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Research paper

Research on the intelligent positioning method of tunnel excavation face

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Abstract: Tunnel construction survey must be necessary to be very quick so that the results can be known as soon as possible. This aim can be achieved through the intelligent positioning method of tunnel excavation face. In this study, the plane parameters of the tunnel cross-section were transformed into the coordinates of the points on the cross-section to realize the automatic transformation of graphic data. According to the theoretical calculation of the lofting point accuracy, the appropriate measurement control network level and measurement accuracy and the appropriate measurement instruments were selected. The fast and intelligent positioning and setting out of tunnel excavation face was realized base on the technology of data communication between computer and measuring instruments. The intelligent positioning method of tunnel excavation face could greatly reduce the time of measurement and positioning, speed up the project progress, reduce the project risk, shorten the construction period and reduce the project cost.

Keywords: tunnel excavation face, intelligent positioning method, graphic data conversion

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1. Introduction

In the survey of tunnel construction, it is necessary to be very quick in order to know the results as soon as possible. The poor working conditions in the tunnel present challenges to the surveying engineers and the measuring instruments and techniques used [1]. At present, intelligent total station instruments have been widely used in the engineering constructions [2–5].The appearance of motor driven steering technology and ATR automatic target recognition technology improves the intelligent level of instruments day by day. With the rapid development of integrated circuit technology, the processing capacity of mobile processing terminals including mobile phones, laptops, tablets and even on-board computers has been greatly improved, and mobile terminal devices are becoming lighter and more convenient. The data communication and transmission technology of the text, image and language information transmitted between data source and data sink is gradually improved through the man-machine interface of electromechanical conversion, photoelectric conversion and acoustoelectric conversion into the electrical signal in the equipment. The modularization and integration technology of software programming and the software programming technology have developed rapidly [6, 7]. These technologies and equipment laid a foundation for the development of a fast and intelligent location of the tunnel excavation. The problem of measuring and positioning the handheld surface of the rotating tunnel and the problem affecting the tunneling accuracy have been solved by using the prism-free ranging of the total station and multi-function calculator programming [8]. The implementation effect of automatic monitoring system Leica measurement robot TM50 in area monitoring project was introduced [9]. It was shown that the system operated stably and the results were reliable through the re-test analysis of multiple systems. The reverse point gyroscope orientation method was adopted in the directional measurement of long distance subway tunnel, and a comparative analysis with the directional measurement results of precise conductor have been made [10, 11]. It is indicated that the gyroscope was effective in the directional measurement of long distance cross-sea tunnel of Qingdao Metro Line 1 and Xiamen Metro Line 3. The limitation of traditional measurement technology could be greatly overcome and more comprehensive information of tunnel section could be obtained by using 3D laser scanner to obtain the information of tunnel section and constructing the coordinate system of tunnel section [12, 13]. The automation of graph data conversion and the fast intelligent positioning measurement of the tunnel excavation line will be realized by converting the plane parameters of the tunnel cross-section into coordinates of the points on the cross-section in this study.

2. Intelligent positioning of tunnel excavation face line

2.1. Graphical data conversion

The purpose of graphic data conversion is to convert the design plane data of the tunnel such as the plane curve, vertical curve, section size and other plane data of the tunnel into computer graphic data.

The graphical data conversion includes the plane coordinates and elevation calculation of the pile point P_0 at a certain mileage of the tunnel.

1. The plane coordinates calculation of the pile point P_0 (x_0, y_0) [5]

The three-dimensional coordinates of the selected point $P(x_{pt}, y_{pt}, z_{pt})$ were measured by the total station on the tunnel excavation face. The three-dimensional coordinates of the point P in the local coordinate system ZH-XYZ are obtained by coordinate transformation (x_p, y_p, z_p), as shown in Fig. 1.

$$\begin{bmatrix} x_p \\ y_p \\ z_p \end{bmatrix} = \begin{bmatrix} \cos\alpha & \sin\alpha & 0 \\ -\sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} x_{pt} - x_{ZHt} \\ y_{pt} - y_{ZHt} \\ z_{pt} - z_{ZHt} \end{bmatrix} \tag{2.1}$$

where $(x_{ZHt}, y_{ZHt}, z_{ZHt})$ is the three-dimensional coordinate of the point ZH on the waist line in the unified left-handed coordinate system of the survey area, and α is the coordinate azimuth angle of the X axis forward of the unified left-handed coordinate system in the same coordinate system of the survey area.

