Inter-Story Drift Ratio Detection of High-Rise Buildings Based on Ambient Noise Recordings

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Abstract: The inter-story drift ratio (IDR) is a crucial parameter in structural health monitoring to judge the safety, stability, and serviceability of buildings. Real-time, continuous, and widely applicable detection on IDRs is essential. However, the current methods present some challenges in conducting such detection, including adverse effects from weather, the requirement for large amounts of space, and fragile instruments. This study proposes an alternative method to overcome these defects to measure IDRs and evaluate the structural conditions using ambient noise recordings. Ambient noise is a random and continuous wave signal with various sources and is modified by its propagating medium. Taking the Zhonghe Building on the campus of Tongji University, Shanghai, China, as an example, 24 three-component seismometers were deployed to capture and record the ambient noise continuously from 20 November 2021 to 9 December 2021. Using analysis of the polarization parameters of ambient noise during the building’s most dangerous time and ordinary time, a deflection curve, IDRs, and harmful IDRs of the Zhonghe Building during the most dangerous time were calculated. The computed maximum drift was 0.06 m, the maximum IDR was $1.140 \times 10^{-3}$, and the maximum harmful IDR was $-2.573 \times 10^{-4}$. These results were compared with the relevant specifications in China, and it was found that the structure was in good condition. The study proposes an alternative method to measure IDRs with high applicability and continuity in real time and underscores the need for further research to achieve a localized and real-time structural health monitoring system.

Keywords: ambient noise; polarization analysis; inter-story drift ratio; structural health monitoring

1. Introduction

The inter-story drift ratio (IDR) is the ratio between the relative translational displacement between two consecutive floors and the story height [1] and is an important parameter for the structural health of buildings under earthquake or wind loads [2]. The related standards in many countries set limits on the IDR values; for example, Table 12.12-1 of the ASCE 7-16 [1] standard in the United States lists the allowable IDR values for different types of structures in different categories, which range from 0.007 to 0.025. The IDR limit for occupied buildings in Section 4.3.6 of the PIP STC01015 Structural Design Criteria [3] is 1/200. Additionally, the Technical Specification for Concrete Structures of Tall Building of China (JGJ3-2010) [4] limit the IDR values of the frame structure to be smaller than 1/550. These restrictions are set to (1) isolate the vertical components from stress cracks or damage to guarantee structural safety; (2) protect the nonstructural components from excessive deformation and damage to guarantee the serviceability of the structure; and (3) guarantee the overall stability of the structure. The IDR is composed of the harmful IDR induced by the deformation of the vertical members and the harmless IDR caused by the rotation of the inferior floor, and harmful IDR can usually reflect the stress of the structural components directly [5].
The IDR is usually obtained based on monitoring the deformation of a structure using trigonometric leveling, digital photogrammetry, GPS, laser scanners, etc. [6]. Most of these methods monitor the changes in the control points on the building surface to obtain the drifts of the structure at floor height and then calculate the IDRs.

However, there are many problems with real-time and lifelong monitoring of a high-rise building using the current methods. For optical instruments, e.g., total stations, weather conditions affect the accuracy and lifetime of the instruments [7]. For example, excessive sunlight affects the infrared rays from the total station and changes its path, affecting the accuracy of the total station; heat also prevents measuring light beams from being concentrated, affecting the performance of the total station on hot days [8]. Although the promotion of no-prism total stations eliminates the dependence on reflective devices, a good line of sight between the total station and the measured object is still essential. If the vision is obstructed, the total station cannot work properly [9]. In actual architectural surveying, it is common to be unable to obtain a good line of sight with measured objects due to insufficient space, etc. Many control points are required for covering the area of study to survey the buildings (Asma 2018) [10], which is very cumbersome to operate. A large amount of space is needed, which restricts the scope of application of these methods. For example, the Chinese Code for deformation measurement of building and structure (JGJ8-2016) [11] limit the distance between the instrument and the building to 1.5- to 2-times larger than the building height in some cases. For a 100 m high building, the instrument should be at least 150 m away. It is difficult to find a suitable place in urban areas. Moreover, the total station is fragile and needs a lot of maintenance, which makes lifelong monitoring unaffordable for most projects. GPS is not an option in many application areas, such as indoor settings [12].

An alternative method that can overcome these challenges is ambient noise recordings, which are the continuous seismic waves captured and recorded by seismometers over a wide frequency band. The ambient noise in the low-frequency band (below 1 Hz) is excited due to natural sources, such as oceans and large-scale meteorological conditions; in the intermediate frequency band (1 to 5 Hz), ambient noise is excited either by natural (local meteorological conditions) or cultural (urban) sources; and in the high-frequency band, ambient noise is generated by cultural sources [13]. During the transmission process, ambient noise is modified by the medium that it passes through. Therefore, it is possible to analyze the changes in medium, that is, the building structure the ambient noise passes through, and indirectly measure IDRs by analyzing ambient noise recordings.

