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Research and Experimentation on the Orthogonal Error Correction Method for Horizontal Displacement Monitoring

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Abstract: Dam deformation monitoring is a critical technical measure to ensure the safe and stable operation of dams. It involves measuring the structural deformation response of engineering dams using monitoring instruments or technological means. By analyzing the regularity and trend of deformation monitoring data, potential safety anomalies can be forecasted and warned against, providing timely and reliable data for the formulation and implementation of risk removal measures. Horizontal displacement, as the most intuitive and effective reflection of the dam's state under the action of internal and external loads and foundation deformation, is an indispensable part of dam safety monitoring. Currently, the plumb line method and the tensioned wire method are mainly used for horizontal displacement monitoring of dams. A plumb line coordinate instrument measures the horizontal deformation in the upstream and downstream directions and the left and right bank directions through two axes, or the radial and tangential horizontal displacements for arch dams. Compared to other principles, optoelectronic plumb line coordinate instruments have better long-term stability and anti-interference ability and are widely used on engineering sites. However, the orthogonality of the two measuring directions of the instrument is often overlooked. This paper starts from the principle of the development of the plumb line coordinate instrument, analyzes the source of instrument orthogonal error, and combines data collection, structural analysis, and experimental verification. By applying methods such as least squares and regression analysis, an effective calibration calculation and error correction method is proposed. This method is then programmed into the developed plumb line coordinate instrument to meet the real-time correction and output of measured values, providing a reliable technical method for the accuracy and continuous real-time remote monitoring of dam horizontal displacement monitoring. It also offers a technical path for the orthogonality testing of plumb line coordinate instruments.

Keywords: Optoelectronic; Horizontal displacement monitoring; Plumb line coordinate instrument; Orthogonal error

1 Introduction

Dam deformation monitoring is a crucial technical measure to ensure the safe and stable operation of dams. It mainly involves measuring the structural deformation response of engineering dams through monitoring instruments or technical means [1, 2]. By analyzing the regularity and trend of the deformation monitoring data, it is possible to forecast and warn against potential safety anomalies, providing timely and reliable data information for the formulation and implementation of risk removal measures, thus ensuring the stable operation of the project safely [3, 4].

Dam deformation monitoring mainly consists of monitoring items such as horizontal displacement, vertical displacement, inclination, joints, and cracks [5, 6]. Horizontal displacement, as the most intuitive and effective reflection of the dam's state under the action of internal and external loads and foundation deformation, is an indispensable part of dam safety monitoring [7, 8]. Horizontal displacement monitoring of dams mainly uses the plumb line method and the tensioned wire method, with common instruments such as optoelectronic, capacitive, and stepper motor types, distinguished by their measuring principles [9, 10]. From working principles to actual application effects, optoelectronic instruments, compared to other principles, have better long-term stability and anti-interference ability [11, 12]. Optoelectronic instruments have gradually replaced stepper motor and capacitive instruments, becoming the mainstream instrument for horizontal displacement monitoring, meeting the needs of most dam safety monitoring practices [13, 14].

Optoelectronic plumb line coordinate instruments measure the horizontal deformation in the upstream and downstream directions and the left and right bank directions through two axes, or the radial and tangential horizontal displacements for arch dams [15]. The accuracy of the two measuring axes is tested separately before the instrument leaves the factory and is installed [16]. The conventional measurement method involves moving the plumb line coordinate instrument in one test direction, selecting points for measurement within the range, while the other measuring direction does not move during the measurement process [17]. Ideally, the angle between the two measuring axes is 90°, but in reality, due to factors such as installation process and casing processing, it is difficult to make the angle between the two measuring axes exactly 90°. However, due to the limitations of the detection method, it is easy to overlook the error caused by the excessive deviation of the angle between the two axes, making the instrument unable to objectively reflect the horizontal deformation in the upstream and downstream directions and the left and right bank directions after being installed on site, causing a certain deviation between the instrument measurement results and the actual direction, thereby affecting the objective reflection of deformation monitoring data on the actual deformation amount. Therefore, improving the accuracy of the instrument measurement direction is an important factor in ensuring the accuracy of the instrument measurement.

This paper starts from the principle of the development of the optoelectronic plumb line coordinate instrument, analyzes the source of instrument orthogonal error, and combines data collection, structural analysis, and experimental verification. An effective calibration calculation and error correction method is proposed, and this method is programmed into the developed plumb line coordinate instrument through firmware, meeting the real-time correction and output of measured values, providing a reliable technical method for the accuracy and continuous real-time remote monitoring of dam horizontal displacement monitoring. It also offers a technical path for the orthogonality testing of plumb line coordinate instruments.

2 Optoelectronic Plumb Line Coordinate Instrument Measurement Analysis

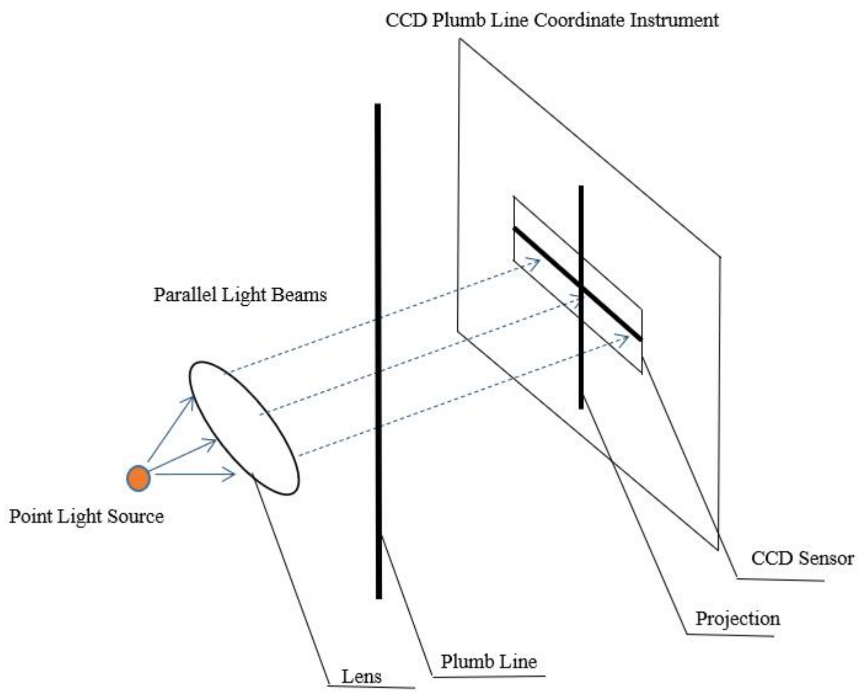
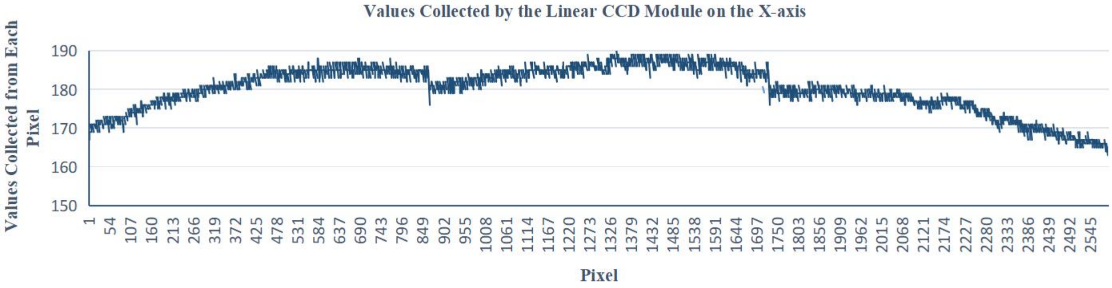