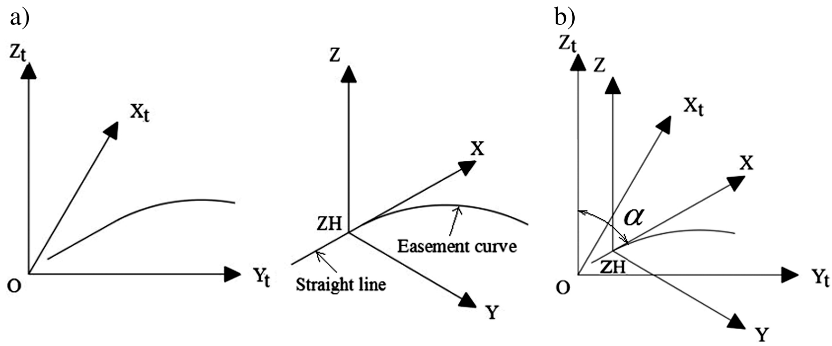

Fig. 1. Coordinate transformation: a) before transformation; b) after transformation

The point $P(x_p, y_p, z_p)$ of the local coordinates of any are known through data acquisition and coordinate transformation. It is assumed that the local coordinate of the middle point P_0 corresponding to the point P is (x_0, y_0, z_0), as shown in Fig. 2.

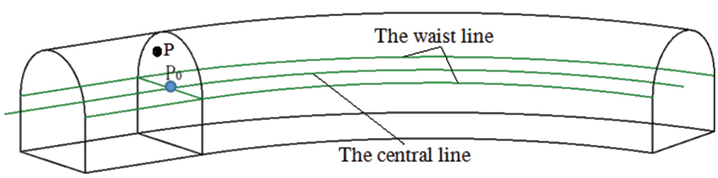

Fig. 2. Schematic diagram of the point P_0 and P

According to the coordinate calculation formula of the point P_0 in the easement curve.

$$\begin{cases} x_0 = L - \dfrac{L^5}{40R^2L_0^2} + \dfrac{L^9}{3456R^4L_0^4} \\ y_0 = \pm\left[\dfrac{L^3}{6RL_0} - \dfrac{L^7}{336R^3L_0^3} + \dfrac{L^{11}}{42240R^5L_0^5}\right] \end{cases} \tag{2.2}$$

where L_0 is the total length of the easement curve, L is the arc length from ZH to P_0, and R is the radius of the circular curve.

Let x_0', y_0', x_0'', y_0'' be the first and second derivatives of x and y with respect to L, respectively. If $x_p \neq x_0$, $y_p \neq y_0$, then $\dfrac{y_0 - y_p}{x_0 - x_p} \cdot \dfrac{dy_0}{dx_0} = -1$, we can get

$$(x_0 - x_p)x_0' + (y_0 - y_p)y_0' = 0 \tag{2.3}$$

Substituting formula (2.2) into formula (2.3), expanding it according to Taylor series, and taking the first term of polynomial, we get

$$dL = -\frac{F_0}{\Delta F_0} \tag{2.4}$$

where

$$F_0 = (x_0 - x_p)x_0' + (y_0 - y_p)y_0' \tag{2.5}$$

$$\Delta F_0 = (x_0')^2 + (y_0')^2 + (x_0 - x_p)x_0'' + (y_0 - y_p)y_0'' \tag{2.6}$$