Currently, many experiments using ambient noise provide many valuable ideas. For example, Aoyama et al. [14] used a long-period signal in the broadband seismic data to detect the tilt change caused by the explosion of the Meakan-dake volcano in Hokkaido, Japan. They successfully understood the relevant characteristics of the propagation medium, such as the inclination of the formation, with the help of the observed ambient noise data. Their findings provide useful knowledge for the experiments of this paper, which intends to understand the inclination characteristics of building structures based on the ambient noise data. Additionally, Silvio De and Bodin [15] analyzed an original set of seismic and meteorological data collected at a newly established PNSN site near the Pacific coast of the Olympic Peninsula in Washington. They found that the correlation of the ambient temperature and wind profiles with the amplitude of the seismic signals was remarkably close for periods greater than 30 s. This discovery provides a preliminary basis for the use of ambient noise to conduct wind-response-related experiments. Takewaki et al. [16] introduced a system identification technique, which used seismic waves to conduct a structural diagnosis of building damage during earthquakes. This technique was applied to high-rise buildings in 2011 off the Pacific coast of the Tohoku earthquake and achieved a satisfactory result. Moreover, Boutin et al. [17] used ambient noise data to conduct a seismic diagnosis of buildings. Their experiments showed that noise measurements can efficiently provide reliable data for understanding the actual building behavior. All these studies provide a theoretical foundation to carry out research on buildings based on ambient noise. How-
ever, except for the research mentioned above, there have been few studies concerning measuring IDRs using ambient noise.

When a building is free from external influence, the IDRs should be stably maintained at an initial value. However, if the building is under an external force, vertical components will be deformed, causing a change in the IDRs. Since ambient noise mainly exists as Rayleigh waves, if the ambient noise is modified by the vertical components that it passes through, the polarization characteristics of the Rayleigh waves separated from the ambient noise will change accordingly. Therefore, the polarization characteristics of the Rayleigh waves can be analyzed to understand the change in the ambient noise and finally understand the change in the vertical components that the ambient noise passed through, which can reflect the change in the drifts of the whole building and, of course, the change in the IDRs.

Since this method is based on seismic waves, control points on the surface of the building, a large space for instruments, and a clear line of sight are all unnecessary. Therefore, the surrounding conditions, e.g., narrow spaces and objects blocking the eyesight, cannot hinder the monitoring. In addition, the survey with instruments can be conducted indoors, which protects the instruments from external disturbances, allowing for undisturbed accuracy, a longer lifespan, and lower maintenance requirements. Therefore, the monitoring can even be conducted in adverse weather conditions, e.g., excessive sunlight, heat, and great gales, which may affect or damage instruments such as total stations. Finally, since the ambient noise is a continuous seismic signal and can be collected at any time, the monitoring conditions for this method are relatively easier to meet, and monitoring can be performed in real time. The monitoring can be conducted in many application areas, even in urban areas and under adverse weather conditions with the help of ambient noise. In summary, the proposed method overcomes some disadvantages of the current mainstream methods, enabling highly applicable, real-time, and continuous IDR measurements.

Based on the descriptions above, this study attempted to combine the polarization characteristics of ambient noise with the change in IDR values. Conducting continuous observations using three-component seismometers, the relationship between the ambient noise and IDRs was analyzed to develop a new IDR monitoring scheme, which could provide the data required for structural maintenance systems in the future.

2. Data Acquisition

This project was conducted examining the Zhonghe Building at Tongji University in Shanghai. Twenty-four SMARTSOLO IGU-16HR 3C three-component seismometers were deployed from the 1st floor to the 21st floor of the Zhonghe Building, as well as at two points in the parking lot and lawn for comparison. The data were collected for 19 consecutive days, from 20 November 2021 to 9 December 2021.

The Zhonghe Building is a 22-story building, including 1 underground floor and 21 aboveground floors. The total height of the building is 102 m, and the height of the aboveground part is 98 m. The aboveground part of the building is composed of seven modules, each of which consists of three floors. Between every two modules, there are 2 m high equipment interlayers as transition layers for the structure. Most of the floors of the Zhonghe Building are 4 m high and consist of approximately nine 16.2 m × 16.2 m rectangular units, with only the B1 level having a height of 6 m.

The stressed areas of each floor are roughly L-shaped blocks, and the stressed areas within the same module are roughly the same. The seven modules spiral up clockwise from bottom to top; the upper module is rotated 90° clockwise from the lower module and is stacked on one side of the L-shaped structure of the lower module.

In general, the structure of the Zhonghe Building can be considered as a frame structure with a viscous damping support system [18]. According to Yuan [19], when a frame
structure is subjected to lateral loads, the relationship between the top drift and the shape function of the distributed load can be presented as follows:

\[
\begin{align*}
\delta_{xe}(x) &= \frac{V_b}{H} \left[ x - \frac{x^{(k+2)}}{(k+2)H^{(k+1)}} \right] \\
Q(x) &= \frac{V_b}{H} (k+1) \left( \frac{1}{H} \right)^k
\end{align*}
\] (1)

where \(x\) is the distance from the computed point to the ground, \(\delta_{xe}(x)\) is the top drift, \(Q(x)\) is the shape function of the distributed load, \(V_b\) is a summation of all lateral forces applied at each story level, \(H\) is the total height, and \(k\) is an exponent related to the structural period.

