

Article

Monitoring Bridge Dynamic Deformation Law Based on Digital Photography and Ground-Based RAR Technology

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Abstract: Dynamic deflection deformation is a crucial index which can reflect the healthy operation of bridges; due to their limitations, monitoring technologies (e.g., sensors, automatic total stations, and GPS) cannot perform high-frequency and whole-process non-contact dynamic deformation monitoring. Therefore, taking the Jinan Fenghuangshan Road Bridge as an example, this paper developed key low-cost and high-precision close-range photogrammetry technology and combined this with GB-RAR technology to remotely monitor bridge dynamic deformation. The results indicate that the measurement accuracy pertaining to the technology, which is based on an isometric virtual surface, is approximately 0.5 mm when the monitoring distance is 250 m, which can meet the accuracy requirements of bridge deformation monitoring. A vehicle's dynamic load is transmitted in the form of a stress wave inside the bridge, and with regard to span, the wave is most significant in the 1/2 to 1/4 range. This study observes that the maximum deflection deformation of the bridge is 47.2 mm, which is within the allowable deformation range of the General Specifications for Design of Highway Bridges and Culverts. The research results herein provide technical support and data reference for safety monitoring, and for the reinforcement and maintenance of bridges such as the Fenghuangshan Road Bridge.

Keywords: close-range photogrammetry; GB-RAR; safety monitoring; wading bridge



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1. Introduction

Water bridges are a critical component of urban transportation infrastructure, crucially facilitating transportation and promoting the prosperity and development of the urban economy. However, due to problems of the bridges themselves and their operation, safety accidents have been caused, seriously endangering people's lives and property safety. Through the analysis of bridge safety accidents, it is observed that the vast majority of bridge accidents are occasioned by the long-term impact of environmental factors that occur during bridge operation such as storms, rain, and snow; weathering and decay; and air oxidation. Furthermore, it was observed that the strength and stiffness of bridges decline. Under the frequent action of dynamic loads such as vehicles and trains, bridges (especially long-span bridges) produce instantaneous abnormal deformation, which destroys the stability of local bridge components and eventually leads to the collapse of the bridge. For example, on 13 July 2019, the abutment of the Tianxin DaFengZouShaGang bridge in Zhuzhou city, Hunan Province, China shifted, causing expansion of the expansion joint of the northern section of the bridge. The cause of the accident is assumed to be the dual role of

flood erosion and heavy vehicle load on the bridge. On 1 November 2020, a major railway traffic accident occurred on Tianjin's coastal new-region Tianjin NanHuanLinGang Railway, resulting in eight deaths, one serious injury, and five minor injuries. Therefore, real-time monitoring of the instantaneous overall dynamic deformation of bridges under the action of dynamic loads such as vehicles and trains crucially enables engineers to comprehend the health status of bridges in a timely manner and execute early bridge safety warnings.

For the dynamic deformation monitoring of bridges with commonly utilized deformation measurement techniques, some shortcomings persist, and traditional measurement methods represented by levels and theodolites can monitor only static deformation over a long period. Automatic total stations are suitable for single-point dynamic tracking measurement [1–5]. When GPS technology is utilized in high-frequency dynamic deformation monitoring, the measurement error is large, and a receiver or GPS signal-receiving antenna should be placed at each point [6–11]. The monitoring frequency of 3D laser scanning technology is exceedingly low. Furthermore, sensor technologies often require contact with bridges, and the packaging technology, compensation technology, and installation requirements of the sensors are more stringent, requiring higher costs [12–15]. Therefore, to optimally realize the dynamic deformation monitoring of bridges, we must explore novel technologies.

IBIS-S (Image By Interferometric Survey of Structures) can monitor small levels of deformation in bridges, and it can realize the real-time monitoring of one-dimensional displacement information in the direction of electromagnetic wave propagation. Gentile and Bernardini [16] conducted an environmental vibration test (AVT) on the Capriaet Bridge in 2008, and they placed 32 WR731A sensors on the bridge for a controlled experiment; the results indicate that the speed measured by the IBIS-S system exhibits good agreement with that measured using traditional sensors, which comprehensively demonstrates the reliability of the IBIS-S system. Wang Junyu [17] adopted stepped-frequency continuous wave and synthetic aperture through a ground interference radar system—micro-deformation monitoring system (IBIS) radar and interferometric technique for the dynamic or static monitoring of ground targets. Additionally, numerous scholars have also utilized the IBIS-S system to conduct vibration tests and safety monitoring on the Jinshajiang Bridge in Sichuan Province, Qingjiang No. 7 Bridge of Baocheng Railway, Zhanglong High-speed Shikongshan Bridge, Hangzhou Qiantang River Bridge, and Beijing–Tianjin high-speed Railway Yangcun Bridge; the scholars achieved satisfactory results.

Furthermore, digital photogrammetry technology can quickly collect data and obtain instantaneous deformation information of monitored objects, so is quite suitable for dynamic deformation monitoring of the measured objects. T. Whiteman et al. [18] utilized a CCD (Charge-Coupled Device) camera and LVDT (Linear Variable Differential Transformer) displacement measurement sensor to monitor the deformation of concrete beams when imposing vertical loads on them. The research results indicate that the measurement accuracy of the digital cameras attained a sub-millimeter level. Jian Ye et al. [19] adopted the method based on edge recognition to take multiple photos of the side of a bridge at different times, combined the images with high-precision algorithms, and processed the image edges to obtain the continuous edge of the bridge; subsequently, they solved the bridge deformation. Hans-Gerd Maas et al. [20] measured the instantaneous deformation values of structures with digital cameras as monitoring equipment, and they noted that digital cameras exhibit immense potential for structural deformation measurement. Ivan Detchev et al. [21] combined digital cameras with image processing technology to propose novel sine-wave curve fitting based on the least-square method, which enhanced measurement accuracy and frequency. Khalid L. A et al. [22] explored the feasibility of smart phones in the deformation monitoring field; using two smart phones, namely LAmia535 and SLAmia 950 XL, vertical displacement was measured. The experiment indicates that smart phones can meet the requirements of digital close-range photogrammetry in regard to precision, cost, and flexibility. Liu Qiongqiong [23] utilized a non-measuring digital camera for the linear monitoring of a bridge, and they utilized direct linear transformation to check the non-measuring

digital camera; thus, data acquisition, extraction, processing, and analysis were achieved. Luo Yunhai [24] utilized a non-measuring digital camera to collect data, and they utilized the P-H algorithm to solve coordinates. After lens distortion correction and focal length error correction of the non-measuring digital camera, a deformation monitoring experiment of the structure they were analyzing was performed in the laboratory. The result is basically consistent with that of the deflection meter. Beginning from basic close-range photogrammetry theory, Liang Fei [25] conducted pier-lean and deck-displacement observation of a bridge by establishing a 3D model method. Wang Hanzhang [26] expanded the principle pertaining to the time baseline parallax method by taking deformation pictures of bridges with a non-measuring digital camera. Two kinds of bridge deformation measurement methods based on edge recognition and image correlation matching were established. Yu Chengxin et al. [27] proposed the image matching time baseline parallax method to overcome the following defect: the digital photography technique based on monocular vision cannot monitor 3D bridge deformation. Their deformation diagram intuitively indicates the bridge structure trend, which addresses the deficiency of traditional measurement techniques in the long-term real-time monitoring of overall bridge deformation. Aiming at addressing the deficiency of traditional deformation monitoring, a non-measuring digital camera was utilized; thus, instantaneous real-time bridge deformation monitoring was conducted. The experiment [28] indicates that deformation monitoring of a bridge structure using digital close-range photogrammetry is easy, and that the instantaneous deformation information of multiple observation points can be obtained simultaneously, with the result accuracy attaining 3/1000.

Therefore, digital photography technology and GB-RAR (ground-based real aperture radar) technology are utilized to jointly monitor the dynamic deformation of bridges and to deeply analyze the deformation characteristics of bridges under the action of vehicle dynamic load; thus, a data reference for the safety evaluation and reinforcement design of bridges is obtained.

2. Monitoring Method of Bridge Dynamic Deformation

2.1. Digital Close-Range Photogrammetry Technology

Differential interferometry is utilized to process radar data collected in the monitoring process by selecting an appropriate reference time base and differential interferometry. A deformation time series of bridge monitoring points can be obtained by calculating the deformation values of corresponding points at different time scales; subsequently, other parameters of bridge dynamic characteristics can be obtained. The main data processing and analysis procedures are as follows:

(1) Reference time base selection

The beginning of radar data acquisition is selected as the reference time base for data processing. Assume that the bridge deformation value at this moment is 0, and based on the radar data at other times, the calculated deformation value is relative to the reference time base.

(2) Windowing treatment

Radar echo data collected by the IBIS-S system are a sample in the frequency domain, which should be focused. In other words, a Discrete Fourier inversion is adopted to convert the frequency domain data into spatial domain data; thus, the deformation information of each resolution unit in the range direction of the radar monitoring region can be extracted. Herein, before focusing on the distance direction of radar monitoring data, a hanning window function is utilized; thus, the radar data signal is windowed to eliminate the side lobe effect.

(3) Differential interferometry treatment

First, the ground-based radar image contains amplitude and phase information, which is reflected by the geometric distance between the radar and the target. Therefore, an

interferometric technique can be utilized to retrieve the displacement change between the radar and target according to the phase change of radar images obtained at different times.

If it is assumed that two scene radar images ($t_1 > t_0$) are obtained at different times, namely t_0 and t_1 , and that the phase value of the same pixel is the same as that of the radar image at the aforementioned times, the following formula applies:

$$\phi_0 = \frac{4\pi S_0}{\lambda} + \phi_{\text{divert},0} + \phi_{\text{air},0} + \phi_{\text{strepitus},0} \quad (1)$$

$$\phi_1 = \frac{4\pi S_1}{\lambda} + \phi_{\text{divert},1} + \phi_{\text{air},1} + \phi_{\text{strepitus},1} \quad (2)$$

where λ denotes the wavelength of the radar transmission signal; S_0 and S_1 denote the geometric distance between the radar and the target at two times, namely t_0 and t_1 ; ϕ_{divert} denotes a phase change occasioned by the interaction of the microwave and monitored object; ϕ_{air} denotes the phase occasioned by atmospheric interference between the radar and monitored object; and $\phi_{\text{strepitus}}$ denotes a random noise phase.

After interference processing, the interferometric phase $\Delta\phi_{10}$ of the radar image at t_0 and t_1 can be obtained as follows:

$$\Delta\phi_{10} = \phi_1 - \phi_0 = \frac{4\pi(S_1 - S_0)}{\lambda} + (\phi_{\text{divert},1} - \phi_{\text{divert},0}) + (\phi_{\text{air},1} - \phi_{\text{air},0}) + \phi_{\text{strepitus}} \quad (3)$$

Assuming that the phase-shift component ϕ_{divert} is constant in the radar images obtained at times t_0 and t_1 , Formula (3) can be simplified as follows:

$$\Delta\phi_{10} = \phi_1 - \phi_0 = \frac{4\pi d_{Lo}}{\lambda} + (\phi_{\text{air},1} - \phi_{\text{air},0}) + \phi_{\text{strepitus}} \quad (4)$$

In Formula (4), $d_{Lo} = R_1 - R_0$ denotes the displacement change between t_0 and t_1 when the target object appears upward in the radar line of sight. By removing the phase component $(\phi_{\text{air},1} - \phi_{\text{air},0})$ occasioned by atmospheric effects and the corresponding noise phase component $\phi_{\text{strepitus}}$, the deformation in the radar line-of-sight direction between t_0 and t_1 can be obtained as follows:

$$d_{Lo} = \frac{\Delta\phi'_{10}\lambda}{4\pi} \quad (5)$$

In Formula (5), $\Delta\phi'_{10}$ denotes the interference phase of the radar image between t_0 and t_1 after removing the phase component affected by the atmospheric effect and other corresponding noise phase errors.

