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Excavation Quality Evaluation of Highway Tunnels Using 3D Laser Scanning

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Abstract: *Accurate evaluation of tunnel excavation quality is critical for subsequent support work, lining construction, and profile control. While 3D laser scanning captures dense and continuous point cloud data, extracting reliable geometric information from long, complex highway tunnels remains challenging due to local clutter and noise. To address this, a comprehensive evaluation workflow is proposed. Multi-station point clouds are first organized via spherical-target registration and preprocessed. Subsequently, a Polar coordinate Cloth Simulation Filtering (P-CSF) method is utilized for robust lining extraction, followed by cross-section extraction and continuous profile reconstruction. By comparing the reconstructed profiles with design contours, overbreak and underbreak are identified. The excavation quality is then comprehensively evaluated using average overbreak depth, profile roughness, longitudinal variation, and the Tunnel Contour Quality Index (TCI). Application to a real-world highway tunnel project with both standard and complex segments demonstrates that the proposed workflow effectively mitigates the influence of attached construction objects, yields highly stable reconstructed profiles, and provides a reliable geometric basis for segment-level excavation assessment in practical construction scenarios.*

Keywords: *3D laser scanning; tunnel point cloud; P-CSF; cross-sectional profile; overbreak and underbreak; excavation quality evaluation*

1. Introduction

Tunnel excavation quality directly affects later support work, lining construction, and final profile control. In large-section highway tunnels, traditional point-based surveying can provide local geometric information, but it cannot describe the full tunnel surface in a fast and continuous way. By contrast, 3D laser scanning can capture dense point cloud data over the whole tunnel surface, so it offers a better basis for contour checking and excavation assessment[1-2]. Real tunnel scenes, however, still make point cloud analysis difficult. Multi-station data must be organized into one continuous model, and the tunnel environment often includes dust, humidity, weak lighting, equipment, and local occlusion[3]. At the same time, measured sections may include not only standard tunnel parts, but also transition zones and widened sections, which make later profile analysis less straightforward.

To address the challenges of point cloud processing in complex environments, various filtering and segmentation strategies have been proposed. Foundational physics-based methods like the Cloth Simulation Filtering (CSF) algorithm[4] have inspired numerous adaptations for tunnel structures, including joint structure detection combined with multi-scale clustering[5] and geometric models supporting accurate concrete consumption estimation[6]. Furthermore, recent advancements have introduced deep learning techniques to this field, such as large-scale semantic segmentation benchmarks for subway tunnels[7] and the adaptation of the Segment Anything Model (SAM) for dim underground scenes[8]. Despite these advancements, achieving a balance between computational efficiency and adaptability to complex tunnel morphologies remains a critical need.

This study is based on a highway tunnel engineering case from the G5 Beijing–Kunming Expressway expansion project. In this work, point clouds from different stations were registered using spherical targets to build a continuous tunnel model. On this basis, this paper develops a practical workflow for tunnel excavation quality evaluation. The workflow includes point cloud preprocessing, P-CSF-based lining extraction, cross-Cross-Section Extraction, profile reconstruction, and comparison between measured and design contours. The study then uses profile deviation to identify overbreak and underbreak and to evaluate section quality in typical tunnel areas. The aim of this study is to provide reliable geometric support for excavation assessment, follow-up lining work, and construction quality inspection in complex tunnel construction scenes.

2. Point Cloud Acquisition and Organization

2.1 Field Data Acquisition

The tunnel point cloud was collected by 3D laser scanning under actual construction conditions. According to the engineering report, a Leica P50 scanner was used in the field. The tunnel environment was enclosed, and the scanned area was affected by weak lighting, high humidity, dust, parked machinery, stacked materials, and limited sight lines in some local areas. These conditions did not change the survey objective, but they increased the difficulty of stable data acquisition.

The value of field scanning lies in its ability to record the tunnel surface as a dense and continuous spatial dataset. This is important for later excavation analysis, because section-based evaluation needs more than a few isolated control points. It needs a geometric record that can preserve the actual tunnel shape over long distances and across different section types. In this sense, field scanning provides the raw geometric basis for later lining extraction, profile reconstruction, and excavation quality evaluation.

