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An innovative geometry control method for short-line match precast segmental bridges

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Abstract. The occurrence of unexpected horizontal offset in the instrument or target will result in accumulated horizontal deviation in segment alignment with traditional short-line match method. A geometry control method, the four-point method, is developed for precast segmental bridges to avoid the influences of unexpected horizontal offset. The concept of the four-point method is elucidated. Furthermore, the detailed instruments and instructions are introduced. Finally, the four-point method is validated through a practical engineering application. According to the survey data, after short-line match precast construction, the vertical deviations on both sides vary between -5 mm and 5 mm in almost all segments, and the horizontal deviations vary between -4 mm and 4 mm in all segments. Without on-site adjustment, the maximum vertical and horizontal closure gaps are 12.3 and 26.1 mm, respectively. The four-point method is suggested to alleviate the issues associated with relatively poor soil conditions in casting yard.

Keywords: four-point method; geometry control method; precast segmental bridges; short-line match; unexpected offset

1. Introduction

Segmental concrete box girder bridges are becoming a preferred structure throughout the world because of their remarkable benefits, such as fast and versatile construction, high controllable quality, low cost and no ground level disruption (Yuen *et al*. 2020, Bender and Janssen 1982, Barker 1980). In recent years, the use of segmental bridges has rapidly increased as a result of the large growth in infrastructure construction and transportation system development in China (Tang 2015, Bu and Ou 2013). The Hongtang Bridge, which was competed in 1990, is the first precast segmental bridge built in China using the span-by-span erection method. This western approach bridge is 1,240 m long with a constant span length of 40 m. The Sutong Yangtze River Bridge (Fig. 1) is a well-known cable-stayed bridge with a main span length of 1,088 m (Wu *et al*. 2015, Wang *et al*. 2016). Moreover, the approach span of the Sutong Yangtze River Bridge is built with short-line precast segments that are 75 m in length. The Jiashao Bridge (Fig. 2), which opened in 2013, is the second sea-cross bridge across Hangzhou Bay; this bridge has a total length 10.137 km and 70-m precast segmental approach spans.

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A precast segmental bridge can be constructed with two available methods: a short-line system or a long-line system. In the short-line casting method, each segment is individually cast between a bulkhead at one end and a previous segment at the other (Roberts *et al*. 1993, 1991). Each segment in the short-line method is a few meters long. In contrast, the long-line casting method involves casting segments on a casting bed of sufficient length to enable collective casting of an entire span or cantilever between field closure pours. The short-line casting method offers some advantages over the long-line casting method. For example, the short-line casting method can be employed for building a beam with any geometry (e.g., straight line, vertical curve and horizontal curve) without a complex form (Turmo *et al*. 2005). Moreover, any desired geometry can be obtained by twisting the position of the cast-against segment (Zhou and Zheng 2016). A major advantage of the short-line casting method is that it requires less casting yard and less formwork than the long-line casting method because the segments are individually cast in the casting yard (Veletzos and Restrepo 2014). Another advantage of the short-line casting method is that it requires minimal erection equipment. Therefore, the short-line casting method has become the most prevalent method for precast segmental bridge construction (Ramos and Aparicio 1996, Megally *et al*. 2009).

One key technology of short-line precast segmental bridges is the geometry control method (Bień 2011, Loper *et al*. 1988, Rostam 2005). In the short-line cast method,

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Fig. 1 Sutong Yangtze River Bridge

Fig. 2 Jiashao Bridge

each segment is cast against the previous one. Since one end of the casting segment is fixed by a steel bulkhead, the geometry of the bridge (e.g., horizontal or vertical curves and superelevation or transitions) is governed by adjusting the previous segment at the other end. Thus, each segment position is determined by its position in relation to the previous segment (Yu 2016). A geometry control procedure is recommended by the American Association of State Highway and Transportation Officials (AASHTO) in "Guide Specifications for Design and Construction of Segmental Concrete Bridges" (AASHTO GSCB-2-1999 1999). In this method, surveyors check the relative positions of segments against each other with six control points, four vertical leveling bolts over the two webs and two horizontal centerline hairpins. Since the focus is exclusively on the relative position between the cast segment and the previous segment, the four vertical control points on the current segment are measured in relation to the previous segment, and the relative horizontal orientation is measured via two horizontal control points. Another similar method is measured with the coordinates of six insert plates (Kumar *et al*. 2008). These methods, called the "six-point method" in this paper, are prevalent and have been effectively validated in many practical projects. With the development of BIM and 3D technology in automation construction (Puri and Turkan 2020, Cheng *et al*. 2022), a number of scholars have implemented BIM and 3D technology to geometry control in the six-point method (Wang *et al*. 2018, Babanagar *et al*. 2023).

With respect to the six-point method, the reference survey coordinate system is located at the midpoint on the bulkhead surface. The measurement system is employed under the assumption that the steel bulkhead at the opposite end of the current segment from the previous segment is maintained absolutely vertical with the top being completely horizontal. This assumption is ensured by the geometry control layout, including the instrument and target (see Fig. 3). In general, the positions of the instrument and target are absolutely stationary, and the surveyors need to check these positions against the permanent datum within a certain period (Jia *et al*. 2021). If these benchmark points are unexpectedly offset for some reasons, such as soil settlement in the position, it would lead to disastrous consequences in the short-line match cast construction (Qi *et al*. 2020); this phenomenon will be detailed in a later section.