Since the purpose of this monitoring is to obtain the settlement information of the pier, the vertical deformation component in the eye direction should be obtained. This vertical component (i.e., the vertical deformation of the pier) can be calculated using a simple geometric projection, which is expressed as follows:

$$d_{de} = \frac{d_{Lo}}{\sin(\alpha)} = d_{Lo} \frac{S}{D} \quad (6)$$

In Formula (6), S denotes the distance from the radar to the target, and $D = S \sin(\alpha)$; additionally, α denotes the angle between the horizontal direction and the radar line of sight.

The geometric relationship between visual displacement and vertical deformation is shown in Figure 1.

(4) Wavelet analysis for denoising

To obtain more accurate deformation time series, the deformation time series obtained in Step (3) is denoised. First, the deformation time series obtained in Step (3) is denoised using wavelet analysis to further remove the noise component; subsequently, the dynamic

characteristic parameters of the bridge are obtained based on the deformation time series after noise removal.

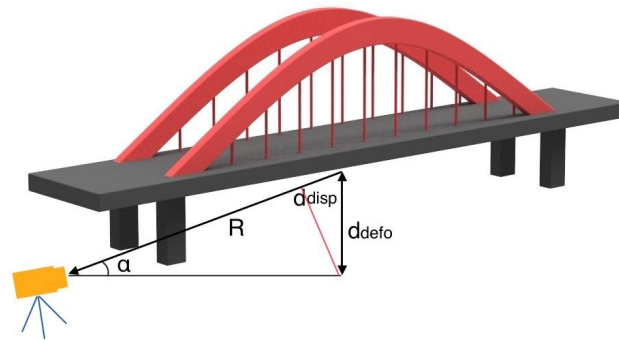


Figure 1. Geometric relationship between visual displacement and vertical deformation.

(5) IBIS-S measurement accuracy

The minimum shape variable that the IBIS-S system can detect is $d_{\min}$, which can be calculated using the following formula:

$$d_{\min} = -\frac{\lambda}{4\pi}(\phi_2 - \phi_1)_{\min} \quad (7)$$

where λ denotes the wavelength of the electromagnetic wave, and its calculation formula is expressed as follows:

$$\lambda = \frac{c}{f} = \frac{3.0 \times 10^8 \text{ m/s}}{17 \text{ GHz}} = 17.649 \text{ m} \quad (8)$$

$(\phi_2 - \phi_1)_{\min}$ denotes the minimum phase difference that can be resolved by the system, and its calculation formula is expressed as follows:

$$(\phi_2 - \phi_1)_{\min} = 1'' = \frac{\pi}{648,000} \quad (9)$$

Therefore, the minimum deformation measured by the IBIS-S technology is 0.000068 mm, and the theoretical measurement accuracy can attain one millionth of a millimeter. However, in actual measurement, due to the role and influence of several factors, the detection accuracy exhibits a certain uncertainty. Therefore, the accuracy of the measurement is limited by the quality of the observation conditions. IBIS-S technology exhibits a nominal accuracy of 0.1 mm in the static monitoring state and 0.01 mm in the dynamic monitoring state.

Ground-based radar interferometry technology measures the relative deformation of the subsequent moment relative to the founding moment. During the measurement process, the stability of the measuring instrument should be ensured, and the temperature, air pressure, and wind speed around the instrument should be kept stable, so as to reduce the interference of external environmental factors on the measurement results and improve the measurement accuracy.

2.2. Digital Photography Deformation Monitoring Technology Based on an Iso-Metric Virtual Plane

The displacement parallax method is based on the isometric virtual plane developed from the time baseline parallax method. The time baseline parallax method is often used to solve data processing problems in close-range photogrammetry deformation monitoring. It is used to arrange a control point around the monitored body, so that the photographic scale of the reference plane is consistent with the deformation monitoring point's photographic scale, and the monitoring accuracy can reach a millimeter level within the monitoring distance range of 10 m. Later, the photographic scale change-time baseline parallax method

is proposed to solve the problem that the photographic axis of the complex monitoring site is not perpendicular to the surface of the monitored body. The reference point is arranged near the photographic equipment to form a reference surface. The photographic scale is transformed by the pinhole imaging principle and correlative mathematical theory. When this method is used for remote monitoring, the reference plane will easily block the monitored body, and the measurement experiment cannot be carried out.

To solve the scenario in which control points cannot be set up during remote monitoring, or the control points severely occlude the monitored target, the isometric virtual plane method is proposed, and its basic principle is depicted in Figure 2. A CCD digital camera is utilized to monitor and shoot the monitored body. The actual reference plane at photography distances H_3 and H_6 , and H_2 and H_5 , are the distances between the optical origin and the front end of the CCD; D_1 denotes the actual length of the picture on the reference plane when the depth of field is H_3 , and D_2 denotes the actual length of the picture on the object plane when the depth of field is H_4 . H_1 and H_4 denote the focal lengths of the digital cameras, whereas N_1 and N_2 denote the maximum pixel values in the horizontal direction of the image plane, respectively, which are fixed and exhibit no relationship with the change in photography distance.

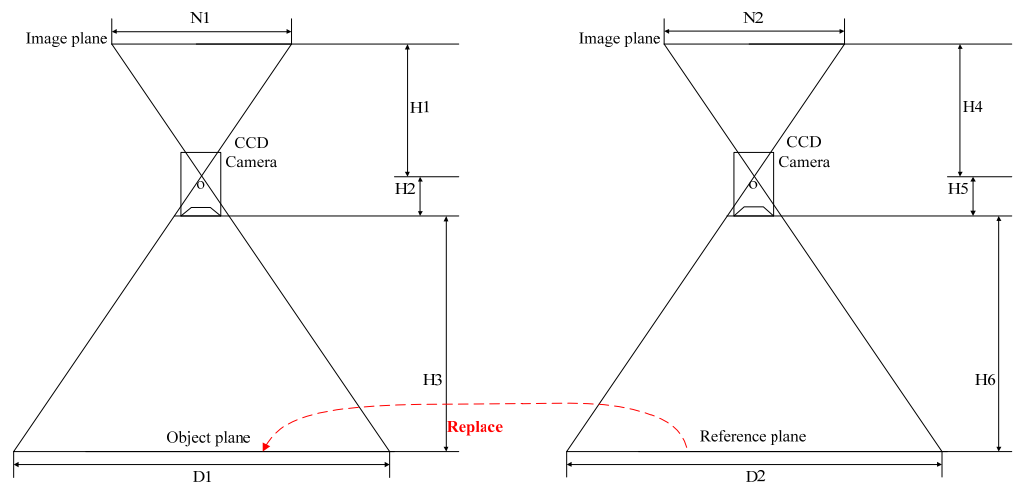


Figure 2. Schematic diagram of the equidistant replacement principle.

Figure 2 shows the relationship between pixel value and photographic distance depicted in Formula (10):

$$\left. \begin{aligned} \frac{H_1 + H_2}{H_3} &= \frac{N_1}{D_1} \\ \frac{H_4 + H_5}{H_6} &= \frac{N_2}{D_2} \end{aligned} \right\} \quad (10)$$

As can be observed from Figure 2, digital photography deformation monitoring technology based on an isometric virtual plane must meet the following conditions:

$$\left. \begin{aligned} N_1 &= N_2, D_1 = D_2 \\ H_1 &= H_4, H_2 = H_5, H_3 = H_6 \end{aligned} \right\} \quad (11)$$

Formula (11) can be obtained as follows:

$$\frac{H_1 + H_2}{H_6} = \frac{N_1}{D_2} \quad (12)$$

Displacement Parallax Method Based on the Isometric Virtual Plane

According to geometric progression pertaining to the depth of field, it can be considered that the photography scale of the isometric virtual plane and monitored target surface's (object plane) photography scale are equal. The displacement of the deformation monitoring point in the isometric virtual plane is transformed into the real displacement of

the deformation point using the mathematical relation. The specific derivation process is as follows:

In Figure 2, the Δx_{IVP}^{df} and Δz_{IVP}^{df} of the deformation points on the isometric virtual plane can be expressed as follows:

$$\left. \begin{aligned} \Delta x_{IVP}^{df} &= \frac{OA}{Oa} \Delta p_x^{df} = Q \cdot \Delta p_x^{df} \\ \Delta z_{IVP}^{df} &= \frac{OA}{Oa} \Delta p_z^{df} = Q \cdot \Delta p_z^{df} \end{aligned} \right\} \quad (13)$$

where Q denotes the photographic scale of the isometric virtual plane, and Δx_{IVP}^{df} and Δz_{IVP}^{df} denote the horizontal and vertical displacements of the deformation points from the object plane, respectively. Δp_x^{df} and Δp_z^{df} denote parallax values in the horizontal and vertical directions of the corresponding deformation points on the photo, respectively. Note that Δp_x^{df} and Δp_z^{df} contain systematic errors.

Expressions for Δp_x^{df} and Δp_z^{df} are depicted in Formula (14):

$$\left. \begin{aligned} \Delta p_x^{df} &= (x_2^{df} - x_1^{df}) - (dx_2^{df} - dx_1^{df}) \\ \Delta p_z^{df} &= (z_2^{df} - z_1^{df}) - (dz_2^{df} - dz_1^{df}) \end{aligned} \right\} \quad (14)$$

where $a(x_1^{df}, z_1^{df})$ and $b(x_2^{df}, z_2^{df})$ denote points with the same name in the zero-point photograph and follow-up photograph, respectively. (dx_1^{df}, dz_1^{df}) and (dx_2^{df}, dz_2^{df}) denote systematic errors in the zero-point photograph and follow-up photograph with the same deformation point. $(\Delta p_x^{df}, \Delta p_z^{df})$ denotes the parallax value of the deformation point on the image plane.

The displacement parallax method based on the isometric virtual plane is shown in Figure 3.

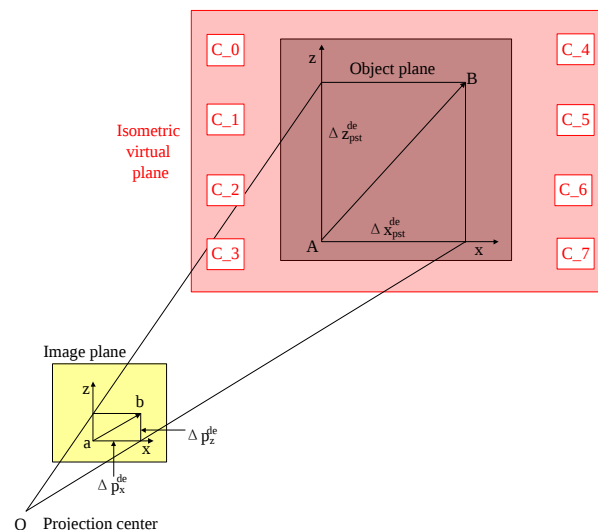


Figure 3. Displacement parallax method based on the isometric virtual plane.

To eliminate the parallax value occasioned by digital camera vibration and tripod movement, the study adopts a fixed and stationary reference plane to match the zero-point photograph and follow-up photograph. Subsequently, the parallax correction value of the corresponding deformation point can be expressed as follows:

$$\left. \begin{aligned} Adv\Delta p_x^{df'} &= \Delta p_x^{df'} - \Delta p_x^{df0'} \\ Adv\Delta p_z^{df'} &= \Delta p_z^{df'} - \Delta p_z^{df0'} \end{aligned} \right\} \quad (15)$$

where $(Adv\Delta p_x^{df'}, Adv\Delta p_z^{df'})$ denotes the correction of parallax in the barycentric coordinate system, and $(x^{df'}, z^{df'})$ and $(\Delta p_x^{df0'}, \Delta p_z^{df0'})$ denote the coordinates and systematic errors of the deformation point in the barycentric coordinate system, respectively.

Subsequently, based on the reference plane, the displacement change value of the deformation point is obtained as follows:

$$\left. \begin{aligned} Adv\Delta x_{IVP}^{df} &= Q \cdot Adv\Delta p_x^{df'} \\ Adv\Delta z_{IVP}^{df} &= Q \cdot Adv\Delta p_z^{df'} \end{aligned} \right\} \quad (16)$$

where $(Adv\Delta x_{IVP}^{df}, Adv\Delta z_{IVP}^{df})$ denotes the displacement change value of the deformation point on the reference plane.