2.2 Multi-Station Registration

A long tunnel point cloud is usually collected from multiple scan stations rather than from a single position. In the reported engineering workflow, point clouds from different stations were registered by using spherical targets. This treatment connected neighboring scans into one continuous model and made later section analysis possible within a unified dataset. After registration, the merged point cloud was transformed into the engineering coordinate system by using site control information, which gave the data a consistent spatial reference for later processing and comparison.

Registration is treated here as the basic step of data organization rather than as the main research focus. Its role is to convert scattered station data into a continuous tunnel model. Once this model is obtained, later analysis can move from data organization to geometric description and excavation evaluation.

2.3 Point Cloud Preprocessing

The registered tunnel model cannot be used directly for excavation evaluation. The raw dataset still contains redundant points and local interference from the construction scene. These points may come from temporary facilities, equipment, and other non-structural objects, and they can reduce the stability of later Cross-Section Extraction and profile recovery. For this reason, the point cloud needs to be organized and cleaned before further analysis, so that the retained data have clearer structural meaning.

Point cloud preprocessing does not change the tunnel geometry itself. Its purpose is to remove data that are not suitable for later analysis and to retain points that better represent the tunnel structure. After this step, the dataset is better suited for lining extraction and section-based evaluation. This process therefore links the registered point cloud with the later geometric analysis of tunnel excavation quality.

3. Lining Extraction and Profile Reconstruction

3.1 Lining Extraction

Tunnel point clouds collected in construction scenes usually contain not only lining points, but also ventilation pipes, water pipes, temporary facilities, equipment, ground accumulation, and local noise. These points can disturb the real tunnel boundary and reduce the stability of later profile analysis. For this reason, lining extraction is needed before section reconstruction. P-CSF based method[9] is used here to separate lining points from surrounding interference. In local section coordinates, each point can be written in polar form as:

$$r_i = \sqrt{(y_i - y_c)^2 + (z_i - z_c)^2} \tag{1}$$

$$\theta_i = \mathrm{atan2}(z_i - z_c, y_i - y_c) \tag{2}$$

where (y_c, z_c) is the section center.

After the cloth surface is fitted in the polar domain, the radial gap between the point and the fitted boundary is used for classification. A point is retained as a lining point when：

$$\Delta r_i = | r_i - r_c(\theta_i) | < T_d \tag{3}$$

where $r_c(\theta_i)$ is the fitted cloth radius and T_d is the classification threshold.

This treatment keeps points that are closer to the real lining surface and suppresses attached objects and local clutter near the tunnel boundary.

3.2 Cross-Section Extraction

After lining extraction, representative cross-sections are taken along the tunnel axis for geometric analysis. The cross-sectional plane should remain consistent with the local tunnel direction, because an unsuitable cutting direction may distort the recovered section shape and affect the later comparison with the design contour. A theoretical zero-thickness cut is not suitable for real tunnel point clouds, since scan points are discrete and unevenly distributed. A thin point band is therefore used instead. For a target position x_0, the section band can be written as.

$$S(x_0) = \{p_i \mid |x_i - x_0| \le \frac{h}{2}\} \tag{4}$$

where h is the slice thickness.

The points in this band are then projected onto the cross-sectional plane to form a two-dimensional cross-sectional point set. This treatment preserves more boundary information and gives a more stable base for profile recovery. In the later engineering application, a slice thickness of 50 mm was used for section analysis.

3.3 Profile Reconstruction

The extracted section points are still discrete, so they cannot be compared directly with the design contour. A continuous measured profile must be reconstructed from the cross-sectional point set before excavation evaluation can be carried out. In the reconstructed workflow, the section points are first grouped by angle, and a representative outer radius is then selected in each angular sector by a high quantile instead of a simple maximum. For the k-th sector, the representative radius can be written as:

$$\hat{r}_k = Q_q(\{r_i \mid \theta_i \in [\theta_k, \theta_{k+1})\}) \tag{5}$$

where $Q_q(\cdot)$denotes the q-quantile.

After that, circumferential median filtering is used to reduce local abnormal oscillation, and shape-preserving interpolation is applied to recover a continuous closed profile. This process reduces the influence of isolated outer points, local density changes, and small gaps in the section band, while keeping the main boundary trend and local geometric changes near the wall foot, arch shoulder, and bottom transition zone. The reconstructed profile therefore provides a direct geometric basis for later comparison with the design contour and for overbreak and underbreak evaluation.

