Deformation monitoring of noncircular tunnels based on 3D laser scanning

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Abstract. Deformation plays an essential role in the safety control of tunnel construction, especially for tunnels with large deformation disasters. Consequently, tunneling professionals need practical ways to monitor tunnel deformation. However, traditional methods are not yet available for 3D monitoring. This study presents a technology for measuring tunnel deformation on using a 3D laser scanner. This technology includes an automatic noise removal algorithm based on spatial features and a measurement technology of absolute coordinates. For point clouds with different times of section with the same mileage, a point-to-point deformation analysis is performed based on the azimuth. Based on the standard grid of point clouds in the longitudinal and circumferential directions of the tunnel, an overall deformation cloud map of the noncircular tunnel is generated. The use of the proposed method in the construction of the Xinzi tunnel of the express connecting Jianshui and Yuanyang in Yunnan province allows engineers to obtain critical information about deformation. Compared with the traditional monitoring method, the proposed approach can meet engineering requirements well.

Keywords. Soft rock; Large deformation; Laser scanning; Deformation monitoring

1. Introduction

Surrounding rock with poor quality often causes considerable deformation and local failure in tunnel construction, thus posing a constant challenge to the availability of transportation construction. Current soft rock tunneling practices have uncovered numerous typical engineering disasters, such as long-time deformation [1]. The large deformation of soft surrounding rock is also one of the most severe challenges in prevention and mitigation; it causes the long-time convergence of the sidewall, vault damage, and collapse [2]. Large deformations account for approximately 11% of all types of accidents. Thus, understanding the dimensional and temporal deformation process in the surrounding rock is crucial for avoiding and controlling deformation hazards.

Tunnel deformation is a typical temporal–dimensional process. Numerous researchers have used various technologies, such as convergence meter, displacement meter, and total station, to monitor the development of tunnel deformation [3-5]. However, these methods encounter the following shortcomings: (1) accession to hazardous environments with a high safety risk is inevitable; (2) these measurement methods are time-consuming and labor intensive; and (3) conventional monitoring technologies are costly because of the abundant consumables in buried sensors [6].

3D laser scanning technology offers new capacities to overcome these limitations and thus has received considerable attention in the last decades [7-9]. The 3D laser scanning method can generate the point cloud from the tunnel interior wall. Thus, deformation can be calculated due to the comparison between point clouds concerning different observational periods [10,11]. Xie applied this
method to the circle TBM tunnel and compared the measurement results with those of total station and numerical simulation, thereby confirming the reliability of TLS for tunnel deformation monitoring [12].

However, the shape of expressway tunnels is always noncircle, and the measurement environment is complex. Moreover, data processing must be further developed for practical application. Thus, a deformation monitoring method based on 3D laser scanning technology is presented in this study. The critical steps for processing the point cloud are also presented. Lastly, this method is applied in the construction of the Xinzhai tunnel.

2. Engineering background

The Xinzhai tunnel is located in Jianshui City, Yunnan Province, China. The tunnel is 680 m long, with a depth of over 60 m. It is an essential part of the expressway connecting Jianshui, Gejiu, and Yuanyang City. As described in Table 1, the surrounding rock of the tunnel is mainly sandstone, limestone, and basalt.

Table 1. Parameters of the ground rock

| Lithology   | γ(kN/m³) | σ(Mpa) | E(Gpa) | μ  | Φ(°) | C(Mpa) |
|-------------|----------|--------|--------|----|------|--------|
| sandstone   | 25       | 20     | 3      | 0.25 | 32   | 0.55   |
| limestone   | 23       | 10     | <1     | 0.3 | 25   | 0.4    |
| basalt      | 23       | <10    | <1     | 0.35 | 25   | 0.4    |

The directions of these geologic structures are mainly distributed in the north-east and east-west. The axis of this tunnel is along the NEE direction, and its cross section is a semicircular arch with 5 m × 5 m size. The tunnel is in the junction of tectonic units and has undergone several geological tectonic movements, as well as geological evolution and magma intrusion. Over time, numerous fault groups and folds have been created by these tectonic movements under complex geological conditions. The F6 fault cuts the tunnel with an angle of 45° close to the exit of the tunnel. The influence width of F6 is as large as 25 m, which consists of soil and breccia. The Guanting–Niujie arc syncline crosses this tunnel at K30+300 with a large angle. The quality rock mass in the core of the syncline is severely poor.

Drilling practice indicates that the quality of the ground is poor because of intensive fractures. Furthermore, the minimum thickness of the cover layer is only 3 m. Consequently, such dense joints and fractures not only weaken the integrity of the rock mass but also lead to large deformation ricks of the tunnel during excavation. The excavation method used is three-bench excavation. In addition to traditional deformation measurement technology, 3D laser scanning is implemented to measure the deformation of the surrounding rock during excavation.