Yuan’s formulas reflect that the function of top drift has a degree that is two units higher than the function of distributed loads. Similar characteristics of the deformation of an idealized frame structure under a horizontal force can be inferred as follows: (1) the deformation is small near the ground; (2) the deformation grows rapidly in the middle floors; and (3) the deformation increases slowly at high-rise floors and peaks at the highest point. According to Sun [20], a viscous damper is better suited for controlling the torsional angular velocity and has no significant effect in controlling inter-story drift. Therefore, the deformation of the Zhonghe Building under a wind load should have similar characteristics to Yuan’s description. However, the Zhonghe Building is a modern building with a complex structure. Therefore, its deformation characteristics may not be completely consistent with the description above.

The structure’s diagram and instrument positions are shown in Figure 1.

![Figure 1. Sketch of the structure of the Zhonghe Building.](image-url)
direction. Seven modules, each consisting of three floors, jointly compose the aboveground part of the building. The stressed areas in the structure are L-shaped blocks divided into two parts: the transverse stress areas highlighted in blue, and the longitudinal stress areas highlighted in red. There are two fixed elevator and stair areas in the southeast and northwest areas. Additionally, the instruments were set in the southeast stair area of each floor for recording and in the parking lot and lawn for comparison.

3. Data and Processing Methods

3.1. Data Pre-Processing

Nineteen days of seismic wave data from 24 three-component seismometers were preliminarily processed. The data recorded were the time series of ambient noise in the vertical, north–south, and east–west directions. According to Bard [21, 22], the ambient noise data were processed in the following way: an anti-triggering algorithm was applied based on a prescribed range of short- (1 s) to long- (30 s) term average amplitude ratios (0.2 < STA/LTA < 2.5) to filter each segment against occasional energy bursts and remove marked transient interference signals.

3.2. Polarization Analysis

3.2.1. Calculating the Polarization Parameters

Wind noise is a wide-band signal, and the frequency range of wind-induced noise differs between studies [23]. According to Asten’s conclusion, monsoons and large-scale meteorological perturbations cause ambient noise in the frequency band of 0.16–0.5 Hz, while cyclones over the oceans excite ambient noise in the frequency band of 0.5–3 Hz [24, 25]. Since the Zhonghe Building is in Shanghai, a coastal city with relatively strong winds, and is in the city center with many surrounding high-rise buildings resistant to cyclones, it is mainly affected by large-scale meteorological perturbations and only slightly affected by cyclones. Therefore, ambient noise in the frequency band of 0.3–0.6 Hz was used to conduct the research, which is slightly higher than the frequency range of monsoons and large-scale meteorological perturbations, as suggested by Asten. The ambient noise in this frequency band can be considered to be generated from the main influencing factor of the Zhonghe Building.

Ideally, the particle motion of a Rayleigh wave is on a vertical plane, and its trajectory is similar to an ellipse limited to a range between the instrument site and the source of ambient noise. However, due to out-of-plane contamination, the actual particle motion will not be two-dimensional and will not be on a plane. The actual particle motion can be described by an ellipsoid defined by three orthogonal semi-principal axes ($\vec{a}_1$, $\vec{a}_2$, and $\vec{a}_3$, where $\vec{a}_1$ and $\vec{a}_3$ are the semi-major and semi-minor axes) (Figure 2a).

In polar coordinates, these axes are defined by $\lambda_X$, $\varphi_X$, and $\theta_X (X = 1, 2, 3)$, where $\lambda$, $\varphi$ and $\theta$ are the lengths, back azimuths (clockwise from the north), and dip angles (from the horizontal plane) of the axes, respectively (Figure 2b). Here, $X$ is the serial number sorted by the length of the axes from largest to smallest, and it is used to specify the axes. In this way, the particle motion of the ambient noise can be fully determined by understanding the nine semi-principal axes parameters.

The polarization orientation of the ellipsoids can be described by the parameters $\varphi_1$ and $\theta_1$ [26], but the parameter $\varphi_1$ is mainly dependent on the source locations of the Rayleigh waves that dominate the microseisms [27], and it is less affected by the structure. However, it is difficult and unnecessary to determine the source of microseisms in buildings under wind loads. Therefore, $\varphi_1$ is unsuitable to calculate IDRs. While the particle motion of Rayleigh waves is always modified by the structure of the building, Rayleigh waves’ $\theta_1$ obeys a stationary stochastic process. Additionally, $\theta_1$ can reflect the angle of the polarization orientation of the ellipsoids based on the horizontal plane, which can represent the rotation angle of vertical components based on the floor plane in a sense and is helpful in calculating IDRs. Therefore, only the parameter $\theta_1$ was used to calculate IDRs for this study.
Further, $\theta_1$ represents the angle between the longest axis of the polarized vibration ellipse and the horizontal plane. Since $\theta_1$ describes the polarization orientation of the ellipsoids, it can reflect the characteristics of the components in the seismic wave propagation path. Although the relationship between the initial value of $\theta_1$ and the initial conditions of structures is weak, the variation in $\theta_1$ is closely related to the changes in structures. In general, when subjected to a horizontal load, the horizontal deformation is certainly large. However, when subjected to horizontal loads, the polarization orientation of the ellipsoids is close to the horizontal direction, causing $\theta_1$ to become small. Conversely, when subjected to vertical loads or when lacking horizontal loads, $\theta_1$ becomes large. Therefore, $\theta_1$ is often negatively correlated with horizontal deformation.