4. Excavation Quality Evaluation Framework

4.1 Comparison between Measured and Design Profiles

Excavation quality evaluation starts from the comparison between the measured profile and the design contour. After profile reconstruction, the measured boundary can be directly related to the corresponding design line, and the local deviation can then be quantified point by point. For the iii-th sampling point on a section, the profile deviation can be written as:

$$d_i = ||P_i|| - P_i^d \tag{6}$$

where P_i is the measured profile point and P_i^d is the corresponding point on the design contour.

This deviation is the basic quantity for later overbreak and underbreak evaluation. It reflects how far the actual excavation boundary departs from the design geometry. A larger deviation means a larger loss of contour control.

4.2 Identification of Overbreak and Underbreak

Overbreak and underbreak are identified from the relative position between the measured profile and the design contour. In a section, the average overbreak depth can be expressed as:

$$O_d = \frac{1}{N}\sum_{i=1}^{N} d_i \tag{7}$$

where N is the number of sampling points on the section.This index describes the overall outward deviation of the measured profile from the design contour. A larger O_d indicates a larger mean overbreak level and a less favorable excavation result.

Beyond local depth, section-based area statistics are also needed. In the thesis work, the area between adjacent measured points and the corresponding design arc was treated as the basic area unit, and the signed area of each unit was used to distinguish overbreak from underbreak. If the signed local area is denoted by S_j, then:

$$S_j > 0 \tag{8}$$

This condition indicates an overbreak unit, while the opposite case is given by:

$$S_j < 0 \tag{9}$$

This condition indicates an underbreak unit.

By summing these local units along the sidewall profile, section overbreak area and section underbreak area can be obtained. This treatment extends pointwise deviation into a clearer geometric description of section error distribution.

4.3 Comprehensive Assessment of Cross-Sectional Quality

A single overbreak value cannot fully describe tunnel profile quality. Profile quality also depends on boundary smoothness and on how the section changes along the tunnel direction. For this reason, three indicators are used together in the later evaluation: average overbreak depth O_d, profile roughness RCL, and longitudinal overbreak variation V_o. The roughness index is defined as the ratio between the measured profile length and the design profile length:

$$RCL = \frac{L_m}{L_p} \tag{10}$$

where L_m is the measured profile length and L_p is the design profile length. A value closer to 1 indicates a smoother boundary, while a larger value indicates stronger local fluctuation.

The longitudinal variation index describes profile stability along the tunnel axis. If a section interval contains M consecutive sections, then the longitudinal overbreak variation can be written as:

$$V_o = \frac{1}{M-1}\sum_{i=1}^{M-1} |O_{d,i+1} - O_{d,i}| \tag{11}$$

A larger V_o indicates a stronger fluctuation of excavation quality along the longitudinal direction. In section-based evaluation, these three indicators are further combined into a TCI-based quality index[10]. In that framework, larger values of O_d, RCL, and V_o lead to a lower quality index, which means poorer profile quality. This treatment makes it possible to compare different tunnel intervals in a more complete way than by using overbreak depth alone.

5. Engineering Application and Results

5.1 Project Background and Data Overview

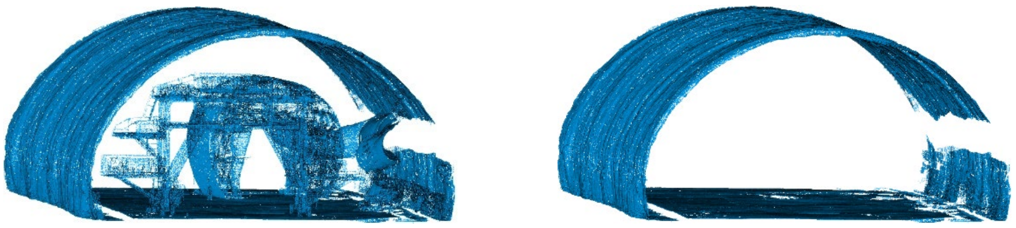
The engineering application was carried out on tunnel sections from the G5 Beijing–Kunming Expressway expansion project. The surveyed areas were located in Zhangjiagou Tunnel and Feiyingguan Tunnel. According to the engineering report, the scanning range extended about 1.0 km from the entrance of Zhangjiagou Tunnel and about 1.5 km from the exit of Feiyingguan Tunnel. The measured area included not only standard main tunnel sections, but also transition sections, emergency parking bays, and other widened parts with more complex geometry. These conditions provided a suitable engineering background for testing section-based excavation evaluation under real construction scenes.

