3D deformation monitoring of subway tunnel

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ABSTRACT: As a kind of modern vehicle, subway has shown us the advantages of safety, speediness, low power consumption, low pollution etc. It has been the main part of the urban high-capacity public traffic system. More and more subway lines appear in order to meet the need of the society. The civil engineering construction especially in Soft Ground must lead to the deformation of the adjacent subway tunnel, and it causes the severe influences to the stabilization and safety of the tunnel. This paper puts forward a kind of three-dimension deformation monitoring method. It can precisely monitor the deformation of the tunnel liner real-time which do not interrupt the subway transport, and expediently provide mechanics analysis on the deformation of tunnel construction. The paper discusses how to build the 3D mathematical model for the subway tunnel by the ground lidar surveying technology. Use the Georobot to survey the deformation of the tunnel cross section and the rail automatically. According to data processing and analysis using a model interpolation method, the 3D digital model of the deformation and displacement for the whole metro is fitted finally. Thus we can obtain the 3D image of the subway deformation in a precision, real-time, stereo and visual way.

1 INTRODUCTION

In order to alleviate the pressure of the ground transportation, urban subway has been programmed or built in big cities. As a kind of modern transportation facilities, subway has shown us the advantages of safety, speediness, low power consumption, low pollution etc. It has been the main part of the Beijing’s high-capacity public traffic system. Along with the development of city in Beijing, more and more civil engineering construction must lead to the deformation of the adjacent subway tunnel. It causes the severe influences to the stabilization and safety of the tunnel, thus endanger the whole urban transportation system. During the construction of periphery foundation ditch engineering and tunnel engineering, how to guarantee the safety of the subway tunnel has been the severe difficulty needed to be solved.

The traditional monitoring method is to set monitoring cross sections on the deformation district of tunnel. By surveying these monitoring points with convergence rule, total station and leveling, we can monitor the deformation of the tunnel structure. Some drawbacks exist here. First, the number of the monitoring points is limited, which can not reflect the deformation tendency. Load analysis of the deformation of tunnel structure is constricted and the corresponding reinforce measure is difficult to carry out. Second, the traditional one has not used the remote monitor method, so it disturbs the transportation of the subway to some extent. Third, the dim light, narrow space and the complicate environment do disturb the safety monitoring.

A method of three-dimension safety deformation monitoring for urban subway is put forward here. It can obtain the 3D digital data of the subway tunnel deformation, which do not interrupt the subway transportation. It can not only precisely monitor the deformation of the tunnel structure and get the tendency of subway deformation, but also provide mechanics analysis on tunnel structure and the rail. This method has been applied to the safety monitoring of the Beijing subway line 1 (Babaoshan Station – Bajiao amusement park Station).

2 THREE-DIMENSION SAFETY MONITORING METHOD

2.1 Model building

Lidar technology is also called three-dimension laser scanning technology, which is a new kind of non-touch surveying method. It can obtain the array geometric
image of survey object from laser point clouds, which were emitted by scan prism and the quick laser ambulator. So the three-dimension space model can be made. This technology can obtain the three-dimension coordinates of one point without reflecting prism, and the speed can reach 100,000 points/second. This technology is well suited for many applications: industrial, architectural, civil surveying, urban topography, reverse engineering, archaeology.

The detailed monitoring project is introduced here:

1. Within the deformation district, set the annular closed survey control network along the middle line of the up-down rail.
2. Put a set of cross section every 3 m following the middle line of tunnel. Set the reflection target on the arch, vertical wall, subgrade of the rail (As Fig. 1 shows), and collect the point clouds information by three-dimension lidar scanner.
3. Based on the NURBS Curved face function (refer with: Eq. 1), the three-dimension model of tunnel is established by the data process such as data joint and registering.

Let the order of polynomial is $p \times q$, NURBS Curved face function can be written as:

$$S(u,v) = \frac{\sum_{i=0}^{m} \sum_{j=0}^{n} w_{i,j} d_{i,j} N_{i,p}(u) N_{j,q}(v)}{\sum_{i=0}^{m} \sum_{j=0}^{n} w_{i,j} N_{i,p}(u) N_{j,q}(v)}$$

where $d_{i,j}$ $(i = 0,1,\cdots,m$ $j = 0,1,\cdots,n)$ represent the control vertex, and $w_{i,j}$ denotes the weight factor of vertex, and $N_{i,p}(u), N_{j,q}(v)$ is gage B spline primary function.