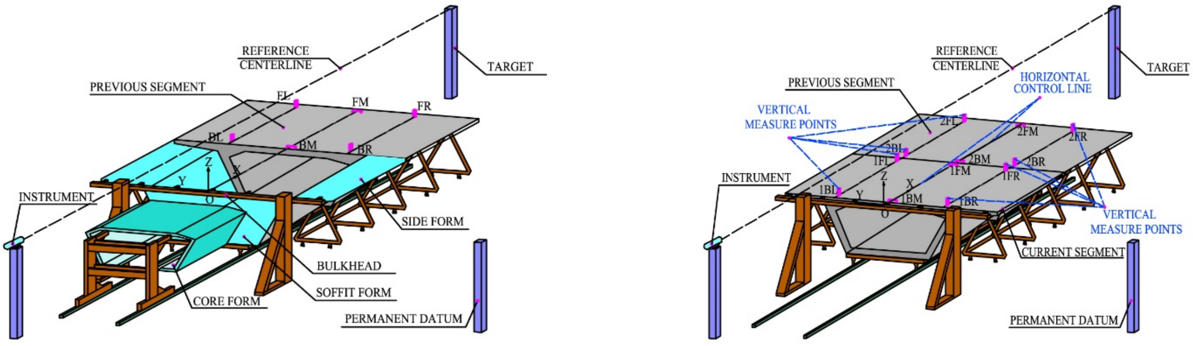
The goal of this study was to develop an innovative geometry control method for short-line match casting that can avoid the influence of unexpected offset in the benchmark points. Hereafter, the geometry control system in the six-point method is introduced, and the reason for the deviation in segment geometry due to unexpected offset is explained. According to the principles of plane geometry, the concept of a new geometry control system called the four-point method is introduced. The detailed instruments and instructions of the four-point method are illustrated. The data from the field studies presented in this paper are used to validate the new geometry control system. Finally, the alignment of the Leqing Bay Bridge, which was built with the four-point method, in the precast phase and the erection phase is presented in this paper.

2. Research significance

Due to the alignment correction method used in short-line match precast construction, the occurrence of unexpected horizontal offset in the instrument or target will result in accumulated horizontal deviation in segment alignment when applying the traditional survey method. An innovative geometry control method, the four-point method, which can be used for short-line match precast segmental bridges to avoid the influences of unexpected horizontal offset is developed. The authors believes that the four-point method will be very useful for short-line match casting to alleviate the issues, especially associated with relatively poor soil conditions in casting yard.

3. Geometry control system in the six-point method

In the six-point method, the control points are measured twice during one casting cycle: once in the match phase and the other in the recheck phase. The local coordinate system is established at the middle of the steel bulkhead following the right-hand rule. In addition, the local coordinate axis is assumed to maintain perfectly vertical in the *Y*-axis and absolutely horizontal in the *X*-axis during each casting cycle. Before measuring the segment position in a casting cycle, the surveyors should calibrate the steel bulkhead position by referencing the orientation between the instrument and the target. After adjusting the position of the bulkhead, six control points of the previous segment—four corner points (BL, BR, FL, and FR) for elevation and two



(a) Wet cast survey (b) As-cast survey

Fig. 3 Geometry survey system in the six-point method

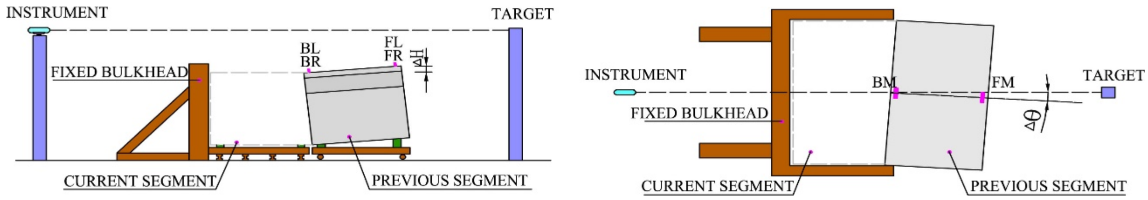


Fig. 4 Segment adjustment sketch

(a) Vertical adjustment (b) Horizontal adjustment

Fig. 5 Alignment adjustment method

points (BM and FM) for centerline—are measured in the match phase, as shown in Fig. 3(a).

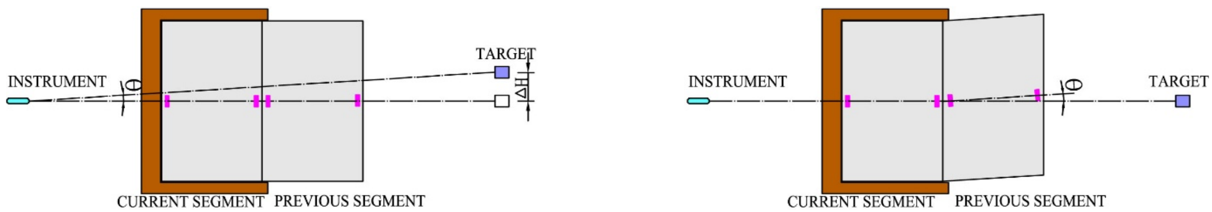
The relative position between the previous segment and the current segment is calculated in advance according to the vertical curvature and plan alignment of the bridge. Because the steel bulkhead and the forms are fixed, the relative position is determined by adjusting the previous segment position (Bridges and Coulter 1979). The forms (the side form, soffit form and core form as shown in Fig. 3) are never adjusted for geometry. The adjustment approaches for the vertical curvature and horizontal alignment are depicted in Fig. 4(a) and (b), respectively. After properly adjusting the previous segment and installing the assemblies, including the reinforcing bar cage, tendons, anchors and inner form, the current segment can be cast. Afterwards, six marks are embedded in the correct positions prior to the concrete final set.