In Figure 2a, the three semi-principal axes of the polarized ellipsoid are defined as follows: $\vec{a}_1 > \vec{a}_2 > \vec{a}_3$, $\vec{a}_1$ is a semi-major axis, and $\vec{a}_3$ is a semi-minor axis. In Figure 2b, $\lambda_X$ is the length of the semi-principal axis, $\varphi_X$ is the back azimuth clockwise from the north, and $\theta_X$ is the dip angle from the horizontal plane. Additionally, $X$ is the serial number sorted by the length of the axes from the largest to the smallest.

According to Guo [26], the required polarization data can be obtained using the polarity analysis method to strengthen the polarization characteristics of seismic stations.

Because the effects of wind are complex and multidirectional, accurate $\theta_1$ data are often not of analytical significance. A data set made up of $\theta_1$ data can better reflect the response characteristics of buildings under wind loads. Therefore, a probability density function can be used to determine the representative $\theta_1$ scope. Additionally, the probability density function $P(\theta_1)$ is used to describe the probability density of that the angle between the longest axis of the polarized vibration ellipse of the collected Rayleigh wave and the horizontal plane meets $\theta_1$. If $P(\theta_1)$ is large, the wave whose angle between the longest axis of its polarized ellipse and the horizontal plane is in the range of $(0, \theta_1)$ dominates in the collected Rayleigh wave. Then, 0.01 is taken as the calculation precision to calculate $\theta_1$ and $P(\theta_1)$.

The target cumulative probability density is the probability density that starts with $\theta_1 = 0$ and accumulates to the target $\theta_1$. For certain target cumulative probability densities, there will always be a unique $\theta_1$ parametric curve that represents the parameter combination with the maximum response.

As shown above, when wind speeds increase, $\theta_1$ decreases. Therefore, an inverted diagram of the wind speeds can be used to more intuitively compare the wind speeds.
and $\theta_1$. By calculating the related coefficient between each target cumulative probability density's $\theta_1$ parametric curve and the diagram of the inverted diagram of the wind speed and taking the maximum of the sum of the related coefficient, the optimal target cumulative probability density can be determined as 98%.

Based on the above, the $\theta_1$ parameter curve was calculated, and the median $\theta_1$ was taken as the parameter when the building is under normal use. Additionally, the $\theta_1$ occurring with maximum wind speed was taken as the parameter when the building is subjected to strong winds. Finally, the difference value between these two parameters was taken as the change value of $\theta_1$ for the analysis.

3.2.2. Estimation of the Inter-Story Drift Ratio
Main Load Analysis of the Floors

For the analysis, determining the floors mainly affected by seismic waves from the wind and distinguishing them from the floors mainly affected by seismic waves from the ground are important to obtain the necessary boundary conditions. These boundary conditions were: (1) the floors whose drift data are unacceptable; and (2) the height of those floors.

As shown in Section 3.2.1, the inverted wind speed curve can be used to intuitively compare the wind speeds and $\theta_1$. If the correlation between the inverted wind speeds and $\theta_1$ is greater, the building is more affected by the wind. If the correlation between the inverted wind speeds and $\theta_1$ is smaller, the building is less affected by the wind. If $\theta_1$ is not subjected to wind loads but to vertical loads such as ground waves, it will be larger than normal and is unacceptable.

The steps to define the floors mainly affected by ground waves are as follows: (1) 0.1 is taken as the calculation precision for a rapid increasing speed of the cumulative probability density and low difficulty in investigating the relationship between the inverted wind speeds and $\theta_1$. With this calculation precision, the $\theta_1$ parameter curve is calculated again; (2) the optimal target accumulation probability density is calculated on the principle of optimizing the related coefficient between the inverted wind speed curve and $\theta_1$ curve (please see Section 3.2.1 for the concept of the target accumulation probability density); (3) the $\theta_1$ parameter curve of the optimal target cumulative probability density is plotted; and (4) the correlation between the inverted wind speeds and $\theta_1$ in the period of the wind speed fluctuations is analyzed using the following methods. If the related coefficient between the $\theta_1$ curve and the inverted wind speed curve is greater than 0 during the wind speed fluctuation period, the floor can be considered to be mainly affected by the wind. If not, the floor can be considered to be mainly affected by ground waves.

Deflection Function Fitting

Generally, the wind load on high-rise buildings is the uniformly distributed load of an inverted triangle, and the shear force is the uniformly distributed load of a triangle [28]. If a high-rise building is regarded as a cantilever beam fixed at one end under a triangularly distributed load, its stress condition can be shown, as indicated in Figure 3.

In Figure 3, H is 98 m, the total height of the aboveground part of the building, X is the distance from the ground to the calculation point, and $q_0$ is the maximum value of the uniformly distributed load of the inverted triangle.

As shown in Figure 3, the bending moment function for the structure is a quadratic function of distance X.

