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Analysis of tunnel displacement accuracy with total station

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ABSTRACT

The remote distance measurement (RDM) method requires only common total stations and not special post-processing software. Moreover, this method is easy to operate and highly accurate results can be obtained. Therefore, RDM is used in the displacement monitoring of tunnel engineering. This study presents the calculation formulas for the crown settlement and wall convergence of tunnel as measured by RDM with total station. The mean error formulas are derived based on error propagation laws. When tunnel displacements measured by using total station with the m_s not more than 2 mm + 2*D* ppm (*D* is the measurement distance) and m_α not more than 1″, the horizontal distance between the rear viewpoint and the monitoring section is in the range of 50–150 m, the horizontal distance between the total station and the monitoring section ranges from 40 m to 60 m, and the total station is near the tunnel centerline, the measurement accuracy can reach 1 mm.

1. Introduction

Displacement monitoring is an important part of the tunnel construction process [1], and has been used extensively in tunnel engineering. This monitoring process provides data that can be used to determine whether or not a tunnel is structurally stable [2]. In addition, the provided data can help ensure that the tunnel support system is adequately controlled, i.e., an adequate margin of safety is established against collapse, excavation face failure, support system failure, and bottom heave. Tunnel displacement monitoring trends are vital to confirming the geotechnical design of a supporting section to adjust to the unforeseen geological conditions in front of the excavation face. Thereby, significant deviations from estimated completion costs and dates can be prevented [3].

Tunnel displacement monitoring includes wall convergence (horizontal displacement) and crown settlement (vertical displacement). Many measuring technologies have been developed for these processes, including but not limited to: tape extensometers, total station survey (or other geodetic methods), photogrammetric devices, and laser profilers (laser scanners) [4,5]. Tape extensometers are traditional monitoring technologies, including invar tapes, wires [6], tape distometers [7], and convergence tapes [8–10]. These technologies have an accuracy of approximately ±0.2 mm over 10–15 m [8,11]. Simeoni and Zanei [7] estimated the accuracy of convergence measurements, under line length changes of at least 0.08 mm, usually approaches 0.25 mm when tape distometers were employed. Tape extensometers are the most accurate of all common measuring technologies, and they are easy to use and maintain. However, these tools can measure only

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the displacement along a specific line, and they obstruct the construction process during tape pulling and being read. Furthermore, these tools require much labor and time in the measurement-process.

A total station survey is a non-contact monitoring method that is easy and quick to implement. In accordance with the regulations of technical code for monitoring of railway tunnels (TB10121-2007, China) [12], the measurement of tunnel displacements can be performed using the non-contact measurement of total station. A diaphragm reflector was selected as the measuring point target, which was attached to the parts embedded in the supporting structure. The accuracy of the measurement could reach 0.5–1 mm [12]. In 1995, Song [13] analyzed the non-contact, 3D-displacement measuring method with free stationing, and determined that its accuracy could reach 10^{-2}–10^{-1} mm level, especially in tunnel cross-section observation. In 2004, Yang et al. [14] proposed a 3D-coordinate, non-contact measurement technique based on two free stations with automatic total station. They also built the corresponding mathematical adjustment model. Moreover, the average absolute error of each 3D-coordinate measuring point could reach 0.8 mm. In 2012, Yuan et al. [15] analyzed non-contact measurement based on 3D free stationing with total station, and noted that the accuracy of measurement by this method could adequately meet the requirements of the code [12] in crown settlement and wall convergence. In addition, only once measurement, both crown settlement and wall convergence could be performed. However, the 3D-measurement requires some special total stations that are usually expensive, along with matched onboard software and post-processing software. Therefore, the cost of the monitoring method is high, and limits its use in tunnel construction. By comparison, the RDM requires only common total station, and no special post-processing software. This method is easy to operate [16,17]. Moreover, the stationing of this measurement method is flexible, and it is easy to obtain the results that are easily visualized [14]. In 2011, Luo and Chen obtained the deformation of the middle wall of a shallow soil tunnel by RDM with total station [18,19]. Then, the deformation law of the middle wall was revealed through the analysis of the measurement results.

At present, however, no final conclusion has been drawn regarding to the accuracy of RDM application in tunnel displacement monitoring. In addition, few studies have been carried out on improving the accuracy of tunnel displacement monitoring. Therefore, the accuracy of RDM using a total station in tunnel was analyzed, in this paper. A systematic research was also conducted on the accuracy which was affected by the location of measurement points and total station in tunnel displacement monitoring, according to the RDM principle.

2. RDM principle of tunnel displacement monitoring with total station

RDM is a measurement method of total station that can indirectly determine the distance and height difference between two points. This method is usually applied to measure two points that are not observed directly, because of existing obstacles, or in certain occasions in which the measuring instrument is difficult to set up or cannot be set up at all between these points.

The principle of RDM in monitoring tunnel displacements with a total station is that the total station can be set up at random in a tunnel to serve as the observation station for measuring slant range, as well as vertical and horizontal angles. Then, the horizontal distance, height difference, and slope distance between any two points can be obtained, based on the measuring principle of trigonometric leveling and the triangle cosine theorem. Fig. 1 shows a sketch of RDM with total station by which the tunnel displacement is monitored. The convergence displacement between any two measuring points can be determined by the trigonometry relation between the total station and the two measuring points. The settlement displacement of one measuring point can be also obtained by the trigonometry relation among the total station, rear viewpoint, and measuring point.

The basic principles of the method are as follows: (1) to obtain the settlement value of one measuring point that is relative to the initial state during a certain period, by comparing the height difference between the measuring point and the rear viewpoint at different times; (2) to determine the convergence value of a convergence measuring line, by comparing the slant range of the convergence measuring line at different times. With reference to the sketch shown in Fig. 2, the Eqs. (1)–(3) give how the horizontal distance D_{PA}, the height difference h_{PA}, and the slant range S_{PA} between points P and A can be obtained through measuring the slant range S_P between points O and P, the slant range S_A between points O and A, the vertical angles α_P and α_A, and the horizontal angle β.

$$h_{PA} = h_P - h_A = S_P \sin\alpha_P - S_A \sin\alpha_A \tag{1}$$

$$D_{PA} = \sqrt{S_P^2\cos^2\alpha_P + S_A^2\cos^2\alpha_A - 2S_PS_A\cos\alpha_P\cos\alpha_A\cos\beta} \tag{2}$$

$$S_{PA} = \sqrt{h_{PA}^2 + D_{PA}^2} \tag{3}$$

If point P is the rear viewpoint and point A is the measuring point of crown settlement, then h_{PA} is the value of relative crown settlement. If point P is the measuring point on the tunnel wall and point A is another measuring point on the opposite tunnel wall, then S_{PA} is the convergence displacement value (Fig. 2(b)).

3. RDM accuracy formula

The effect of earth curvature and atmospheric refraction was negligible in this study, due to the short measuring distance and relatively consistent temperature. Eqs. (1)–(3) can be transformed by total differentiation as follows:

$$dh_{PA} = \sin\alpha_A dS_A + \frac{1}{\rho}S_A\cos\alpha_A d\alpha_A - \sin\alpha_P dS_P - \frac{1}{\rho}S_P \times \cos\alpha_P d\alpha_P \tag{4}$$