A Leica P50 scanner was used for field acquisition, and a total of 82 scan stations were collected. Point clouds from different stations were registered by using spherical targets and then transformed into the engineering coordinate system to form a continuous tunnel model for later analysis. The field environment included weak lighting, high humidity, dust, parked machinery, material stacking, and locally restricted visibility. These conditions increased the difficulty of data collection and also reflected the practical background of the engineering application.

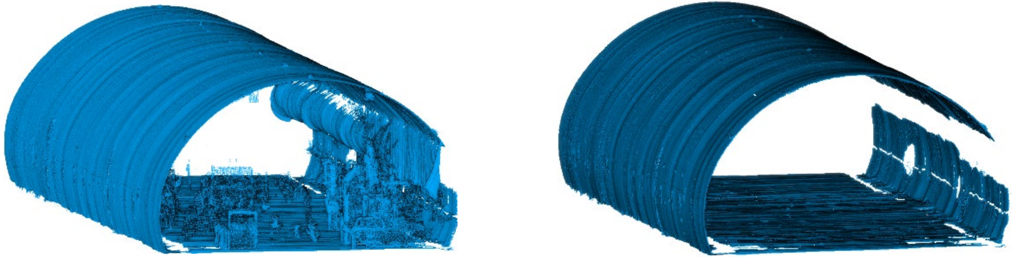
5.2 Results of Lining Extraction and Profile Reconstruction

Even after multi-station organization, the tunnel point cloud still contained non-structural objects from pipes, temporary facilities, equipment, and local clutter near the tunnel boundary. These objects can blur the real lining contour and reduce the stability of later section reconstruction. For this reason, lining extraction is an essential step before section-based excavation evaluation. In the present workflow, P-CSF-based extraction was used to retain points closer to the actual lining surface and to suppress attached objects around the tunnel boundary. The visual difference before and after lining extraction should be presented in Figure 1. This figure is expected to show that the extracted result preserves the main tunnel contour more clearly and provides a cleaner geometric basis for later section reconstruction.

After lining extraction, representative cross-sections were taken along the tunnel axis and projected onto the cross-sectional plane for profile recovery. The reconstructed measured boundary formed a continuous contour that could be compared directly with the design profile. In standard sections, the recovered contour showed a stable overall shape. In widened sections and other locally complex areas, the main geometric trend was still retained, which made later deviation analysis possible under practical tunnel conditions. These results indicate that the combination of lining extraction and profile reconstruction can support section-level excavation evaluation in both regular and locally complex tunnel areas.



(a) Typical section A before lining extraction *(b) Typical section A after lining extraction*



(c) Typical section B before lining extraction *(d) Typical section B after lining extraction*

Figure 1. Comparison of tunnel point clouds before and after lining extraction.

5.3 Results of Overbreak and Underbreak Evaluation

The reconstructed measured profiles were further compared with the design contours to identify overbreak and underbreak in typical cross-sections. This step converted the tunnel point cloud from a large three-dimensional dataset into a more direct geometric description at the section level. In standard sections, the difference between the measured and design boundaries showed a relatively regular deviation pattern. In widened sections and transition areas, the deviation distribution became more complex, and local differences within the same section became more evident. Under these conditions, section-based evaluation gave a clearer engineering interpretation than direct visual inspection of the raw point cloud alone. The MATLAB-based overbreak and underbreak calculation result should be presented in Figure 2. This figure can directly show the local deviation pattern and make it easier to identify areas with stronger geometric departure from the design contour.

The overbreak and underbreak results also show that excavation quality cannot be represented well by a single local deviation alone. Some sections may have similar mean deviation, but their local fluctuation and boundary stability can still differ. This point is important in practical tunnel assessment, because construction control depends not only on whether the contour moves outward or inward, but also on how stable the boundary remains within a section and along the tunnel direction. For this reason, geometric deviation needs to be read together with a broader section-quality indicator.