The second derivation of the deflection line allows for computing the curvature, depending on the stiffness and the bending moment of the considered static system, and their relationship is as follows [29]:

$$\frac{M}{\varphi} = EI$$

where $EI$ is the stiffness of the component. According to Ćurić [30], the idealized $\frac{M}{\varphi}$ curve of a reinforced concrete component can be represented by three straight lines, which
means that if the concrete can be sustained in one condition, \( M \) and \( \varphi \) can be considered as homogeneous functions. For any normal building, its concrete components always align in one condition, without changing drastically. Therefore, the bending moment function shall be the second derivative of the building deflection function. Based on this, it can be concluded that (1) the deflection function of the building structure should be a quartic function of the distance \( X \), and (2) the derivative of the deflection curve function is a cubic function of the distance \( X \).

![Figure 3. Stress model diagram under wind load.](image)

As shown in Figure 4, the parameter \( \theta_1 \) data do not correspond to IDRs but rather to the tangential slope of the deflection curve calculated indirectly at specific heights; if there is no initial inter-story drift, the change value of \( \theta_1 \) (\( \Delta \theta_1 \)) can be considered to be the tangent angle of the deflection curve at each floor’s height, and \( \tan \Delta \theta_1 \) can be considered as the tangent slope of the deflection curve at each floor’s height.

Because \( \tan \Delta \theta_1 \) approximately equals the tangent slope of the deflection curve and the data set formed by the tangent slope at specific heights and the corresponding heights can be used to fit the derivative function of the deflection curve, the data set formed by \( \tan \Delta \theta_1 \) and its corresponding heights can be used to fit the derivative function of the deflection curve. The following steps can be used to fit the Zhonghe Building’s deflection function:

1. Use the data set formed by \( \tan \Delta \theta_1 \) and its corresponding heights to fit the derivative function of the deflection curve \( f(x) \).
2. The deflection function \( \rho(x) \) can be calculated via the following formula:

\[
\rho(x) = \int_{x_{\text{min}}}^{x_{\text{max}}} f(x) \, dx
\]

where \( x \) is the distance from the ground to the calculation point and \( x_{\text{max}} \) is 98 m, the maximum height of the aboveground part of the building, \( x_{\text{min}} \) is 0 m.
Calculation of the IDRs

The IDR is the ratio between the relative translational drift between two consecutive floors and the story height. Therefore, the IDR $\alpha$ can be calculated via the following formulas:

$$
\begin{align*}
\alpha_i &= \frac{\Delta \rho_i}{\Delta x_i} \\
\Delta \rho_i &= \rho_i(x_{i+1}) - \rho_i(x_i) \\
\Delta x_i &= x_{i+1} - x_i
\end{align*}
$$

where $i$ and $i + 1$ are the floor numbers. $\rho_i(x_i)$ and $\rho_i(x_{i+1})$ represent the deflections of the $i$th and $i + 1$th floors, respectively. $x_i$ and $x_{i+1}$ represent the heights of the $i$th and $i + 1$th floors, respectively.

The safety of the building can be verified by calculating the maximum IDR as follows:

$$
\begin{align*}
\alpha_{\text{max}} > \frac{1}{550}, \text{ unqualified} \\
\alpha_{\text{max}} \leq \frac{1}{550}, \text{ qualified}
\end{align*}
$$

3.3. Meteorological Data

The hourly ground wind speed data of the Shanghai Hongqiao International Airport provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) were used in the research, with wind speed referring to the wind speed at approximately 10 m above the ground.

The distance between the wind data station and the experimental site is approximately 18.6 km, and the calculated average wind speed is 6.99 m/s. The wind propagation time was calculated using the average wind speed to correct the wind speed time. The corrected wind speed chart is shown in Figure 5.
In Figure 5, the maximum wind speed was 23.5 m/s at 10:15 a.m. on 30 November 2021, reaching the speed level of a strong gale, which may cause slight damage to the top of the building [31]. Additionally, the median wind speed was 9.33 m/s, representing the wind speed of the building under normal conditions.

The parameter \( \theta_1 \) at 10:15 on 30 November 2021 was taken as the polarization parameter under the strongest wind conditions, and the median of \( \theta_1 \) was taken as the polarization parameter under normal conditions.

4. Results and Analysis

4.1. Results and Analysis of the Main Loads of the Floors

Through correlation analysis, the floors that were not mainly affected by the wind can be determined. Including the fault stations, the floors that were mainly not affected by the wind but by ground waves were floors 1 to 9.

A comparison diagram between the \( \theta_1 \) curve of the floors 1 to 9 under the best cumulative probability density with a statistical accuracy of 0.1 and the inverted wind speed curve during the wind speed fluctuation period (from 29 November to 2 December) is shown in Figure 6.

In Figure 6, comparisons between the wind speed curve and the \( \theta_1 \) curve of the nonwind-affected floors in the strong gale period marked with black boxes show a poor correlation between the \( \theta_1 \) curve and wind speed curve. Additionally, the comparison between the wind speed curve and the \( \theta_1 \) curve of the typically wind-affected floors in the strong gale period marked with a red box shows a good correlation.