The displacement parallax method based on the isometric virtual plane requires the photographic axis to be perpendicular to the monitored object surface to ensure that the solution result represents the movement direction of the monitored body.

3. Monitoring Experiment Pertaining to Dynamic Bridge Deformation

3.1. Brief Introduction of the Bridge

This study considers the Fenghuangshan Road Bridge; thus, it analyzes the deformation rule of the water-wading bridge under the action of a vehicle dynamic load. The Fenghuangshan Road Bridge, built in 2009, is located in Tianqiao District, Jinan City, Shandong Province, and it is built across the Xiaoqing River for both transportation and as a place to view the landscape. The bridge is a two-way four-lane bridge with a total length of 96 m and a total width of 31.3 m. The automobile design load is city-A class, and the design standard of the sidewalk load is 5 Kpa uniform load.

The location diagram of Fenghuangshan Road Bridge is shown in Figure 4.

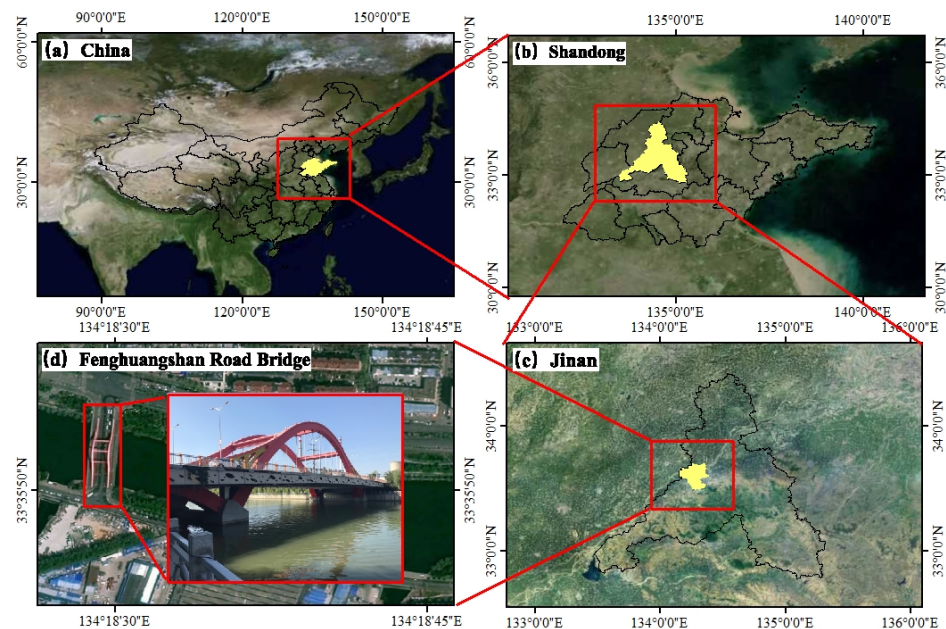


Figure 4. Location diagram of Fenghuangshan Road Bridge.

3.2. Microwave Interference Measurement Technology Monitoring the Dynamic Deformation of the Bridge

When monitoring the dynamic deformation of the Fenghuangshan Road Bridge of Xiaoqing River, the micro-deformation monitoring system was placed on the sidewalk directly below the bridge, and a 5° angle was formed between the line of sight and the horizontal direction (Figure 5).

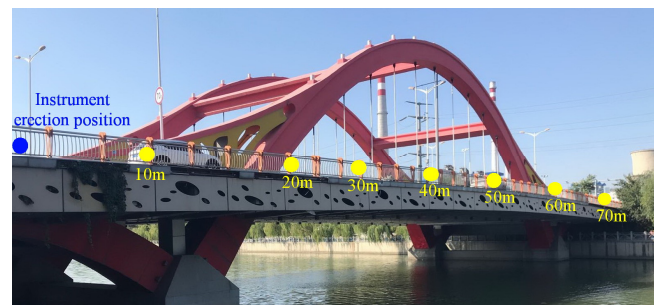


Figure 5. Relative position of monitoring points on Fenghuangshan Road Bridge.

When a vehicle passes the bridge, the monitoring frequency of the instrument is set to 50 Hz and 100 Hz, and the dynamic deformation time series of the bridge is obtained.

IBIS DATA VIEWER was utilized to process the monitored data, Rangebin Selection was selected, and multiple Rbin points were selected as the main monitoring points for bridge deformation according to the location of the distance monitoring instruments. The following were selected as deformation monitoring points for data processing: one mid-span position, two 1/4 span positions, two 1/8 span positions, and two bridge head positions. The processing results are detailed in Section 4.

3.3. Monitoring Bridge Dynamic Deformation Based on the Isometric Virtual Plane Method That Incorporates the Digital Photography Technique

To realize the goal of monitoring dynamic bridge deformation using close-range photogrammetry, fixed-frame camera equipment that is suitable for a total station was designed, and the camera equipment and telescope were matched in the line-of-sight direction; subsequently, bridge deformation was monitored at a distance from the bridge. The monitoring equipment and site are depicted in Figures 6 and 7. The specific monitoring process is as follows:



Figure 6. Test site. (a) Layout of deformation point beacons; (b) overview of five warp point beacons.

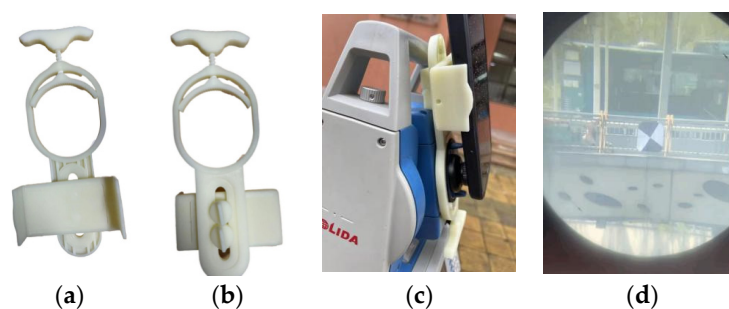


Figure 7. Remote monitoring of the close-range photogrammetry technical equipment and monitoring diagram. (a) Front view; (b) reverse view; (c) installation instruction; (d) field monitoring chart.

- ① Deformation monitoring points were arranged at the middle span, 1/4 spans, and 1/8 spans of the bridge, and the total station was placed on the sidewalk on the south bank of the Xiaoqing River. After centering, leveling, aiming, and focusing, the support and photography equipment were installed. Meanwhile, the close-range photogrammetry measuring device for remote monitoring was approximately 100 m away from the bridge.
- ② During the red light period, multiple instances of remote monitoring with close-range photogrammetry measuring devices were utilized to simultaneously take multiple sets of photos of the corresponding monitoring position of the bridge at high speed, and the group of photos with the highest quality was selected as the reference photos (zero photos).
- ③ During the green light period, when large buses or heavy trucks passed by, multiple instances of remote monitoring with close-range photogrammetry measuring devices were utilized to monitor the bridge and to collect multiple sets of photos. The group of photos with the highest quality was selected as the corresponding position for follow-up photos, and a total of 208 follow-up photos were taken.

4. Analysis of Bridge Deformation Characteristics

4.1. Dynamic Deformation Characteristics of the Fenghuangshan Road Bridge Based on GB-RAR Technology

To facilitate the analysis pertaining to the dynamic deformation characteristics of the bridge, distances from the instrument monitoring positions of 10 m (near the north end of the bridge, point A), 20 m (northern 1/8 span, point B), 30 m (northern 1/4 span, point C), 40 m (middle span, point D), 50 m (southern 1/4 span, point E), and 60 m (southern 1/8 span, point F) and 70 m (near the south end of the bridge, point G) were extracted, and global and local graphs of the bridge at different monitoring moments were drawn, as depicted below.

Furthermore, this study utilizes IBIS technology to monitor a spectrum map of the Fenghuangshan Road Bridge (Figure 8), and observes that the frequency of the bridge is 10 Hz, which clarifies the forced vibration state related to its own characteristics under the action of vehicle dynamic load.

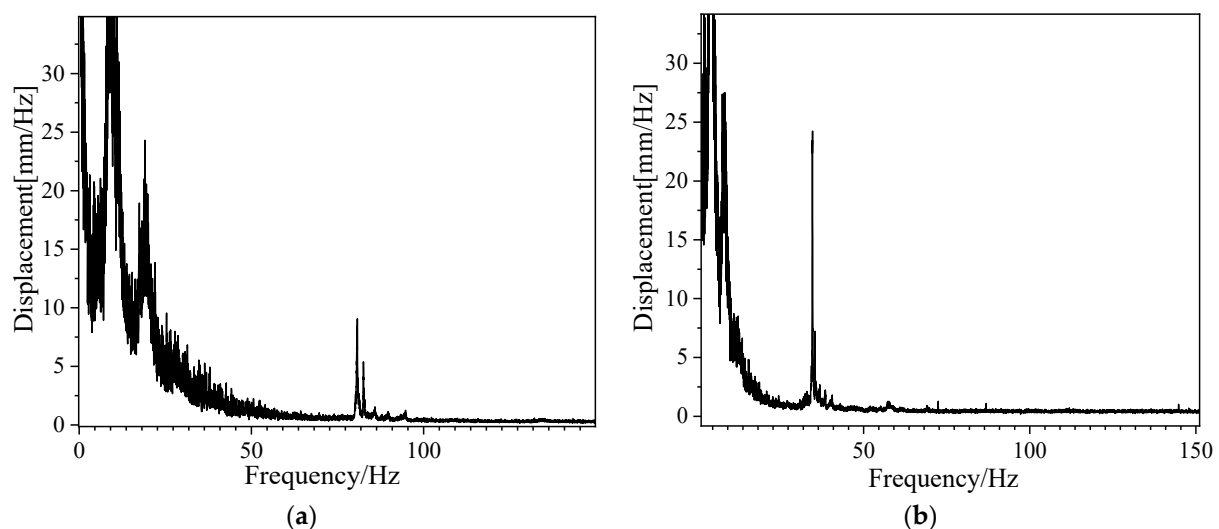


Figure 8. Bridge spectrum diagram. (a) The monitoring frequency is 50 Hz; (b) the monitoring frequency is 50 Hz.

4.1.1. Dynamic Deformation Characteristics of the Bridge with a 50 Hz Sampling Frequency

Under a 50 Hz sampling frequency, the IBIS micro-deformation monitoring system was utilized to monitor the Fenghuangshan Road Bridge, and the monitoring time was

2272.59 s. Some of the monitoring data were extracted to draw the deflection deformation time series curve of the bridge at different positions (Figure 9).

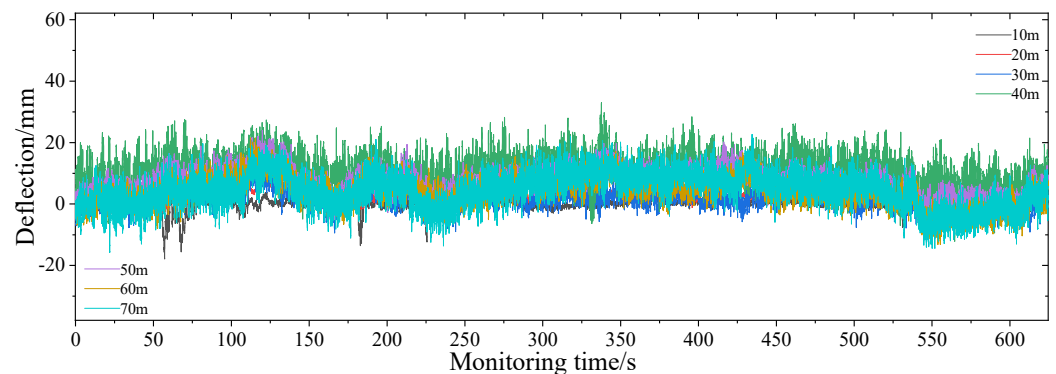


Figure 9. Schematic diagram pertaining to the dynamic deformation characteristics of bridge with a 50 Hz sampling frequency.