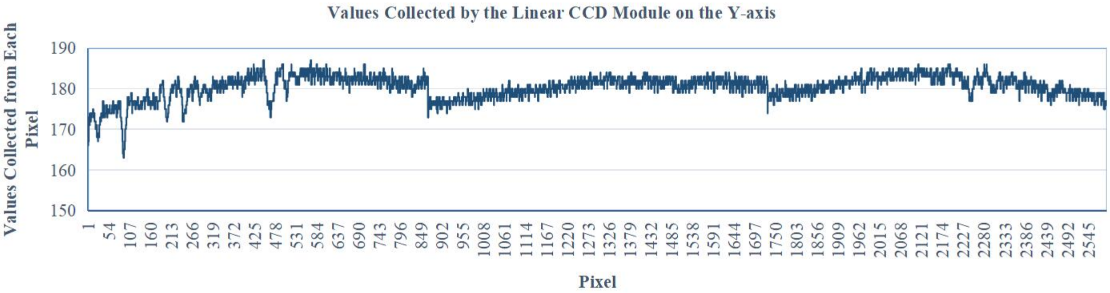
Figure 1. Schematic diagram of the optic path principle of the plumb line coordinate instrument (single direction) under ideal conditions

The working principle of the optoelectronic plumb line coordinate instrument is that a point light source generates parallel light beams through a lens, which are then blocked by the plumb line to create light of different intensities that irradiate the surface of a linear CCD (as shown in Figure 1). The photoelectric conversion function of the linear

CCD's photosensitive units transforms the optical image projected onto the photosensitive units into electrical signals "pixels," i.e., converting the spatial distribution of light intensity into a spatial distribution of charges of varying sizes proportional to the light intensity, forming a series of time-sequential pulse sequences of varying amplitudes. By calculating the distribution of pulse sequence amplitudes, the range of the plumb line shadow is located, thus determining the two-dimensional coordinates of the plumb line within the horizontal measurement range [18].

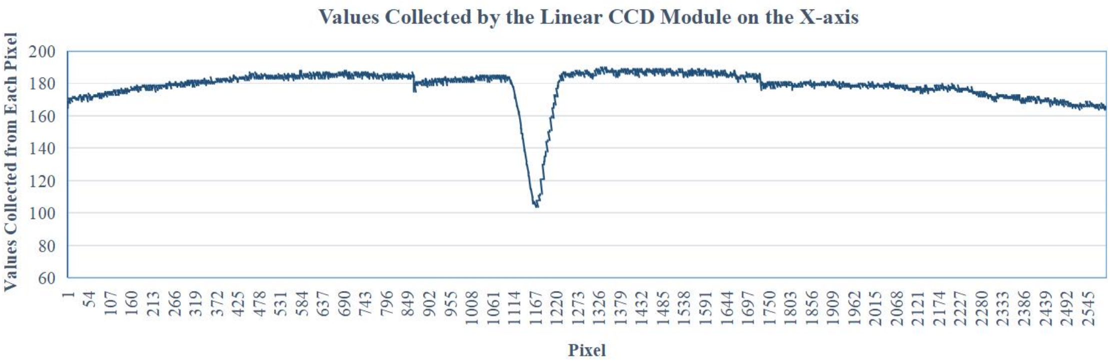


(a)

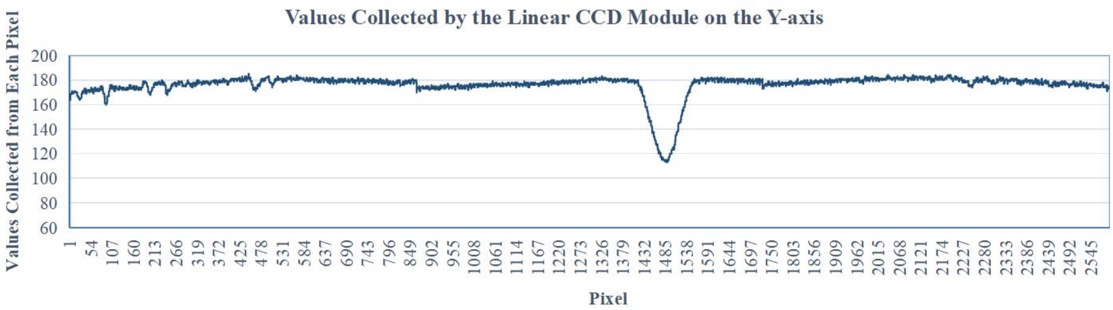


(b)

Figure 2. Curve graph of linear CCD module acquisition values (without plumb line)



(a)



(b)

Figure 3. Curve graph of linear CCD module acquisition values (with plumb line)

The parallel light of the instrument is formed by a point light source passing through a Fresnel lens. The collimation of the parallel light and the intensity of the light irradiated onto the linear CCD module both deviate from the ideal values to a certain extent. Taking a set of linear CCD data collected by the developed plumb line coordinate instrument as an example, as shown in Figure 2, the time-sequential pulse sequences of the linear CCD are acquired using an AD chip. The calculated amplitude of each pixel point varies within a certain range, with the X-axis amplitude variation range being 10.55%, and the Y-axis amplitude variation range being 9.38%. The measurement data show that the output parallel light of the instrument is not uniform in intensity under ideal conditions, and different parallel light output values still have certain differences. In the experiment, by adjusting the resistance value of the LED series resistor, the intensity of the light from the point light source was adjusted, making the shadow range of the plumb line blockage more distinct relative to other areas.