As indicated in the description of \( \theta_1 \) in Section 3.2.1, if the floors are mainly affected by the wind, the greater the wind speed, the stronger the wind effect and the smaller the parameter \( \theta_1 \). During the strong gale period, when the wind speed suddenly increased, the \( \theta_1 \) curve should have a wave crest with a consistent inverted wind speed curve.

As shown in Figure 6, during the wind speed fluctuation period, for the \( \theta_1 \) curve of the floors 1 to 9, instead of having a wave trough, the \( \theta_1 \) curve had a wave crest, straying from the inverted wind speed curve. However, as a typical wind-affected floor, the \( \theta_1 \) curve of the 15th floor was relatively consistent with the inverted wind speed curve and had a wave trough.

This indicates that there was a strong vertical response and a weak horizontal response to wind occurring at floors 1 to 9. The cause of this vertical response is complex. This may be due to the resonance between the wind speed and the structure and the responses generated through super positioning with ground waves. This may also be due to Shanghai
Line 10, which passes under the Zhonghe Building of Tongji University, generating large ground waves.

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Figure 6. Analysis diagram of the $\theta_1$ curve and wind speed curve.

Having nothing to do with the horizontal deformation of floors, the vertical response usually does not affect IDRs. However, $\theta_1$ is usually influenced by these vertical responses, and it will be larger than normal. Due to these vertical responses, the $\theta_1$ parameters obtained from the instruments of floors 1 to 9 can be considered to deviate from reality and should not be accepted in the next calculation.
4.2. Results and Analysis of $\theta_1$

A polarimetric analysis was performed on the data from 24 stations over 19 days from 20 November 2021 to 9 December 2021.

The processing results for the stations that can display the full time and full spectrum are listed in Table 1, where $\Delta \theta_1$ is the difference value between the $\theta_1$ at 10:15 on 30 November 2021 and the median of $\theta_1$.

**Table 1. Results for the polarization parameters.**

<table>
<thead>
<tr>
<th>Floor</th>
<th>$\Delta \theta_1^o$</th>
<th>Height/m</th>
<th>$\tan \Delta \theta_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>13</td>
<td>-0.054757</td>
<td>56</td>
<td>-0.00096</td>
</tr>
<tr>
<td>16</td>
<td>-0.09</td>
<td>70</td>
<td>-0.00157</td>
</tr>
<tr>
<td>17</td>
<td>-0.07</td>
<td>74</td>
<td>-0.00122</td>
</tr>
<tr>
<td>18</td>
<td>-0.020511</td>
<td>78</td>
<td>-0.00036</td>
</tr>
<tr>
<td>20</td>
<td>-0.032471</td>
<td>88</td>
<td>-0.00057</td>
</tr>
<tr>
<td>21</td>
<td>-0.021921</td>
<td>92</td>
<td>-0.00038</td>
</tr>
</tbody>
</table>

As seen in Table 1, except for unacceptable floors 1–9 (obtained from Section 4.1), the listed floor was evenly distributed on the remaining part of the building, providing good data support for the fitting. The distribution of the polarization parameters shows the following: (1) the $\Delta \theta_1$ parameters of the middle floors rapidly increased and (2) the $\Delta \theta_1$ parameters of high-rise floors decreased slightly.

The reason for these distribution characteristics is as follows: (1) To a certain extent, $\Delta \theta_1$ has a positive correlation with IDR. (2) Based on the assumption of the cantilever beam in Section 3.2.2, the bottom of the building should not have any deformation as a fixed end. This makes IDR and $\Delta \theta_1$ equal to 0 when the height is 0. (3) The middle floors are the places where the maximum IDR occurs, which was determined by the bending characteristics of the building structure. The flexural deformation was angular deformation, which was inherited by the upper floor, so it was cumulative. The shearing deformation was not cumulative. In the middle floors, although the bending moment and shear both decreased, the accumulated speed of flexural deformation between adjacent floors was so fast that the decrease in shearing deformation was covered. Therefore, the IDR and $\Delta \theta_1$ in these floors also increased quickly and peaked here. (4) In high-rise floors, the accumulated speed of flexural deformation slowed down, but shear deformation still decreased rapidly. This makes the total deformation between adjacent floors decrease, resulting in decreasing IDR.

4.3. Results and Analysis of Deflection Function Fitting

The obtained data set of $\Delta \theta_1$ and the height of the corresponding station were imported into MATLAB in order to fit the derivative function of the deflection function, and its corresponding expression was determined as follows:

$$f(x) = 7.795 \times 10^{-9}x^3 - 7.453 \times 10^{-7}x^2 - 2.106 \times 10^{-6}x + 2.584 \times 10^{-6}$$ (6)

where $x$ is the distance from the ground to the calculation point and $f(x)$ is the derivative of the deflection function.