The analysis indicates that the bridge fluctuates up and down around a certain horizontal line at different positions, which is consistent with the motion characteristics of nonlinear elastic deformation. From Figure 10, it is observed that during the period from 7.940 s to 7.974 s at point A at the southern end of the bridge, the data fluctuate from the highest value (24.8 mm) to the lowest value (3.28 mm); the time is 0.035 s, the vibration period is 0.07 s, and the vibration frequency is 14.28 Hz. During the period from 279.40 s to 279.12 s, the deformation value changes from 30.5 mm to -3.4 mm; the time is 0.08 s, the vibration period is 0.16 s, and the vibration frequency is 6.25 Hz.

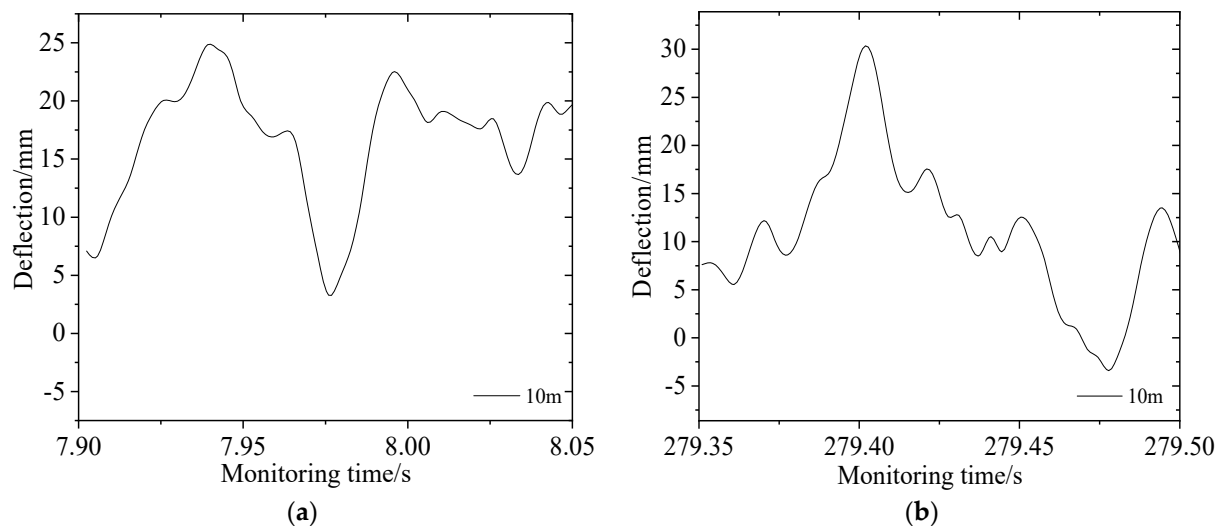


Figure 10. A 50 Hz sampling frequency: first monitoring results. (a) 7.90–8.05 s; (b) 279.35–279.50 s.

From Figure 11a, it can be observed that the deformation value pertaining to point C of the northern 1/4 span of the bridge is -9.6 mm at 311.85 s and 38.0 mm at 311.96 s, with a 47.6 mm amplitude, a 0.22 s period, and a 4.5 Hz frequency. In Figure 11b, the initial deformation fluctuation range at point C is -6.5 mm to 5 mm, and it suddenly changes to -43.8 mm at 316.30 s.

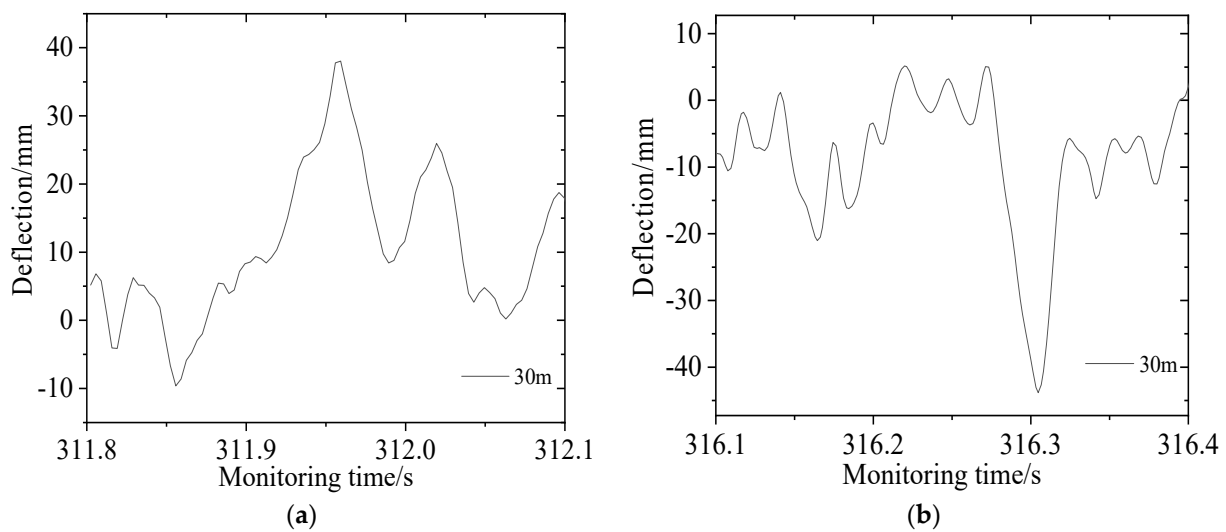


Figure 11. A 50 Hz sampling frequency: second monitoring results. (a) 311.8–312.1 s; (b) 316.1–316.4 s.

From Figure 12a, it can be observed that the southern 1/4 span at point E of the bridge deforms by 9.3 mm at 288.71 s and -16.8 mm at 288.59 s, with a 26.1 mm amplitude, a 0.24 s vibration period, and a 4.2 Hz vibration frequency. In Figure 12b, the point deforms by 3.5 mm at 311.42 s and 26.1 mm at 311.54 s, with a 22.6 mm amplitude, a 0.24 s vibration period, and a 4.2 Hz vibration frequency.

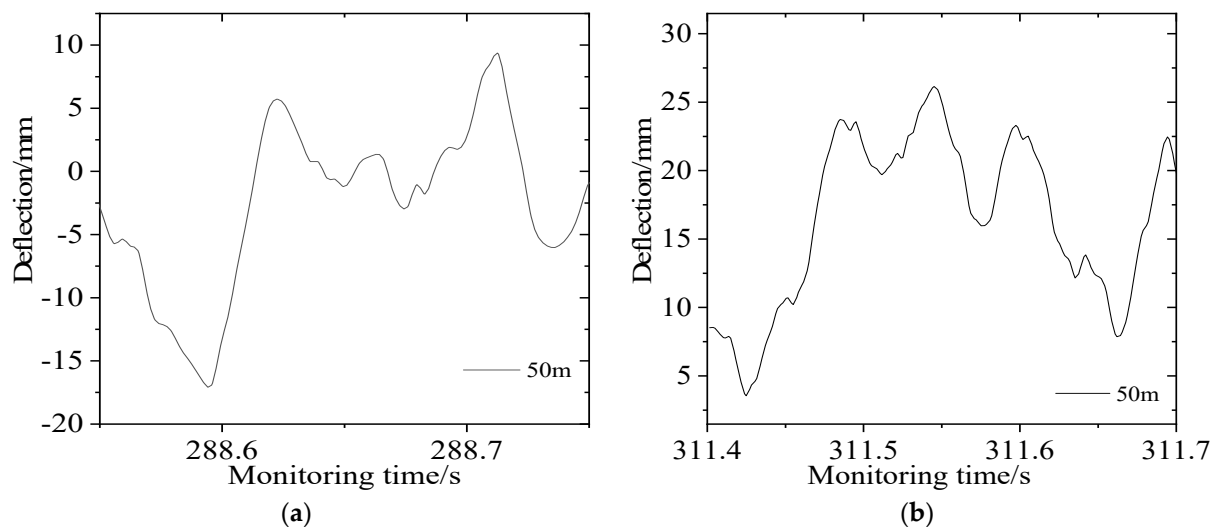


Figure 12. A 50 Hz sampling frequency: second monitoring results. (a) 288.55–288.75 s; (b) 311.4–311.7 s.

From Figure 13, it can be observed that under the simultaneous action of vehicle dynamic load, different positions of the bridge exhibit different deformation characteristics. The deformation at point C is the largest, followed by point E; additionally, the deformation at point A is the smallest. The deformation of point C at 48.65 s is 11.4 mm, and the deformation in the reverse direction after 0.07 s is -19.2 mm. The time from adjacent wave peaks to troughs is approximately 0.07 s, the vibration period is 0.14 s, and the vibration frequency is 7.14 Hz. Additionally, the point deforms by 10.6 mm at 308.82 s and -38.3 mm at 308.89 s, with a 48.9 mm amplitude, a 0.14 s vibration period, and a 7.14 Hz vibration frequency.

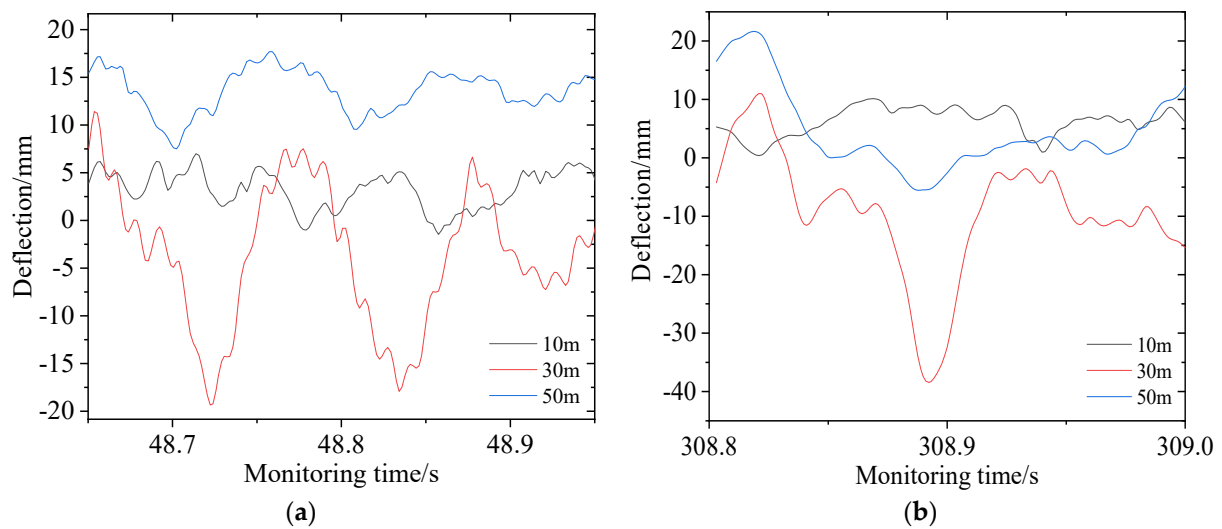


Figure 13. A 50 Hz sampling frequency: third monitoring results. (a) 48.65–48.95 s; (b) 308.8–309.0 s.

To describe the differences in movement characteristics at different bridge positions in detail, deformation data of the bridge from 1800 s to 1830 s during the monitoring period were extracted; a dynamic deformation trend comparison diagram was drawn at different bridge positions; the gravity direction was defined as the negative direction, and vice versa as the positive direction. From Figure 14, it can be observed that during this period, the deflection deformation trend at different bridge positions exhibits a “V” shape, first decreasing and subsequently increasing, among which the phenomenon is more apparent at 10 m, 20 m, 30 m, and 70 m, and the maximum deflection deformation values are −11.43 mm, −8.22 mm, −11.8 mm, and −16.24 mm, respectively. The maximum negative deflections at 40 m, 50 m, and 60 m are −8.48 mm, 9.56 mm, and 10.86 mm, respectively.

