Research on On-Site Monitoring and Measurement Technology of Tunnel

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Abstract. The frequent occurrence of tunnel safety accidents threatens the safety of people’s lives and property, and the research on the on-site monitoring and measurement technology of tunnels is very necessary. Practical applications of tunnel on-site monitoring and measurement technology include electronic total station and micro-deformation monitoring radar. Among them, radar interferometry technology is used for deformation monitoring in on-site monitoring and measurement, such as vault settlement. The built millimeter wave radar deformation measuring instrument can complete the vault settlement monitoring of the tunnel on-site monitoring. During the tunnel construction period, it is necessary to make a selection according to the specific engineering objectives, adopt appropriate observation and test methods, obtain new deformation displacement information, and analyze and predict the deformation of the construction.

Keywords. On-site monitoring and measurement, deformation and displacement monitoring, micro-deformation monitoring radar.

1. Introduction

In recent years, many tunnel safety accidents have occurred, resulting in many casualties and great economic losses. Each accident occurred in the tunnel has some auratic reactions, such as excessive settlement rate, non-convergence of surrounding rock, abnormal sound of steel arch, initial branch and surface crack and other deformations. During the concrete construction process, the deformation displacement monitoring is generally used as the basis for construction monitoring. Therefore, the displacement amount and the displacement rate or the displacement-related quantity are used to judge the stability of the surrounding rock and the supporting structure.

At present, the main method of data collection at home and abroad is to organize a measurement team at the construction site, and use some monitoring instruments to track and measure the deformation of the tunnel, that is, on-site monitoring and measurement. The main items of on-site monitoring and measurement include deformation data such as vault settlement, convergence deformation, and surface settlement. On-site monitoring and measurement has been widely used in the construction of roads, railways, hydropower stations, subsea tunnels, etc. In the aspect of deformation monitoring technology for on-site monitoring and measurement, the literature [1] introduced an automatic monitoring system for tunnel deformation composed of an electronic level, but the system can only perform one-dimensional automatic measurement for tunnel deformation [2]. Yang Songlin combined with high-precision three-dimensional measurement method and appropriate data processing technology, proposed the theory and method [3] of dual station and free station of the...
total station for three-dimensional coordinate non-contact measurement, single-station independent coordinate line, and dual-station independent coordinate line. Xiong Fei studied the measurement method of tunnel vault settlement based on total station [4]. However, due to the influence of light and dust environment in the tunnel, the total station is unstable in measurement accuracy, which is easy to cause wrong measurement and misjudgement, which poses potential risks to tunnel construction safety. Therefore, there is an urgent need for new deformation measurement techniques and instruments that are immune to the effects of light and dust.

The radar can realize the target detection and parameter measurement by transmitting electromagnetic waves, and can work around the clock, and use differential interferometry technology to obtain high-precision deformation information of the observation points. A large number of academic reports have been published abroad to prove the feasibility of using this technology to monitor the health of bridges, windmills and high buildings [5-9]. Therefore, how to apply radar interferometry technology to the field monitoring and measurement of tunnels have become a hot and a difficult problem.

2. Monitoring Method of Tunnel Structure Deformation

2.1. Total Station

The total station is based on optical technology to realize the deformation monitoring of the observation points, which has the following advantages: (1) High degree of automation and easy operation. The error caused by manual operation is greatly reduced; (2) The system has high precision, and the retesting and re-checking on the left and right sides can meet the measurement requirements; (3) Non-contact measurement has obvious advantages in the measurement of large-span tunnels. (4) The software is easy to operate and can provide timely feedback.

The total station triangulation method is used to measure the settlement, as is shown in figure 1. The measurement point is located on the center line of the vault, at which point the reflective sticker is fixed. The reference point is located on the tunnel floor and is measured using the total station prism mode. The total station can be placed freely at any position on the tunnel floor, and the slant range, vertical angle and horizontal angle are measured, and then the horizontal distance, height difference and slant distance of the measuring point are calculated.

2.2. Quasi-distributed Optical Fiber Sensing Technology

At present, fiber grating sensing technology is widely used in the field of engineering structure monitoring, so tunnels are also one of its application fields. In addition to its own advantages of fiber optics, such as anti-electromagnetic interference and corrosion resistance, it can connect fiber gratings
with different center wavelengths in series to realize quasi-distributed monitoring of structures, thus further realizing measurements of multiple measurement points.

Generally, when light passes through the fiber grating, only the light satisfies the equation (1) and the center wavelength $\lambda_B$ is reflected at the grating do the rest of the light pass. When the grating is stretched, extruded, and deformed by heat, the center wavelength of light drifts.

