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*Research Article*

# Field Experiments for Wind Loads on a Low-Rise Building with Adjustable Pitch

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A wind engineering research field laboratory, which consists of a full-scale low-rise building and two towers, has been constructed by Tongji University near Shanghai Pudong International Airport to study the characteristics of near-ground wind field and wind pressure on low-rise buildings. The full-scale building, whose roof pitch could be adjusted ranging from 0° to 30°, is 10 m in length, 6 m in width and 8 m in eave's height. It is employed to study the wind pressure on the gable roof of low-rise building with different roof pitches. This paper explicitly and concretely discusses the filed facility, data measurement system, data acquisition system, and tap location to provide references for related researchers. Besides, two pieces of time-histories of ten-minute-length wind pressures are analyzed at 0° and 20° roof pitches respectively to compare with those of a wind tunnel test on a rigid model of 1 : 30 scale. The results show that the tendency for the mean and fluctuating wind pressure distributions between the two kinds of tests is nearly similar.

## 1. Introduction

According to the survey of wind hazard, the main reason resulting in casualties and property losses is the damage and collapse of the low-rise buildings in villages and small towns during tropical storm periods [1]. The low-rise buildings are generally not damaged due to structure vibration because of their high stiffness and low height, which is different from tall buildings [2, 3]. The investigation shows that the failure of low-rise buildings usually starts from the local failure of envelope. So it is very important to study how to prevent the failure of envelope for the wind resistance of low-rise buildings.

At present, the available method for this research is based mainly on wind tunnel test, while the field measurement is seldom employed for its high investment of resources and time taking. On the other hand, there is a gap between the results of field measurement and wind tunnel test due to reasons such as the inaccurate simulation in wind tunnel of the Reynolds effect and high turbulence at atmosphere surface layer. Therefore, field measurement has become the most reliable way to master the action mechanism of wind loads and is the most authoritative reference to modify the method of physical and numerical modeling [4].

In the last four decades, there have been a number of notable full-scale studies of wind loads on low-rise buildings, which permit researchers to make appropriate comparisons with wind tunnel measured data and numerical simulation results. In the early 1970s, the BRE (Building Research Establishment) in the UK commenced a program of full-scale measurements on a special constructed experimental building with two stories in Aylesbury, England [5]. In the late 1980s, another famous full-scale experiment on a low-rise building was set up in Lubbock, TX, USA [6, 7]. Almost at the same time, a new full-scale experiment was commenced in Silsoe, UK [8, 9]. It consisted of a steel frame building with variable eave types. At the beginning of twentieth century, a 6 m cube was constructed at the Silsoe Research Institute in an open country exposed position [10]. During the late 2000s, the researchers from Hunan University in China put forward the idea of a removable low-rise building and successfully developed field measurement


Figure 1: Measurement site.


Figure 2: The terrain of test building.

(a) Pitch of 0°

(b) Pitch of 30°

Figure 3: Full-scale low-rise test building.

Table 1: Field measurement laboratories of low-rise buildings.

| Name | Site | Size (length × width × height) | Roof pitch | Feature |
|---|---|---|---|---|
| Aylesbury test | UK | 13.3 m × 7 m × 5 m | Variable | Adjustable roof pitch between 5° and 45° |
| TTU experiment | USA | 9.1 m × 13.7 m × 4 m | 2° | Rotatable building |
| Silsoe (steel frame) | UK | 24.3 m × 12.93 m × 4.14 m | 10° | Variable eave styles |
| Silsoe (cube) | New Zealand | 6 m × 6 m × 6 m | 0° | Adjustable cube pitch |
| HNU building | China | 6 m × 4 m × 4 m | 1.1° | Removable building |
| TJU building | China | 10 m × 6 m × 8 m | Variable | Adjustable roof pitch between 0° and 30° |

Table 2: Specifications of the pressure transducer.

| Specifications | CYG1220 | CYG1516 |
|---|---|---|
| Range | 0 ∼ ±1 Kpa | 0 ∼ ±2.5 Kpa |
| Response frequency | More than 20 Hz | More than 200 Hz |
| Input voltage | DC 24 V | DC 24 V |
| Output signal | 4 ∼ 20 mA | 4 ∼ 20 mA |
| Rated accuracy | Less than 0.5% FS | Less than 0.5% FS |
| Compensation temperature | 0 ∼ 50°C | 0 ∼ 50°C |

