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Research on dynamic analysis method of pier safety based on time-frequency domain combination

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Abstract: *This paper studies the dynamic analysis method of pier safety based on time-frequency domain, aiming to provide an effective means to evaluate the safety performance of pier under dynamic load. Firstly, the accelerometer is used to arrange measuring points at different parts of the pier to obtain the dynamic time history data of each part. In the data preprocessing stage, the methods of baseline correction and band-pass filtering are used to process the acceleration time history data. Baseline correction eliminates long-term drift in the data, while bandpass filtering helps remove noise and interference, improving the signal-to-noise ratio of the data. Then, the displacement time history data of different measuring points are calculated by digital integration method. At the same time, the acceleration response spectrum of each measuring point is calculated by the response spectrum method to reveal the response characteristics of the pier under different frequency dynamic loads. In order to evaluate the safety of pier, Pearson correlation coefficient method is used to calculate the difference of displacement time history data and acceleration response spectrum at different measuring points. By comparing the correlation between different measuring points, a bridge pier safety evaluation coefficient is constructed to evaluate the safety performance of bridge pier quantitatively. In order to verify the feasibility and effectiveness of the proposed method, a numerical simulation model is also established for case calculation. By simulating the response of pier under specific dynamic load and comparing, the applicability of this method in dynamic analysis of pier safety are proved.*

Keywords: *Time-frequency domain; Bridge pier; Security; Dynamic analysis*

1. Introduction

As an indispensable part of modern transportation infrastructure, bridge undertakes the important task of connecting various regions and promoting economic development [1]. Its safety is not only directly related to the smooth transportation, but also closely related to the safety of people's lives and property. In the bridge structure, the pier, as the main supporting structure, bears the bridge's own weight and the load of passing vehicles, and needs to resist the invasion of natural factors such as wind, water and earthquake [2]. Therefore, the dynamic performance evaluation of bridge piers has become the key link in bridge safety evaluation, which is of great significance to ensure the long-term stability and safe operation of Bridges [3].

In the process of bridge operation, it will inevitably be affected by various dynamic loads. These dynamic loads include vehicle loads, wind loads, earthquake loads and so on [4]. They all have a vibration effect on the pier. Vehicle load is the most common dynamic load in the daily operation of bridge. With the increase of traffic flow and vehicle load, the vibration impact of bridge pier is also increasing. The wind load mainly affects the wind stability of the bridge, especially in the area with strong wind, the vibration response of the bridge pier is particularly significant. Earthquake load is one of the most serious natural disasters that Bridges face. Strong earthquake will cause severe vibration of bridge piers, and may even cause bridge collapse. The vibration effects of these dynamic loads on bridge piers are not only related to the overall stability of the bridge [5], more directly affect the safety of people's lives and property.

The traditional methods of pier safety evaluation mainly rely on static test and appearance inspection. Static test tests the bearing capacity and deformation of piers by applying static loads. Although it can reflect the stress state of piers to a certain extent, it can not fully evaluate the performance of piers under dynamic loads. The appearance inspection determines whether there are cracks, spillage and other damage conditions by observing the surface condition of the pier, but this method is limited by the

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experience and judgment of the inspector, and it is difficult to find potential problems inside the pier. Therefore, the traditional assessment methods are insufficient in comprehensiveness and accuracy, and can not meet the needs of modern bridge safety assessment.

With the rapid development of sensor technology and signal processing technology, pier safety evaluation method has been widely concerned by the academic and engineering circles. Sensor technology can collect dynamic time history data of bridge piers in real time, including acceleration, displacement, strain and other parameters, providing rich data sources for dynamic performance evaluation of bridge piers. The signal processing technology can preprocess and analyze the collected data, and extract useful information, so as to realize the real-time monitoring and evaluation of the dynamic performance of the pier. This method has the advantages of non-destructive, real-time and high accuracy, which can overcome the shortcomings of traditional assessment methods and provide a new idea and technical means for the security assessment of bridge piers.