2.2 Real-time safety monitoring system

The 24 hour safety monitoring is necessary to guarantee the safety of both the tunnel structure and transportation of the subway. Considering the high density of the subway’s transportation, we adopt the remote automatic monitor system to real-time monitor the tunnel structure, vertical wall, and subgrade of the rail by the Georobot.

2.2.1 Measurement principle of Georobot

Georobot is often called automatic electronic total station (ETS). It is a kind of intelligent electronic total station, which is able to search target automatically, recognize, trace, collimate precisely and obtain the 3D coordinates.

Target points observation of tunnel deformation adopts free stationing principle of Georobot. Reflection sheets are set on the target points. To achieve higher resolution and improve reliability of observation data, Georobot can finish redundant observation automatically under the control of on-board software. Then adjustment of observation data of different periods, 3D coordinates values in different periods will be done by post-software of computer, finally we can get 3D coordinate displacement of target points: $(\Delta X, \Delta Y, \Delta Z)$. For observation networks of free stationing, we choose indirect adjustment model to process data. Let $t$ be necessary observation number and $n$ be total observation number ($n > t$). Then adjustment model is:

$$B^T P B \hat{x} + B^T P l = 0.$$  \hspace{1cm} (2)

taking $N = B^T P B, U = B^T P l$, we get $N \hat{x} + U = 0$, so that $\Delta \hat{x} = N^{-1} U$.

The corresponding error equation by the matrix is:

$$V = B \deltax + l,$$  \hspace{1cm} (3)

where $V = [v_1, v_2, \ldots, v_n]^T, \deltax = [x_1, x_2, \ldots, x_n]^T$,

$$l = [l_1, l_2, \ldots, l_n]^T = d - L.$$  \hspace{1cm} (4)

The above-mentioned method is that gets displacement by comparing coordinates of observation points. In the course of subway tunnel deformation analysis, we also consider lateral vector after observation value adjustment of different periods:

$$d^{(k)}_y = [(x_i - x_j)^2 + (y_i - y_j)^2 + (z_i - z_j)^2]^{1/2}.$$  \hspace{1cm} (5)

$$\Delta d^{(k)}_y - \Delta d^{(k-1)}_y = \Delta_{k-1,k}.$$  \hspace{1cm} (6)

where, $x_i, y_i, z_i$ are adjustment value. $k$ is observation times of tunnel deformation, $\Delta_{k-1,k}$ is the convergence of measurement lines, they do not include error from possible displacement of base points, so they can accurately reflect tunnel deformation. By regressive analysis of these adjustment deformation values of different periods, we can conclude forecasting results of tunnel structure deformation.

2.2.2 The setting of Georobot

The specially made instrument pier is put outside the right of the first rail. Georobot is forced to be fixed
on the instrument pier through the pedestal and is protected with the glass cover. 6–16 reflecting sheets are installed for each monitoring station, which is distributed in the arch, vertical wall, orbit drainage ditch, rail fastener and so on. With the monitor program, Georobot collects the coordinates automatically and transports the data to the control server via data wire.

3 ENGINEERING APPLICATIONS

The thermal pipeline engineering of Babaoshan south road crosses over the structure of Beijing subway line 1 (Babaoshan Station – Bajiao amusement park Station). Engineering construction causes the subway tunnel deformation. The kilometer post of the tunnel deformation district is from K3+770 to K3+810.

The safety monitoring result is shown as follows: the accumulative deformation value of the max deformation point on the tunnel structure is +1.90 mm; the max accumulative value of the rail deformation is +1.86 mm; the max differential settlement of the rail subgrade is −0.29 mm. So such conclusion can be made that the accumulative displacements of both tunnel structure and rail caused by the engineering construction are less than 2 mm, which is within the allowed deformation range and put no influences on the subway transportation.

4 CONCLUSIONS

This method of three-dimension safety monitoring has the advantages of high automation and three-dimensional measurement. It can be applied to the safety monitoring of high-rise building, side slope, deep foundation ditch engineering and so on. Of course this method is not so mature. Its theory needs to be further researched through engineering experience.

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