Although the cast match is assumed to be perfect in the match phase, the relative position changes after casting due to several factors, such as the segment weight, concrete vibration, concrete curing, and temperature. The purpose of the geometry survey in the recheck phase is to determine the magnitude and direction of movement or casting error. The elevation change is measured by eight points (1BL, 1BR, 1FL, and 1FR in the current segment and 2BL, 2BR, 2FL, and 2FR in the previous segment), and the centerline position is rechecked by four points (1BM and 1FM in the previous segment and 2BM and 2FM in the current segment), as shown in Fig. 3(b).

Small changes are not concerning as long as these changes are known and recorded in each casting cycle. Compensation can be made to avoid geometry errors with respect to the whole bridge (Huang *et al*. 2013). Hence, if segment one has moved to the left, segment two will now be adjusted to the right. The same procedure holds for any vertical adjustment. Fig. 5(a) illustrates the vertical geometry adjustment. If segment 2 is cast H higher than segment 1, segment 3 should be cast H lower than segment 2 in the next casting cycle, thereby completing the vertical adjustment. Similarly, as illustrated in Fig. 5(b), if the centerline of segment 2 is cast at an orientation of θ to the reference centerline, segment 3 should be cast at an orientation of θ in the opposite direction to the reference centerline. Through this adjustment method, proper bridge alignment is achieved.

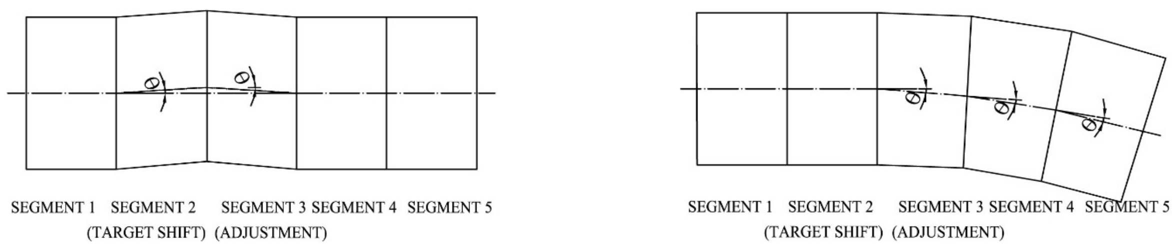
However, because the casting yard is usually built for the project on available land, while cost-effective and allowing for minimized shipping efforts, the soil condition may result in uneven settlement (Tang 2000, Mondorf *et al.* 1997). The bulkhead is assumed to be absolutely stationary, but if the positions of the instrument or target shift during a casting cycle due to uneven settlement, it will result in a nonnegligible influence on the bridge alignment. Note that only the movement of the instrument or target that occurred after the match survey and before the recheck survey in one casting cycle is of concern. However, the movement that occurred after the recheck survey of the current casting cycle and prior to the match survey of the next casting cycle can be neglected with respect to the bridge segment because the bulkhead is reset in each casting cycle. In addition, as the vertical adjustment is determined by measuring the relative elevations between the current segment and the previous segment in the recheck phase, the vertical movements of the instrument or target have no influence on the vertical alignment of the bridge. In contrast to the vertical measurement, the horizontal measurement is determined by the orientation between the centerline in the previous segment and the reference centerline through the instrument and target. Therefore, the horizontal measurement can be affected by the horizontal movement of the instrument or target, which shifts the reference centerline. Provided that the current segment perfectly matches the previous segment after casting and that the target is offset to the original position at a distance of ΔH in the horizontal direction, the actual state is illustrated in Fig. 6(a). In the recheck survey phase, the surveyors will note that the previous segment centerline has an angle of θ relative to the reference centerline. However, because the ΔH offset is unexpected and unknown, the surveyors draw an improper conclusion, as depicted in Fig. 7(a). Therefore, the surveyors cast the next segment at an orientation of θ in the opposite direction in an attempt to correct the alignment, as shown in Fig. 6(b).

The offset can be noticed and corrected by checking the permanent datum (see Fig. 3) prior to the match survey in one casting cycle. However, the surveyors do not check the permanent datum in each casting cycle because the permanent datum check always takes a substantial amount of time. Actually, the surveyors recheck the permanent datum in a period, which is typically one month or longer. If the movement occurred in only one segment casting and stopped prior to the following casting cycle, the horizontal alignment deviation will accumulate until the next permanent datum check is performed. Provided that all cast segments perfectly match and one unexpected offset occurred during the segment 2 casting cycle, it will result in the incorrect conclusion that a rotational movement of θ occurred in segment 2. Afterwards, the centerline of segment 3 will be cast at an orientation of θ in the opposite direction for compensation, as shown in Fig. 7(a). Therefore, segment 3 will cast at an orientation of θ relative to segment 2 for compensation, which is a misunderstanding. Afterwards, because the reference centerline is already rotated to an orientation of θ, segment 4 will be cast at an orientation of θ relative to segment 3, and this process continues for each successive segment. Finally, the actual horizontal alignment is illustrated in Fig. 7(b). The accumulated deviation in horizontal alignment may exceed the permissible value. For example, assume that the length between the instrument and target is 40 m and that an unexpected relative offset of 4 mm occurred in the horizontal direction during the segment 2 casting cycle, as depicted in Fig. 7. Each segment length is assumed to be 3 m. The unexpected offset is found and corrected after the next ten casting cycles. In this circumstance, the horizontal deviations in each subsequent casting segment are calculated, and the final accumulated deviation reaches 16.5 mm, as shown in Fig. 8. Furthermore, if the unexpected movement increment occurred during each casting cycle, the total deviation would be too substantial to neglect.