This paper aims to propose a dynamic analysis method of pier safety based on time-frequency domain combination. The accelerometer installed on the pier is used to detect the dynamic time history data of different parts of the pier, and then a series of signal processing means are used to preprocess and analyze the data. First, the baseline correction technology is used to eliminate DC offset and trend items in the data to ensure the accuracy and reliability of the data. Then, bandpass filtering technology is used to remove noise interference in the data and retain useful vibration signals. Then, the acceleration data is converted into displacement data by digital integration technology, so as to reflect the vibration of the pier more directly. In addition, the response spectrum analysis technique is also used to evaluate the vibration response of the pier at different frequencies to understand the change of its dynamic characteristics. Finally, Pearson correlation coefficient method is used to analyze the vibration correlation between different parts to judge whether there is potential damage or abnormality.

2. Related research at home and abroad

At present, scholars at home and abroad have carried out a lot of in-depth and detailed research work in the field of pier dynamic performance evaluation, these efforts not only promote the development of relevant theories, but also achieve many fruitful results with practical application value[6-10].

In the data acquisition link, accelerometer has become the first choice tool in the dynamic response monitoring of bridge structure with its unique advantages. The small size and light weight of the accelerometer make it convenient to install in various key parts of the bridge structure without causing too much burden on the structure itself. At the same time, its high sensitivity and easy installation characteristics also greatly improve the efficiency and accuracy of data acquisition. Through the acceleration time history data collected by the accelerometer, we can intuitively understand the response of the bridge structure under the dynamic load, which provides valuable first-hand information for the subsequent data processing and analysis.

In data processing, baseline correction and bandpass filtering are two common preprocessing methods. Baseline correction can effectively remove the phenomenon of baseline drift caused by instrument zero drift or environmental factors, making the data more real and reliable. By setting a reasonable frequency range, bandpass filtering removes the noise signal that is not in the range, so as to further improve the signal-to-noise ratio of the data. The combination of these two pretreatment methods can significantly improve the accuracy and reliability of data, and lay a solid foundation for the subsequent dynamic response analysis.

In the aspect of pier safety evaluation, scholars at home and abroad have put forward a variety of evaluation methods and indicators, aiming at a comprehensive and accurate evaluation of pier safety. Among them, Pearson correlation coefficient method is favored because of its simple calculation, easy to understand and wide application. By calculating the correlation coefficient between displacement time history data and acceleration response spectrum at different measuring points, the similarity and difference between them can be intuitively reflected. When the correlation coefficient is high, it indicates that the dynamic response data of different measuring points have good consistency, and the overall performance of the pier is good. When the correlation coefficient is low, it may mean that there are some potential safety hazards or damage to the pier. Therefore, Pearson correlation coefficient method provides an effective quantitative method for pier safety evaluation.

However, although many achievements have been made in the field of pier dynamic performance evaluation, there are still some problems to be solved. In terms of data processing, although preprocessing methods such as baseline correction and bandpass filtering have been widely used, some special cases may still be encountered in practical applications, such as complex noise signal and difficult to completely eliminate baseline drift phenomenon. These problems may have some impact on the accuracy and reliability of data, so it is necessary to further study more effective data processing methods. In the aspect of pier safety evaluation, many evaluation methods and indexes have been proposed, but how to establish a scientific and reasonable evaluation method and index system is still a difficult problem. Different evaluation methods and indicators may have different ememphasis and scope of application, so it is necessary to consider various factors comprehensively and select the most suitable evaluation methods and indicators to evaluate the safety of bridge piers comprehensively and accurately.

3. Dynamic analysis method of pier safety based on time-frequency domain combination

3.1. Calculation principle

The method is based on the following core principles:

(1) Pre-processing of acceleration data: removing noise and drift in acceleration time history data through baseline correction and bandpass filtering to improve data accuracy. The purpose of baseline correction is to remove the overall bias of the data and ensure that the data fluctuates around the zero mean; Bandpass filtering is to remove noise outside the frequency range and retain useful vibration information.

