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Research and Application of Verticality Detection Method for Circular Pier with Equal Section

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Abstract: This article presents four techniques for assessing verticality: the plumb line approach, the total station distance technique, the three-point centering method, and the centroid method. Given the significant error associated with the total station horizontal distance technique when measuring circular piers, this paper proposes the centroid method. This method calculates verticality by determining the coordinates of the center points at both ends of the pier. Experimental findings indicate that the centroid method achieves accuracy in measuring the verticality of circular piers comparable to the three-point centering method, while offering a faster inspection process. Furthermore, the paper explores the concept of composite verticality and validates the effectiveness of the centroid method in measuring composite verticality and its practical applications through comparative experiments.

Keywords: Verticality; Centrality method; Synthetic verticality

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1. Introduction

During the construction and acceptance of bridges, the verticality of pier columns serves as a critical parameter for both process control and final evaluation. For tall piers, various methods have been developed to assess verticality [1–3]. This study focuses on the measurement of verticality, particularly examining the detection techniques and practical applications for circular piers with constant cross-sections. Throughout the experimental process, multiple measuring instruments and approaches were employed, and an in-depth analysis was conducted on the various factors influencing the accuracy of verticality measurements. Among these methods, the horizontal distance technique has gained widespread adoption in bridge pier verticality assessments due to its straightforward principle and clear outcomes. However, when applied to cylindrical piers, the curvature of the surface introduces complexities, as the inclination of the bridge can directly impact the measured tilt values [4]. To address this specific challenge, this paper proposes an innovative verticality detection method designed to enhance the precision of measurements for circular piers.

2. Verticality specification requirements

The verticality of the pier serves as a critical indicator for assessing construction quality during both construction control and acceptance testing. It is also a key measured element, designated as item 11. The permissible deviation for pier verticality, as outlined in relevant specifications [5], can be found in **Table 1**.

Table 1. The specified value or allowable deviation of pier verticality.

Check items		Specify values or allowable deviations
Full height verticality (mm)	H ≤ 5m	≤ 5
	5m < H ≤ 60m	< H/1000, and ≤ 20
	H > 60m	≤ H/3000, and < 30

3. Method for measuring the verticality

3.1. Plumb line method for measuring verticality

The plumb line technique is a procedure for assessing verticality using a suspended weight attached to a line [6]. During the assessment, the vertical line is secured at the top of the pier, and the horizontal distance between this line and the concrete edge of the pier column is measured with a steel rule at the base of the pier. The ratio of the difference in readings between the upper and lower steel rules to the length of the vertical line represents the verticality of the detection surface [7]. Compared to other methods, the plumb line approach is more visually straightforward; however, it imposes stricter on-site requirements, such as needing auxiliary equipment to lift the line and weight. Additionally, the detection outcomes are highly sensitive to wind speed [8].

3.2. Vertical measurement by total station flat distance method

Figure 1 shows the schematic diagram of the total station flat distance method. The horizontal distance method involves positioning the measurement point as close as possible to both the top and bottom ends of the pier column. Based on the alignment direction, establish the vertical and transverse axes of the structure. Set up a total station at both the vertical and horizontal testing fronts of the structure. Measure the horizontal distance HD_1 from the upper surface to the instrument and the height difference VD_1 between the instrument's horizontal plane and the upper surface. Additionally, measure the horizontal distance HD_2 and height difference VD_2 from the instrument's level to the upper surface [9]. Once data collection is complete, use the formula $\Delta D = HD_1 - HD_2$ to calculate the slope of the structure within the tested height range, which represents the tilt value. Finally, apply the formula $B = \Delta D/(VD_1 - VD_2) \times 100$ to determine the verticality of the structure within the tested height range [10, 11].

Upon measuring the circular pier, it was discovered that the results contained significant errors. The line of sight for the circular pier does not lie in the same plane when measured using the horizontal distance method, which leads to considerable inaccuracies in the verticality data. Consequently, alternative measurement approaches have been further considered [12, 13].

