Thus the overall wind environment of Shanghai workers villages is unsatisfactory.

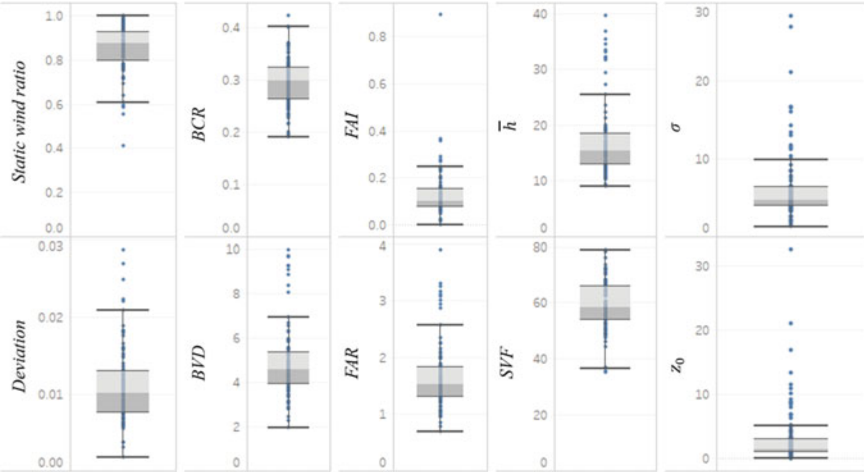

Fig. 5. Box-and Whisker plot for all indicator result distribution of wind simulated models, dots represent each number result, the left and right boundaries of each subgraph represent the lower and upper limit value respectively, and left and right boundaries mean the lower and upper quartile, and central dividing line represent median.

3.3 The Correlation Between Spatial Morphology and Wind Environment

Comprehensive scatterplots, data distribution of every indicator and relevant calculated Pearson correlation coefficient are shown in a matrix visualization (Fig. 6). In the matrix, the darker red the color is, the higher the positive correlation between the two indicators is explained, while the darker blue the color is, the higher the negative correlation between the two indicators is explained, corresponding correlation coefficients are also marked, and the range of which is 0–1. Through comprehensive analysis, it can be preliminarily determined that: (1) Within environmental indicators, Static wind ratio strongly correlated to wind deviation. (2) Between environmental and morphological indicators, **i.** Site area size strongly correlated to deviation, following a linear negative correlation. **ii.** BCR, BVD, FAR weakly correlated to static wind ratio, and all present positive correlation. **iii.** FAI and wind deviation show slight correlation, following a positive correlation. **iv.** z0 and deviation show weak correlation, following a positive correlation.

To further obtain quantitative relationships between morphological and environmental indicators, linear regression is conveyed. Based on its result, Fig. 7 shows the correlation and significance (P value) of coefficients. In general, the results are as follows: (1) Unfortunately, all data have a low degree of fitting. It illustrates that the real model's wind environment is more complex, as a result of numerous elements acting together, and that the link with specific morphological markers is weak. (2) Wind speed standard deviation and site area size show the highest regression coefficient among all indicators, which is close to 0.3 (Fig. 7a) and respond great significance ($P < 0.0001$) It remains to be explored why the site size is negatively related to wind-speed standard deviation. (3) Relatively speaking, BCR indicates higher correlation than other morphological indicators, but merely does it explain the regression relationship between the two indicators so far.