Placing a 1.2mm diameter plumb line at any position within the measurement range, the amplitude of the pulse sequence is calculated in the same way, as shown in Figure 3. The measurement data show that the shadow area blocked by the plumb line is not an ideal square wave, due to scattering and reflection of the light path, the edge of the blocked shadow area changes gradually.

The developed plumb line coordinate instrument outputs the shadow area of the plumb line in the form of displacement values through filtering and threshold setting, etc. By calculating according to methods such as exceeding the threshold and locating feature points, the shape shown in Figure 3 gives an X-axis displacement value of 22.59mm and a Y-axis displacement value of 29.45mm.

According to the conventional detection method, the plumb line coordinate instrument is moved in one test direction for point selection measurement within the range, while the other measuring direction does not move during the measurement process. Taking a single measurement as an example, the shape of the measurement point is shown in Figure 4. When detecting using this method, it does not cover the range of both measuring directions, making the measurement results limited.

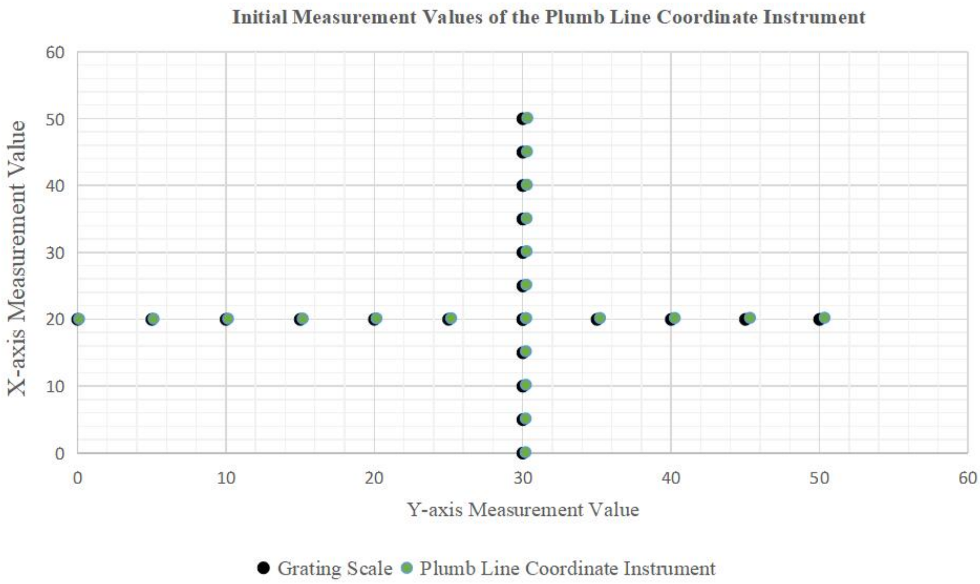


Figure 4. Comparison of initial measurement values and standard values under conventional measurement

3 Analysis of Orthogonal Error in Optoelectronic Plumb Line Coordinate Instruments

This paper measures the initial values of X/Y using an automatic measurement platform, which positions the output through two perpendicularly installed gratings. The automatic measurement platform has been calibrated for length indication and orthogonality by a testing organization and serves as the measurement standard for the plumb line coordinate instrument. The automatic measurement platform fixes the plumb line in place while moving the plumb line coordinate instrument on the platform. The two measuring axes of the platform are controlled by the host computer, which sends instructions to the stepper motors. The stepper motors then move the platform's bearings to move the instrument to a rough adjustment position. After moving the instrument, the host computer will fine-tune the instrument's position based on the real-time output of the gratings to reach a predetermined position within the accuracy range of the gratings. Once the instrument is stable at the predetermined position, it will output the measurement value at that time, i.e., the measured values of X/Y.

During automatic measurement, the two axes of the plumb line coordinate instrument move sequentially across a measuring range of 50mm, with a fixed measurement interval. The measurement values of the two axes are shown in Figure 5. The black dots represent the standard axis output values of the automatic measurement platform, and the green dots represent the measurement values of the plumb line coordinate instrument. The figure shows that there is a certain deviation between the measurement values of the plumb line coordinate instrument and the output values of the gratings. Additionally, when the automatic measurement platform moves along one axis, the real-time displacement measurement value of the other axis of the plumb line coordinate instrument also changes.

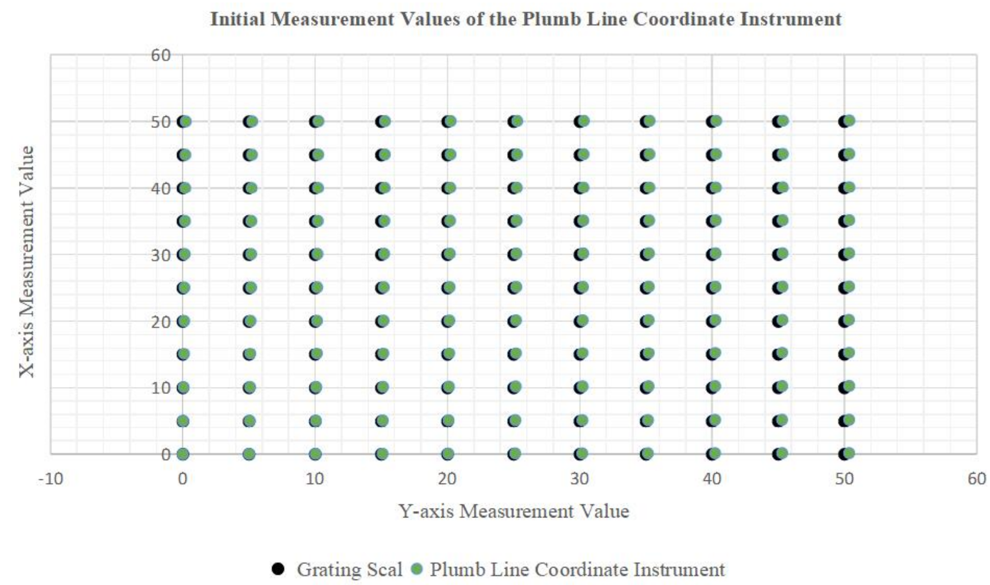


Figure 5. Comparison of initial measurement values and standard values of the plumb line coordinate instrument

According to the measurement index requirements of the instrument, it should meet a resolution ≤ 0.02 mm, basic error $\leq 0.5\%$FS, and non-repeatability $\leq 0.1\%$FS. The resolution, basic error, and non-repeatability technical indicators for the X and Y axes are calculated respectively.

