Design and Construction of the Bridges on Guangzhou Metro Line 4

X.H. HE1ab, X.L. MENG2 and L. J. LI2

1 School of Civil Engineering & Architecture, Central South University, China
2 GuangZhou Metro Corporation, China

Abstract

Elevated rail transit has been developed in some big cities in China in recent years. However, specialized codes for design of the bridges in the elevated rail transit system have not yet been established. Based on the prestressed concrete (PC) box girder bridges on Guangzhou metro line 4, some technical features of design principle and technology requisition, ensemble plan and design load of bridges on urban rail transit are explored. At the same time, due to the first time used on a large scale in mainland of China, the short-line match method technology and the principles of the coordinate transformation are briefly introduced, and the formulas of spatial dimensional coordinate transformation for geometric shape control and calculating the translation amounts of precasting by the short-line method are deduced. In addition, some of the methods for the geometric shape control of the precasting by the short-line method and cantilever assembly of the segments are also briefly discussed.

Keywords: elevated rail transit, bridge, design principle, short-line match method, geometric shape control

Corresponding author: Email: xuhuihe@mail.csu.edu.cn
Presenter: Email: xuhuihe@mail.csu.edu.cn

1877–7058 © 2011 Published by Elsevier Ltd. Open access under CC BY-NC-ND license.
doi:10.1016/j.proeng.2011.07.014
1. INTRODUCTION

With the development of economic and society, the construction of fast rail transit systems is becoming a trend for development and modernization of city infrastructure. Due to superior efficiency, environment-friendly and aesthetic value, urban elevated rail transit has been developed and applied in some big cities in China. Guangzhou is one of the important cities of developing urban rail transportation, before the 16th Guangzhou Asian games 2010, the total length of metro lines is up to 255 km. Guangzhou metro line 4 is one of the main metro lines from north to south with a total length of 56 km includes viaduct bridges of almost 30 km from Xinzao to Nansha. The Xinzao to Huangge section began operations on Nov. 26 2006, and Huangge to Nansha section opened to traffic on May 1st 2007. The bridges on Guangzhou metro line 4 are all prestressed concrete (PC) box girder bridges, and main bridge types include simply supported bridges, continuous beam bridges and a large span continuous-rigid frame bridge. Guangzhou metro line 4 is the first time to use short-line match method on a large scale. The construction planning map and typical bridges of Guangzhou metro line 4 are shown in Figure 1.

![Figure 1 Guangzhou metro line 4: (a) planning map; (b) typical bridge](image)

Based on the Guangzhou metro line 4 viaduct bridges, this paper first investigates the design the technology problem of design principle and technology requisition, ensemble plan and design load of bridges on urban rail transit. Then a three dimensional (3D) coordinate transformation formula of geometric control for short-line match method is deduced in this paper, and some methods and measures for geometric control of the precasting by segment short-line match method and cantilever assembly of the segments are also briefly discussed.

2. Design description

2.1. Design principle and technology requisition

As an important urban landscape, the principle of beauty, economy, advancement and practicality is required. In order to satisfy the scale harmony needs, the bridge height to span ratio is 1/2.3, the box girder height to bridge height ratio is 1/4 to 1/5, the pier width to girder height ratio is 1/1.6. On the basis of sight beauty, the design must satisfy the operation function of safety, durability, economy. At the same time, the structure design should aim at standardization and series for easy construction.
Due to specialized codes for design of this type of vehicle loading in the urban rail transmit system have not yet been established, bridge design thus usually refer the relative national railway design codes. The vertical deformation allowable value is $L/2000$ for span less than 30 m, and $L/1500$ for span larger than 30 m. The first lateral natural frequency should not less than $90/L$.

2.2. Span arrangement and cross-section layout

The PC box girder structures of Guangzhou metro line 4 are aimed at the concise and unified appearance, convenience for factorial production and standardized construction. Consequently, 30 m span simply supported box girder bridges is selected as a standard span in general districts, 20m, 25m, 27.5m, 32.5, 40m and 41.9 m as the adjustment spans. While for the crossing over river and intersection nodes, the continuous beam or continuous-rigid frame bridges are used in order to reduce its interference with the on-site ground and ship transportation and nearby residents. The largest bridge is 80+120+120+80 m Shawan continuous rigid frame bridge, the Shiqiaoli bridge is the largest continuous bridge consisting of two centre spans of 80 m and two side spans of 52.5 m each.