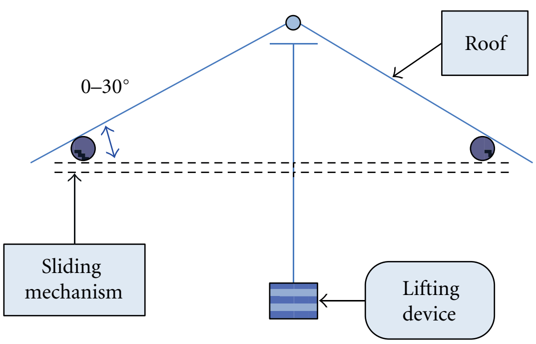



Figure 4: Elevating system.

Figure 5: Sliding guiding device.

of wind loads on that building during a typhoon [11, 12]. The information about these experiments is summarized in Table 1.

Another field measurement research in China was developed by Tongji University from the year 2008. The building used for field measurement was built at the coast of China near Shanghai Pudong International Airport. The plane size of the building is 10 m × 6 m and the eave height is 8 m. The main feature of this building is that the pitch of roof can be adjusted from 0° to 30° by using the lifting device. The architectural appearance of the pitch-adjustable building was designed according to the typical characteristics of the low-rise buildings in villages in South China.

## 2. Pressure Measurement System

Pudong New District in Shanghai is an area where strong wind, especially strong typhoons, frequently occurs each year. A field laboratory has been set up by State Key Laboratory of Disaster Reduction in Civil Engineering of Tongji University to study the turbulence characteristics of near-ground wind and wind loads on full-scale low-rise buildings. The field laboratory is located in a flat area close to the Yangtze River's estuary and near Shanghai Pudong International Airport (see Figure 1). It consists of a test building and two meteorological towers. The surrounding terrain can be considered as exposure category B according to the Chinese national load code (GB50009-2001) [13] and the exposures around the facility are of inhomogeneous roughness situations (see Figure 2).

*2.1. Test Building.* The steel structure test building has three single-story internal rooms, 3 m, 2.5 m, and 1.5 m in height for each story, respectively. The recording equipment is housed on the middle floor. The test building features an adjustable roof pitch from 0° to 30°. Figure 3 shows the full-scale building with 0° and 30° roof pitches.

Figure 4 shows the elevating system design. A hinge method is used for the connections between the gable roof and the ridge girder. In order to ensure the stability of the roof, a sliding guiding device is designed to control the motion of the side beam, which is shown in Figure 5. Three lifting devices, as shown in Figure 6, are mounted

(a) Active device

(b) Passive device

Figure 6: Lifting devices.

(a) CYG 1220

(b) CYG 1516

Figure 7: Photos of two types of pressure sensors.

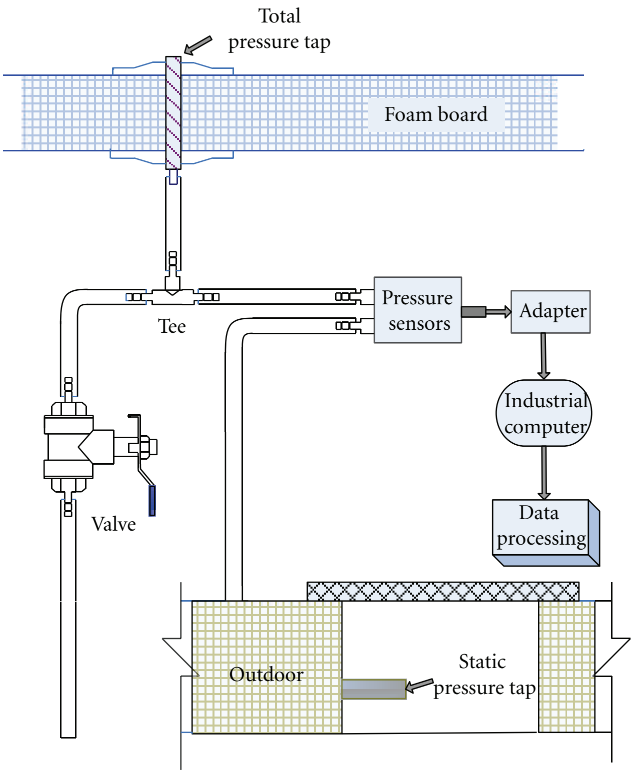



Figure 8: Pressure measurement system of CYG 1220.