If $x_p = x_0 \neq 0$, substituting equation (2.2) into equation (2.6), expanding it according to Taylor series, and taking the first term of polynomial, we obtain

$$F_0 = -x_p + L - \frac{L^5}{40R^2L_0^2} + \frac{L^9}{3456R^4L_0^4} \tag{2.7}$$

then

$$\Delta F_0 = 1 - \frac{L^4}{8R^2L_0^2} + \frac{L^8}{384R^4L_0^4} \tag{2.8}$$

If $y_p = y_0 \neq 0$, in a similar way, and therefore

$$F_0 = -y_p \pm \left(\frac{L^3}{6RL_0} - \frac{L^7}{336R^3L_0^3} + \frac{L^{11}}{42240R^5L_0^5}\right) \tag{2.9}$$

then

$$\Delta F_0 = \pm\left(\frac{L^2}{2RL_0} - \frac{L^6}{48R^3L_0^3} + \frac{L^{10}}{3840R^5L_0^5}\right) \tag{2.10}$$

where the right side of equations (2.5)–(2.10) are obtained by substitution of the initial value of L, which is solved through iteration. Supposing that the initial value of L is $L_{00} = 1$ m for the first iteration, the first correction number dL_1 will be known when F_0 and ΔF_0 is calculated. Then, $L_1 = L_{00} + dL_1$ is taken as the new initial value of L. Similarly, the second correction number dL_2 of L can be calculated. The iteration will end when $|dL_n|$ (n is a natural number) is less than a certain limit value, then

$$L_n = L_{00} + dL_1 + dL_2 + \cdots + dL_n \tag{2.11}$$

Finally, the plane coordinates of P_0 will be calculated.

2. The elevation Z_0 calculation of the pile point P_0

Since the coordinates of point ZH is known and the coordinates of the point P_0 have been calculated, the elevation Z_0 of point P_0 can be calculated according to coordinates of the point ZH, P_0 and HZ and the elevation of ZH and HZ waist lines.

3. Determining the contour points of the whole section

As shown in Fig. 3, VV is the waist line whose elevation is Z_0. The semicircle radius (r) above the waist line and its top elevation $Z_{\text{top}} = (Z_0 + r)$ are known. The width of the rectangle below the waist line is $2r$, and its height is equal to $Z_0 - Z_{\text{bottom}}$. Where, Z_{bottom} is the bottom elevation of the middle line of the tunnel. Line VV and P_{i1}, P_{i2} $(i = 1, 2, \ldots, 6)$ are horizontal and O is the sampling point.

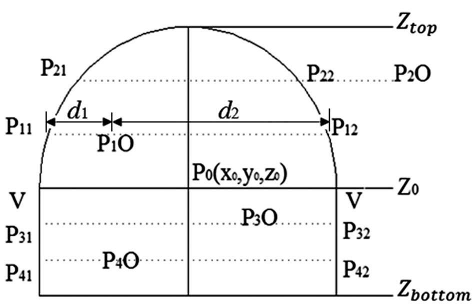

Fig. 3. Schematic diagram of tunnel cross-section

a) If $z_0 \le z_P \le z_{\text{top}}$

Assuming $d_1 = \sqrt{(x_0 - x_p)^2 + (y_0 - y_p)^2}$, $d_2 = \sqrt{r^2 - (z_0 - z_p)^2}$;

When $d_1 = d_2$, the points are on the sideline as shown in Fig. 3;

When $d_1 < d_2$, the contour points P_{11} and P_{12} are obtained by measuring $d_2 \pm d_1$ horizontally from the point p_1 to the opposite direction in the section as shown in Fig. 3;

When $d_1 > d_2$, the contour points P_{21} and P_{22} are obtained by measuring $d_1 \pm d_2$ horizontally from the point p_2 to the same direction in the section as shown in Fig. 3.