The detection results for the X axis are as follows:

Technical Indicator	Detection Results	Specification Requirements [19]	Conclusion
Resolution r_x	0.01 mm	≤ 0.02 mm	Meets
Basic Error δ_x	0.70%FS	$\leq 0.5\%$FS	Does Not Meet
Non-Repeatability R_x	0.42%FS	$\leq 0.1\%$FS	Does Not Meet

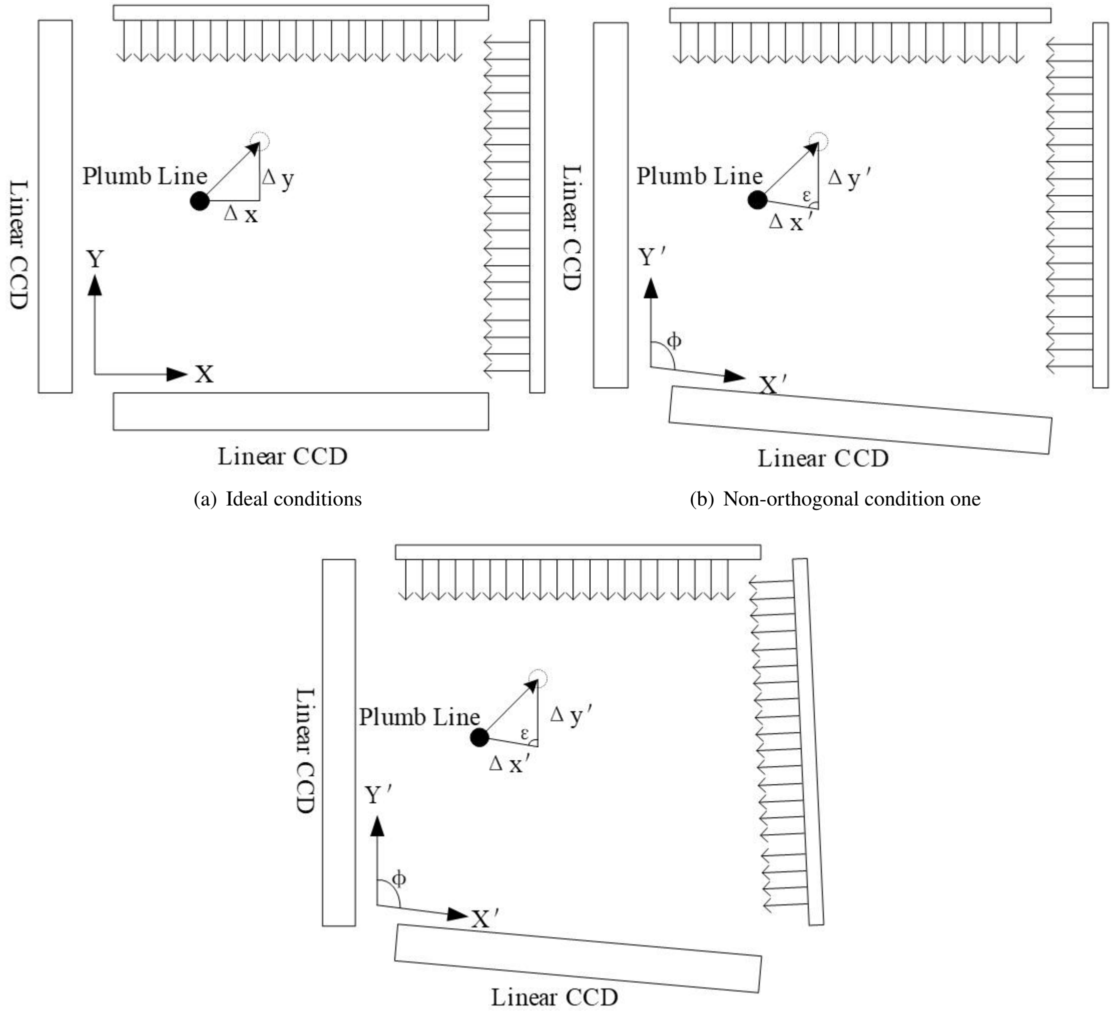
The detection results for the Y axis are as follows:

Technical Indicator	Detection Results	Specification Requirements [19]	Conclusion
Resolution r_y	0.01 mm	≤ 0.02 mm	Meets
Basic Error δ_y	0.42%FS	$\leq 0.5\%$FS	Meets
Non-Repeatability R_y	0.34%FS	$\leq 0.1\%$FS	Does Not Meet

Initial measurements, without calibration, cannot meet the technical requirements of measurement, necessitating calibration of the initial measurement values. Measurement instruments typically perform univariate linear calibration, but even after such calibration, the basic error and non-repeatability of the instrument still cannot meet the specifications.

The measurement purpose of the CCD plumb line coordinate instrument is to provide accurate and reliable measurement data for the horizontal displacement monitoring of the dam body in two orthogonal directions. If the angle between the two measuring directions of the instrument deviates significantly from 90°, it will cause an error in the measurement results.

Theoretically, when the two measuring directions of the CCD plumb line coordinate instrument meet the 90° requirement, the instrument can avoid such errors. However, considering the instrument installation process, it is difficult for the parallel light beams of the two measuring directions and the linear CCD receiving surface to meet the 90° requirement, and there is no direct and effective method to verify whether the internal parallel light beams and the linear CCD receiving surface meet the orthogonality requirements. Furthermore, from the internal composition of the instrument, the ”point light source” is not a true single-point initial light source in the strict sense, with specific parameters such as divergence angle and light intensity, and the performance characteristics of the chosen lens will also affect the transmission density of the ”parallel light beams” and the trajectory of light. All these factors will cause errors in the measurement results of the linear CCD.



(a) Ideal conditions

(b) Non-orthogonal condition one

(c) Non-orthogonal condition two

Figure 6. Horizontal cross-section diagram of the plumb line measurement point

From the above analysis, it is apparent that for the horizontal displacement monitoring of the linear CCD, whether from its internal installation structure or from the characteristics of the optical devices involved, the orthogonal error caused is difficult to eliminate at the physical level. The two displacement measuring directions cannot be guaranteed to be exactly orthogonal. As shown in Figure 6, if the measurement results are directly located from the shadow range of the CCD module, there will be a certain deviation from the standard coordinate system X/Y. The actual measurement results are the measurement values of the two offset coordinate axes X' and Y'.

Due to the presence of non-orthogonal errors, this displacement value cannot be directly output as the Y-axis measurement value of the instrument; meanwhile, due to the high precision requirements of this instrument in engineering. How to improve the measurement accuracy of the instrument in the standard X/Y axes is the focus of this study.