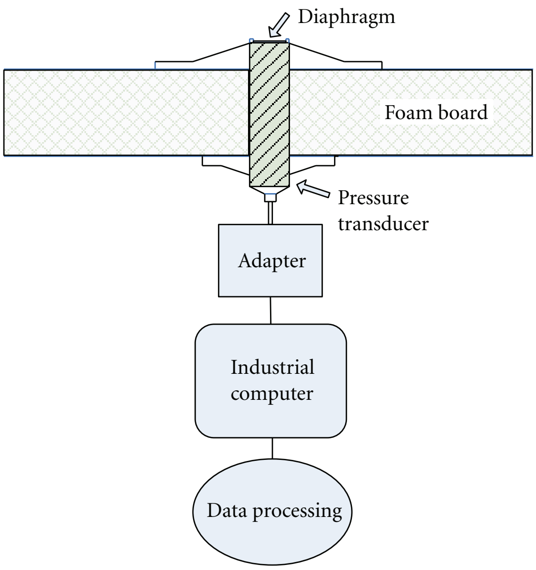



Figure 9: Pressure measurement system of CYG 1516.

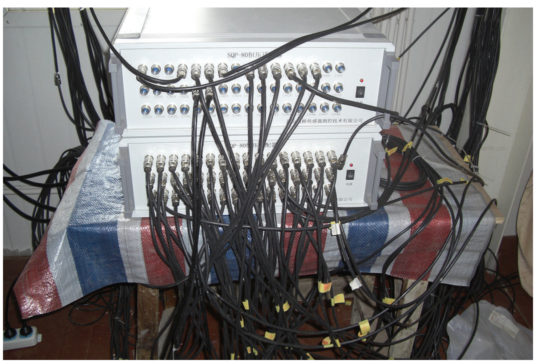


Figure 10: Photo of adapter.

on the columns. Of these, the one located on the middle column is the active device; the other two are passive ones. The active device is driven by a servo motor, which is the difference between the active and the passive devices. With the ridge being lifted by these devices, the roof pitch will change.

*2.2. Wind Pressure Measurement and Data Acquisition System.* Two types of pressure transducers are used to measure surface pressures of the test building's roof. They are all developed by Kunshan Shuangqiao Sensor Measurement Controlling Co. Ltd. Of these, 94 microdifferential pressure sensors, CYG1220, are mounted to study the wind pressure without rain, and 20 other diaphragm pressure sensors, CYG1516, are installed under the roof to study the wind-rain-induced effects on pressure. The photos of two kinds of transducers are shown in Figure 7, and specifications of the pressure transducers are given in Table 2.

Figure 8 shows the pressure measurement system of CYG1220. The transducers are mounted on the inside surface

Figure 11: Photo of industrial computer.

of the steel roof. For each transducer, a 20 cm length of tube extends down from the pressure tap on the roof and connects to a tee. A 30 cm length of tube extends from the tee to the active side of the transducer. A 1.5 m long tube extends down from the tee down to the floor and is sealed by a valve, which acts as a dam to collect rainwater. The tubes, extending down from the static side of the transducers, are connected together by tees. The static system extends to a box below ground outdoors through a long tube to obtain ambient atmospheric pressure for reference.

Figure 9 shows the pressure measurement system of CYG1516. The transducers' structures and diaphragms are made of stainless steel and can prevent rainwater from entering inside. The electric line at the end of each transducer is connected to the recording system, and then, diaphragm strain is converted to an analog output voltage proportional to the pressure signal.

An industrial computer with 2G RAM and 2.4 GHz coprocessor is used for data acquisition. Two conversion boards supplied by National Instruments Corporation are used to capture the incoming signals, and each one is an 80-channel and 16-bit A/D board. Cycling scanning has been adopted for the minimum requirement of dynamic responsibility, which is completely satisfied with the data collection for 160 channels. The sampling frequency of each transducer is 20 Hz. Zero calibration of all the transducers is checked before data collection. Figure 10 shows the photo of two adapters together with 160 channels, and Figure 11 shows the industrial computer.