b) If $z_{\text{bottom}} \leq z_P \leq z_0$
Assuming $d_1 = \sqrt{(x_0 - x_p)^2 + (y_0 - y_p)^2}$, $d_2 = r$;
When $d_1 = d_2$, the points are on the sideline as shown in Fig. 3;
When $d_1 < d_2$, the contour points P_{31} and P_{32} are obtained by measuring $d_2 \pm d_1$ horizontally from the point p_3 to the opposite direction in the section as shown in Fig. 3;
When $d_1 > d_2$, the contour points P_{41} and P_{42} are obtained by measuring $d_1 \pm d_2$ horizontally from the point p_4 to the same direction in the section as shown in Fig. 3.

c) If the point P satisfies $z_p > z_{\text{top}}$ or $z_p < z_{\text{bottom}}$, the point shall be discarded and the data shall be collected again.

Repeating the steps above, the contour line of the tunnel edge line will be determined when the density of the edge points meets the requirements.

2.2. Data communication

It is very important that using remote communication to control electronic total station, improve the work of field survey efficiently, reduce labor intensity and ensure the quality of field data collection to realize the automation of loaning-out survey. The mobile intelligent device should be a convenient device with large amount of data storage, stable system, convenient secondary development and high degree of visualization. At the same time, the device could be suitable for modern construction site measurement.

As shown in Fig. 4, the use of serial port communication to control and operate total station is conducive to the realization of real-time data transmission between total station and the outside world, which is beneficial to the broadening of the usage function of total station. The system can transmit the original field observation information from the total station to the mobile intelligent device or other hardware device in real time. The mobile

Fig. 4. The serial port of total station

intelligent equipment receives these data and combines with the intelligent positioning measurement system of tunnel excavation face line, then the palm face intelligent positioning measurement will be realized.

2.3. Secondary development of software

The general ideas of software secondary development are as follows: (1) The 3D coordinate (X, Y, Z) of a certain point A on the tunnel excavation face is measured by using the total station with prism ranging function free; (2) According to the plane curve elements, the point $A(X, Y)$ will be used to calculate the shortest distance D from this point to the central line and the corresponding mileage K of the pile point; (3) The design elevation of the point A is calculated according to the mileage K; (4) The horizontal and vertical deviation components d_x and d_y on the corresponding arc segment between the point A and the design point are calculated according to the design section of the mileage K and the elevation of point A and the distance D measured; (5) The position of the point A is measured according to the values of the deviation components d_x and d_y. The coordinate values of the point A should be re-measured to check whether it is consistent with the design coordinates. The method of point by point approach should be applied to the whole calculation process. When $\Delta D = \sqrt{d_x^2 + d_y^2}$ meets the requirements of computational accuracy, it ends.

2.4. Operation process

At first, a total station is set up near the tunnel excavation face to connect the mobile device data processing terminal, set up communication parameters and carry out station construction. When the station construction accuracy meets the requirements of setting out, the software of the intelligent positioning measurement system for tunnel excavation face will be opened, and new engineering documents will be created. The survey and setting out process will be started when the horizontal and vertical curve elements and tunnel section parameters input in advance are correct. The software can intelligently judge and round the section mileage where the tunnel excavation face is located, automatically call up the design section parameters of the mileage section, and present it to the operator in the form of man-machine dialogue. Once the information is confirmed, the distance between the points to be lofted can be set to carry out surveying and setting out. The software will drive the total station laser to point automatically to the position of the target points. Once the technicians make the mark, it will automatically jumps to the next point positioning, so as to complete the survey and the positioning process of the tunnel excavation face. The process of intelligent positioning and surveying system for excavation boundary of tunnel excavation face is shown in Fig. 5.