(2) Calculation of displacement time history: the acceleration time history data is converted into displacement time history data by digital integration method. This is because measuring displacement directly is often more difficult than measuring acceleration, and acceleration data can be integrated to obtain displacement information.

(3) Calculation of acceleration response spectrum: Response spectrum is a method to convert acceleration time history data into frequency-dependent acceleration response peaks, which is often used in structural dynamic analysis. It can reflect the maximum response of the structure under different frequency seismic action.

(4) Data difference analysis: Pearson correlation coefficient method was used to calculate the difference of displacement time history data and acceleration response spectrum between different measurement points, and to evaluate the vibration response consistency of bridge piers at different parts.

(5) Safety evaluation: According to the displacement time history data, acceleration response spectrum and its difference analysis results, the safety evaluation coefficient of bridge pier is comprehensively calculated to quantify the safety state of bridge pier under different incentives.

3.2. Calculation process

Firstly, accelerometers installed at different parts of the pier are used to collect dynamic time history data. The accelerometer can capture the acceleration change of bridge pier under dynamic load. The raw acceleration data collected often contains noise and baseline drift, so it needs to be pre-processed.

Baseline correction removes the overall shift of acceleration data by the following formula:

$$a_c(t) = a_r(t) - a_w(t) \quad (1)$$

Where $a_c(t)$ is the corrected acceleration, $a_r(t)$ is the original acceleration, and $a_w(t)$ is the average of the original acceleration. Then, the band-pass filtering formula is applied to remove high-frequency noise and low-frequency drift, and the filtered acceleration data is obtained:

$$a_f(t) = \frac{{w_0}^2}{s^2+2\delta w_0 s+{w_0}^2} a_c(t) \quad (2)$$

Where s is the Laplacian variable, w_0 is the natural frequency, and δ is the damping ratio.

After the acceleration data is preprocessed, the next step is to convert it into displacement time history data by double integration. The calculation of displacement time history is very important to evaluate the deformation of pier. The displacement time history is calculated as follows:

$$d(t) = \int_0^t (\int_0^\tau a_f(t)(\tau')\, d\tau') d\tau \quad (3)$$

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Where $d(t)$ is the displacement.

Acceleration response spectrum is an important tool to evaluate the response characteristics of structures under dynamic loads of different frequencies. According to the filtered acceleration time history data, the acceleration response spectrum can be calculated. The calculation of the acceleration response spectrum is usually achieved by numerical integration or approximate calculation using the standard response spectrum formula. The following formula is used to calculate the acceleration response spectrum value of period T:

$$S_a(T) = \max_{0 \leq t \leq \text{duration}} \left| \frac{1}{T} \int_{t-T/2}^{t+T/2} a_f(t) \mathrm{d}t \right| \tag{4}$$

After obtaining the displacement time history data and acceleration response spectrum, the next step is to calculate the difference between the data at different measuring points by using Pearson correlation coefficient method. By comparing the responses of different measuring points, the vibration response consistency of piers at different parts can be evaluated. The Pearson correlation coefficient formula is as follows:

$$r = \frac{\sum_{i=1}^{n}(d_i-\bar{d})(a_i-\bar{a})}{\sqrt{\sum_{i=1}^{n}(d_i-\bar{d})^2 \sum_{i=1}^{n}((a_i-\bar{a}))^2}} \tag{5}$$

Where d_i and a_i are the displacement and acceleration data of the i th measuring point respectively, $\bar{d}$ and $\bar{a}$ are their average values respectively, and n is the number of data points. Finally, according to the displacement time history data, acceleration response spectrum and its difference analysis results, the safety evaluation coefficient of bridge pier is calculated comprehensively.