*2.3. Tap Locations.* According to previous field measurement and wind tunnel tests, the extreme negative pressure usually occurs at the windward corner during oblique wind direction for gable roof buildings, and the gradient of pressure is larger than those at other locations. From the wind rose of Shanghai, shown in Figure 12, southeast wind is the prevailing wind direction in Shanghai [14]. Therefore, more transducers are put at the southeast corner. The locations of pressure taps are shown in Figure 13, and the photos of tap locations at the southeast corner roof are shown in Figure 14.

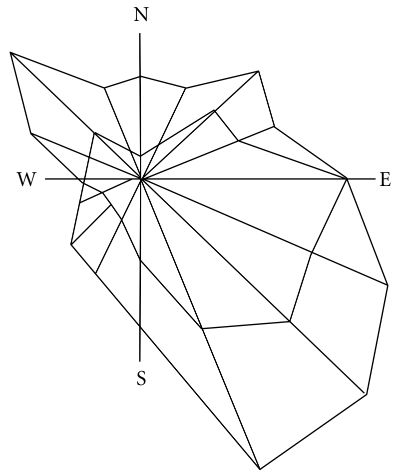



Figure 12: Wind rose of Shanghai.

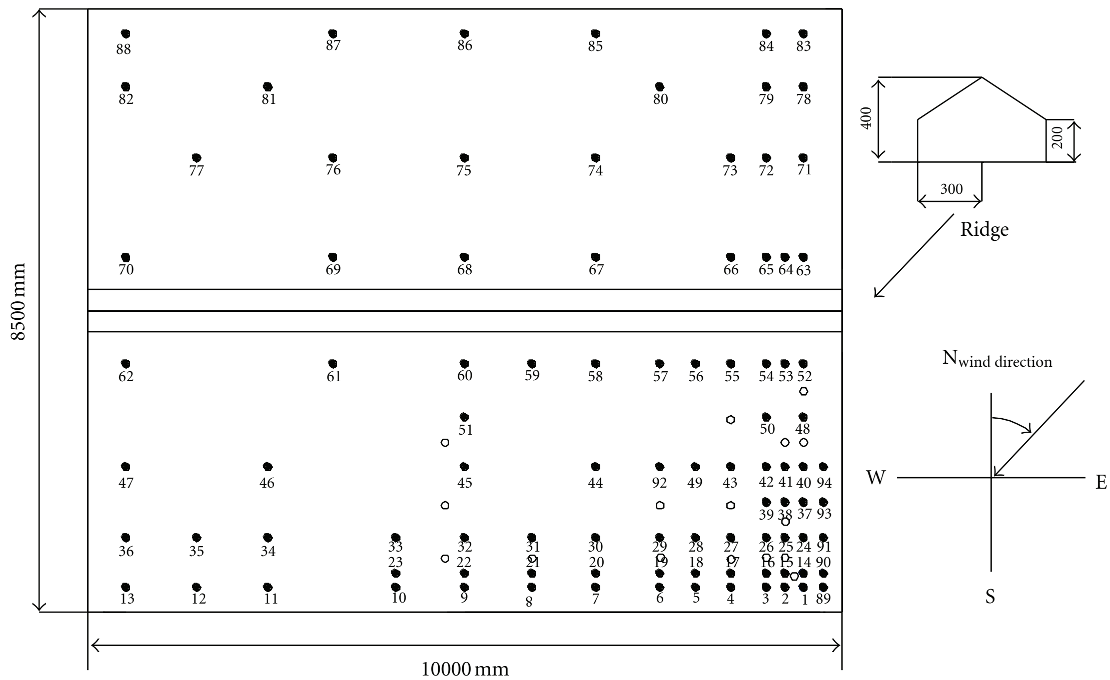
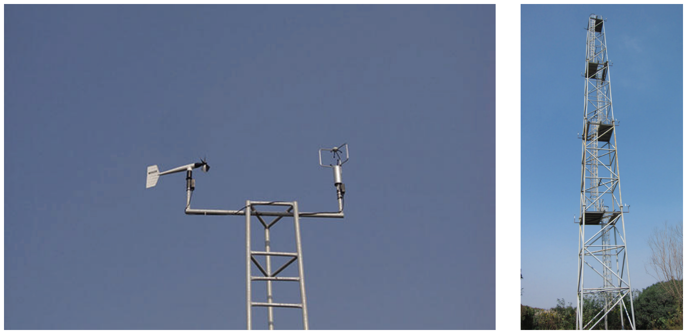



Figure 13: Layout of pressure taps on the surface of roof (•: CYG 1220°: CYG 1516).