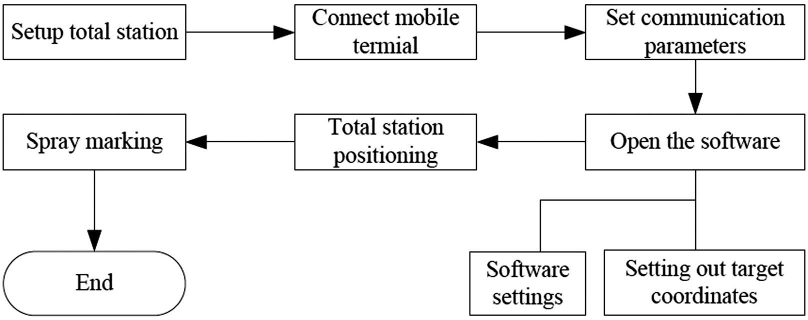

Fig. 5. Process of intelligent positioning system for tunnel excavation face

3. Application examples

The Changmao Mount Tunnel which is a double-line tunnel is located in Yinjiaxi Township, Yongding District, Zhangjiajie City. The starting and ending mileages of the tunnel are DK188+820 and DK193+504 with a total length of 4684 m. The maximum and minimum burial depth of the tunnel body are 240 m and 27 m respectively. The tunnel entrance from DK188+820 to DK189+568.378 is on the curve of R = 5500 and the tunnel exit from DK192+681.681 to DK193+504 is on the curve of R = 6000. The rest part of the tunnel body is on the straight line. The longitudinal slopes of the tunnel are 3.5‰/1780, –8.5‰/2280 and –17.4‰/24.

There are many tunnel lining types in Chang Mao Mount Tunnel. Due to the widening of line spacing in the curve and the heightening and widening of the catenary anchor, there are various cross-section sizes. The tunnel mileages and cross-section sizes are shown in Table 1.

Table 1. Line spacing and the size of the structure to be widened in the tunnel

The mileage of the tunnel		Line spacing (m)		The size widened w (cm)
Starting	Ending	Starting	Ending	
DK188+552	DK192+684	4.4	4.4	0
DK192+684	DK192+888	4.4	4.5	10
DK192+888	DK193+504	4.5	4.524	20

It can be seen from table 1 that there are three types of the tunnel cross-section sizes at the different mileages. The specific cross-section sizes are shown in Figs. 6–8.

The intelligent positioning system for tunnel excavation face has been successfully applied in the project of Changmao Mount Tunnel. The time of the traditional lofting method and the intelligent positioning method for face excavation are shown in Tables 2–4.

It can be seen from the statistical tables above that the intelligent positioning method for tunnel excavation face can greatly reduce the measurement and positioning time, accelerate the project progress, reduce the project risk, and shorten the project duration.

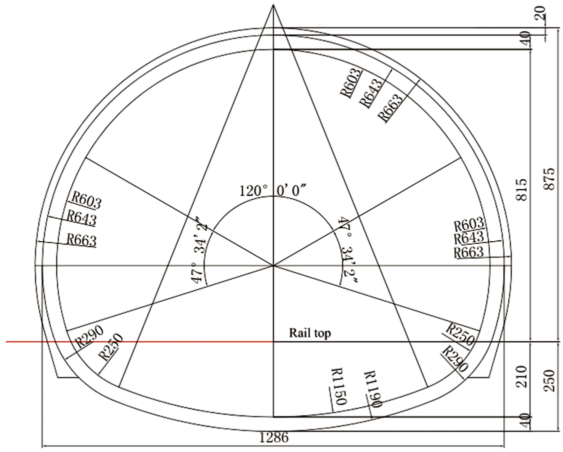

Fig. 6. The tunnel cross-section of the IIIy-2 surrounding rock (w = 0)

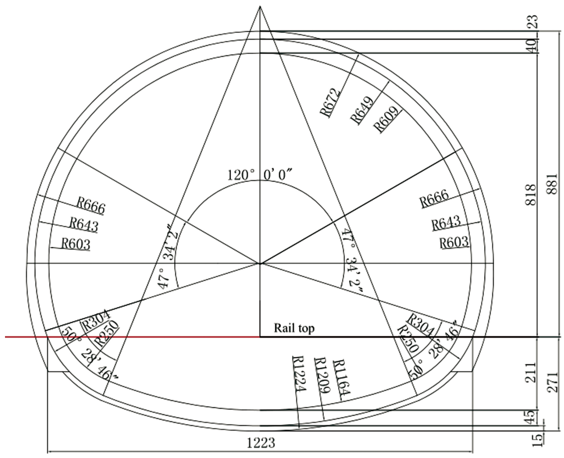

Fig. 7. The tunnel cross-section of the IVy-2 surrounding rock (w = 10)