According to the rail network planning and vehicle gauge, the cross-section layout of bridges is identified as: 0.2m (anti-collision wall) +8.9 m (two tracks and a passenger evacuation platform) +0.2 m (anti-collision wall) (Xiong 2005). The cross-section layout of 30m simply supported bridge is shown in Figure 2. For the segment precast bridge, the standard segment length is 2.5 m for simply supported bridge based on the capability of construction, lift and transportation.

![Figure 2 Typical cross-section](image)

2.3. LIM load

The Guangzhou metro line 4 is the first metro line to use the linear induction motor (LIM) metro system in China. The LIM metro system is a new urban transportation system incorporating element of maglev and traditional rail transportation (Hiroshi 1999). The total length of the train is 71 m with four vehicles. The width of the vehicle body is 2.8 m. The average axle weight is 101 kN (design value is 120 kN). The maximum design velocity of the LIM train is 90 km/h (Pang and Gao 2006).
3. Short-line match method

In terms of the site conditions and comparison results, except for cast-in-place using balance cantilever method and integral framework, the main construction methods in Guangzhou metro line 4 are short-line match precasting method and full-span precasting method. The line on north of Shawan river via hillock and countryside, the full-span precasting and erection method was adopted. However, in the south of Shawan river, the metro line built on the main load of Shinanlu, the short-line match precasting method was adopted. Due to the short-line method is more complicated than long-line method and other construction methods, and it is the first time to use on a large scale in mainland of China, the emphsis of this paper is to investigate the key technology of short-line method.

3.1. Coordinate transformation principles

Short-line match method is an effective approach to precast bridge in a limited field. The method divides a girder into several segments and only one moulding board is required to precast. The precasting geometric shape control of short-line method is performed by adjusting the spatial position of matching segment relative to casting segment (local coordinate) to ensure the bridge design shape (global coordinate). Therefore, the coordinate transformation between global and local coordinates is required for the precasting geometric shape control of short-line method. The main procedures are: (1) confirming the global coordinates system in terms of design shape and the control points global coordinates of each joint; (2) calculating the direction cosines of every local coordinate and their translation relative to global coordinates; (3) translating the global coordinates of each control point to corresponding local coordinates; and (4) calculating the translation of each segment from casting position to matching position. It is noted that the first segment no matching segment, but only float end moulding board, and the translation calculation of the last segment is not necessary.

3.2. Formulas for transformation of the spatial coordinate

As shown in Figure 3, it is assumed that there are three control points on each joint of bridge segments, $L$ means left control point, $M$ means middle point and $R$ means right control point, $L$ and $R$ control the segment elevation, and $M$ controls the plane shape. In global coordinate $(X, Y, Z)$ system, $Z$ is assumed as vertical direction, $X$ is girder axis direction, and $Y$ is lateral direction. The $i$th joint control points are $M_i$, $L_i$ and $R_i$, respectively, whose coordinate components in global coordinate system are $X_{M_i}$, $Y_{M_i}$, $Z_{M_i}$, $X_{L_i}$, $Y_{L_i}$, $Z_{L_i}$, $X_{R_i}$, $Y_{R_i}$, and $Z_{R_i}$, respectively. The vector \( \{\delta_i\} = [\delta M_i, \delta L_i, \delta R_i]^T \), \( \{\rho M_i\} = [X_{M_i}, Y_{M_i}, Z_{M_i}]^T \), \( \{\rho L_i\} = [X_{L_i}, Y_{L_i}, Z_{L_i}]^T \), \( \{\rho R_i\} = [X_{R_i}, Y_{R_i}, Z_{R_i}]^T \).