(a) Inside (b) Outside

Figure 14: Photos of tap locations at corner roof.



(a) 10 m tower (b) 40 m tower

Figure 15: Photos of towers.

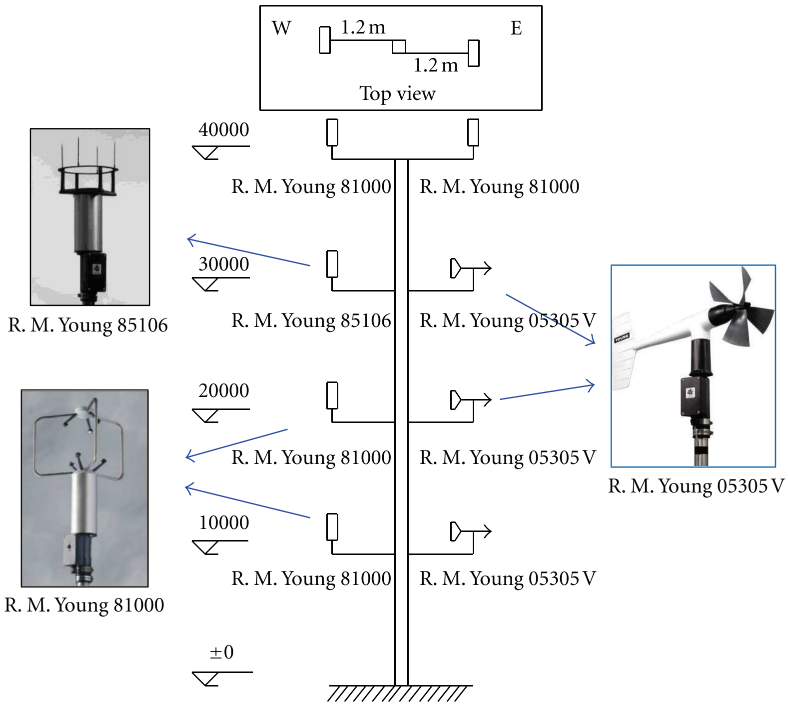


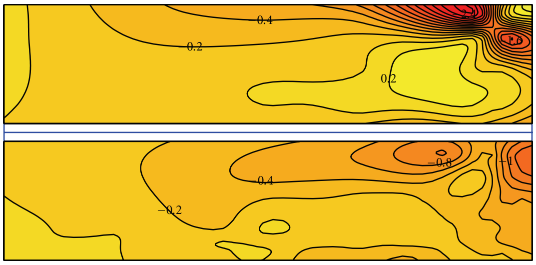

Figure 16: The arrangements of anemometers (unit: m).

## 3. Wind Velocity Measurement System

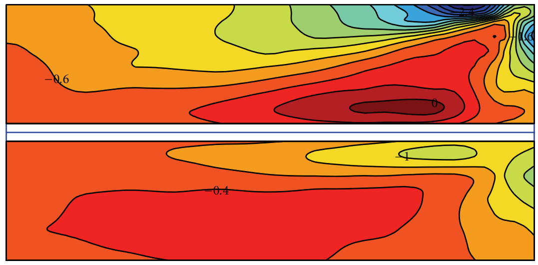
*3.1. Field Facility and Instrumentation.* The field laboratory also consists of two self-supporting steel towers. The photos of the towers are shown in Figure 15. One tower is 10 m in height and located about 25 m to the east of the test building. It is used to support two anemometers installed on the top to collect wind velocity data. The wind velocity data can be converted to total reference pressure which is used to calculate the pressure coefficient of each tap on roof surface.

The other tower is 40 m in height and about 35 m far from the building in the north. To study the turbulence characteristics of strong wind near ground, eight anemometers were installed on the tower at the height of 10, 20, 30, and 40 m, respectively. The types of the anemometers are R. M. Young 81000, R. M. Young 85106, and R. M. Young 05305V, and their sampling frequencies are 20, 4, and 20 Hz, respectively. The arrangement of anemometers is displayed in Figure 16 and specifications of different types of anemometer are shown in Table 3.