(a) Actual state (b) Incorrect conclusion

Fig. 6 Segment positions when unexpected offset occurs



(a) Mistaken alignment (b) Actual alignment

Fig. 7 Horizontal alignment after correction

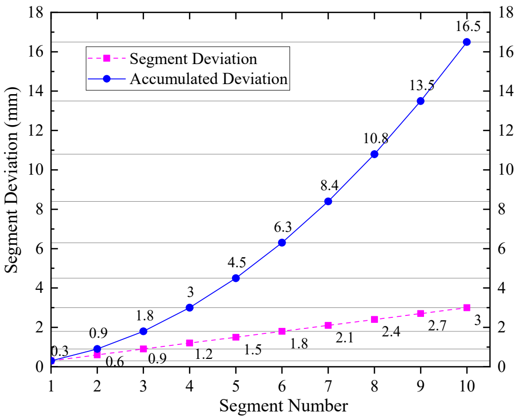


Fig. 8 Horizontal accumulated deviation as a result of one unexpected horizontal offset in the target

4. Principles of the four-point method

According to the previous discussion, the unexpected relative offset between the instrument and target leads to poor horizontal alignment in the six-point method. The fundamental reason for this phenomenon can be attributed to the measurement method of the segment centerline, which is based on the line between the instrument and the target. This alignment issue can be effectively solved by providing an approach to measure the horizontal position of the segment with the relative position of the segment, which is similar to the approach used for the elevation measurement. With regard to the horizontal measurement, this paper develops an innovative method of geometry control with four control points in each segment, and this method is called the four-point method.

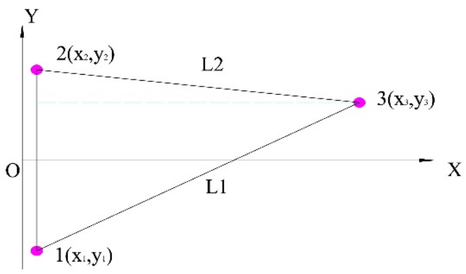


Fig. 9 Coordinate calculation of the unknown point

In the four-point method, there are four control points in each segment: BL, BR, FL, and FR. The control points are embedded at the same locations as the four corner control points in the six-point method. By measuring the elevations of these four control points, the relative vertical positions can be achieved similar to the six-point method. The relative horizontal positions can be determined by measuring the horizontal distances between the control points of the current segment and those of the previous segment instead of using the segment orientation measurement from the six-point method. The theoretical horizontal distances between the control points in a segment can be calculated in advance with the vertical and horizontal alignment of the bridge.

The reference survey coordinate system in the four-point method is similar to that in the six-point method, as shown in Fig. 3. Based on the principles of plane geometry, an unknown point can be determined by two given points and the distances between the given points and the unknown point in a plane, as illustrated in Fig. 9. The coordinates of point 1 and point 2 are (x_1,y_1) and (x_2,y_2), respectively. The distance from point 1 to point 3 is $L1$, and the distance from point 2 to point 3 is $L2$. The coordinates of the unknown point, point 3, can be calculated with the following equations. According to the Pythagorean theorem, Eq. (1) is presented as follows

$$\begin{cases}(x_3-x_1)^2+(y_3-y_1)^2=L1^2\\(x_3-x_2)^2+(y_3-y_2)^2=L2^2\end{cases} \tag{1}$$

where $x_2 = x_1$ and $y_2 = -y_1$ in the reference survey coordinate system. Hence, Eq. (1) can be rewritten as follows

$$\begin{cases}(x_3-x_1)^2+(y_3-y_1)^2=L1^2\\(x_3-x_1)^2+(y_3+y_1)^2=L2^2\end{cases} \tag{2}$$

By subtracting the two formulas in Eq. (2), the coordinate y3 can be calculated as follows

$$y_3=\frac{L2^2-L1^2}{4y_1} \tag{3}$$

Then, Eq. (3) can be substituted into Eq. (2) to solve for the coordinate x3 (positive value), as shown hereafter in Eq. (4)

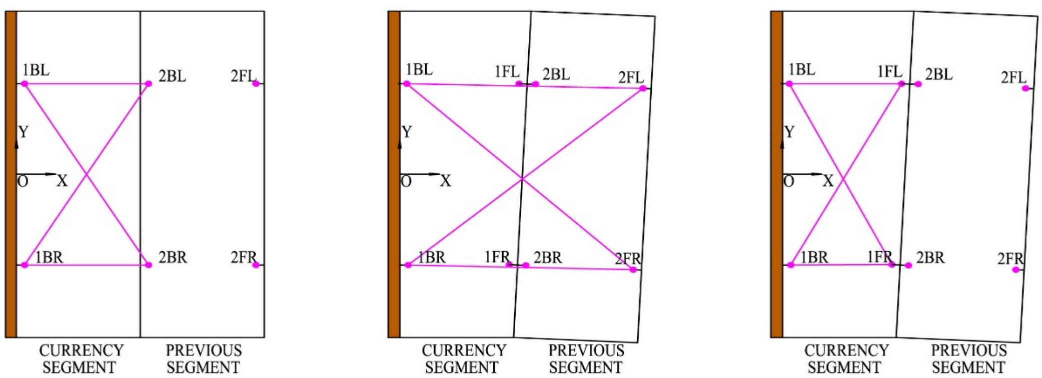


Fig. 10 Geometry control measurements in the four-point method

$$x_3 = x_1 + \sqrt{L1^2 - \left(\frac{L2^2 - L1^2}{4y_1} - y_1\right)^2} \quad (4)$$