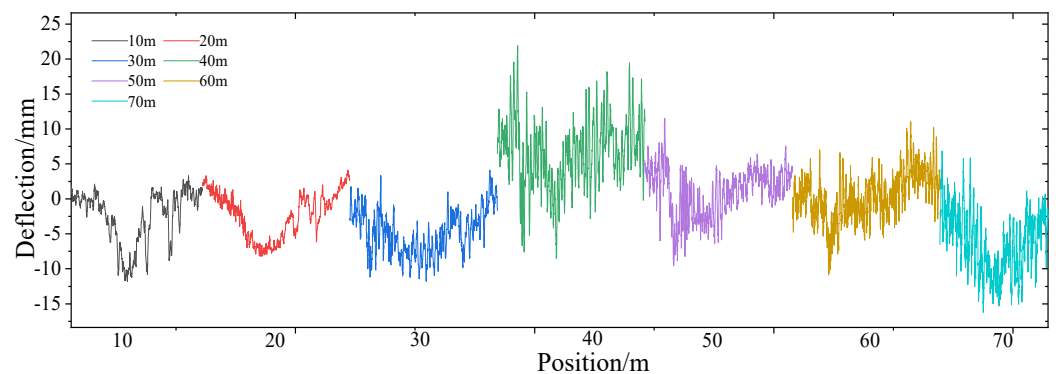


Figure 14. Comparison of dynamic deformation trends of bridge at different positions.

Judging from the maximum negative deflection deformation, the overall deformation of the bridge is a cosine curve. Therefore, during the green light period, the northern section of the bridge moves downward under the influence of the dynamic vehicle load. The dynamic load forms a stress wave inside the bridge and transmits an upward movement trend to the middle of the bridge, thus offsetting the influence of the gravity action of vehicles. The downward movement trend in the middle section of the bridge is weakened. When the dynamic load is transmitted to the southern end of the bridge with a downward movement trend, the influence of the vehicle gravity load on the bridge deformation is strengthened.

To further verify the judgment pertaining to the overall bridge deformation, this study extracts the monitoring data of the seven characteristic positions of the bridge at six different times, namely, 152 s, 157 s, 162 s, 167 s, and 177 s, and obtains the overall

deformation trend of the bridge. Meanwhile, the study extracts the monitoring data of the corresponding positions at 234 s, 239 s, 244 s, 249 s, 254 s, and 259 s, and obtains the corresponding overall bridge deformation trend.

From the deformation curves depicted in Figures 15 and 16, it can be observed that the stress wave wavelength formed by the vehicle dynamic load during the green light is approximately 30 m, the transfer distance is approximately 50 m, and the local time is approximately 70 m, which is the furthest distance in the process of distance monitoring position between 20 m and 50 m. The deflection deformation attains 24.8 mm, the amplitude attains 32.9 mm, and the vibration period is approximately 0.006 s.

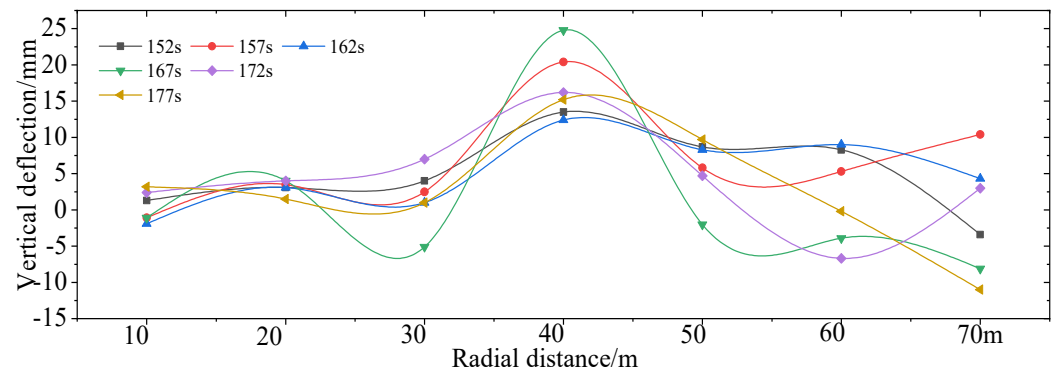


Figure 15. Overall deformation of the bridge at different times with a 50 Hz sampling frequency.

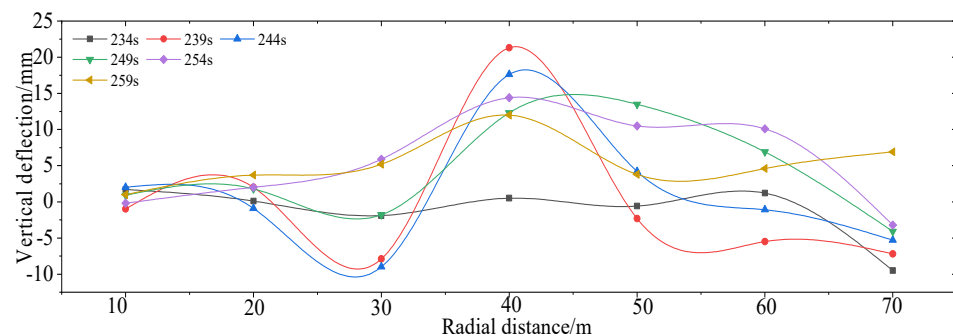


Figure 16. Overall deformation of the bridge at different times with a 50 Hz sampling frequency.

4.1.2. Dynamic Deformation Characteristics of the Bridge with a 100 Hz Sampling Frequency

Under the 100 Hz sampling frequency condition, the IBIS micro-deformation monitoring system was utilized to monitor the Fenghuangshan Road Bridge, and the monitoring time was 1230.38 s. Part of the monitoring data was extracted to draw the deflection deformation time series curve of the bridge at different positions (Figure 17).

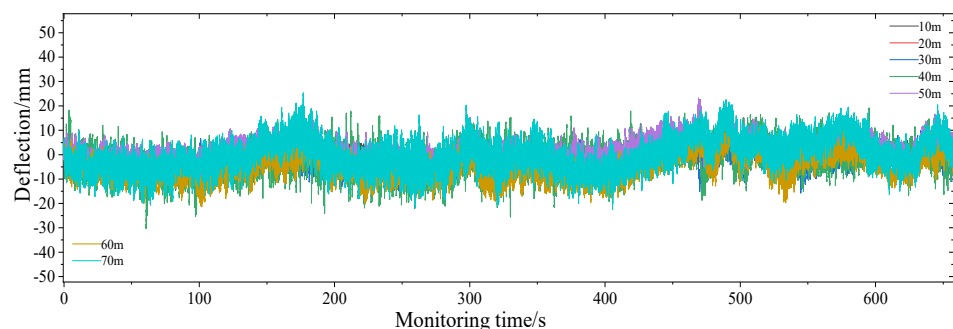


Figure 17. The 100 Hz sampling frequency monitoring diagram.

It was observed that the different positions of the bridge fluctuate around a certain horizontal line, which is consistent with the motion characteristics of nonlinear elastic deformation. It can be observed from Figure 18 that point C at the southern end of the bridge deformed -1.2 mm at 155.47 s and continued to move along the gravity direction, and that it deformed -47.2 mm at 156.05 s and deformed in an inverted “V” shape at 61.6 s to 61.8 s; furthermore, the maximum deformation value of the antigravity direction was 26.6 mm.

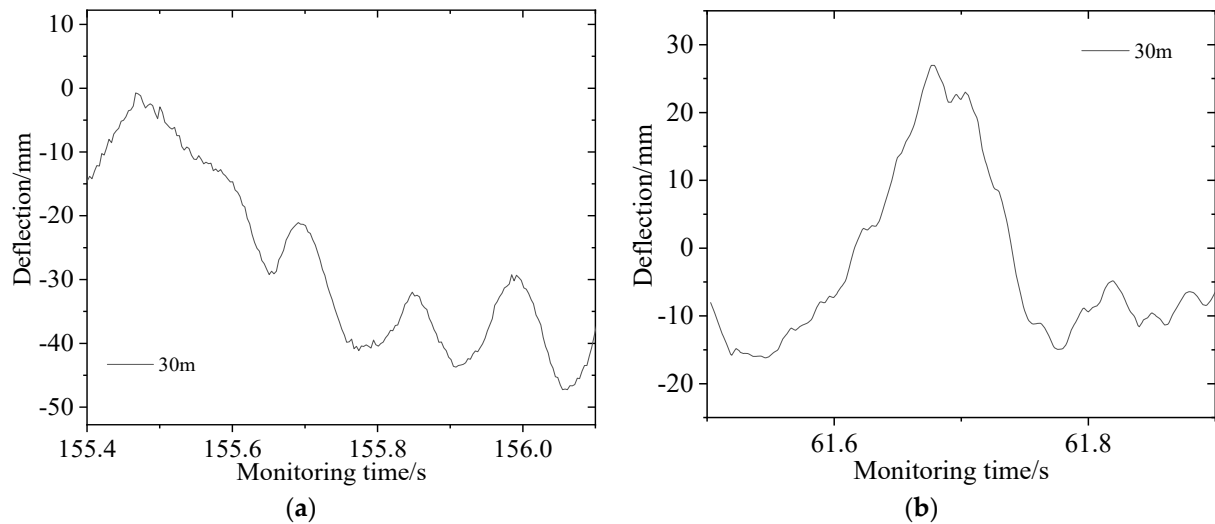


Figure 18. The 100 Hz sampling frequency: first monitoring results. (a) 155.4–156.1 s; (b) 61.5–61.9 s.

As can be observed from Figure 19, during the period from 155.70 s to 156.00 s, the minimum deformation value of bridge point E is 10.2 mm, the maximum deformation value is 23.2 mm, the amplitude is 13 mm, the vibration period is 0.12 s, and the vibration frequency is 8.33 Hz. Additionally, deformation of this point is -16.6 mm at 383.18 s and -2.43 mm at 383.26 s. The vibration period is 0.16 s, and the vibration frequency is 6.25 Hz.

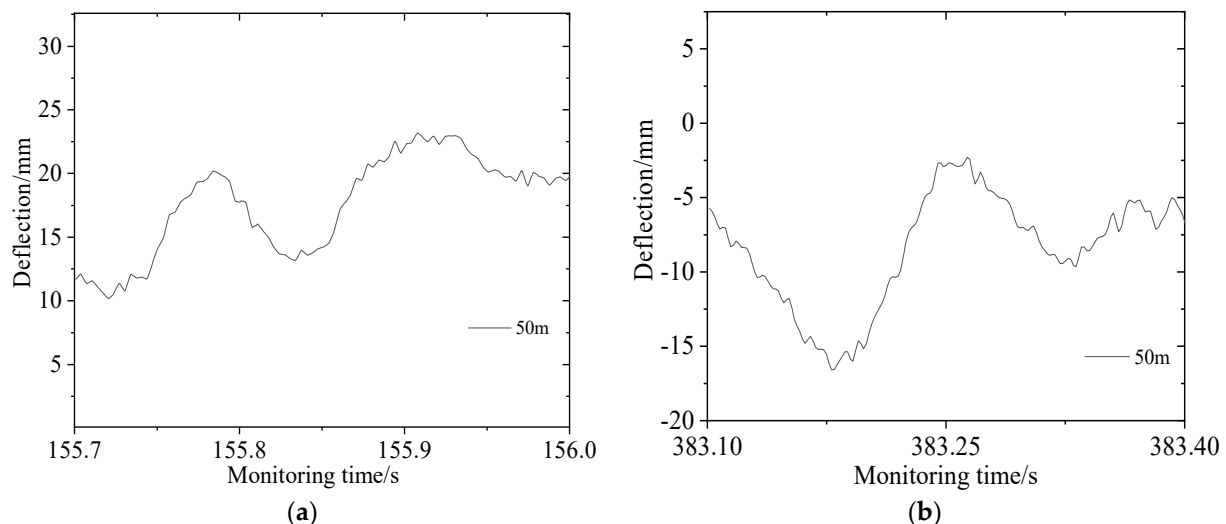


Figure 19. The 100 Hz sampling frequency: second monitoring results. (a) 155.7–156.0 s; (b) 383.1–383.4 s.