3. 3D laser scanning technology

3.1. Data collection

Accuracy and efficiency play critical roles during the acquisition of point clouds. Different data acquisition schemes determine the quality and accuracy of the original point cloud, thus affecting result accuracy. The major factors that affect the point cloud density are measurement distance, scanning resolution, and incidence angle.

As shown in Fig. 1, the station is located at DK13+495. The disc targets and a total station are used to obtain the absolute coordinates of the point cloud.
3.2. **Preprocessing**

3.2.1. **Denoising.** During the excavation, a substantial amount of dust is generated because of the blast and transport in the tunnel. Thus, practical scanning applications are subjected to severe challenges related to noise. This study proposes a denoising process, which is based on the spatial position character of the points. The proposed denoising process includes the following phases:

1) The number of neighbors (parameter $n$) is defined.
2) A point $P$ from the point cloud is randomly selected.
3) The $n$ neighbors of point $P$ are searched by using a built-in function (i.e., KNN search in MATLAB).
4) Once the neighbors of $P$ have been found, the optimal plate fitting is conducted.
5) The fitted plate is moved to point $P$ along the norm direction.
6) The average perpendicular distance between the neighbors and the plate (denoted as $f$) is calculated. If this distance exceeds the threshold, then point $P$ should be regarded as a noise point.

![Figure 2. Denoising process](image)

The resolution of the point cloud in the application is approximately 0.3 mm; thus, $n$ is set to 12. The $f$ distribution of each point is shown in Fig. 3 and accords with the characteristic of normal distribution. We define $u+a*\sigma$ as the threshold. $u$ and $\sigma$ are the mean and std of the normal distribution, respectively. Thus, the threshold is 0.004 in this study.
3.2.2. Coordinate transformation. To monitor the deformation of the tunnel, the multiphase point cloud at different periods must be compared and analyzed. Given that the positions of the TSL station are not fixed in every measurement, the point cloud data concerning different periods should be transformed into a united coordinate system. Specifically, the relative positions of point clouds are converted to the absolute positions in the geodetic coordinate system by using the Bursa model. This model consists of three translation quantities, three rotation angles, and the scale factor $\lambda$. The transformation formulation is expressed as

$$X' = \Delta X + \lambda RX$$

where $X$ and $X'$ represent the relative and geodetic coordinates, respectively; $\Delta X$ is the translation matrix; and $R$ is the rotation matrix.

$$R_x = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \theta & -\sin \theta \\ 0 & \sin \theta & \cos \theta \end{bmatrix}, \quad R_y = \begin{bmatrix} \cos \psi & 0 & \sin \psi \\ 0 & 1 & 0 \\ -\sin \psi & 0 & \cos \psi \end{bmatrix}, \quad R_z = \begin{bmatrix} \cos \gamma & -\sin \gamma & 0 \\ \sin \gamma & \cos \gamma & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

(2)

The absolute position of the center of three targets is calculated as the origin. Then, $R$ can be expressed as

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \lambda R \begin{bmatrix} X' \\ Y' \\ Z' \end{bmatrix}.$$  

(3)

Consequently, $\Delta X$ is obtained as

$$\begin{bmatrix} \Delta X \\ \Delta Y \\ \Delta Z \end{bmatrix} = \begin{bmatrix} X_g \\ Y_g \\ Z_g \end{bmatrix} - \lambda R \begin{bmatrix} X'_g \\ Y'_g \\ Z'_g \end{bmatrix}.$$  

(4)

With the rotation and translation matrix, the multiperiod point cloud data can be transformed from the relative coordinate system of different stations to a uniform coordinate system. According to the designed file, the central tunnel axis and mileage coordinates can also be transformed into the same coordinate system. The Y-axis in this system can be parallel to the central tunnel axis through coordinate rotation, which is convenient for the extraction of the tunnel section.

4. Deformation analysis

4.1. Cross-section extraction
First, the midpoints of the tunnel with regular spacing are extracted in accordance with the design document. Then, the midpoints are used to acquire the sections at different mileages by taking the points close to the midpoint at $y = y_k$ out of the point cloud. The thickness of the sections is determined by a threshold $\Delta y$. We set the slice thickness to 1, 5, 10, and 50 mm. The sections with different slice thicknesses are shown in Fig. 4. When $\Delta y$ is less than 10 mm, the section is intermittent. Thus, $\Delta y$ is set to 10 mm in this study.

\[ \Delta y = 1 \text{ mm} \quad \Delta y = 5 \text{ mm} \quad \Delta y = 10 \text{ mm} \quad \Delta y = 50 \text{ mm} \]

