Tunnel Monitoring Method Based on 3D Laser Scanning Technology
Cheng-hui WAN and Xi-ping HE
School of Water Conservancy and Ecological Engineering, Nanchang Institute of Technology, Nanchang 330099, Jiangxi Province, China

Keywords: 3D laser scanning, Tunnel monitoring, Radial convergence, Cross section, Deformation analysis.

Abstract: When monitoring tunnel by obtaining magnanimous scattered point clouds with 3D laser scanning technology, it is difficult for accurate processing and analyzing of deformation, mainly due to the inability of determination of the tunnel 3D model datum by scanning single points. This article extracts feature points with the cross-section position as datum, and analyzes the tunnel diameter convergence and displacement variation tendency of cross section overall position. The experiments indicate that tunnel deformation analysis with utilizing feature points in the cross-section obtains better analysis result, and the method has definite values when applied in practice.

Introduction
In traditional deformation monitoring, there are multiple fixed observation points installed on the monitored objects for periodical observation of the tunnel convergence variance \(^{1-3}\). Due to the limit of tunnel boundary, surveying instruments is unable to conduct real-time, fast and extensive monitoring of tunnel deformation. In comparison, the terrestrial 3D laser scanner can sample 3D coordinate data with higher measuring precision and super high density, and the magnanimous data forms a 3D scattered point cloud model, which effectively avoid the locality and one-sidedness brought by the traditional monitoring based on the analysis result based on one certain observation point, that is the limitation of the analysis method where point prevails area \(^{4}\).

The advantage of 3D laser scanning technology determined its future wide application in the deformation monitoring field, but the traditional monitoring mode based on observation points is not suitable for the deformation monitoring using 3D laser scanner. The traditional points distribution is not applicable for global and specific point cloud data, and the monitoring data also need new processing methods \(^{5,6}\). Through the comparison of data obtained by utilizing 3D laser scanning technology and traditional measuring method, it is concluded that the 3D laser scanner can obtain arrayed geometric data of 3D surface of complex terrain, thus new optional methods were brought out for better deformation monitoring \(^{7-10}\). From the practical aspects, this article presents establishes an efficient and practical tunnel data sampling and processing method which is compatible with 3D laser scanner, build up the 3D model of monitored objects and corresponding model matching based on the deformation analysis and method studying of 3D monitored object module, analyzes the potential tunnel variance tendency and forms an overall forecasting model based on 3D tunnel.

Tunnel Data Sampling of 3D Laser Scanning
In this experiment terrestrial 3D laser scanner FARO Focus3D is used for the scanning monitoring of the underground tunnel after shield construction between Dalian Road and Changyang Road of No.12 metro line. Figure 1(a) is the tunnel scanning using scanner, with 5 set sphere targets. The 3D laser scanning conduct two-cycle data sampling, then generate 3D coordinate file after preprocessing. Figure 1(b) shows the 3D model of tunnel point cloud, where there is no fixed observation point.
Scanned Tunnel Data processing

3D Tunnel Modeling and Data Sampling

Shape feature points of cross section are adopted to replace the role of the deformation observation point. As shown in figure 2 the cross section curves are sampled every 1 meter after building triangular irregular network model, for the comparison of tunnel convergences.

Grid division is conducted on the cross section curve, and the intersection points are sampled as the feature points of cross section. As shown in Figure 3, the horizontal and vertical feature points are respectively sampled.

Datum of Tunnel 3D Model

3D monitoring cross section model is built by 3D laser scanning of point clouds. When calculating and comparing of variations of different periods, there are related questions: One is the datum position of the cross section. Coordinate can be matched by suing traditional monitoring datum points, and cross section position can be sampled by setting the position of the tunnel monitoring planar targets. For long-term tunnel monitoring, the cross section position should be set to compare the effect of convergence deformation on tunnel. Figure 4 shows the 3D coordinate system by matching certain position in the tunnel, building cross section by X and Y, and Z represents axial horizontal direction.
Second is the datum of cross-section circle center. The position variation of cross-section points, that is, the tendency of placement variance of cross-section diameter and overall tunnel, is calculated.

1. The convergences of tunnel cross-section points are similar with that of symmetry points set on the tunnel wall traditionally. The distance variance of two points is then compared. Due to the density of feature points distribution on the cross section obtained by scanning, the tunnel diameter convergence can be more specific. The distance $l_i$ between symmetry points and distance variance $\Delta_k$ of different phase are calculated as follows

$$l_i = \sqrt{(X_i - X_j)^2 + (Y_i - Y_j)^2}$$

$$\Delta_k = l_i - l_k$$

2. For overall tunnel placement variance, reference circle with center coordinate as $O(X_0, Y_0)$, is fitted by sampling cross-section feature points. The placement variances of circle center on the cross section are compared. Based on the least square principle, the position of circle center is calculated as follows

$$\sum V_i V_i = \min$$

$$V_i = \sqrt{(X_i - X_0)^2 + (Y_i - Y_0)^2} - R$$

where the number of feature points $i = (1, 2, \ldots n)$ and $R$ is the designed tunnel diameter. Circle center coordinate $O(X, Y)$ can be calculated by fitting iterative calculation. The error $m_o = \pm \sqrt{\frac{V_i V_i}{n}}$.