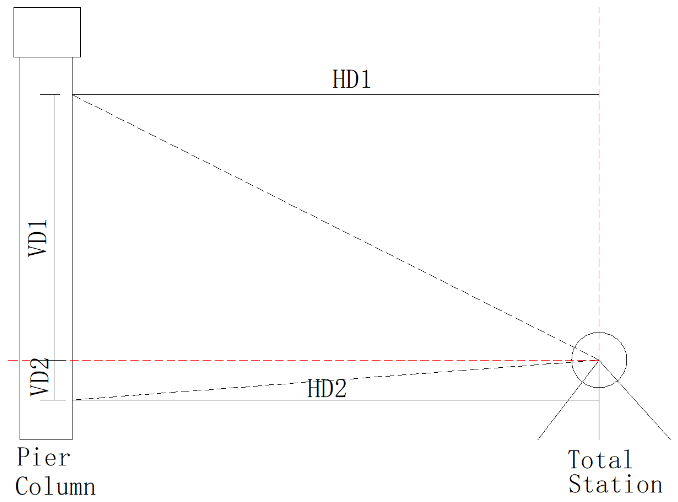

Figure 1. Schematic diagram of total station flat distance method

3.3. Measuring the verticality of round pier by three-point circle method

Figure 2 shows a diagram of the three-point circle fixing method.To measure the verticality of the round pier, at an arbitrary location on the top surface of the pier at the same height, measure three points. Their three-dimensional coordinates are $A_1(X_1,Y_1,Z_1)$, $A_2(X_2,Y_2,Z_2)$, and $A3(X_3,Y_3,Z_3)$, where $Z_1=Z_2=Z_3$. Next, at the same height on the bottom of the pier, measure another three points at any position. The three-dimensional coordinates for these points are $B_1(x_1,y_1,z_1)$, $B_2(x_2,y_2,z_2)$, and $B_3(x_3,y_3,z_3)$, with $z_1=z_2=z_3$. Using the general equation of a circle, the center coordinates of the circles can be determined as $O(X,Y,Z)$ and $P(x,y,z)$. Based on the center coordinates of circles O and P, the offsets in the x-direction $Dx=X–x$, the y-direction $Dy=Y–y$, and the height difference in the Z-direction $H=Z–z$ can be calculated. At this point, the longitudinal alignment deviation of the bridge is given by Dx/H , while the transverse alignment deviation is represented by Dy/H [14, 15].

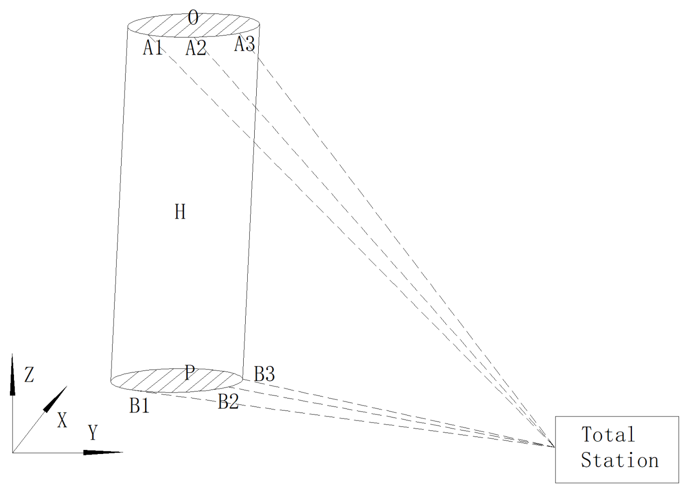

Figure 2. Schematic diagram of three-point circle fixing method

3.4. Centroid method for measuring the verticality of circular pier

Using the centroid method shown in **Figure 3**, the total station is set up on the test front of the longitudinal and transverse structures respectively. Aim at one edge of the upper surface of the pier and record the horizontal Angle HL1. Then keep the vertical brake of the instrument and turn the instrument to the other edge of the pier and record the horizontal Angle HL2. After the horizontal data is obtained, the horizontal angle of the center point is calculated. Keeping the instrument upright, measure the coordinates of the center point on the upper surface *(X1, Y1, Z1)*. Similarly, measure the coordinates of the center point of the lower surface *(X2, Y2, Z2)*, and calculate the verticality (%), $B = \sqrt{(X_1-X_2)^2+(Y_1-Y_2)^2}/(Z_1-Z_2) \times 100$ of the structure within the test height range according to the following formula. Through the above steps and calculation methods, the slope and verticality of the structure can be accurately measured and calculated. Compared with the three-point circle method, the centroid method only needs to measure two points in the same plane, which is more convenient and fast.