**Figure 4.** Section extracted with different $\Delta y$

### 4.2. Deformation analysis method

For noncircular tunnels, structural sections have various styles, such as straight wall arch, curved wall, composite lining, and multiarch structures. These sections are complex; thus, the method of comparing the design section with the point cloud section or the section modelling in the deformation analysis is difficult to use. In this study, multistage homonymous points are determined by the circumferential azimuth of each point on the cross-section point cloud. By comparing the coordinate changes of the same point at different monitoring periods, the deformation information of the section is obtained. The specific steps are as follows:

1) For the transformed section point cloud data, the point $P_i (x_i, z_i)$ is obtained by projecting it onto the $x$–$z$ plane. Based on the point coordinate $P_0 (x_0, z_0)$, coordinate translation is performed to make the middle point translate to the coordinate origin $O(0,0)$, and a new section point cloud $P_i' (X_i', Z_i')$ is obtained;
2) The azimuths of points are calculated in accordance with their positions. Then, the points are divided into several sections with a uniform interval of $0.1^\circ$. The distances between each section and $O$ are also calculated as $L$.
3) The difference between $L$ at different times is regarded as the deformation of the tunnel, as shown in Fig. 5.
4.3. Monitoring results and analysis

The deformation of the Xinzhai tunnel from K13+480 to K13+500 is shown in Fig. 6. The convergence deformation of the tunnel can be seen in the picture. Given the asymmetrical pressure, the deformation of the right side of the tunnel is significantly larger than that of the left side. Some interference can also be observed because of the shotcrete process and cables in the tunnel.

The deformation of the x- and z-directions from K13+488 to K13+500 is extracted. Fig. 7(a) represents the deformation of the x-direction. The horizontal deformation shows a clear convergence trend. The deformation value in the range from the vault to the abutment is small (approximately 0–10 mm). The deformation below the abutment gradually increases and reaches the maximum value, which is approximately 15 mm, at the arch foot. The deformation increases with the decrease in the distance from the excavation. Fig. 7(b) shows the result of z-direction deformation. The deformation of the tunnel is stable in the vertical direction, with a value of 0–10 mm.
As shown in Fig. 8, the monitoring result at the vault (G2) and abutment (G1 and G3) is also extracted from K13+480 to K13+500 for further analysis. Considering the bias effect, the settlement deformation of G3 is slightly larger than that of G1. Close to the excavation surface, the deformation value tends to increase. To verify the accuracy of 3D laser scanning, a total station is used to monitor the deformation of the G1, G2, and G3 measuring points of the K13+484 and K13+493 sections. The results are shown in Table 2. The maximum difference between the results of TSL and total station is 1.489 mm, and the maximum relative error is 38.65%. Given the short interval between monitoring periods, the deformation of the section has not fully developed, resulting in a small deformation value and a high relative error. Nevertheless, the value of absolute error is small. Therefore, the deformation monitoring method in this study can meet the requirement.
Figure 9. Deformation at points (a) G1 and (b) G1 and G2

Table 2. Comparison of results between laser scanning and total station

| Deformation (mm) | G1     | G2     | G3     | G1     | G2     | G3     |
|------------------|--------|--------|--------|--------|--------|--------|
| Total station    | −7.7   | −4.5   | −10.5  | −3.4   | −4     | −2.1   |
| Laser scanner    | −6.387 | −3.011 | −9.042 | −4.714 | −4.164 | −2.012 |
| Error (mm)       | 1.313  | 1.489  | 1.459  | −1.314 | −0.164 | 0.088  |
| Relative error   | 17.06% | 33.1%  | 13.89% | 38.65% | −4.1%  | 4.18%  |

5. Conclusion
This study presents a deformation monitoring method based on TLS technology. The Xinzhai tunnel of the Jianzhai Expressway in Yunnan Province is taken as an example. In the preprocessing of the point cloud, an automatic denoising algorithm based on the space features is proposed. The noise and normal points have evident differences in terms of spatial characteristics. Through the automatic denoising algorithm proposed in this study, the discrete noise points caused by dust near the inner wall of the tunnel are effectively eliminated, thus ensuring the accuracy of subsequent analysis. The cross section in the Xinzhai tunnel is noncircular; thus, the ellipse fitting method cannot be applied for deformation analysis. Therefore, a novel point-to-point comparison of multiphase point clouds is proposed. The point cloud of each section of the continuously extracted tunnel is compared in two phases on the basis of the distance to the central axis and the azimuth angle. The target section angle deformation result is obtained during the measurement, and the deformation value of each point is compared with the monitoring results of the traditional total station. By contrast, data show that the method of extracting section deformation in this study has high accuracy, which can reach 1–2 mm, thus meeting the requirements of engineering measurement.

6. References
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