Since the installation angle of the instrument has various possibilities, compensating for the angular error in each case is not suitable for mass production. This paper intends to start from the initial measurement data and correct the orthogonal error through data calibration, allowing for the measurement correction of the installed instrument and greatly improving the efficiency of the factory output.

4 Data Calibration Method Analysis

To determine the optimal method for instrument error correction, this paper analyzes several calibration methods.

(1) Univariate Linear Calibration

For the X and Y axes, this paper establishes linear curves separately, with the linear calibration model as follows [20]:

$$\widetilde{V_x} = k_x V_x + c_x$$
$$\widetilde{V_y} = k_y V_y + c_y$$

$\widetilde{\mathrm{V}}_{\mathrm{x}}$ and $\widetilde{\mathrm{V}}_{\mathrm{y}}$ represent the calculated values after calibration, $\mathrm{V_x}$ and $\mathrm{V_y}$ represent the initial measurement values, $\mathrm{k_x}, \mathrm{c_x}$, and $\mathrm{k_y}, \mathrm{c_y}$ are the calibration parameters for the X and Y axes, respectively.

During the calibration process, a grid method is used, with the two axes of the plumb line coordinate instrument moving in sequence across a measurement range of 50mm, with a measurement interval of 5mm. This can obtain two sets of data: the nominal values of the grating scale and the measurement values of the plumb line coordinate instrument. Using the least squares method for linear calibration, the corresponding parameters can be obtained.

These parameters are written into the firmware of the plumb line coordinate instrument, and the original measurement values are calculated and output. It has been found through experiments that the calculated values still have a significant deviation after calibration. It was observed during calibration that when the X axis does not move and the Y axis moves over a large range, the deviation of the measurement value of the X axis will exceed the instrument's allowable precision, and vice versa.

(2) Multivariate Linear Calibration

Due to the correlation between the two measurements, if only linear/non-linear calibration of a single axis is used, it cannot meet the accuracy requirements. This paper establishes interconnected multivariate linear curves for the X and Y axes, with the linear calibration model as follows:

$$\widetilde{\mathrm{V_x}} = \mathrm{a_1\ V_x + b_1\ V_y + c_1}$$
$$\widetilde{\mathrm{V_y}} = \mathrm{a_2\ V_x + b_2\ V_y + c_2}$$

$\widetilde{\mathrm{V_x}}, \widetilde{\mathrm{V_y}}$ represent the calculated values after calibration, $\mathrm{V_x}$ and $\mathrm{V_y}$ represent the initial measurement values, a_2, b_1, c_1, and a_2, b_2, c_2 are the calibration parameters for the X and Y axes, respectively.

During the calibration process, the grid measurement method is also used to obtain two sets of data: the nominal values of the grating scale and the measurement values of the plumb line coordinate instrument. By using regression analysis, the corresponding calibration parameters are obtained. However, the calculated values still have a certain deviation after calibration, and although the accuracy has been improved compared to the linear calibration method, it still does not meet the instrument's accuracy requirements.

(3) Multivariate Non-linear Calibration

To further improve the accuracy of the instrument and correct the orthogonal error of the instrument, this paper proposes using multivariate non-linear calibration, with the non-linear calibration model as follows:

$$\widetilde{\mathrm{V_x}} = c_1 + a_1 \times V_x + b_1 \times V_y + d_1 \times V_x^2 + e_1 \times V_y^2 + f_1 \times V_x \times V_y$$
$$\widetilde{\mathrm{V_y}} = c_2 + a_2 \times V_x + b_2 \times V_y + d_2 \times V_x^2 + e_2 \times V_y^2 + f_2 \times V_x \times V_y$$

$\widetilde{V_x}, \widetilde{V_y}$ represent the calculated values after calibration, V_x and V_y represent the initial measurement values, $\mathrm{a_2},\ \mathrm{b_1}, \mathrm{c_1},\ \mathrm{d_1}, \mathrm{e_1}, \mathrm{f_1}$ and $\mathrm{a_2},\ \mathrm{b_2}, \mathrm{c_2},\ \mathrm{d_2}, \mathrm{e_2}, \mathrm{f_2}$ are the calibration parameters for the X and Y axes,respectively. Through experimental verification, this calibration method can correct the orthogonal error of the two measuring axes within the accuracy range. The specific correction process and calibration calculation method are detailed in the next section.

5 CCD Plumb Line Coordinate Instrument Error Correction Method

This paper has determined an effective orthogonal error correction method through testing and experimental verification, with the specific steps as follows (Figure 7):

Step S101: Based on the range of the plumb line coordinate instrument along the X and Y axes, divide the range of the X and Y axes into multiple grids according to a preset rule to create a grid diagram (as shown in Figure 8). Establish corresponding grid coordinates for each grid point in the grid diagram, where each grid point's coordinate value is $(\mathrm{H_x}, \mathrm{H_y})$, with $\mathrm{H_x}$ and $\mathrm{H_y}$ representing the grid point's coordinates along the X and Y axes, respectively. The following steps use this standard grid diagram to calibrate the plumb line coordinate instrument. It should be noted that the X and Y axes are two orthogonal axes on the horizontal plane.