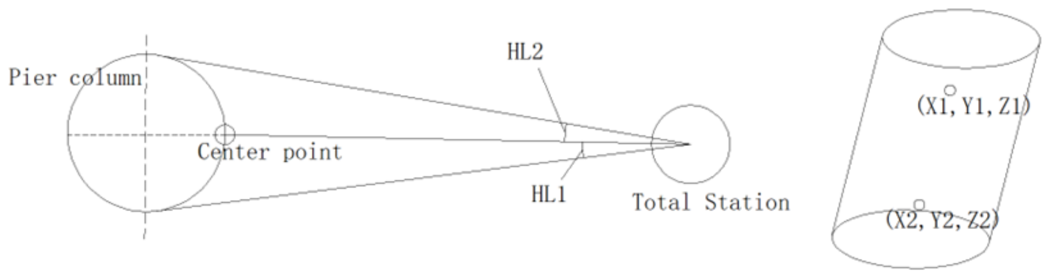

Figure 3. Line of sight diagram of centroid method

4. A specific study of synthetic verticality

By conducting research on specific projects, it has been observed that bridge piers do not only tilt in a single direction but also integrate two sets of data in the vertical plane using the principle of force synthesis. To ensure the accuracy of these findings, two distinct measurement techniques were employed. Initially, the pier was stabilized and then tilted at a specific angle in a particular direction. The plumb line method was used to assess verticality while maintaining the tilt angle constant as shown in **Figure 4**.

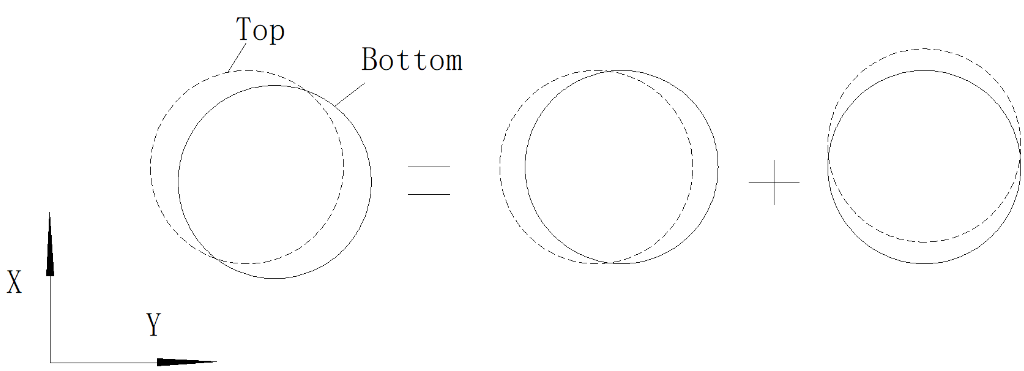

Figure 4. Schematic diagram of the mutual influence of the tilt of cylindrical piers along and across the bridge

Meanwhile, the centroid method was applied to measure the X and Y coordinates. Subsequently, the results from the three-point circle fixation method and the plumb line method were compared, as shown in **Table 2**.

Table 2. Comparison data table of centroid method

Inclined bearing	Point position	Verticality measured by the three-point circle method	ΔHD Horizontal distance (m)	ΔVD height difference (m)	Verticality measured by centroid method (%)	Resultant verticality (mm) by centroid method	Vertical method (mm)
South west	West	-4.6	-0.0545	1.2077	-4.5	5.6	5.9
South west	South	-3.8	-0.0438	1.1526	-3.8		
North west	South	15.0	0.1833	1.2208	15.0	17	17
North west	West	-8.2	-0.0962	1.1798	-8.2		
North east	South	5.8	0.0728	1.2398	5.8	11	11
North east	West	9.5	0.1169	1.2368	9.5		
South east	West	9.7	0.1126	1.2362	9.9	14	13.8
South east	South	-9.7	-0.1146	1.9200	-9.6		

Based on the data, it is evident that the centroid method can efficiently evaluate the resultant verticality and minimize the impact of the offset angle on the deviation. Experimental results indicate that the centroid method demonstrates higher accuracy than the horizontal distance method when measuring round piers. Through engineering application, a comparison with the measured data from the three-point circle fixing method shows good consistency between the two methods, indicating they possess significant practical value in engineering applications.

5. Conclusions

By comparing the two measurement approaches, it is evident that the centroid method offers greater accuracy compared to the horizontal distance method. Additionally, it is also quicker and more practical than both the three-point circle fixing method and the plumb line method. Furthermore, upon conducting a detailed examination of the deviation outcomes, it becomes evident that this approach possesses certain constraints in providing precise ratings when critical components such as piers and abutments sustain significant damage. Similarly, limitations arise when a single component is in an exceedingly deteriorated state.

Disclosure statement

The authors declare no conflict of interest.

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