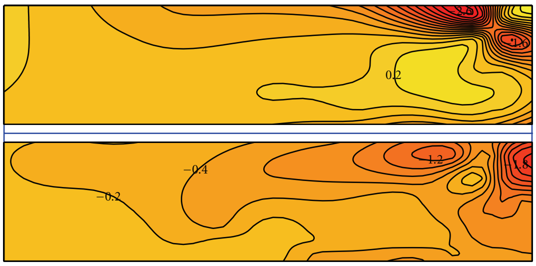
*3.2. Data Acquisition System.* Another industrial computer type PXI-1031 is used for data acquisition by National Instruments Corporation, and the machine combines a 4-slot PXI backplane with a structural design that has been optimized for maximum usability in a wide range of applications. A DC power from National Instruments is used to provide the power through the DC input connector on the rear panel of the chassis. The PXI-1031 backplane is a 32-bit PCI, so the 64-bit compact PCI cards operate in 32-bit mode in this chassis.



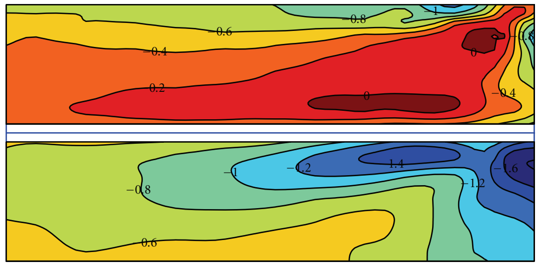
(a) Case of field measurement (FM1)



(b) Case of wind tunnel (WT1)

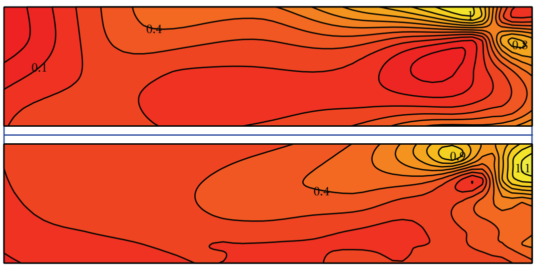


(c) Case of field measurement (FM2)

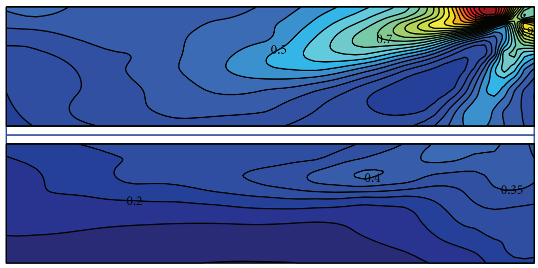


(d) Case of wind tunnel (WT2)

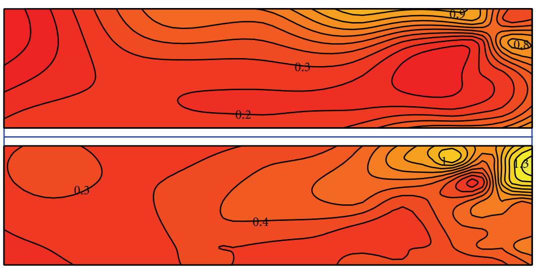
FIGURE 17: Contours of mean wind pressure coefficients.



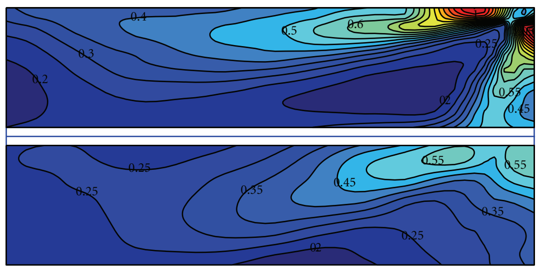
(a) Case of field measurement (FM1)



(b) Case of wind tunnel (WT1)



(c) Case of field measurement (FM2)



(d) Case of wind tunnel (WT2)

FIGURE 18: Contours of RMS wind pressure coefficients.

## 4. Recent Field Measurement Results and Comparison with Wind Tunnel Test

*4.1. Preparation for Analysis.* A wind tunnel test rigid model was in 1/30 scale based on the full-scale test building to compare the wind pressure on the roof between full-scale experiment and wind tunnel tests. The test was performed in TJ-2 Boundary Layer Wind Tunnel in Tongji University. The wind tunnel cross-section is 3 m in width, 2.5 m in height, and 15 m in length. Wind field condition corresponding to roughness exposure B in the Chinese code was simulated in the wind tunnel at a length scale of 1/30. Table 4 shows the parameters for cases of field measurement during strong wind of normal climate and the wind tunnel test.