In the four-point method, there are three measurement steps: step 1 is in the match phase and step 2 and step 3 are in the recheck phase. Fig. 10(a) depicts step 1 in the match phase. The previous segment should be set at the proper position relative to the current position in this phase. As points 1BL and 1BR are fixed to the bulkhead, they are the two given points in the reference coordinate system. Point 2BL is an unknown point and can be determined with the horizontal distances of 1BL-2BL and 1BR-2BL. Similarly, point 2BR can also be determined with the horizontal distances of 1BL-2BR and 1BR-2BR. Because the previous segment is a rigid body, the proper relative horizontal position is achieved when the positions of points 2BL and 2BR are determined. After the in-situ construction, the match segment position will be changed for the same reason as the six-point method, and the relative position need to be measured in the following recheck phase. Fig. 10(b) depicts step 2 in the recheck phase. After casting the current segment, the relative horizontal position may change. The recheck survey measures the magnitude and direction of the movement for correction in the next casting cycle. As the horizontal distances of 1BL-2FL, 1BL-2FR, 1BR-2FL, and 1BR-2FR are measured, the relative horizontal position can be obtained in the recheck phase. Note that the relative position can also be obtained by points 2BL and 2BR. Whereas, due to longer distances decreasing the measurement error, points 2FL and 2FR are recommended. Fig. 10(c) depicts the control point position of the current segment recorded at four distances. The purpose of this step is to determine the relative position for the match phase of the next casting cycle. Therefore, the four-point method can record the proper relative position, including the relative vertical position and the relative horizontal position in each casting cycle. The vertical and horizontal alignment of the bridge can be corrected with the same aforementioned method. In conclusion, the four-point method is a new geometry control method for short-line match casting that can eliminate the influence of unexpected relative offset in the target position.

5. Instruments and instructions for the four-point method

The control point marker in the four-point method is a piece of stainless steel, as illustrated in Fig. 11. Note that the size of the marker can be customized to fit the size of the box. These markers are embedded with a horizontal alignment to the surface of the top slab and a vertical alignment to the end of the segment. In addition, the back markers are connected to the steel bulkhead, and the front markers are connected to the previous segment through the installed component. The components are depicted in Fig. 12. Markers 1BL and 1BR are connected to the bulkhead with a bolted coverplate through a roller, and markers 1FL and 1FR are fixed to the previous segment with a coverplate through four bolts. Each segment marker is set in the match phase instead of embedded in the wet concrete, as is done in the six-point method. The purpose of this embedding approach is to provide the distance measurement points in the match phase. These four coverplates are removed by loosening the bolts during the recheck phase.

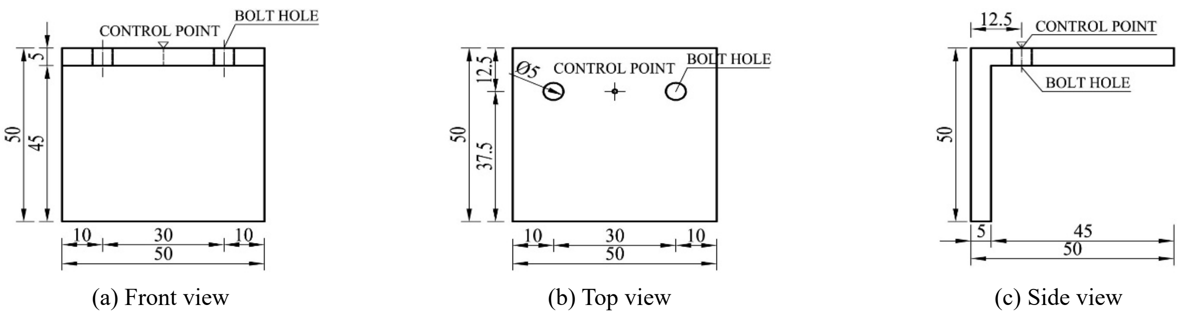


Fig. 11 Stainless steel marker (units: mm)