The deflection function expression can be obtained by integrating its derivative function, as shown below:

$$\rho(x) = 1.949 \times 10^{-9}x^4 - 2.484 \times 10^{-7}x^3 + 1.053 \times 10^{-6}x^2 - 2.584 \times 10^{-6}x$$ (7)

where $x$ is the distance from the ground to the calculation point and $\rho(x)$ is the function of deflection. Its curve is shown in Figure 7.
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The obtained data set of $\Delta \theta$ and the height of the corresponding station were imported into MATLAB in order to fit the derivative function of the deflection function, and its corresponding expression was determined as follows:

$$f(x) = 7.795 \times 10^{-9}x^7 - 7.453 \times 10^{-11}x^6 - 2.106 \times 10^{-10}x + 2.584 \times 10^{-10}$$ (6)

where $x$ is the distance from the ground to the calculation point and $f(x)$ is the derivative of the deflection function.

The deflection function expression can be obtained by integrating its derivative function, as shown below:

$$\rho(x) = 1.949 \times 10^{-9}x^8 - 2.484 \times 10^{-11}x^7 + 1.053 \times 10^{-10}x^6 - 2.584 \times 10^{-10}x$$ (7)

where $x$ is the distance from the ground to the calculation point and $\rho(x)$ is the function of deflection. Its curve is shown in Figure 7.

![Figure 7. Diagram of deflection curve.](image)

In Figure 7, the overall deflection was close to 0 at floors near the ground, increasing rapidly in the middle floors and slowing down in the high-rise floors. The maximum drift occurring at the 21st floor was 0.06 m. The deflection curve is consistent with the theoretical model of the building’s horizontal deformation under a wind load.

As described in Section 2, generally, the analyzed structure is a frame structure with a viscous damping support system [18]. Its idealized deformation has the following characteristics [19]: (1) the deformation is small near the ground; (2) the deformation grows rapidly in the middle floors; and (3) the deformation increases slowly at high-rise floors and peaks at the highest point. The deflection curve in Figure 7 satisfies this description. However, at high-rise floors, although the deflection curve had a trend to slow down, it was still growing rapidly. This is because the structure of the Zhonghe Building is not completely the same as the ideal structure proposed by Yuan. In the Zhonghe Building, the flexural deformation is unignorable, maintaining the growth of the upper floor’s drift according to the angular slope of the lower floors, even at high-rise floors. Therefore, the fitted deflection curve can be considered consistent with the result of current mainstream theoretical models for the structure of the Zhonghe Building.

In Figure 7, the change in the growth rate of deflection represents the change in IDRs. If IDRs increase, the calculated floor will be more inclined than the floor below, making the deflection growth rate increase quickly. If IDRs decrease, the calculated floor will be only slightly more inclined than the floor below, making the deflection growth rate increase slowly. However, deflection always increases as long as IDRs are positive. With these conclusions, Figure 7 shows that the deflection grew rapidly at floors 1–15, so the IDRs will increase in this range; the deflection grew slowly at floors 16–21, so the IDRs may decrease in this range.

In addition, the total drift was 0.06 m from the 21st floor to the ground with a height of 98 m, so the total IDR between the 21st and ground floors can be calculated as $6.122 \times 10^{-4}$. The IDR limit in the Technical Specification for Concrete Structures of Tall Building of China (JGJ3-2010) [4] is 1/550 and approximately $1.818 \times 10^{-3}$, which is obviously larger than the
total IDR. The structural health of the Zhonghe Building is preliminarily qualified through the examination of the total IDR.

4.4. Results and Analysis of the Calculated IDRs

The known floor height data and the deflection function were used to obtain each floor’s drift and calculate the D-value of the drift and height data of adjacent floors to obtain the calculated IDRs. Then, the calculated IDRs were compared with the IDR limit in the Technical Specification for Concrete Structures of Tall Building of China (JGJ3-2010) [4] to analyze the condition of the Zhonghe Building.

The calculated IDRs are shown in Figure 8.

In Figure 8, the calculated IDRs increased at floors 1–14 and decreased at floors 15–21; the maximum IDR occurring at the 14th floor, 62 m, was $1.140 \times 10^{-3}$.

The maximum IDR was $1.140 \times 10^{-3}$ at 62 m, which is less than the IDR limit of $1/550$, which is approximately $1.818 \times 10^{-3}$, from the Technical Specification for Concrete Structures of Tall Building of China (JGJ3-2010) [4], and larger than the total IDR of $6.122 \times 10^{-4}$ obtained from Section 4.3.

This shows that the maximum IDR does not equal the total IDR from the top floor to the ground, although the difference between the calculated maximum IDR and total IDR is acceptable. If the total IDR from the top floor to the ground is widely used to replace the maximum IDR, this would obviously lead to a decline in accuracy.

After checking the IDRs, it can be determined that the structural stiffness of the Zhonghe Building of Tongji University meets the requirements and remains stable under loads at the highest wind level of 9.

4.5. Results and Analysis of the Harmful IDR

IDRs are comprehensive parameters in structural health monitoring, but this also makes IDRs less representative in some areas requiring special attention, such as the stress in structure. According to Liu [5], compared with IDRs, harmful IDRs can more directly reflect the stress in structures.
Using the calculated IDRs from Section 4.4 and the secant method introduced by Cai [32], the D-value of the IDRs of adjacent floors was calculated as the harmful IDRs of the lower floor. The harmful IDRs are shown in Figure 9.