4. Case verification

4.1. Engineering background

In order to verify the feasibility and effectiveness of the method proposed in this paper, a concrete engineering background case is designed, and the geometric model and dynamic analysis model of bridge pier are constructed by using advanced computer aided design and finite element analysis software. First of all, we use Rhino 7.0, a professional 3D modeling software, according to the design drawings and actual requirements, to accurately establish the geometric model of the pier. The design height of the pier is 22 meters, the typical cylindrical structure is adopted, and the diameter of the pier is set in detail according to the design requirements. In the modeling process, we fully consider the structural details of the pier, such as pier section changes, reinforcement layout, etc., to ensure the accuracy and authenticity of the model. Once the geometric model was built, it was seamlessly imported into Abaqus, a powerful finite element analysis software, for further calculations and analysis. Abaqus is widely used in the field of civil engineering because of its rich material model, powerful solving ability and high precision analysis results. After importing the model, we carried out detailed material property definition and meshing according to the actual material and structural characteristics of the pier. In particular, considering the important influence of the stress-strain relationship on the dynamic response of the whole structure, the stress-strain curve in the form of double broken lines is used to describe the mechanical properties of the reinforcement. This curve not only considers the elastic stage of the steel bar, but also fully considers the strain hardening stage, which more accurately simulates the nonlinear behavior of the steel bar during the stress process. The established numerical simulation model is shown in Figure 1.

In order to verify the effectiveness of the method proposed in this paper under extreme conditions, a case of falling rock impacting the pier is designed. In this working condition, it is assumed that a falling rock with a diameter of 1 m hits the middle area of the pier at a speed of 10 m/s, resulting in a certain degree of damage in this area. This design not only simulates the possible rockfall disaster in nature, but also fully considers the dynamic response characteristics of the pier under extreme impact load. In order to comprehensively evaluate the dynamic response and safety of the pier after rockfall impact, we selected several measuring points on the pier for data collection. The measuring point near the damaged area is used to monitor the displacement and acceleration response of the pier in this area. At the same time, measuring points were also set up at two normal locations away from the damaged area for comparison and reference. Among them, the measurement points at the damaged location are numbered 2, and the locations away from the damaged area are numbered 1 and 3. Finally, 0.05g and 0.3g seismic waves were input for safety assessment.

ISSN 2616-5767 Vol.7, Issue 6: 138-144, DOI: 10.25236/AJETS.2024.070620

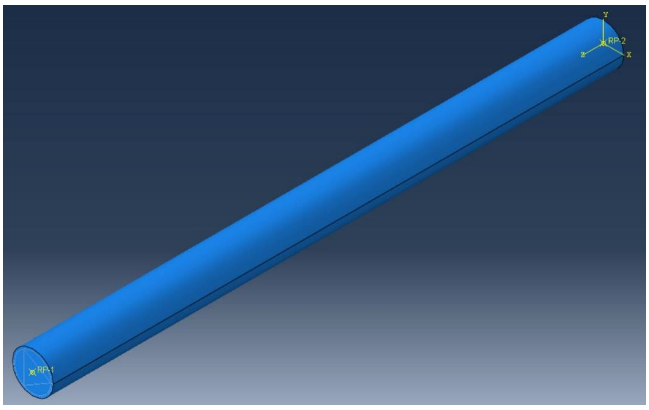

Figure 1: This paper establishes the numerical simulation condition.

4.2. Result analysis

After collecting enough dynamic time history data, this paper uses baseline correction and band-pass filtering to preprocess the acceleration time history data to eliminate noise and interference, in which the band-pass filtering range is 0-50Hz. Then, the displacement time-history data of different measuring points were calculated by digital integration method (see FIG. 2 and FIG. 3), and the acceleration response spectra of different measuring points were calculated by response spectrum method (see FIG. 4 and FIG. 5).