It can be observed from Figure 20 that under the action of vehicle dynamic load, different bridge positions exhibit different deformation characteristics, with the largest deformation at point C, the second at point E, and the smallest deformation at point A. In Figure 20a, point C is deformed by -26.0 mm at 274.60 s and returns to the peak position at 274.82 s. The vibration period is 0.22 s, and the vibration frequency is 4.54 Hz. Point E

of the bridge attains a trough at 274.76 s, deformation is -5.5 mm, and a peak is attained after 0.12 s. The deformation is 3.5 mm, the vibration period is 0.24 s, and the vibration frequency is 4.17 Hz. In Figure 20b, the deformation characteristics of point A are similar to those of point E. Point C fluctuates exceedingly, and the deformation is 27.1 mm at 381.99 s.

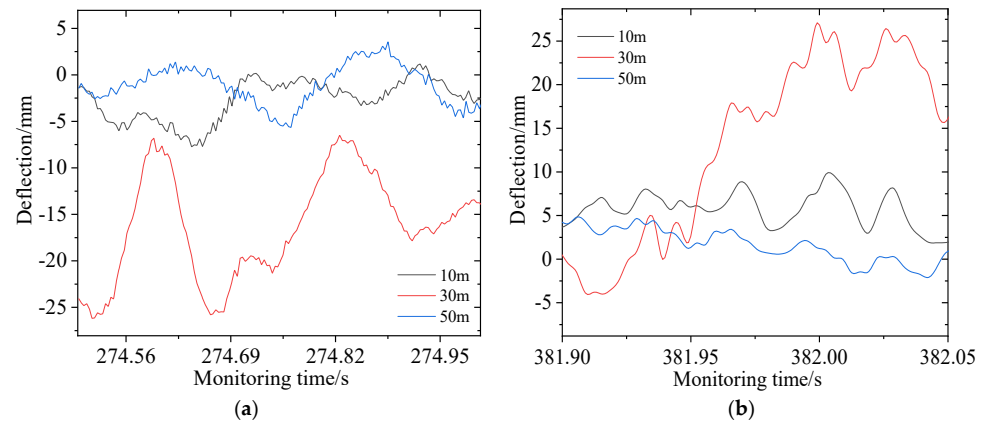


Figure 20. The 100 Hz sampling frequency: third monitoring results. (a) 274.5–275 s; (b) 381.90–382.05 s.

To comprehensively describe the differences in the motion characteristics of different bridge positions, this study extracts the bridge deformation data at 1000s~1075s during the monitoring period, and it creates a comparison chart that depicts the dynamic deformation trend of different bridge positions, defining the direction of gravity as the negative direction and vice versa. As can be observed from Figure 21, during this period, the deflection deformation trend at different bridge positions presents an inverted “V” shape, first increasing and then decreasing. At points A, B, F, and G, the maximum deformation values are 7.54 mm, 6.34 mm, 9.63 mm, and 22.12 mm, respectively, and the maximum positive deflection at point D is 12.78 mm. The minimum negative deflection is -16.24 mm.

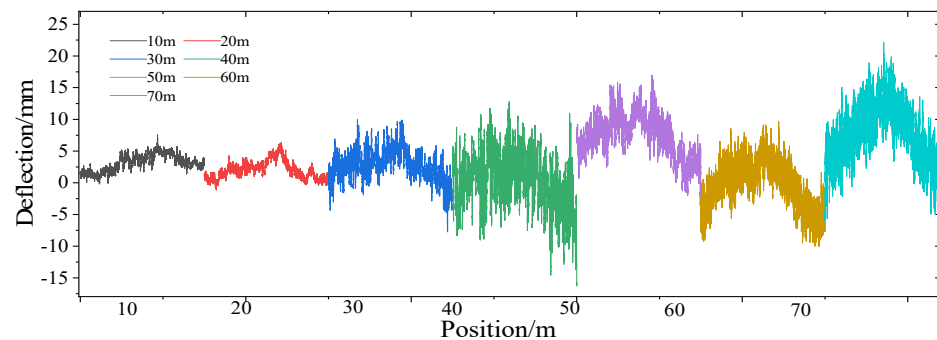


Figure 21. Bridge deformation trend at different distances at a certain time period with a 100 Hz sampling frequency.

Judging from the maximum forward deflection deformation, the overall deformation of the bridge exhibits a sinusoidal curve. Because, during the green light, the northern bridge section is affected by the dynamic load of vehicles, rebound deformation subsequently occurs under the action of self-rigidity. The greater the impact of the dynamic load of the vehicles, the stronger the rebound deformation. Meanwhile, the rebound deformation of the bridge across the middle and the northern bridge sections is the strongest.

To further verify the judgment on the overall bridge deformation, the monitoring data pertaining to seven characteristic bridge positions at six different times, namely, 175 s, 180 s, 185 s, 190 s, 195 s, and 200 s, were extracted, and the overall deformation trend chart of the bridge was designed. Meanwhile, the monitoring data pertaining to 410 s, 415 s, 420 s, 425 s, 430 s, and 435 s were extracted, and the corresponding overall deformation trend chart of the bridge was designed.

From the deformation curves illustrated in Figures 22 and 23, it can be observed that the stress wave formed by the dynamic load of the vehicles during the green light is approximately 40 m, the vibration period is approximately 0.008 s, and the transmission distance is approximately 70 m, which is most strongly reflected in the process pertaining to 30 m to 70 m from the monitoring position. Interestingly, point G of the bridge exhibits a 20.1 mm deformation at 175 s and a -14.5 mm deformation at 415 s, which is the maximum deformation position of the bridge in this period.

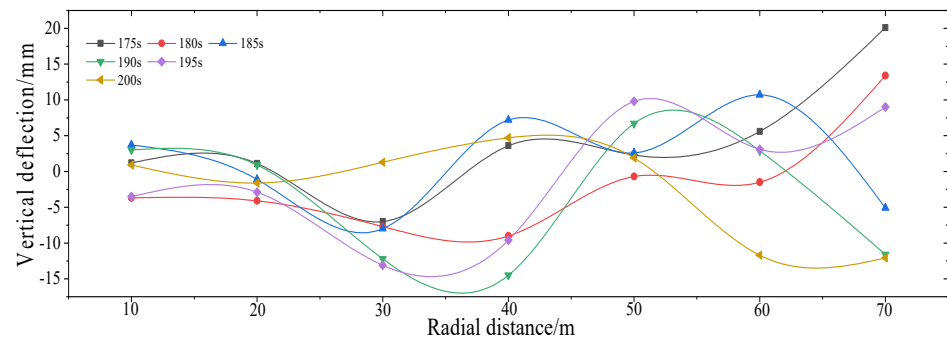


Figure 22. The overall deformation of the bridge at different times with a 100 Hz sampling frequency.

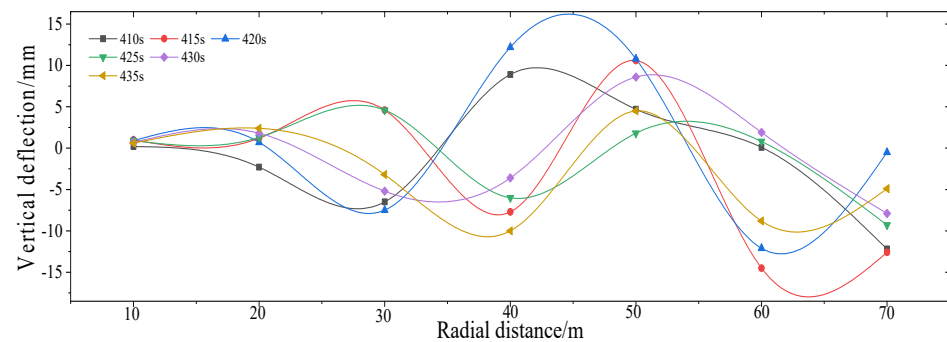


Figure 23. The overall deformation of the bridge at different times with a 100 Hz sampling frequency.

In summary, the maximum deformation position of the bridge occurs at point C pre-near the span, and its deformation fluctuates between -47.2 mm and 38.0 mm, which does not exceed the allowable bridge deformation value in Gong Lu Qiao Han She Ji Tong Yong Gui Fan (when a bridge is composed of reinforced concrete or prestressed concrete, the maximum deformation shall not exceed $1/600$ of the span of the bridge under test).

4.2. Dynamic Deformation Characteristics and Accuracy Evaluation of the Bridge Based on the Digital Photography Technique

4.2.1. Remote Monitoring of Close-Range Photogrammetry Technology Accuracy Evaluation

To verify the feasibility of the remote monitoring of bridge dynamic deformation based on the isometric virtual plane digital photography technique, this study evaluates the measurement accuracy before the bridge deformation monitoring experiment. The details are as follows:

- ① Install a prism and monitored signs in a stable area; thus, the prism is in the same position as the monitored signs, which is convenient for the accurate measurement of the actual distance of monitored signs from the monitoring device.
- ② Along the vertical line, utilize technology equipment pertaining to the remote monitoring of close-range photogrammetry. Thus, signs 250 m, 225 m, 200 m, 175 m, and 150 m away are monitored to obtain corresponding high-quality photos (Figure 24).
- ③ After obtaining an external image, utilize dynamic data processing software to add control points and monitoring points. Data processing is performed using the time-

difference method based on the time baseline, and a photography scale at different monitoring distances is obtained (Table 1).

Table 1. Pixel correction table at different distances.

Monitoring Distance/m	DX0	DZ0	Scale Coefficient M
250	−27.18	81.19	1.12
	−54.94	163.75	1.12
	−83.1	252.1	1.12
	−109.01	330.85	1.13
225	−27.34	87.61	1.01
	−55.88	180.98	1.02
	−83.28	274.42	1.01
	−110.36	364.51	1.03
200	−11.16	104.23	0.89
	−22.76	216.12	0.89
	−33.53	332.91	0.91
	−44.96	441.04	0.91
175	−33.84	124.19	0.76
	−68.08	249.96	0.76
	−101.59	378.17	0.77
	−134.4	496.57	0.76
150	−43.68	138.05	0.67
	−89.11	288.25	0.66
	−132.17	428.06	0.67
	−174.38	562.61	0.67

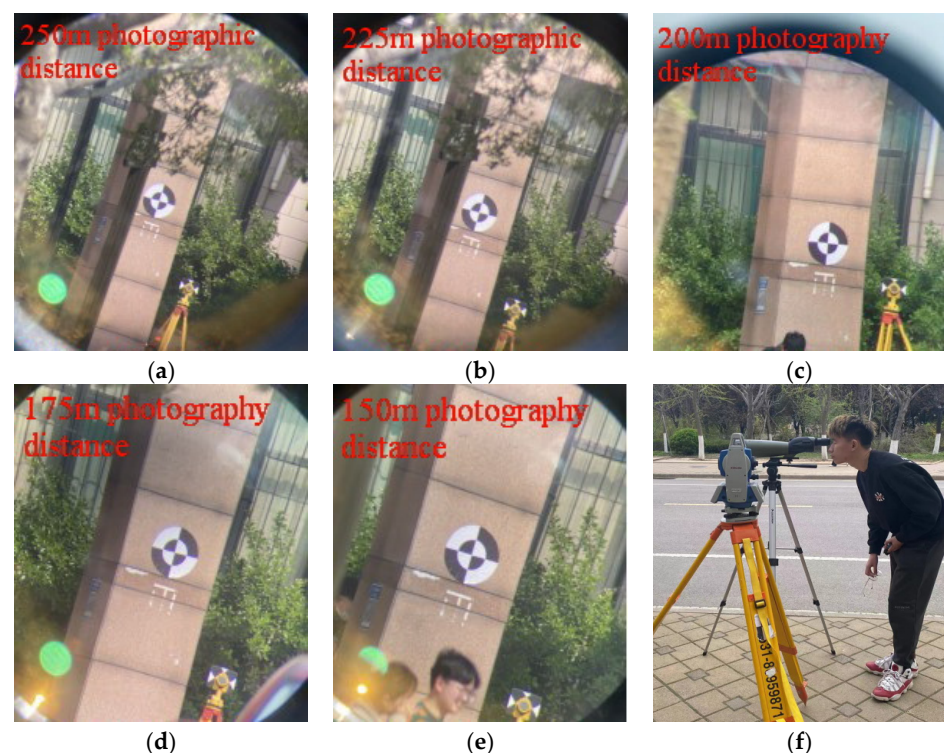


Figure 24. Assessment diagram of over-the-horizon accuracy. (a) A 250 m photographic distance; (b) 225 m photographic distance; (c) 200 m photographic distance; (d) 175 m photographic distance; (e) 150 m photographic distance; (f) observer.