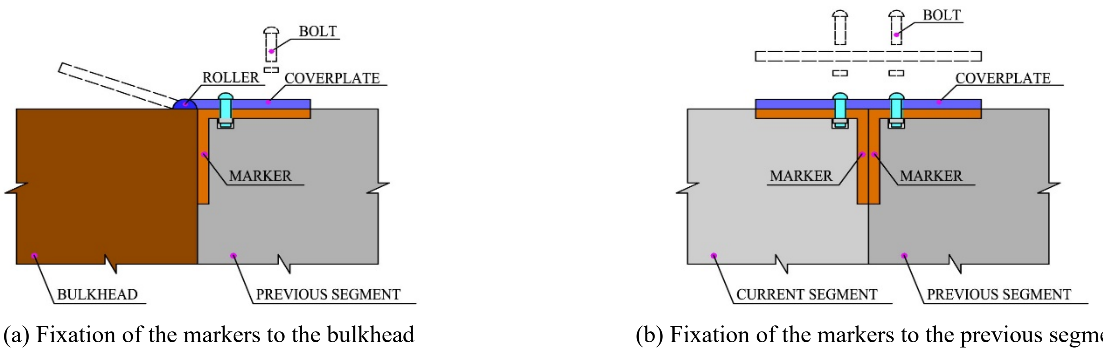


Fig. 12 Schematic of the components and connectors

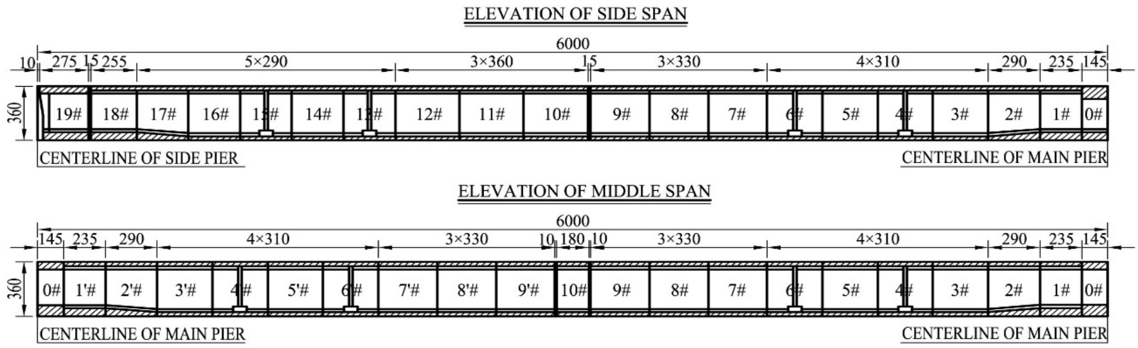


Fig. 13 Segment layout of the Leqing Bay Bridge (units: cm): (a) elevation of the side span; and (b) elevation of the middle span

Fig. 14 Cantilever erection of the Leqing Bay Bridge

The key technology of the four-point method is the horizontal distance measurement. The distance can be measured with a total station or laser distance meter. With regard to laser measurement, a fixed laser distance meter and a leveling platform for horizontal laser emission are employed. The measurement error of the distance is less than or equal to 1 mm either by total station or by laser instrument. Provided that the distance between 1BL and 1BR is 10 m and each segment is 3 m in length, the measurement error in the *X*-axis is 1 mm, and the error in the *Y*-axis is 1.8 mm in the worst case. Mostly, the error is less than 1 mm in the two directions because the error can be neutralized during each casting cycle. Thus, the error is acceptable for engineering applications.

6. Practical engineering application of the four-point method

6.1 Project background

A short-line match precast segmental bridge was built with the four-point method as a portion of a sea-cross connector across Leqing Bay in Zhejiang Province, China. The total length of the sea-cross bridge is 10.088 km with a 365-m main span cable-stayed bridge for the navigation channel and hundreds of 60-m approach spans. A typical approach bridge is a five-span, prestressed concrete box bridge with individual span lengths of 60 m. Fig. 13 depicts that each span is composed of twenty segments with a maximum length of 3.6 m. All segments are designated as *n*-*p* or *n*-*p*' where *n* represents the span number in the five-span bridge, *p* represents the segment number in the small mileage direction and *p*' represents the segment number in the big mileage direction. According to the segment construction, the side span set two 15-cm wet joints (one at the midspan and the other near the end pier section), and the middle span set two 10-cm wet joints both near the midspan. All segments were cast using the short-line match method and erected using the cantilever method with a bridge erecting machine, as shown in Fig. 14. The sea-cross bridge project was accomplished in 2017 after four years of construction.

Fig. 15 depicts the typical cross section with an inclined web. The constant depth of the segment is 3.6 m, and the total width is 16.05 m with 3.5-m-wide flanges on both sides. The thicknesses of the top slab and bottom slab are 28 and 27 cm, respectively. The segment concrete is C55, which is well suited to offshore corrosive environments.

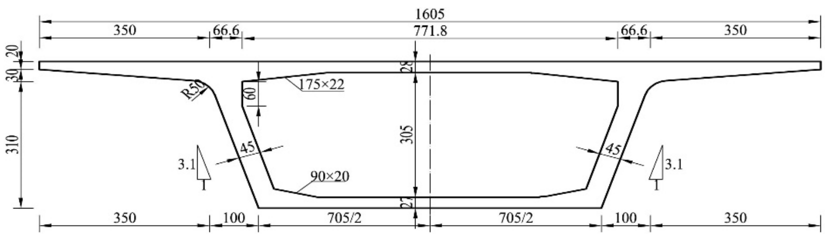


Fig. 15 Typical cross section (units: cm)

Fig. 16 Segment storage yard for the Leqing Bay Bridge

A microexpansion early-strength C55 concrete was employed in the wet joint. The axial compressive strength of C55 is 7,975 psi. These types of concrete are commonly used in Chinese bridge engineering applications. The concrete box girder was prestressed longitudinally and transversely with prestressing tendons. The tendons were composed of Φ15.24 mm seven-wire strands with an ultimate strength of 269,770 psi. The size of the longitudinal tendons varied from 15 strands to a maximum of 22 strands. The transverse tendons in the top slab were four-stand tendons. Inside the box girder, 22-strand tendons were installed as external tendons.

All casting cells were operated on a 2-day cycle in the project. After two days of proper curing, the segment concrete strength was sufficiently strong to remove the forms. Afterwards, the segment was moved to the segment carrier as the match segment for the next casting cycle. In addition, it was necessary to keep the concrete surface wet throughout the succeeding operations wherein the segment acted as a match segment. Then, after a 2-day cycle, the segment was transferred to a spray curing zone before the next segment was moved to the segment carrier. After three days of curing in the spraying zone, the segment was finally transferred to the storage yard, as shown in Fig. 16. Because the erection operations were later than expected, the segments were stored for three months before erection, and the segments were supported at three points—two points under one web and one point under the other web—to avoid warping.