![Diagram of harmful IDRs and IDR limit.](image)

**Figure 9.** Diagram of harmful IDRs and IDR limit.

In Figure 9, the harmful IDRs increased at floors 1–6, decreased at floor 7–14, and increased reversely at floors 15–21; the harmful IDR curve had two peaks: approximately $1.280 \times 10^{-4}$ at the 6th floor and approximately $-2.573 \times 10^{-4}$ at the 19th floor.

In Figure 9, two peaks in the harmful IDR curve occurred at the 6th floor and 19th floor, indicating that these two floors may be the most dangerous places withstanding destructive shear stress. This result is different from Section 4.4, which showed that the most dangerous place should be the 14th floor. This may be because harmful IDRs are more focused on the stress condition of structural components, but IDRs are a comprehensive parameter for structural health, reflecting not only the stress conditions but also the serviceability of non-structural components and overall stability of the structure. Therefore, the dangerous zones indicated by harmful IDRs may be different from the one by IDRs.

In general, by reflecting the stress condition of structural components, harmful IDRs play an important role in structural health monitoring. The reliability of structural components on the 6th floor and 19th floor may need more attention when storms occur.

The maximum harmful IDR ($-2.573 \times 10^{-4}$) was at the 19th floor and was smaller than the maximum IDR in Section 4.4, meeting the requirements of the Technical Specification [4].

**5. Conclusions**

In this paper, a monitoring approach was proposed based on ambient noise recordings to measure IDRs of structures and monitor the structural health through three parameters: the total IDR, the maximum IDR, and harmful IDRs. The feasibility of the proposed method was investigated through a field test using the Zhonghe Building on the campus of Tongji University, Shanghai, China. The results indicate:

1. The IDRs of the Zhonghe Building can be monitored using ambient noise.
2. The parameter $\tan \Delta \theta_1$ of the building’s structure can be approximately regarded as the tangent slope of the deflection curve at one point.
3. The data set for $\Delta \theta_1$ and the height can be used to fit the deflection function of the building.
4. Using the deflection function, IDRs can be calculated.
5. The calculation of harmful IDRs can be integrated using IDR data and the secant method. The dangerous places indicated by harmful IDRs and IDRs are different. Structures on the 6th floor and 19th floor may need more attention when storms occur.
6. The credible IDRs of the Zhonghe Building of Tongji University during the measurement period were far lower than the IDR limit required by the Chinese standards. The overall structure is reliable.

The use of ambient noise recordings provides a very attractive alternative for current optical IDR monitoring measurement applications. Ambient noise recordings were able to provide detailed and continuous information on the IDRs of structures and partially solved some problems in application, e.g., adverse effects from weather, requirement for large amounts of space, and fragile instruments, in comparison to the conventional method using total stations.

The proposed monitoring approach was proven to be credible in the measurement of IDRs. This study demonstrated the applicability and potential of the monitoring system based on ambient noise recordings for the monitoring of structural health. Assumptions on the distribution of structural stress and wind loads were accepted for generality since they can effectively generalize the typical conditions of most buildings in great gales. Therefore, the proposed approach was first tested based on these assumptions. It should be noted that actual buildings and wind loads may be much more complex, with different boundary conditions, e.g., body type of buildings, distribution of wind loads, topographic conditions, etc. In future work, the proposed method should be tested on such complex conditions and be strictly compared with the work of total stations. Additionally, apart from the assumptions and limitations stated throughout the article, adequate consideration should be given to the inevitable uncertainties.

Future research will focus on establishing an intelligent monitoring system for IDRs with functions of localized computing, real-time information updating, and network transmission. In this system, seismometers fixed indoors will record raw data and transmit them online; meanwhile, a data center records transient $\theta_1$ and the median of the collected $\theta_1$ in real time and provides real-time IDRs and a dynamic result on structural health. Ambient noises are continuous seismic waves, meaning that their greatest potential is the ability to provide continuous and real-time information of building structures. In the future, structural health monitoring may focus more on real-time changes in structure, and at that time, the proposed method providing real-time information on IDRs of structures will play an important role. Future studies will also include practical applications in the laboratory and on existing buildings.

Additionally, future studies should include applications in the resilience monitoring and structural design optimization of buildings during earthquakes. Due to the characteristic that the frequency of ambient noise usually corresponds to its source, the proposed method can be applied to conduct the real-time and convenient detection of some basic parameters of buildings in a variety of stress conditions. For example, when analyzing a real-time variation in IDRs, which can be conveniently measured through the proposed method, the total recovery process of the building can be recorded. The expected value of the total recovery time, the maximum likelihood recovery curves, etc., can be computed indirectly, which are important parameters for an effective and accurate evaluation model of building resilience according to Takewaki et al. [33]. The resilience evaluation of building structures is an important part for structural health monitoring. Through applying the proposed method, a real-time and dynamic resilience evaluation system can be possible.

Moreover, with the real-time evaluation system described above, the proposed method can be applied in structural design optimization. With an input velocity adjustment method of the critical double impulse [34], a designed earthquake meeting usage requirements can be excited accurately. By applying the proposed method, real-time variations in the
conditions of components under excited earthquakes can be detected, which is important information for understanding the process of structural stress and deformation and optimizing structural design finally.

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