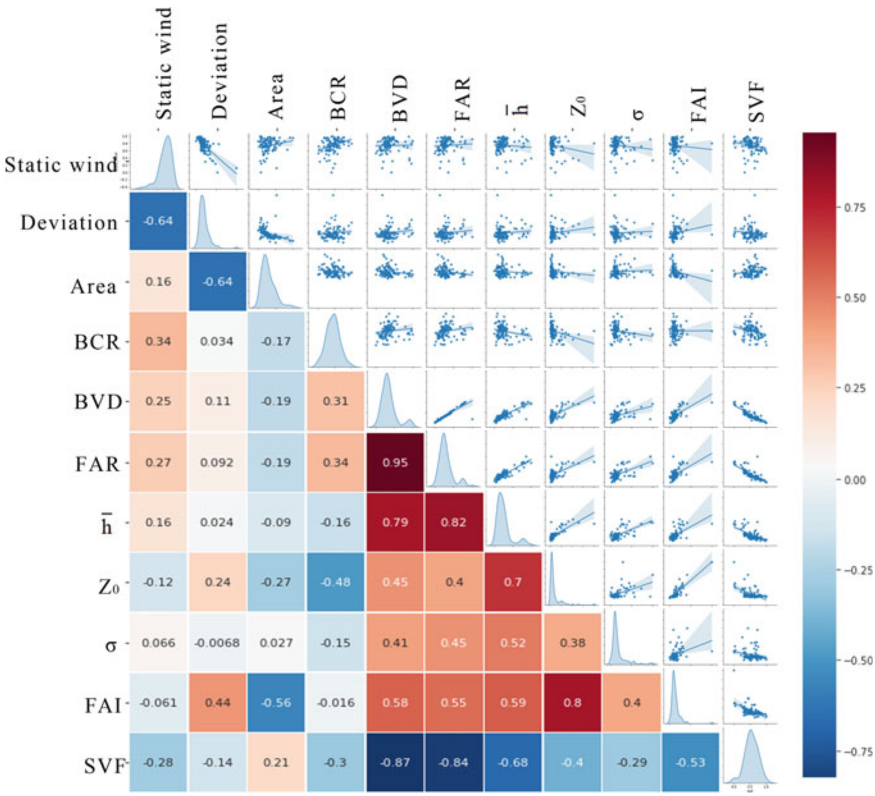

Fig. 6. Pearson correlation and scatterplots matrix

The regression analysis shows that increasing the building coverage of 0.94% in the workers villages, the ratio of the area of the static wind zone in summer will increase subsequently by 10%, with a site area of 1.4–18.1 hectares, a building volume density of 1.97–9.97, and an average building height of 8.9 to 39.6 m. In the workers villages with a site area of 1.4–18.1 hectares, a building volume density of 1.97–9,97, and an average building height of 8.9 to 39.6 m, the building site area is reduced by about 1.5 m^2 and the summer wind speed dispersion increases by 10%.

4 Conclusions

In this study, numerical simulations were used to analyze the wind environment and verify the influencing factors for 100 workers villages neighborhoods in Shanghai. Correlation analysis and regression analysis of wind environment indicators are conducted. The following findings provide researchers and planners with a deeper understanding of pedestrian level wind conditions in residential areas in Shanghai and similar climatic regions.

(1) The correlation analysis reveals that, among the morphological indicators, building coverage, building volume density and volume ratio correlate more significantly with

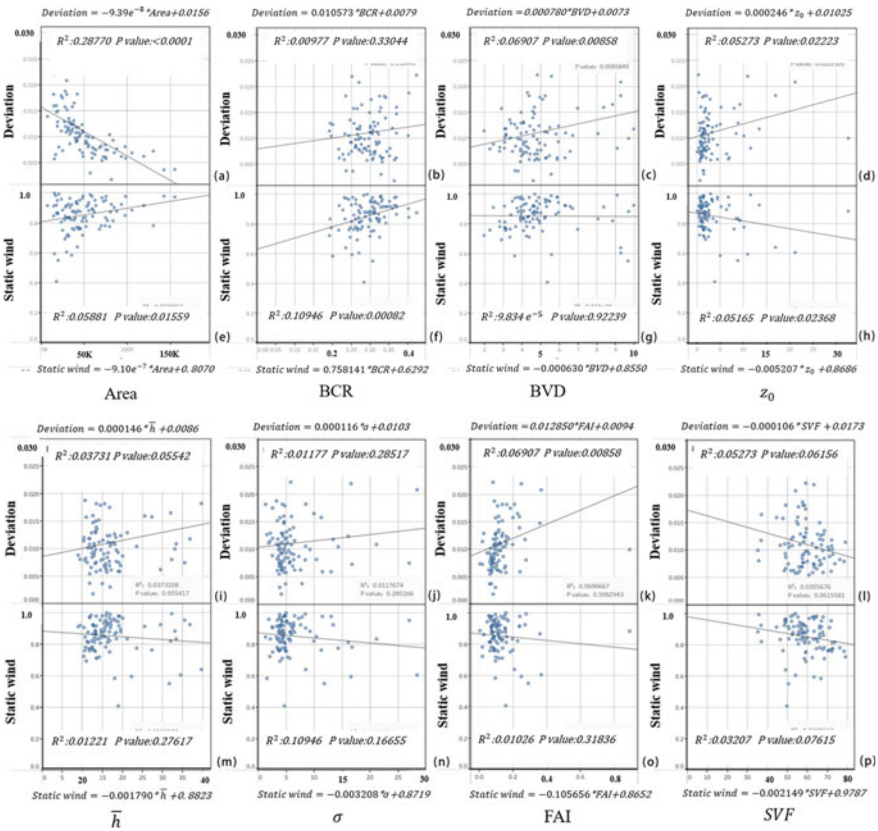

Fig. 7. Scatterplots of environmental and morphological indicators

the area ratio of the static wind zone. This conclusion may also be superimposed by multiple indicators. (2) Frontal area index, building coverage ratio, building volume density and floor area ratio are the four morphological indicators which affect the outdoor wind environment of Shanghai workers villages. These indicators can be used for urban renewal and renovation of old neighborhoods. (3) It can be seen that there is a correlation between morphological indicators and environmental indicators, but they don't have a high enough fitting precision. The main reason is conjectured to be the presence of more anomalies in the data analysis that affect the degree of fit. Furthermore, the measured data are based on real world model, which adds more uncertainties compared with idealized models.

In the subsequent study, more dimensions of environmental data such as wind speed ratio may be added and correlation analysis may be conducted. In addition, this study mainly uses linear regression equation to analyze the correlation between the indicators, but the correlation between wind environment and building morphology cannot be described by a simple linear equation. The N-S equation is a two-linear nonlinear equation, and should also be explored and analyzed in conjunction with the k-s turbulence model, etc. For further research, we hope to use black-box operation through machine learning to fit morphological and environmental indicators more intelligently and effectively, and better find the correlation between the data.

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