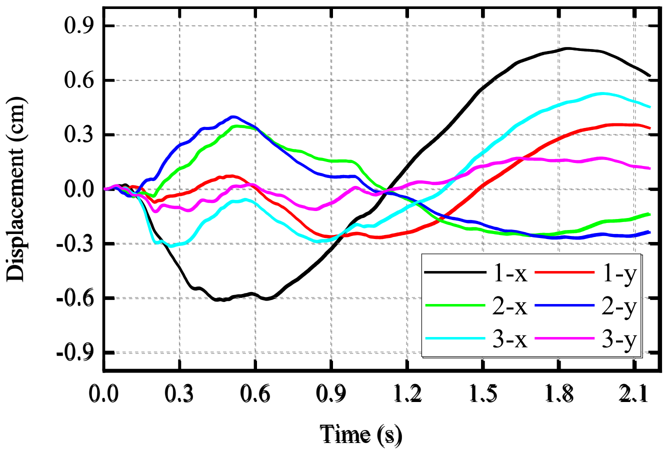

Figure 2: Displacement time history of different measuring points under the action of 0.05g seismic wave.

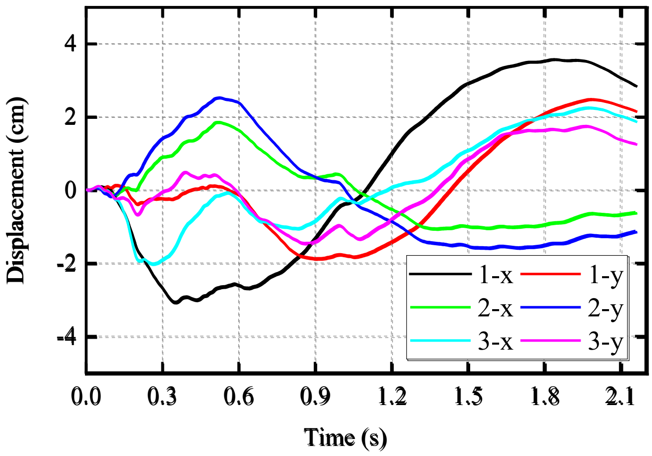

Figure 3: Displacement time history of different measuring points under the action of 0.30g seismic wave.

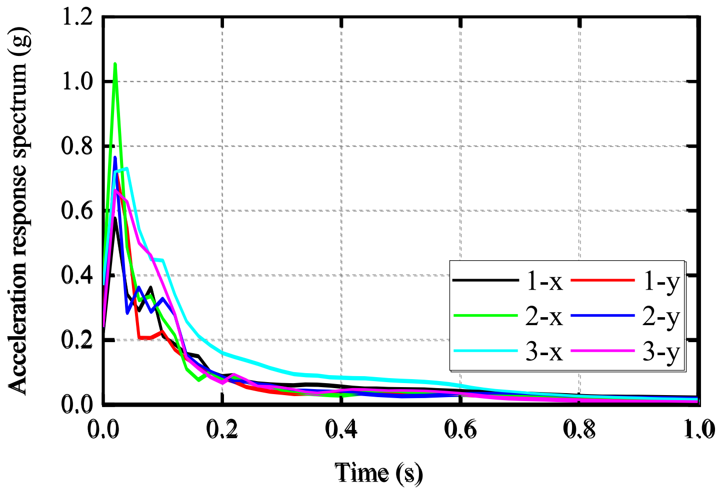

Figure 4: Acceleration response spectra of different measuring points under the action of 0.05g seismic wave.