After data processing, it is observed that when the monitoring distance is 150 m, the photography scale is approximately 0.66 mm/pixel. When the monitoring distance is 175 m, the photographic scale is approximately 0.76 mm/pixel; when the monitoring distance is 200 m, the photographic scale is approximately 0.90 mm/pixel; when the monitoring distance is 225 m, the photographic scale is approximately 1.02 mm/pixel; and when the monitoring distance is 250 m, the photographic scale is approximately 1.12 mm/pixel. According to the close-range photogrammetry experiment, measurement technology equipment pertaining to the remote monitoring of close-range photogrammetry was utilized at 250 m, 225 m, 200 m, 175 m, and 150 m, which can be equivalent to the close-range photogrammetry technology at 8 m, 6 m, 4 m, and 2 m, respectively, with a mean square error of approximately 0.5 pixels. Therefore, it can be considered that the remote monitoring of bridge dynamic deformation using digital photography technology based on the isometric virtual plane can meet the accuracy requirements of the deformation monitoring experiment and is feasible.

4.2.2. Dynamic Deformation Characteristics of the Bridge Based on Digital Photography Technology

Based on the remote monitoring of close-range photogrammetry technical equipment, which is acquired using high-speed bridge photos, the displacement data at mid-span (deformation point 3), 1/4 span (deformation points 2 and 4), and 1/8 span (deformation points 1 and 5) of the bridge were extracted and processed, and the local position and overall deformation time series curves of the bridge were designed (Figures 25–27). The displacement data are illustrated in Tables 2–4.

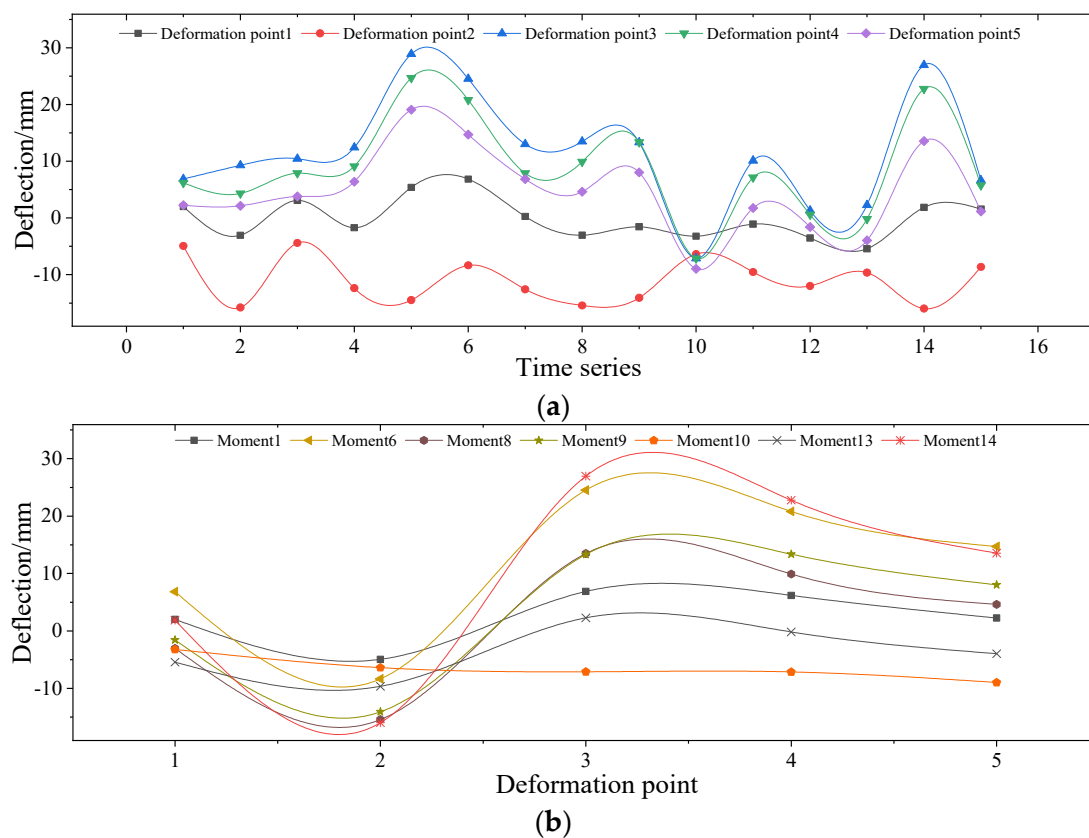


Figure 25. Deflection deformation time series curve of the bridge. (a) Deflection deformation time series curve of bridge local position; (b) overall deformation of the bridge at different times.

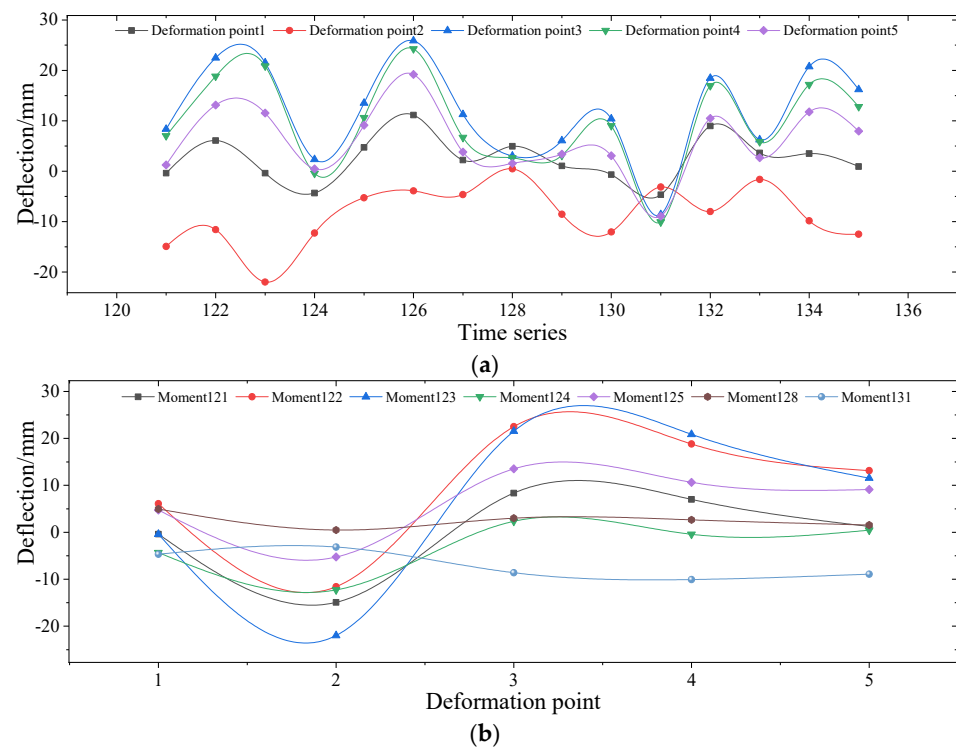


Figure 26. Deflection deformation time series curve of the bridge. (a) Deflection deformation time series curve pertaining to the local position of the bridge; (b) overall deformation of the bridge at different times.

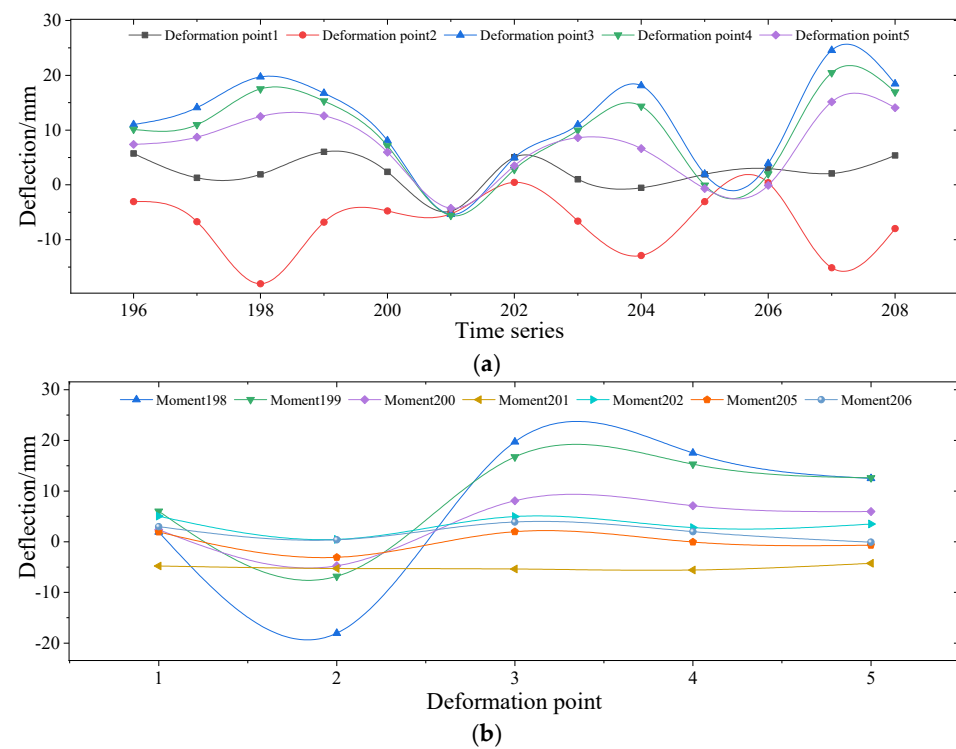


Figure 27. Deflection deformation time series curve of the bridge. (a) Deflection deformation time series curve pertaining to the local position of the bridge; (b) overall deformation of the bridge at different times.

Table 2. Deflection deformation of deformation points under different time series (mm).

Time Series	Deformation Point 1	Deformation Point 2	Deformation Point 3	Deformation Point 4	Deformation Point 5
1	2	−4.93	6.87	6.19	2.26
2	−3.05	−15.79	9.29	4.33	2.15
3	3.09	−4.4	10.44	7.9	3.8
4	−1.72	−12.37	12.42	9.12	6.4
5	5.38	−14.47	28.9	24.69	19.09
6	6.85	−8.35	24.52	20.8	14.71
7	0.26	−12.58	13.02	7.89	6.85
8	−3.04	−15.42	13.47	9.92	4.62
9	−1.55	−14.07	13.32	13.37	8.03
10	−3.2	−6.38	−7.11	−7.13	−8.97
11	−1.08	−9.52	10.12	7.14	1.76
12	−3.53	−11.99	1.32	0.59	−1.59
13	−5.44	−9.64	2.29	−0.18	−3.95
14	1.87	−15.97	26.96	22.77	13.56
15	1.56	−8.63	6.64	5.74	1.15

Table 3. Deflection deformation of deformation points under different time series (mm).

Time Series	Deformation Point 1	Deformation Point 2	Deformation Point 3	Deformation Point 4	Deformation Point 5
121	−0.39	−14.92	8.35	7.01	1.24
122	6.1	−11.59	22.49	18.82	13.12
123	−0.39	−21.98	21.52	20.86	11.53
124	−4.33	−12.27	2.35	−0.43	0.46
125	4.73	−5.26	13.52	10.64	9.11
126	11.14	−3.9	25.88	24.25	19.19
127	2.21	−4.65	11.26	6.68	3.8
128	4.95	0.47	3.01	2.65	1.55
129	1.06	−8.54	6.06	3.12	3.38
130	−0.68	−12.05	10.39	9.01	3.06
131	−4.67	−3.14	−8.6	−10.07	−8.91
132	8.98	−8	18.45	16.96	10.48
133	3.63	−1.63	6.25	5.83	2.67
134	3.5	−9.84	20.74	17.19	11.76
135	0.93	−12.51	16.2	12.8	7.94

Table 4. Deflection deformation of deformation points under different time series (mm).