Table 2. The time of the traditional lofting method and the intelligent positioning method for palm face excavation of grade III surrounding rock tunnel

The operation procedure	Number	Total time of the traditional lofting method (h)	Total time of the intelligent positioning method (h)	Total time saved (h)
Erection of total station	1 station	0.17	0.17	0.00
Calculating coordinates	55 targets	0.92	0.00	0.92
Positioning	55 targets	0.92	0.46	0.46
Marking	55 targets	0.92	0.46	0.46
Total time		2.93	1.09	1.84

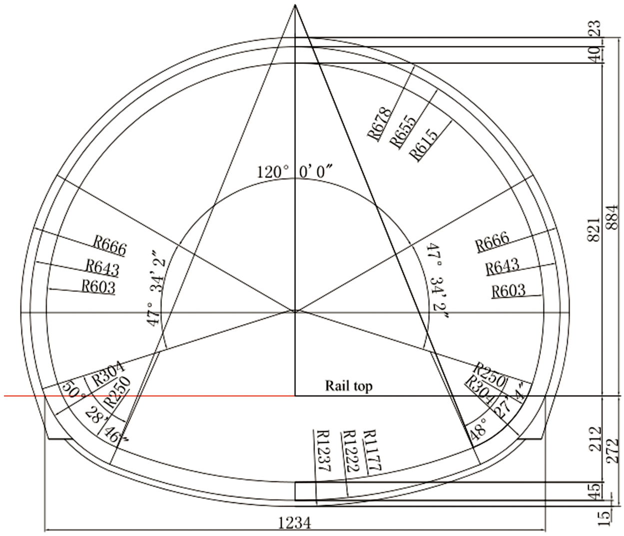

Fig. 8. The tunnel cross-section of the IVy-2 surrounding rock (w = 20)

Table 3. The time of traditional lofting method and intelligent positioning method for palm face excavation of grade IV surrounding rock tunnel

The operation procedure	Number	Total time of the traditional lofting method (h)	Total time of the intelligent positioning method (h)	Total time saved (h)
Erection of total station	1 station	0.17	0.17	0.00
Calculating coordinates	57 targets	0.95	0.00	0.95
Positioning	57 targets	0.95	0.48	0.47
Marking	57 targets	0.95	0.48	0.47
Total time		3.02	1.13	1.89

Table 4. The time of traditional lofting method and intelligent positioning method for palm face excavation of grade V surrounding rock tunnel

The operation procedure	Number	Total time of the traditional lofting method (h)	Total time of the intelligent positioning method (h)	Total time saved (h)
Erection of total station	1 station	0.17	0.17	0.00
Calculating coordinates	65 targets	1.08	0.00	1.08
Positioning	65 targets	1.08	0.54	0.54
Marking	65 targets	1.08	0.54	0.54
Total time		3.41	1.25	2.16

4. Conclusion

The plane parameters of the tunnel cross-section were transformed into the coordinates of the points on the cross-section to realize the automatic transformation of graphic data. The rapid intelligent positioning process of tunnel excavation face was realized based on the intelligent positioning method. At the same time, the amount of the field surveyors was reduced, the total construction time was shortened. The research results have been successfully applied in the construction project of Changmao Mount Tunnel.

Through data optimization and software secondary development, the plane parameters of tunnel section can be converted into the coordinates of a certain point on the cross-section to realize the automation of graphic data conversion. The efficiency of the method was more than twice as high as that of the traditional lofting method. The accuracy of positioning and setting out was greatly improved, and the reliability reached 100%.

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