The surface pressure on the body is usually expressed in the form of a nondimensional pressure coefficient [15]. A general time-varying pressure coefficient $C_{p_i}$ is as follows:

$$C_{p_i} = \frac{p_i - p_\infty}{p_0 - p_\infty}, \quad (1)$$

where $p_i$ is the pressure of tap $i$; $p_0$ is a total reference pressure; $p_\infty$ is a static reference pressure. In this paper, the

Table 3: Specifications of anemometers.

| Specifications | | R.M. Young 81000 | R.M. Young 85106 | R.M. Young 05350 V |
|---|---|---|---|---|
| Wind speed | Range | 0 ∼ 40 m/s | 0 ∼ 70 m/s | 0 ∼ 50 m/s |
| | Resolution | 0.01 m/s | 0.1 m/s | — |
| | Accuracy | ±0.05 m/s (0 ∼ 30 m/s) | ±0.1 m/s (0 ∼ 30 m/s) | 0.2 m/s |
| Wind direction | Range (horizontal) | 0 ∼ 360° | 0 ∼ 360° | 0 ∼ 360° |
| | Range (vertical) | ±60° | 0 | 0 |
| | Resolution | 0.1° | 1° | — |
| | Accuracy | ±2° (1 ∼ 30 m/s) | ±2° | ±3° |
| Sampling frequency | | 4–32 Hz (20 Hz used) | 1 Hz | 20 Hz |
| Working temperature | | −50 ∼ 50°C | −50 ∼ 50°C | −50 ∼ 50°C |

Table 4: Cases of field measurement (FM) and wind tunnel (WT) test.

| Parameters | FM1 | FM2 | WT1 | WT2 |
|---|---|---|---|---|
| Test type | Full-scale | Full-scale | Wind tunnel | Wind tunnel |
| Scale proportion | 1 : 1 | 1 : 1 | 1 : 30 | 1 : 30 |
| Roof pitch | 0° | 20° | 0° | 20° |
| Mean wind speed at eave (m/s) | 8.58 | 9.97 | 9.02 | 9.02 |
| Mean wind direction | 41° | 43° | 40° | 45° |
| Turbulence intensity | 0.233 | 0.221 | 0.247 | 0.241 |
| Sampling frequency (Hz) | 20 | 20 | 312.5 | 312.5 |
| Sample time and data length | 10 min | 10 min | 38.4 s | 38.4 s |
| | 12000 | 12000 | 12000 | 12000 |

mean wind speed was measured at the height of the eave of test building.

*4.2. Pressure Distribution on Roof Surface.* For comparison, Figure 17 shows the contour graph of mean wind pressure on the roof based on field measurement and wind tunnel tests, and Figure 18 displays the contour graph of RMS (root mean square) fluctuating wind pressure. The results indicate that the distribution patterns of mean and fluctuating pressure agree well with each other. From either field measurement or wind tunnel test results, it is observed that there are two pairs of conical vortices occurring at the windward of roof as well as the backside of ridge. In these regions, the negative pressure is larger than in other regions. However, there is an evident gap for magnitudes of mean and fluctuated pressure coefficients between field measurement and wind tunnel test results. The discrepancies are probably caused by inadequate simulation of turbulence intensities in atmospheric surface layer, small-scale turbulence content, inaccurate detail structure of wind tunnel model, the stationary state of wind flow, and the Reynolds and Jensen number effects. Further research is needed to interpret the deterministic reason for the discrepancy in the magnitudes.

## 5. Conclusions

Pudong New District in Shanghai is an area that strong wind, especially strong typhoons, frequently occurs each year. Therefore, a field laboratory was constructed by State Key Laboratory of Disaster Reduction in Civil Engineering of Tongji University to study the turbulence characteristics of near-ground wind field and wind effects on full-scale low-rise gable-roof buildings. The field laboratory described in this paper is the first project in China for wind effects based on the measurement on a fixed low-rise building. The full-scale building's roof pitch angle could be adjusted from 0° to 30°, which facilitates the study on the wind effects of low-rise building with different pitches. The details of the project are explicitly and concretely given to provide reference for related researchers. More importantly, results of the field measurement can allow researchers to make a comparison with those from physical and numerical modeling to provide guidance for the improvement of the wind tunnel test as well as computational fluid dynamic (CFD) technology.

## Acknowledgments

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