Time Series	Deformation Point 1	Deformation Point 2	Deformation Point 3	Deformation Point 4	Deformation Point 5
196	5.73	−3.05	11.01	10.13	7.39
197	1.29	−6.73	14.11	10.98	8.72
198	1.92	−18.05	19.72	17.52	12.49
199	6.03	−6.82	16.74	15.31	12.61
200	2.37	−4.76	8.08	7.11	5.96
201	−4.79	−5.28	−5.38	−5.58	−4.26
202	5.04	0.46	4.97	2.8	3.5
203	1.02	−6.61	10.99	9.96	8.62
204	−0.53	−12.9	18.12	14.37	6.63
205	1.92	−3.07	1.98	−0.05	−0.67
206	2.98	0.39	3.9	2	−0.08
207	2.08	−15.13	24.56	20.46	15.15
208	5.37	−7.98	18.45	16.95	14.08

Figure 25a depicts the overall bridge deformation trend at the 1–15 time series; the maximum deformation of the bridge occurs at 5 o'clock; deformation of point 3 is 28.9 mm and that of point 4 is 24.69 mm. From Figure 25b, it can be observed that the overall shape of the bridge at 10 moment is a horizontal line, and that the overall shape of the bridge at points 6, 8, 9, and 14 at the moment is descending from south to north, then rising; finally, it exhibits a descending cosine curve. The single cycle transmission is approximately 50 m, the amplitude is approximately 44.32 mm, and the vibration period is 0.01 s.

Figure 26a depicts the overall bridge deformation trend at time series 121–135, and the maximum deformation of the bridge occurs at 126; the deformation of point 3 is 25.88 mm, and the deformation of point 4 is 24.25 mm. From Figure 26b, it can be observed that the overall shape of the bridge at time 128 is a horizontal line, and that the overall shape of the bridge at times 122, 123, 124, and 125 first indicates a significant cosine curve that descends, rises, and subsequently falls from south to north. Meanwhile, the overall shape of the bridge at time 131 is a sine curve that rises, falls, and, subsequently, rises from south to north. The transmission distance of a single cycle is approximately 50 m, the amplitude is approximately 47.86 mm, and the vibration period is 0.01 s.

Figure 27a indicates the overall deformation trend of the bridge at the time series 196–208, and the maximum deformation of the bridge occurs at time 207; the deformation of point 3 is 24.56 mm, and the deformation of point 4 is 20.46 mm. From Figure 26b, it can be observed that the overall shape of the bridge at time 201 is a horizontal line, and that the overall shape of the bridge at times 198, 199, and 200 is a significant cosine curve from south to north, which descends, rises, and falls, successively. The single cycle transmission distance is approximately 50 m, the amplitude is approximately 42.61 mm, and the vibration period is 0.01 s.

When vehicles pass over the bridge, a dynamic load is generated, which includes both a vertical-direction gravity load and a horizontal-direction impact load. This kind of dynamic load is transmitted in the form of a stress wave. Under the action of the stress wave, deflection deformation of the bridge occurs in both the vertical direction and the horizontal direction. The location where stiffness occurs can produce resistance to deformation under the action of self-stiffness, and then radius deformation occurs. After springing back several times, it finally returns to the initial position. In this study, there was a vibration deformation trend.

5. Conclusions

This study utilizes the Jinan Fenghuangshan Road Bridge as the research object. It uses close-range photogrammetry and GB-RAR technology to remotely monitor the dynamic deformation law of the bridge under a dynamic load. The deformation characteristics of the bridge are analyzed from multiple dimensions, and the main conclusions are as follows:

- (1) Remote monitoring using close-range photogrammetry measuring equipment based on the isometric virtual plane method was adopted for monitoring at 250 m, 225 m, 200 m, 175 m, and 150 m. The measuring errors are 0.56 mm, 0.51 mm, 0.45 mm, 0.38 mm, and 0.33 mm, which can meet the accuracy requirements of deformation monitoring.
- (2) Herein, the maximum deformation of the Fenghuangshan Road Bridge is measured at a 1/4 bridge span, the maximum deformation along the gravity direction is −43.8 mm, and the maximum deformation in the anti-gravity direction is 38.0 mm. Under the resonance of the bridge and the dynamic load of vehicles, the deformation law pertaining to the local position of the bridge is positive or exhibits an inverted “V” shape, and the deformation law of the bridge is a horizontal straight line and sine and cosine curves.
- (3) Based on the interferometric technique and digital photography technique, it is observed that the dynamic load of the vehicles is transmitted in the form of a stress wave inside the Fenghuangshan Road Bridge, and that the wavelength is approximately

44 m, the amplitude is approximately 44.93 mm, the vibration period is approximately 0.088 s, and the vibration is more significant in the $1/4 \sim 1/2$ bridge-span range.

Although close-range photogrammetry has achieved good results in bridge monitoring in this paper, it also exposes the limitations of this technology. For example, when the technology is used for remote monitoring, the monitoring range is too small to measure the whole dynamic deformation of the monitored body at the same time. When multiple photographic equipment is used to monitor at the same time, cooperation between the monitoring equipment cannot be fully realized. Therefore, in the future, it will be necessary to develop large-scene photography equipment to overcome the limitations of the current technology.

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References

1. Cosser, E.; Roberts, G.W.; Meng, X.; Dodson, A.H. Measuring the Dynamic Deformation of Bridges Using a Total Station. In Proceedings of the 11th International FIG Symposium on Deformation Measurement, Santorini, Greece, 1 January 2003.
2. Lekidis, V.; Tsakiri, M.; Makra, K.; Karakostas, C.; Klimis, N.; Sous, I. Evaluation of dynamic response and local soil effects of the Evripos cable-stayed bridge using multi-sensor monitoring systems. *Eng. Geol.* **2005**, *79*, 43–59. [\[CrossRef\]](#)
3. Psimoulis, P.A.; Stiros, S.C. Measurement of deflections and of oscillation frequencies of engineering structures using Robotic Theodolites (RTS). *Eng. Struct.* **2007**, *29*, 3312–3324. [\[CrossRef\]](#)
4. Yu, J.Y.; Zhao, X.D.; Meng, X.L.; Li, L.F. Experiment of Dynamic Monitoring of Bridge Structures Using Robotic Total Station. *China J. Highw. Transp.* **2014**, *27*, 55–63, 92.
5. Zhou, X.; Liang, G.H. Application of intelligent total station in bridge vibration deformation monitoring. *Eng. Technol. Res.* **2020**, *15*, 130–131.
6. Kashima, S.; Yanaka, Y.; Suzuki, S.; Mori, K. Monitoring the Akashi Kaikyo Bridge: First Experiences. *Struct. Eng. Int.* **2001**, *11*, 120–123. [\[CrossRef\]](#)
7. Nakamura, S. GPS Measurement of Wind-induced Suspension Bridge Girder Displacements. *J. Struct. Eng.* **2000**, *126*, 1413–1419. [\[CrossRef\]](#)
8. Qiao, Y.; Sun, C.Z.; Miao, C.Q. Monitoring Dynamic Characteristics of Long-span Suspension Bridge Based on GPS Technology. *Bull. Surv. Mapp.* **2012**, *3*, 1–4.
9. Guo, J.J.; Dai, L.J.; Lu, Y.C. Study of Method for Realtime Survey on Humen Bridge by GPS (RTK). *Bull. Surv. Mapp.* **2000**, *4–5*, 12.
10. Liu, Z.Q.; Yue, D.J.; Zheng, D.H. Dynamic Deformation Monitoring and Analysis for Long-span Bridges in Operation Based on GPS/BDS Observations. *Bull. Surv. Mapp.* **2018**, *10*, 107–112.
11. Huang, S.X.; Liu, X.; Yang, Y.B.; Zhang, Y. Experiment and Result for Measuring Dynamic Characteristics of Large Bridge Using GPS. *Geomat. Inf. Sci. Wuhan Univ.* **2004**, *29*, 198–200.
12. Liu, W.; Chen, S.; Hauser, E. Lidar-based bridge structure defect detection. *Exp. Tech.* **2011**, *35*, 27–34. [\[CrossRef\]](#)
13. Matsumoto, K.; Arturo Linan Panting, C.; Kitratporn, N.; Takeuchi, W.; Nagai, K.; Iwasaki, E. Performance Assessment Using Structural Analysis and Spatial Measurement of a Damaged Suspension Bridge: Case Study of Twantay Bridge, Myanmar. *J. Bridge Eng.* **2018**, *23*, 1–14. [\[CrossRef\]](#)
14. Xu, J.J.; Guo, X.W.; Liao, Y.; Zhang, H.B. The Test on Bridge Deflection Deformation Monitoring by Terrestrial Laser Scanning. *J. Geod. Geodyn.* **2017**, *37*, 609–613.

15. Liu, S.Z. The Ground 3D Laser Scanning and Digital Close-Range Photogrammetry in Bridge Deformation Detection. Master's Thesis, Shandong University of Science and Technology, Qingdao, China, 2013.
16. Gentile, C.; Bernardini, G. Radar-based measurement of deflections on bridges and large structures. *Eur. J. Environ. Civil. Eng.* **2010**, *14*, 495–516. [[CrossRef](#)]
17. Wang, J.Y. Micro-deformation Monitoring Radar (IBIS System). *Urban Geotech. Investig. Surv.* **2011**, *101–105*, 108.
18. Whiteman, T.; Lichti, D.D.; Chandler, I. Measurement of deflection in concrete beams by close-range digital photogrammetry. *Symp. Geospat. Theory* **2002**, *1*, 9–12.
19. Ye, J.; Fu, G.; Poudel, U.P. Edge-Based Close-Range Digital Photogrammetry for Structural Deformation Measurement. *J. Eng. Mech.* **2011**, *137*, 475–483. [[CrossRef](#)]
20. Maas, H.G.; Hampel, U. Photogrammetric Techniques in Civil Engineering Material. *Test. Struct. Monit.* **2006**, *72*, 39–45.
21. Datchev, I.; Lichti, D.; Habib, A.; El-Badry, M. Multi-dimensional and Multi-temporal motion estimation of a beam surface during dynamic testing using low-frame rate digital cameras. *Appl. Geomat.* **2017**, *9*, 127–141. [[CrossRef](#)]
22. Khalid, L.A.E. Using smart phones for deformations measurements of structures. *Geod. Cartogr.* **2017**, *43*, 66–72.
23. Liu, Q.Q. Research and Application of Non-Metric Camera Photogrammetry in the Alignment of the Bridge Monitoring. Master's Thesis, Southwest Jiaotong University, Chengdu, China, 2015.
24. Luo, Y.H. A Study of Monitoring Bridge's Deformation by Non-metric Digital Camera. Master's Thesis, Guangdong University of Technology, Guangdong, China, 2013.
25. Liang, F. The Application of Digital Close-Range Photogrammetry in Bridge Deformation Measurement. Master's Thesis, Chongqing Jiaotong University, Chongqing, China, 2010.
26. Wang, H.Z. Study on Bridge Static and Dynamic Test Based on Close-Range Photogrammetry. Master's Thesis, Jilin University, Jilin, China, 2013.
27. Yu, C.; Zhang, G.; Zhao, Y.; Liu, X.; Ding, X.; Zhao, T. Bridge monitoring and warning system based on digital measurement technology. *J. Shandong Univ. (Eng. Sci.)* **2020**, *50*, 115–122.
28. Zhang, G.J.; Yu, C.X. The Application of Digital Close-Range Photogrammetry in the Deformation Observation of Bridge. *GNSS World China* **2016**, *1*, 91–95.

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