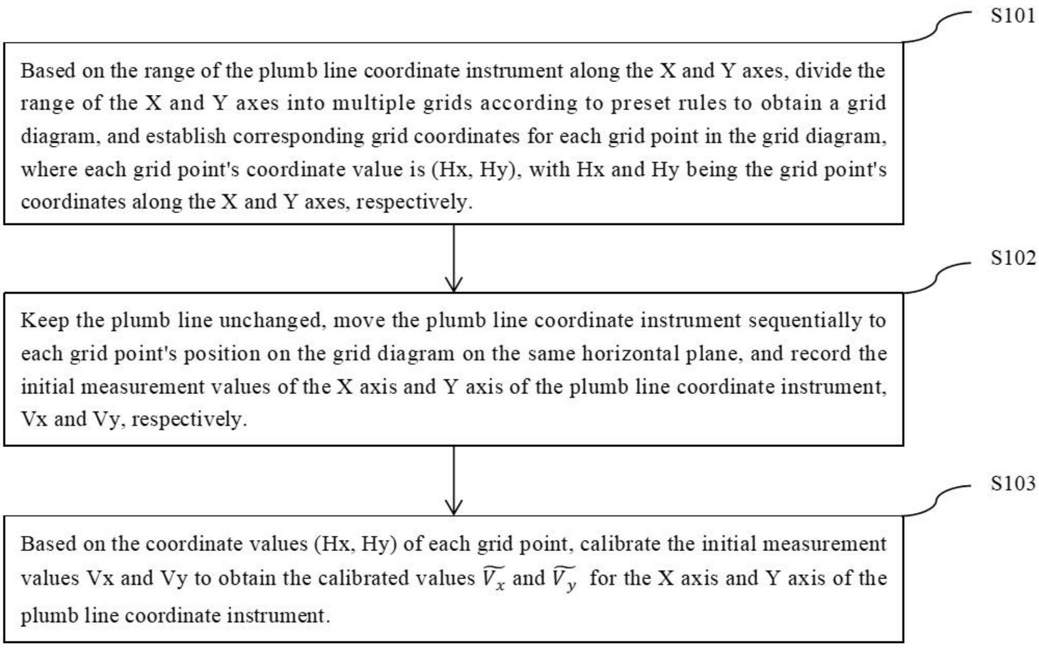


Figure 7. Error correction process for the plumb line coordinate instrument

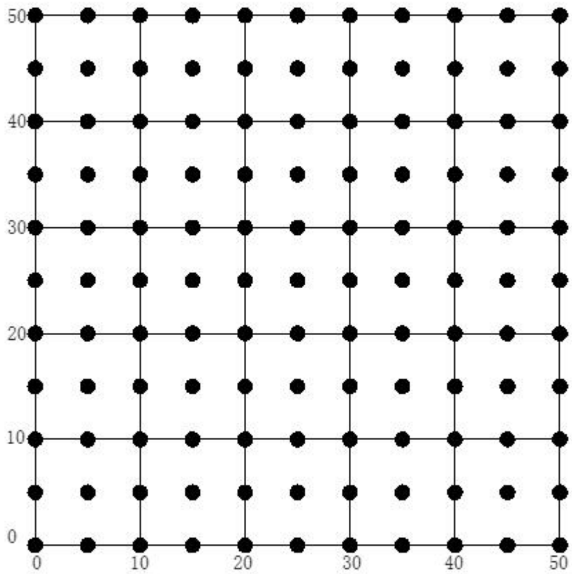


Figure 8. Horizontal cross-section diagram of the plumb measurement point

By dividing the range of the X and Y axes into multiple grids at equal intervals, the grid points in the grid diagram thus established will form an equidistant array. This arrangement facilitates the control of moving the plumb line coordinate instrument to each grid point's position on the same horizontal plane sequentially and can simplify the computation for regression analysis and fitting processing to some extent. Of course, other different division rules can also be applied, dividing the measurement points of the X and Y axes into grids with certain deviations in spacing.

Step S102: Keep the plumb line unchanged and move the plumb line coordinate instrument sequentially to each grid point's position on the grid diagram on the same horizontal plane, and record the initial measurement values of the X and Y axes of the plumb line coordinate instrument, V_x and V_y.

By comparing V_x and V_y with the standard grid point coordinates (H_x, H_y) on the grid diagram, the deviation of the initial measurement values V_x and V_y can be understood.

Step S103: Based on each grid point's coordinate values $(\mathrm{H_x}, \mathrm{H_y})$, calibrate the initial measurement values V_x and V_y to obtain the calibrated values $\widetilde{V}_x$ and $\widetilde{V}_y$ for the X and Y axes of the plumb line coordinate instrument.

In the above steps, calibrating the initial measurement values V_x and V_y based on each grid point's coordinate values $(\mathrm{H_x}, \mathrm{H_y})$ means finding the relationship function between the initial measurement values V_x and V_y and the standard values H_x and H_y in the grid diagram. Using this relationship function, calculate the calibrated values $\widetilde{V_x}$ and $\widetilde{V_y}$ for the X and Y axes of the plumb line coordinate instrument. This method allows for correcting the errors of the plumb line coordinate instrument to obtain measurements that meet the accuracy requirements.

6 CCD Plumb Line Coordinate Instrument Calibration Calculation Method

The steps to calibrate the initial measurement values V_x and V_y based on each grid point's coordinate values $(\mathrm{H_x}, \mathrm{H_y})$ to obtain the calibrated values $\widetilde{\mathrm{V_x}}$ and $\widetilde{\mathrm{V_y}}$ for the X and Y axes of the plumb line coordinate instrument include (as shown in Figure 9):

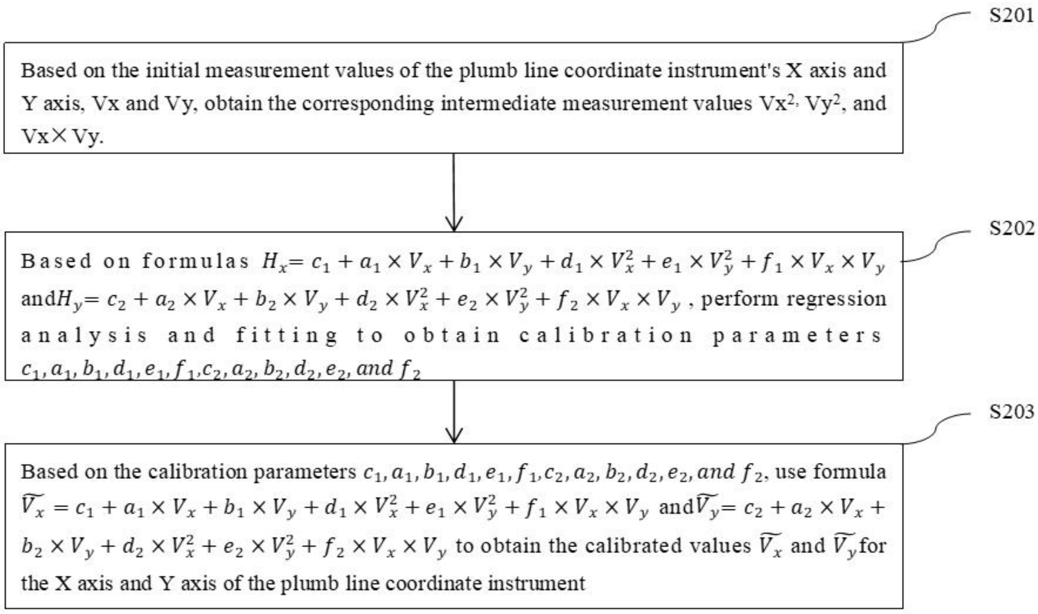


Figure 9. Calibration calculation process for plumb line coordinate instrument measurement values

Step S201: Based on the initial measurement values V_x and V_y of the X and Y axes of the plumb line coordinate instrument, obtain the corresponding intermediate measurement values V_x^2, V_y^2, and $V_x \times V_y$ to provide specific original data support for regression analysis and fitting.