6.2 Application of the four-point method

Leqing Bay is a natural bay located at the northern entrance to the East China Sea in Zhejiang Province. The bridge casting yard was near the bridge site to provide efficient construction. The geological condition of the casting yard was a typical alluvial plain, and the soil condition was relatively poor. Prior to precast construction, soil stabilization work was conducted to prevent soil settlement. Afterwards, the instruments and targets for short-line match precast construction were set. Through one month of continuous observation, some instruments and targets exhibited observable offset. Although the soil was strengthened, the maximum offset is as high as 3 mm in the first month. Considering the poor soil condition, the four-point method was employed with the short-line match precast construction for the Leqing Bay Bridge.

Table 1 Lofting data in the match phase of segment 3-5

Vertical control	Elevation (m)	Horizontal control	Distance (m)
2BL	-0.0012	2BL-1BL	3.1010
2BR	0.0033	2BL-1BR	9.1011
2FL	-0.0020	2BR-1BR	3.0986
2FR	-0.0028	2BR-1BL	9.1037

Table 2 Survey data in the recheck phase of segment 3-5

Vertical control	Elevation (m)	Horizontal control	Distance (m)
2FL	-0.0027	1BL-2FL	6.1819
2FR	-0.0049	1BL-2FR	10.5509
2BL	-0.0010	1BR-2FL	10.5561
2BR	0.0021	1BR-2FR	6.1691
1FL	-0.0005	1BL-1FL	3.0762
1FR	0.0011	1BL-1FR	9.0906
1BL	-0.0024	1BR-1FL	9.0958
1BR	-0.0017	1BR-1FR	3.0710

With respect to the four-point method, the procedures in the match phase are listed as follows: 1) The length of the new segment is lofted by adjusting the 2BL-1BL and 2BR-1BR distances within 1 mm error in the *X*-axis simultaneously; 2) The horizontal position of the new segment is lofted by adjusting the 2BL-1BR and 2BR-1BL distances within 1 mm error in the *Y*-axis simultaneously; 3) The vertical position of the new segment is lofted by adjusting the elevations of 2BL, 2BR, 2FL and 2FR within 1 mm error in the *Z*-axis simultaneously. In the recheck phase, the horizontal distances of 1BL-2FL, 1BL-2FR, 1BR-2FL, 1BR-2FR, 1BL-1FL, 1BL-1FR, 1BR-1FL and 1BR-1FR are measured, and the elevations of all eight markers are measured. The lofting and measurement data of segment 3-5, which is the number five segment in the third span, are listed in Tables 1 and 2, respectively. As point 1BL and 1BR are fixed, the segment measurement data in the local coordinate system are calculated in Table 3. According to the coordinates of 2FL and 2FR, the deviation in the centerline of segment 3-5 is calculated as 0.4 mm relative to segment 3-4 in the *Y*-axis by designed computer programs. Then, the deviation is recorded and corrected in the next casting cycle.

6.3 Geometry control result

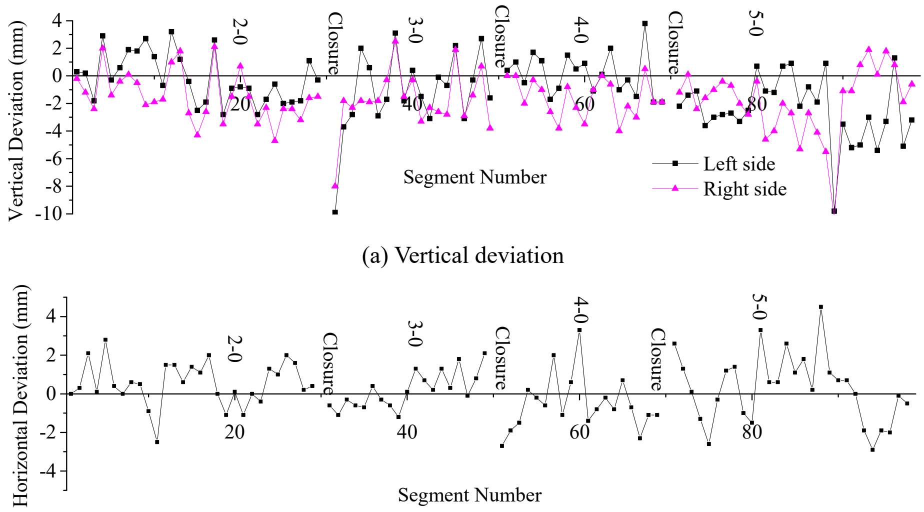
Using the four-point method in the Leqing Bay Bridge precast construction, all segments were cast in a couple of months. Fig. 17(a) illustrates the vertical deviations in the precast segments relative to theoretical vertical alignment on both sides in the precast phase. As the closure segment connected with the wet joint in the middle span, segments 2-10, 3-10 and 4-10 didn’t need to match other segments. The vertical deviations on both sides varied between -5 mm