Taking the strain monitoring of the tunnel vault settlement as an example, the rock mass structure exerts a load to the fiber grating, which makes the grating pitch $\Lambda$ change, and further makes central wavelength $\lambda_B$ drift. The strain change of the structure is obtained by measuring the offset of the center wavelength.

$$\lambda_B = 2n_{eff}\Lambda$$  \hspace{1cm} (1)

$n_{eff}$ is the effective refractive index of the fiber grating.

2.3. Micro-deformation Monitoring Radar

Through the targeted application of radar deformation monitoring technology, the online monitoring characterized by high-precision automation of surrounding rock and surface deformation of the tunnel is realized, and the real-time online displacement deformation data is used as the basis for on-site structural stability analysis in emergency.

The micro-deformation monitoring radar realizes on-line convergence monitoring and relative settlement monitoring of the vault through interferometric measurement technology. The micro-deformation monitoring radar uses the phase difference between the two echoes to estimate the small deformation of the target, and the theoretical precision can reach 0.01 mm, its principle is shown in figure 2. The radar acquires the displacement change $d$ of the target by interferometry, which can be expressed as equation (2).

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\begin{align*}
    d &= \frac{\lambda}{4\pi}(\varphi_2 - \varphi_1) \\
    \varphi_1 &\text{ is the first target measurement phase; } \varphi_2 \text{ is the second measurement phase; } d \text{ is the amount of displacement of the target on the radar line of sight between measurements.}
\end{align*}
\]

Among them, $\lambda$ is the radar operating wavelength; $\varphi_1$ is the first target measurement phase; $\varphi_2$ is the second measurement phase; $d$ is the amount of displacement of the target on the radar line of sight between measurements.

The micro-deformation monitoring radar system is quick and convenient to install and free from harsh environmental interference. It has high precision test data, wireless transmission, real-time data interconnection, and provides decision information for on-site rescue support in emergency.
3. Test and Verification
On-site monitoring and measurement of tunnel are based on radar, the loading weights are 10 Kg, 20 Kg, 30 Kg, 40 Kg and 50 Kg respectively, and the radar installation position is the vertical height of 2.754 m. The weight loading positions are shown in table 1.

Table 1. Readings after each load weight is stable.

| Loading weight | Loading position | Readings of millimeter wave radar after stable loading | Readings of millimeter wave radar after stable loading |
|----------------|------------------|------------------------------------------------------|------------------------------------------------------|
| 10 Kg          |                  |                                                      |                                                      |
| 20 Kg          |                  |                                                      |                                                      |
| 30 Kg          |                  |                                                      |                                                      |
| 40 Kg          |                  |                                                      |                                                      |
| 50 Kg          |                  |                                                      |                                                      |

The each weight group was measured five times using millimeter wave radar and dial indicator. Each measurement was subjected to loading and unloading successively. One of the loading weights of each group was taken as an explanation. Table 1 shows the readings after 10 Kg was loaded stably for the second time row by row, readings after 20 Kg was loaded stably for the fifth time, readings after 30 Kg was loaded stably for the forth time, readings after 40 Kg was loaded stably for the forth time, readings after 50 Kg was loaded stably for the first time.

After the millimeter-wave radar of each group is stabilized, due to the measurement results of the millimeter radar wave and the measurement results of the dial gauge are the same, only the 10 Kg loading condition is expressed. Under the symmetrical 10 Kg loading condition, five times of repeated measurement of “loading→unloading” is performed. After the loading is stabilized, the measurement results of the millimeter radar wave and the measurement results of the dial gauge are respectively shown in tables 2 and 3.
Table 2. Measurement result of millimeter wave radar.

| Times of measurement | Measurement results (mm) | After loading is stable | After unloading is stable |
|----------------------|--------------------------|-------------------------|--------------------------|
| Initial reading      |                          | 0                       |                          |
|                      | Measurements (mm)        | Readings (mm)           | Variation (mm)           | Readings (mm) | Variation (mm) |
| The 1st time         | -0.510                   | 0.010                   | 0.010                    |
| The 2nd time         | -0.510                   | 0.000                   | 0.000                    |
| The 3rd time         | -0.520                   | 0.010                   | 0.010                    |
| The 4th time         | -0.520                   | 0.000                   | 0.000                    |
| The 5th time         | -0.520                   | 0.000                   | 0.000                    |
| Average value        | -0.516                   | 0.004                   | 0.004                    |
| Variation variance   |                          | 2.4 × 10^{-5}           | 2.4 × 10^{-5}            |

Table 3. Measurement results of dial indicator.