Step S202: Based on the formulas $H_x = c_1 + a_1 \times V_x + b_1 \times V_y + d_1 \times V_x^2 + e_1 \times V_y^2 + f_1 \times V_x \times V_y$ and $H_y = c_2 + a_2 \times V_x + b_2 \times V_y + d_2 \times V_x^2 + e_2 \times V_y^2 + f_2 \times V_x \times V_y$, using the least squares method for regression analysis and fitting, obtain the calibration parameters $\mathrm{c_1, a_1,\ b_1,\ d_1, e_1, f_1}$ and $\mathrm{c_2, a_2,\ b_2,\ d_2, e_2, f_2}$.

In the steps above, by inputting each grid point's coordinate values $(\mathrm{H_x}, \mathrm{H_y})$ from the grid diagram and the initial measurement values $\mathrm{V_x}$ and $\mathrm{V_y}$ recorded when the plumb line coordinate instrument is moved to the corresponding grid point's plumb line into the formula for regression analysis and fitting, the calibration parameters $\mathrm{c_1, a_2,\ b_1,\ d_1, e_1, f_1}$ and $\mathrm{c_2, a_2,\ b_2,\ d_2, e_2, f_2}$ can be obtained.

Step S203: Based on the calibration parameters $c_1, a_1, b_1, d_1, e_1, f_1$ and $c_2, a_2, b_2, d_2, e_2, f_2$, use the formulas $\widetilde{\mathrm{V_x}} = c_1 + a_1 \times V_x + b_1 \times V_y + d_1 \times V_x^2 + e_1 \times V_y^2 + f_1 \times V_x \times V_y$ and $\widetilde{\mathrm{V_y}} = c_2 + a_2 \times V_x + b_2 \times V_y + d_2 \times V_x^2 + e_2 \times V_y^2 + f_2 \times V_x \times V_y$ to obtain the calibrated values $\widetilde{V_x}$ and $\widetilde{V_y}$ for the X and Y axes of the plumb line coordinate instrument.

In the steps above, the initial measurement values V_x and V_y of the plumb line coordinate instrument are calibrated and transformed into the corresponding calibrated values $\widetilde{V_x}$ and $\widetilde{V_y}$ using the calibration formula, and this calibration formula is written into the firmware program of the plumb line coordinate instrument. The plumb line coordinate instrument will directly output the corresponding $\widetilde{V_x}$ and $\widetilde{V_y}$, thereby being able to output values consistent with the standard values H_x and H_y in the standard grid diagram, completing the error correction of the plumb line coordinate instrument. This prevents the situation where the displacement measurement values of the two directions of the plumb line coordinate instrument cannot fully meet the orthogonality requirements, causing the output values of the plumb line coordinate instrument to have a large error. The output values after calibration calculation compared with the standard grid values are shown in Figure 10, where the calibrated measurement values have coincided with the standard values measured by the grating scale. The calibration method proposed in this paper is suitable for the calibration and measurement of optoelectronic plumb line coordinate instruments before development and factory release.

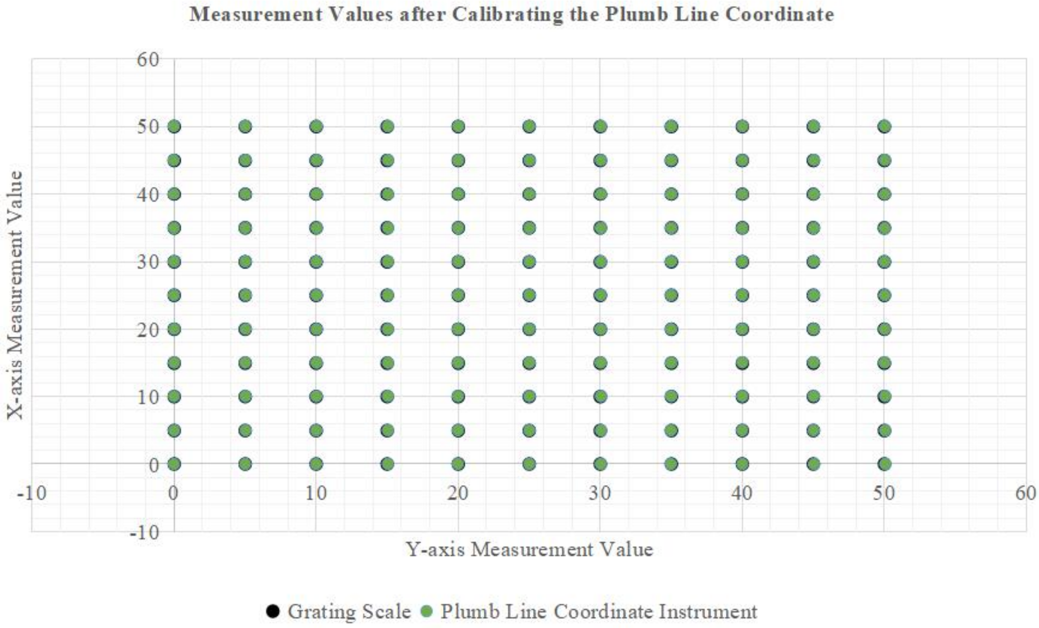


Figure 10. Comparison of calibrated measurements and standard values of the plumb line coordinate instrument

The detection results for the X axis are as follows:

Technical Indicator	Detection Results	Specification Requirements [19]	Conclusion
Resolution r_x	0.01 mm	$\leq$ 0.02 mm	Meets
Basic Error δ_x	0.2%FS	$\leq$ 0.5%FS	Meets
Non-Repeatability R_x	0.05%FS	$\leq$ 0.1%FS	Meets

The detection results for the Y axis are as follows:

Technical Indicator	Detection Results	Specification Requirements [19]	Conclusion
Resolution r_y	0.01 mm	$\leq$ 0.02 mm	Meets
Basic Error δ_y	0.19%FS	$\leq$ 0.5%FS	Meets
Non-Repeatability R_y	0.04%FS	$\leq$ 0.1%FS	Meets

7 Conclusion

The optoelectronic plumb line coordinate instrument measures the horizontal deformation of dams in the upstream and downstream directions and the left and right bank directions through two axes, or the radial and tangential horizontal displacements for arch dams. The accuracy of measurements from both axes plays a fundamental role in the reliable analysis of deformation monitoring data and in forecasting and warning against potential safety anomalies of dams. This paper starts from the principle of the development of the optoelectronic plumb line coordinate instrument, analyzes the source of instrument orthogonal error, and combines data collection, structural analysis, and experimental verification. Using least squares and regression analysis, it proposes effective calibration calculations and error correction methods, improving the reliability of measurement values compared to conventional linear calibration methods. This method has been programmed into the developed plumb line coordinate instrument through firmware, meeting the real-time correction and output of measured values, providing a reliable technical method for the accuracy and continuous real-time remote monitoring of dam horizontal displacement. It also offers a technical path for the orthogonality testing of plumb line coordinate instruments. This paper mainly focuses on the calibration analysis of the optoelectronic plumb line coordinate instrument, and the applicability of the calibration method requires further exploration and research.