Table 3 Survey data of segment 3-5 in the local coordinate system

Control point	X (m)	Y (m)	Z (m)
2FL	6.1944	-4.2766	-0.0027
2FR	6.1816	4.2794	-0.0049
2BL	3.1014	-4.2784	-0.0010
2BR	3.0964	-4.2775	0.0021
1FL	3.0762	-4.2798	-0.0005
1FR	3.0835	4.2763	0.0011
1BL	0.0125	-4.2800	-0.0024
1BR	0.0125	4.2800	-0.0017

and 5 mm in all spans except segments 2-9' and 5-9. The results showed that elevation deviations in segment 2-9' on the right side and left side were -8 mm and -9.9 mm, respectively. Similarly, the elevation deviations in segment 5-9 on the right side and left side were -10.4 mm and -9.8 mm, respectively. These obvious errors may be due to cast machine movement in their casting cycles. The horizontal deviations in the precast segments relative to the theoretical plan alignment on both sides in the precast phase are plotted in Fig. 17(b). It was concluded that the horizontal deviations varied between -4 mm and 4 mm in all spans. In summary, the elevation and horizontal deviations in the precast phase demonstrated that the four-point method is acceptable for use in short-line match precast construction.

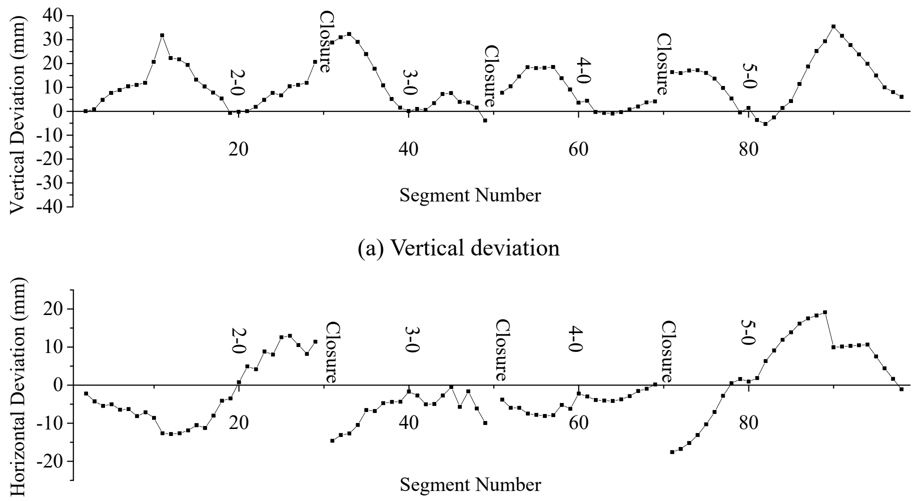
Attention should also be given to alignment control during the erection phase. In this phase, the general concept is to attach the segments in an alternate manner at opposite ends of cantilevers supported by piers. Nevertheless, the actual alignment needs to be compared with the theoretical alignment for the proper final alignment. Once the observed segment deviation exceeds the allowable range of standard provisions, small erection corrections should be conducted,



(a) Vertical deviation

(b) Horizontal deviation

Fig. 17 Deviations in the segment alignment in the precast phase



(a) Vertical deviation

(b) Horizontal deviation

Fig. 18 Deviations in the segment alignment in erection phase such as shimming or wet joint adjustment. Considering the additional monetary and time increases these corrections would pose on erection construction, the segments of the Leqing Bay Bridge were erected without on-site adjustment, and the geometry deviations in the segments were ensured to remain within the tolerance limits according to measurement results throughout the whole erection construction. The vertical deviations and horizontal deviations in the segments before closure construction of the middle spans are plotted in Figs. 18(a) and (b), respectively. Because the relative positions of the control points in a segment are fixed, the graphs are plotted with the right side control point data. There was an accumulated deviation in the segments from the pier to the cantilever end. This accumulation was attributed to the initial uneven section deformations in the pier segments, i.e., segments 1-19, 2-0, 3-0, 4-0, 5-0 and 5-19. The maximum vertical gap (at the span 4 closure) and the max horizontal closure gap (at the span 2 closure) were 12.3 and 26.1 mm, respectively. The geometry deviation results slightly exceeded the recommended value of 25 mm. However, considering that no on-site adjustment was employed, it was acceptable for the Leqing Bay Bridge.

7. Conclusions

When the six-point method is used in short-line match casting, the segment horizontal alignment is determined with a reference centerline between the instrument and the target. However, if unexpected horizontal movement occurs in the instrument or the target and is not noticed, it will result in accumulated horizontal deviation in the segment alignment due to the correction method in short-line match construction. This paper introduced an innovative geometry control method called the four-point method, which can be used in short-line match precast segmental bridges to avoid the influence of unexpected horizontal offset. Instead of measuring the segment orientation, the four-point method determines the relative horizontal position of the segment by using distance measurements between control points. Therefore, the proper relative positions of the segments can be measured by the elevation and distance measurements to avoid external influences, such as target offset due to uneven soil settlement.

The markers and components in the four-point method are introduced in this paper. When the distances are measured with either a total station or a laser instrument, the measurement error should be less than 1 mm in the two directions and is acceptable in engineering practice. Furthermore, the new survey control method was applied to a practical engineering application: the Leqing Bay Bridge. After short-line match precast construction, the vertical deviations in the segment geometry on both sides varied between -5 and 5 mm over the entire span except for two segments, whose deviations were as great as -10 mm due to the cast machine movement in their casting cycles, and the horizontal deviations varied between -4 and 4 mm over the entire span. Finally, without on-site adjustment during erection, the maximum vertical and horizontal closure gaps were 12.3 and 26.1 mm, respectively. In summary, the new survey control method was successfully validated through a practical engineering application. As a result, the four-point method is suggested for short-line match casting to alleviate the issues associated with relatively poor soil conditions in a casting yard.

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