Circle coordinate of same position by two scanning, the offset $\Delta x$ in $X$ axis and $\Delta y$ in $Y$ axis is made to obtain the overall variance of tunnel as shown below:

$$\begin{cases} 
\Delta x = X_i - X_s \\
\Delta y = Y_i - Y_s 
\end{cases}$$

Deformation Analysis Based on Tunnel 3D Monitoring Object Model

Tunnel Convergence Analysis

For the deformation analysis of the tunnel cross-section position, the tunnel diameter convergence analysis is similar to the traditional method. The distance of the two symmetric points in the axial direction of the cross section is calculated. As shown in Figure 4, there are 157 feature points sampled, which are distributed in horizontal and vertical direction. According to this distribution, the points in corresponding position is selected as symmetric points, e.g., (2) and (79), (80) and (157) in horizontal direction, or (40) and (119), (41) and (118) in vertical direction. With the formula (1) and (2) the tunnel convergence is calculated. From table, it can be learnt that the convergence in the horizontal direction is smaller while the one in the vertical direction is bigger, which complies with the tunnel deformation tendency. The diameter convergence can be obtained depending on the comparison of more symmetric points on the tunnel cross-section.
Figure 5. The Distribution of Convergent Symmetric Points on Cross Section.

Table 1. Convergence Error of Tunnel Cross Section.

<table>
<thead>
<tr>
<th>Cross Section</th>
<th>ID Number Of Symmetric Point</th>
<th>First Convergence Distance (Mm)</th>
<th>Second Convergence Distance (Mm)</th>
<th>Convergence Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal</td>
<td>2-79</td>
<td>5498.982</td>
<td>5497.132</td>
<td>0.750</td>
</tr>
<tr>
<td></td>
<td>157-80</td>
<td>5497.903</td>
<td>5496.964</td>
<td>0.939</td>
</tr>
<tr>
<td>Vertical</td>
<td>40-119</td>
<td>5484.993</td>
<td>5483.763</td>
<td>1.230</td>
</tr>
<tr>
<td></td>
<td>41-118</td>
<td>5486.223</td>
<td>5484.888</td>
<td>1.335</td>
</tr>
</tbody>
</table>

Variance Tendency of Overall Tunnel Placement

Figure 4 indicate the arrangement consequence of cross-section in Z axis, where the designed radius of the experimental tunnel is 2.75m. The circle center coordinates is calculated according to formula (3) and (4). In table 3 the vector comparison of cross-section circle center placements from two scannings is conducted to obtain the overall placement variance of the tunnel cross section. From the variance of circle center placement it can be learnt that it is smaller in the horizontal direction while bigger in vertical direction, with overall subsidence trend.

Table 2. Placement variance of fitting circle of tunnel cross section.

<table>
<thead>
<tr>
<th>First scanning</th>
<th>X(mm)</th>
<th>Y(mm)</th>
<th>Δx (mm)</th>
<th>Δy (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>O₁</td>
<td>3670.191</td>
<td>-62.119</td>
<td>-0.639</td>
<td>1.039</td>
</tr>
<tr>
<td>O₂</td>
<td>3682.285</td>
<td>-71.434</td>
<td>-0.772</td>
<td>1.459</td>
</tr>
<tr>
<td>O₃</td>
<td>3687.140</td>
<td>-71.829</td>
<td>0.280</td>
<td>0.579</td>
</tr>
<tr>
<td>O₄</td>
<td>3697.636</td>
<td>-93.171</td>
<td>0.089</td>
<td>1.317</td>
</tr>
<tr>
<td>O₅</td>
<td>3716.811</td>
<td>-108.007</td>
<td>0.582</td>
<td>1.335</td>
</tr>
<tr>
<td>O₆</td>
<td>3726.693</td>
<td>-118.050</td>
<td>-1.221</td>
<td>2.592</td>
</tr>
<tr>
<td>O₇</td>
<td>3733.413</td>
<td>-138.028</td>
<td>-1.522</td>
<td>2.136</td>
</tr>
<tr>
<td>O₈</td>
<td>3750.718</td>
<td>-157.830</td>
<td>-0.632</td>
<td>0.732</td>
</tr>
</tbody>
</table>

Conclusion

The tunnel deformation monitoring based on 3D laser scanner is currently under research. Due to the precision and datum problem of scattered point cloud 3D model, it is difficult to analyze the data after obtaining magnanimous data scanned. This article obtains tunnel cross-section, precisely matches cross-section placement, obtains the feature points in cross-section, conduct tunnel diameter convergence with feature points, as well as gets the overall placement variance of cross-section, builds up the model of tunnel convergence and overall deformation, samples feature points data of tunnel cross-section, fits the reference circle, and calculates the circle center coordinates. Afterwards, it also compares the placement variance of each previous and next circle centers, in order to get the overall tunnel variance tendency.

Acknowledgements

Many thanks to the funding support of No. 20151BAB207051 project of science and technology office of Jiangxi province.
References