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Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

References

[1] S. Jittiwut, V. Rangsarit, S. Unpong, S. Kumpee, N. Rungtip, P. Jirayut, and S. Sirichete, "Development of dam safety remote monitoring and evaluation system," *J. Disaster Res.*, vol. 16, no. 4, pp. 607–617, 2021. https://doi.org/10.20965/jdr.2021.p0607

[2] J. H. Slinger and H. S. Vreugdenhil, "Coastal engineers embrace nature: characterizing the metamorphosis in hydraulic engineering in terms of four continua," *Water*, vol. 12, no. 9, p. 2504, 2020. https://doi.org/10.3390/w12092504

[3] Q. M. Guedes and I. da Silva, "Technical report: Shell dam horizontal displacement monitoring – comparative study using geodetic measurement, optical plumb and gps technologies," *J. Appl. Geodesy*, vol. 3, no. 4, pp. 249–255, 2009. https://doi.org/10.1515/JAG.2009.025

[4] O. I. Fedorova and V. Y. Gorshkov, "Electrical monitoring in diagnostics of the soil hydrotechnical structures on the example of studying earthfill dam," *Power Technol. Eng.*, vol. 57, no. 1, pp. 39–44, 2023. https://doi.org/10.1007/s10749-023-01620-x

[5] B. P. Wu, B. Cui, and D. H. Zhong, "Web-based 3D visualization of dam safety monitoring," *Adv. Mater. Res.*, vol. 594, pp. 2927–2931, 2012. https://doi.org/10.4028/www.scientific.net/AMR.594-597.2927

[6] G. A. Sentosa, A. Azzaqy, S. G. Wardani, O. Setyandito, A. S. Ambiarto, and A. J. Pierre, "Construction scheduling and monitoring control of dams based on BIM," *IOP Conf. Ser.: Earth Environ. Sci.*, vol. 1169, no. 1, p. 012033, 2023. https://doi.org/10.1088/1755-1315/1169/1/012033

[7] F. F. Zhou, S. Y. Mao, Y. W. Huang, and L. Hu, "Design and implementation of wire alignment transducer based on linear array CCD and CAN field-bus communication," *J. Yangtze River Sci. Res. Inst.*, vol. 38, no. 4, pp. 150–154, 2021. https://doi.org/10.11988/ckyyb.20200838

[8] S. Esmaielzadeh, M. J. Mahmoodi, and M. J. S. Abad, "Application of signal processing techniques in structural health monitoring of concrete gravity dams," *Asian J. Civ. Eng.*, vol. 24, no. 7, pp. 2049–2063, 2023. https://doi.org/10.1007/s42107-023-00624-2

[9] S. Xie, "Investigation on fast response performance of dam deformation monitoring system with wireless sensor and virtualizing," *Int. J. Multimed. Ubiquitous Eng.*, vol. 11, no. 7, pp. 193–204, 2016. http://doi.org/10.14257/ijmue.2016.11.7.20

[10] S. Oliveira, A. Alegre, E. Carvalho, P. Mendes, and J. Proença, "Seismic and structural health monitoring systems for large dams: Theoretical, computational and practical innovations," *Bull. Earthquake Eng.*, vol. 20, no. 9, pp. 4483–4512, 2022. https://doi.org/10.1007/s10518-022-01392-1

[11] Z. Han, Y. Li, Z. Zhao, and B. Zhang, "An online safety monitoring system of hydropower station based on expert system," *Energy Rep.*, vol. 8, no. 4, pp. 1552–1567, 2022. https://doi.org/10.1016/j.egyr.2022.02.040

[12] J. R. Ribas, J. C. Severo, L. C. Felix, and K. P. Perpetuo, "Prioritization of hydroelectric power plant earth dam safety procedures: A multi-criteria approach," *Environ. Earth Sci.*, vol. 80, no. 24, p. 815, 2021. https://doi.org/10.1007/s12665-021-10096-9

[13] B. Zhao, "Research and design of dam deformation monitor based on linear CCD," Ph.D. dissertation, Hunan University, Changsha, 2015.

[14] S. Wang, Y. Xu, C. Gu, T. Bao, Q. Xia, and K. Hu, "Hysteretic effect considered monitoring model for interpreting abnormal deformation behavior of arch dams: A case study," *Struct. Control Health Monit.*, vol. 26, no. 10, p. e2417, 2019. https://doi.org/10.1002/stc.2417

[15] W. Dai, N. Liu, R. Santerre, and J. Pan, "Dam deformation monitoring data analysis using space-time kalman filter," *ISPRS Int. J. Geo-Inf.*, vol. 5, no. 12, p. 236, 2016. https://doi.org/10.3390/ijgi5120236

[16] T. J. Wang, B. Yang, and H. Y. Yang, "Dam deformation monitoring and data analysis based on cloud model," *Adv. Mater. Res.*, vol. 459, pp. 479–482, 2012. https://doi.org/10.4028/www.scientific.net/AMR.459.479

[17] F. B. Li, Z. K. Li, Q. Li, and B. Liu, "Research on deformation measurement technology of large dams," *Adv. Mater. Res.*, vol. 422, pp. 172–175, 2012. https://doi.org/10.4028/www.scientific.net/AMR.422.172

[18] F. F. Zhou, F. Zhang, Z. D. Du, and C. Hu, "Design and implementation of intelligent monitoring instrument for dam deformation based on microprocessor and multi-communication," *J. Yangtze River Sci. Res. Inst.*, vol. 41, no. 2, pp. 167–172, 2024. https://doi.org/10.11988/ckyyb.20221224

[19] *Photoelectric (CCD) vertical coordinate instrument*, Std. DL/T 1061-2020, 2020.

[20] G. Zhao and X. Xu, “The information domain confidence intervals in univariate linear calibration,” *Commun. Stat. Simul. Comput.*, vol. 51, no. 10, pp. 5620–5630, 2022. https://doi.org/10.1080/03610918.2020.1777302