For the segment need casting, the joint between fixed end moulding board and the finished segment is looked as the fore joint, so a local coordinate system can be confirmed. In the local coordinate system, the origin of coordinates is the $M$ point of the fore joint, $X$ axis is defined by the two adjacent $M$ points, $Y$ axis is defined from $M$ point to $L$ point of fore joint, and $Z$ axis can be confirmed by $X$ and $Y$.

As shown in Figure 4, the rear joint of the $i$th segment is numbered 0 or $i-1$, the number of the $i$th segment fore joint is same to the segment number, there are one fore joint and one rear joint fore each segment, the fore joint of the $i$th segment is same to the rear joint of the $i-1$th segment. While a segment is located in the casting position, the fore joint is thus located on the fixed moulding board.
In the global coordinate system, the coordinate vectors of u, v and w axis in the local coordinate system of the \( i \)th joint are 
\[
\begin{align*}
\{u_i\} &= \{\delta M_{i-1}\} - \{\delta M_i\}, \\
\{v_i\} &= \{\delta L_i\} - \{\delta M_i\}, \\
\{w_i\} &= \{u_i\} \times \{v_i\},
\end{align*}
\]
respectively. The angles between \( \{u_i\} \) and X, Y, Z axes of global system are \( \alpha_{i1}, \beta_{i1}, \gamma_{i1} \), the angles between \( \{v_i\} \) and \( \hat{X}, \hat{Y}, \hat{Z} \) axes of global system are \( \alpha_{i2}, \beta_{i2}, \gamma_{i2} \), the angles between \( \{w_i\} \) and \( \hat{X}, \hat{Y}, \hat{Z} \) axes of global system are \( \alpha_{i3}, \beta_{i3}, \gamma_{i3} \), respectively. Then the direction cosines of three axes of local coordinate system are:

\[
\begin{align*}
[\cos \alpha_{i1}, \cos \beta_{i1}, \cos \gamma_{i1}]^T &= \frac{\{u_i\}}{\|u_i\|} \\
[\cos \alpha_{i2}, \cos \beta_{i2}, \cos \gamma_{i2}]^T &= \frac{\{v_i\}}{\|v_i\|} \\
[\cos \alpha_{i3}, \cos \beta_{i3}, \cos \gamma_{i3}]^T &= \frac{\{w_i\}}{\|w_i\|}
\end{align*}
\]

Then the transformation matrix from global coordinate direction to \( i \)th local coordinate is:

\[
[T_i] =
\begin{bmatrix}
[\cos \alpha_{i1} & \cos \beta_{i1} & \cos \gamma_{i1}] \\
[\cos \alpha_{i2} & \cos \beta_{i2} & \cos \gamma_{i2}] \\
[\cos \alpha_{i3} & \cos \beta_{i3} & \cos \gamma_{i3}]
\end{bmatrix}
\]

The control point coordinate of \( j \)th joint in the \( i \)th local coordinates system can be obtained as follows:

\[
\{\delta_j\}_i = [T_i]\{\delta_j\}_j + \{\Delta\}
\]

where, \( \{\delta_j\}_j \) is control point coordinate of \( j \)th joint in the global coordinates system; \( [T_i] \) is the coordinate transformation matrix of control point, is a block matrix, i.e.

\[
[T_i] =
\begin{bmatrix}
t_i & 0 & 0 & 0 \\
0 & t_i & 0 & 0 \\
0 & 0 & t_i & 0 \\
0 & 0 & 0 & t_i
\end{bmatrix}
\]
\{\Delta\} is the translation of the origin of local coordinates system relative to the origin of global coordinates system. If the origin of local coordinates system is located in the \(M\) control point of the \(j\)th joint, namely \(M_j\), then:

\[
\{\Delta\} = -\left[\delta M_j, \delta M_j, \delta M_j, \delta M_j\right]^T
\]  

(7)