| Times of measurement | Measurement results (mm) | After loading is stable | After unloading is stable |
|----------------------|--------------------------|-------------------------|--------------------------|
| Initial reading      |                          | 4.924                   |                          |
|                      | Measurements (mm)        | Readings (mm)           | Variation (mm)           | Readings (mm) | Variation (mm) |
| The 1st time         | 4.500                    | 5.004                   | 0.013                    |
| The 2nd time         | 4.495                    | 4.995                   | 0.004                    |
| The 3rd time         | 4.479                    | 4.998                   | 0.007                    |
| The 4th time         | 4.479                    | 4.998                   | 0.007                    |
| The 5th time         | 4.493                    | 4.982                   | -0.009                   |
| Average value        | 4.4892                   | 4.9954                  | 0.044                    |
| Variation variance   |                          | 7.5 × 10^{-5}           | 5.3 × 10^{-5}            |

After the load is stable, the millimeter wave radar measures the average value $V_{\text{Radar}}=0.516$ mm; the average measurement value of dial indicator $V_{\text{Dial indicator}}=0.5018$ mm; $V_{\text{Radar}} - V_{\text{Dial indicator}}=0.0142$ mm; The deviation ratio of the radar measurement value to the average value of the dial gauge is 2.83%. The variance of the millimeter wave radar measurement variation $\sigma^2=2.4 \times 10^{-5}$; the variance of the dial indicator measurement variation $\sigma^2=7.5 \times 10^{-5}$. It is indicated that the data of the five sets of repeated measurements are in good agreement, and the consistency of the millimeter wave radar measurement results is better than that of the dial indicator.

After the unloading is stabilized, the average measurement value of millimeter wave radar $V_{\text{Radar}}=0.004$ mm; the average measurement value of dial indicator $V_{\text{Dial indicator}}=0.0044$ mm. After
the unloading is stable, the initial deviance readings of the two measured values vary little, and the mean deviation value between the two is $V_{\text{Radar}} - V_{\text{Dial}}$ indicator$=0.0004$ mm; after unloading, it can return to the initial reading very well. The variance of the millimeter wave radar measurement variation $\sigma^2=2.4 \times 10^{-5}$; the variance of the change value of the dial indicator measurement value $\sigma^2=5.3 \times 10^{-5}$. It is indicated that the data of the five sets of repeated measurements are in good agreement, and the consistency of the millimeter wave radar measurement results is better than that of the dial indicator.

By analyzing the measurement results of the millimeter radar wave and the measurement results of the dial indicator after the weight-loaded millimeter wave radar of each group are stabilized, the average measurement value of five groups $V_{\text{Radar}} - V_{\text{Dial}}$ indicator $=0.0142$ mm, the deviation of measurement reading is less than or equal to 0.02 mm under the symmetrical 10 kg loading condition. Under the symmetrical 20 kg loading condition, the average measurement value of five groups $V_{\text{Radar}} - V_{\text{Dial}}$ indicator $=0.015$ mm, the deviation of measurement reading is less than or equal to 0.02 mm. Under the symmetrical 30 kg loading condition, the average measurement value of five group $V_{\text{Radar}} - V_{\text{Dial}}$ indicator $=0.0032$ mm, the deviation of measurement reading is less than or equal to 0.01 mm. Under the symmetrical 40 kg loading condition, the average measurement value of five groups $V_{\text{Radar}} - V_{\text{Dial}}$ indicator $=0.0022$ mm, the deviation of measurement reading is less than or equal to 0.01 mm. Under the symmetrical 50 kg loading condition, the average measurement value of five groups $V_{\text{Radar}} - V_{\text{Dial}}$ indicator $=0.027$ mm, the deviation of measurement reading is less than or equal to 0.03 mm.

The measurement results of each group indicate that the variation variance of millimeter wave radar measurement is smaller and the data consistency is better. The test is mainly from the monitoring values of dial indicators and radars under several different weights. The average value indicates that the accuracy and traditional tools meet the requirements in a same magnitude, and the variances indicate that the divergence meets the requirements.

4. Conclusion

In summary, the on-site monitoring and measurement of tunnels is mostly implemented by the total station in China, but the total station is limited by the lighting conditions and dust environment in the tunnel, and the measurement accuracy is greatly reduced. In view of the fact that the radar adopts differential interference technology, it can also obtain the deformation information of the observation points, and the radar can work all day and around the clock, the accuracy is not affected by the illumination conditions, and the theoretical precision can reach 0.01 mm, which is much higher than the existing total station system. The test results verify that the millimeter wave radar measurement variance is smaller and the data consistency is better. Therefore, during the tunnel construction period, a series of high-efficiency and high-precision observation and test methods are needed to obtain new deformation displacement information and feedback it to the design and construction in order to modify the construction parameters, adjust the construction measures as well as analyze and predict construction deformation.

Acknowledgments

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