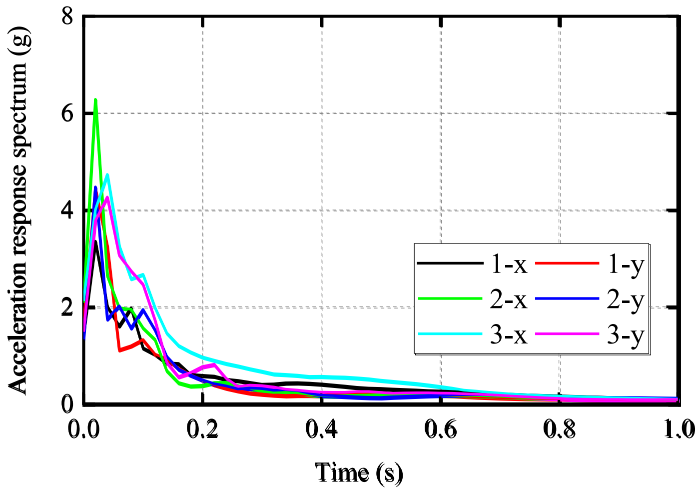

Figure 5: Acceleration response spectra of different measuring points under the action of 0.30g seismic wave.

Table 1: Safety evaluation coefficient of bridge pier at different positions under seismic wave action.

Measuring point	1		2		3	
Position	x	y	x	y	x	y
0.05g- Single	0.945	0.764	0.895	0.788	0.883	0.850
0.30g- Single	0.939	0.819	0.871	0.695	0.866	0.822
0.05g- Comprehensive	0.721		0.699		0.746	
0.30g- Comprehensive	0.769		0.593		0.707	

Finally, Pearson correlation coefficient method was used to calculate the difference of displacement time history data and acceleration response spectrum of different measuring points in x direction and y direction, so as to obtain the safety evaluation coefficient of bridge piers, as shown in Table 1. Among them, "single" refers to the result of distinguishing the direction of the measurement point, and "comprehensive" refers to the superposition of the x direction (tangential pier) and the y direction (radial). It can be seen from the data in Table 1 that there are significant differences in the safety evaluation coefficients of bridge piers under different seismic wave intensities (0.05g and 0.30g) and different modes of action (single and comprehensive). Under the action of 0.05g seismic wave alone, the safety evaluation coefficient of each measuring point in x direction is generally higher than that in y direction, which indicates that the pier has better seismic performance in x direction. With the increase of seismic wave intensity to 0.30g, although the safety evaluation coefficient in the x direction is still higher than that in the y direction, the gap between the two is narrowed, reflecting that the increase of seismic wave intensity has a more significant impact on the seismic performance of bridge piers in the y direction. Under the action of 0.30g earthquake, the comprehensive safety evaluation coefficient of test site 2 drops to 0.593,

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becoming the lowest value in all conditions, indicating that this location may face greater safety risks under the comprehensive action of strong earthquakes, reflecting its damage, and proving the feasibility of this method for safety evaluation.

5. Conclusions

The purpose of this paper is to explore an efficient and accurate method for pier safety assessment to cope with the increasingly complex bridge engineering safety challenges. By integrating advanced signal processing technology, the dynamic response characteristics of bridge piers can be comprehensively monitored and analyzed. In the data processing stage, the baseline correction and bandpass filtering technology are used to eliminate the noise and baseline drift in the original data and improve the accuracy and reliability of the data. Then, the acceleration time history data is converted into displacement time history data by digital integration method, which provides an intuitive and quantified basis for the deformation analysis of bridge piers. At the same time, the acceleration response spectra of different measuring points are calculated by using the response spectrum method, which further reveals the response characteristics of bridge piers under dynamic loads of different frequencies. In this study, Pearson correlation coefficient method was introduced to quantify the overall coordination and local damage degree of bridge piers under dynamic load by calculating the difference of displacement time history data and acceleration response spectrum at different measuring points. On this basis, the safety evaluation coefficient of bridge pier is constructed, which provides scientific quantitative index for the safety state of bridge pier. In order to verify the feasibility and effectiveness of the proposed method, a numerical simulation model is also established to simulate the dynamic response of the pier under specific working conditions, and the calculated results are compared with the measured data. The results show that the proposed method has high accuracy and applicability in the dynamic analysis of pier safety, and can provide strong technical support for the health monitoring and maintenance management of bridge structures.

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