When calculating the displacement of the \(i\)th segment from casting position to matching position, the \(i\)th local coordinates system is first calculated, then calculating the coordinates of the \(i-1\)th joint and \(i\)th joint in the \(i\)th and \(i+1\)th local coordinates system \(\{\delta_{i-1}\}^i, \{\delta_{i}\}^i, \{\delta_{i+1}\}^i, \{\delta_{i+1}\}^i\), the final translation amounts \([D_i]\) as obtained by:

\[
[D_i] = \begin{bmatrix}
\{\delta_{i-1}\}^i_{i+1} - \{\delta_{i-1}\}^i_i \\
\{\delta_i\}^{i+1}_{i+1} - \{\delta_i\}^i_i
\end{bmatrix}
\]

(8)

where, the local coordinates \(X, Y\) of \(M\) points and \(Z\) of \(L, R\) have control function, and the other points are redundant, but have effects of inspection. Based on the MATLAB platform, a special software of precasting geometric shape control was programmed, which has been validated by other commercial software.

4. CASE STUDY

4.1. Precasting geometric shape control

The total length of the elevate bridges on Guangzhou metro line 4 from south Shawan river to Jingzhou is around 20 km, include different span PC simply supported bridge and 6 continuous PC bridges. All the bridges were precasted by short-line method except for several turnout beams using cast-in-place method. The standard segment length is 2.5m with different end segment length for different span simply supported bridge, and 8m to 10 m length of pier top segments and 0.95 m to 2.45m closure sections length for continuous bridge.

In fact, it is difficult to set control points in joints for actual segments. Therefore, in Guangzhou metro line 4, the six control points include 4 elevation control points the vector \((L, R)\) and two central axes control point \((M)\) were placed onto the segment section with 20 cm distance to segment edges (joint) by using nails, as shown in Figure 5. Based on the measurements of six coordinates and aforementioned coordinate transformation formula and special software, the theoretical relative locations of matching segment were obtained. Due to measure errors and unavoidable location change of matching segment, the construction error of segment is inevitable, which can be amended and compensated by adjusting the next matching segment. The precise measurement is very important for precast geometric shape control of short-line match method.

4.2. Erection geometric shape control

The erection geometric shape control is performed based on the six point coordinates of precasting, and the segment erection quality is decided by segment precasted quality in a very large extent. The erection geometric shape control of simply supported bridge in Guangzhou metro line 4 is relatively easy for using bridge erecting machine and all segments erected at one time, as shown in Figure 6.
The continuous bridges were constructed using cantilever erection method (see Figure 7), and variable cross-section increase the difficult of segments precasting and erection. The test erection is important to confirm the adjustment quantity for cantilever erection. After obtaining the adjustment quantity, the relative correct steps such as changing joint epoxy resin adhesive thickness or adding new concrete joint are required. If the correct quantity is too large to ensure the six coordinates, the recalculating is necessary for cantilever erection geometric shape control.

5. CONCLUSIONS

Guangzhou metro line 4 viaduct bridges have become a beautiful urban landscape and convenient transportation system for the residents of south Guangzhou. As the first time to use short-line match method on a large scale in mainland of China, the application is successful. As long as the geometric shape control technologies were mastered and extended commendably, and ensure the segment precasting quality, the short-line match method must be developed and applied in the bridge construction in China. The design and construction experience of Guangzhou metro line 4 provide an important engineering reference for correlative bridges in the future.
ACKNOWLEDGMENTS

The work described in this paper was supported by grants from the National Science Foundation of China (Project No.50808175) and Guangzhou Metro Company (Project No. J4KC037).

REFERENCES

[1] Hiroshi. (1999). Matsumaru. Hitachi Contributes to Railway Systems for the 21st Century. Hitachi Review, 48(3): 124-125.

[2] John J. Sun, Gernot Komar (2008). Advance Segmental Precast/Prefabrication Technology and Its application in Major Bridge Engineering. Proceedings of 2008 China International High-speed Railway Bridge Technology Exchange Collection, Beijing, pp. 94-103.

[3] Pang, S. H. and Gao, W. (2006), “The linear motor vehicle in Guangzhou metro line 4”, J. Urban Rapid Rail Transit, 19(11), 77-78. (In Chinese).

[4] Xiong Anshu (2005). Design of the Pre-cast Segmental Box Beams of the 4th Guangzhou Metro Line. Traffic Engineering and Technology for National Defence, 5, pp. 19-21. (In Chinese).