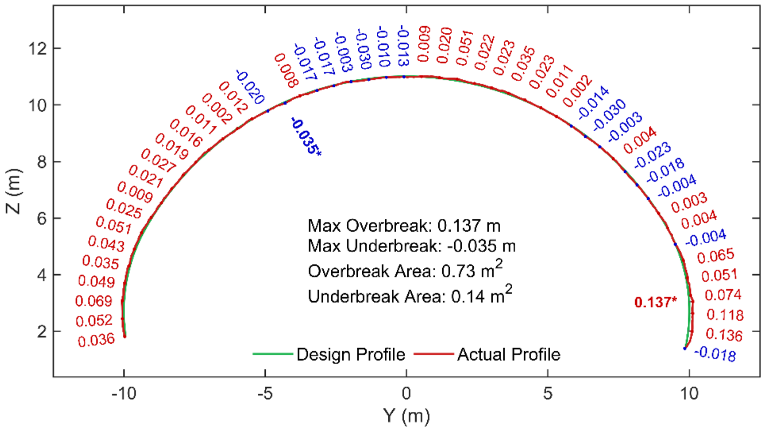


Figure 2. Overbreak and underbreak result for a typical tunnel cross-section.

5.4 Segment-Level Quality Assessment and Engineering Significance

Segment quality was further evaluated by combining average overbreak depth, profile roughness, and longitudinal overbreak variation into a TCI-based index. In this framework, a higher score indicates better quality, while a lower score indicates stronger geometric fluctuation and poorer contour control. The score distribution for different tunnel segments is shown in Figure 3. Compared with a single deviation result, the TCI score provides a more complete description of segment quality and makes the difference between tunnel segments easier to identify.

The results also show that segment quality is not controlled by one factor alone. Some segments may have similar mean overbreak depth, but their local roughness and longitudinal stability can still differ. Under such conditions, the TCI score helps reveal the overall quality level more clearly. This makes the evaluation result easier to read at the segment level and more useful for later engineering judgment.

From an engineering point of view, the TCI result provides a clearer basis for judging which intervals are relatively stable and which intervals need more attention. When read together with the lining extraction result in Figure 1 and the overbreak and underbreak result in Figure 2, the score distribution in Figure 3 forms a complete interpretation chain from point cloud organization to excavation quality evaluation. This result is useful for identifying sections with poor contour control, supporting local correction, and providing quantitative evidence for later support work, lining preparation, and construction quality inspection. Under long tunnel conditions with changing section types and local complexity, such a structured evaluation result is more informative than isolated point measurements or qualitative visual judgment alone.

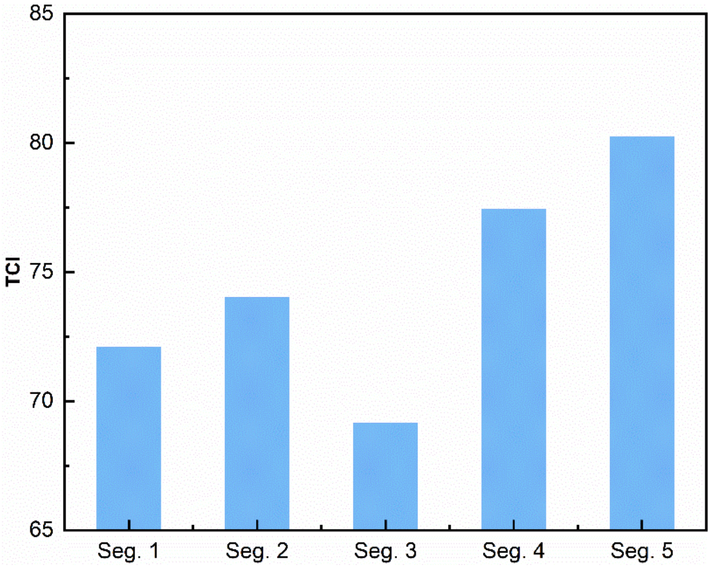


Figure 3. TCI scores of different tunnel segments.

6. Conclusions

A practical workflow for tunnel excavation quality evaluation based on 3D laser scanning was established. In this workflow, multi-station point clouds were organized by spherical-target registration, and the processed data were then used for lining extraction, cross-Cross-Section Extraction, profile reconstruction, and geometric evaluation. This workflow provides a direct link between tunnel point cloud data and section-based engineering assessment

(1) A continuous tunnel point cloud model provides a more complete geometric basis than traditional local point measurements in long and complex tunnel scenes. After point cloud organization and preprocessing, the retained data are more suitable for later excavation analysis.

(2) P-CSF-based lining extraction, combined with cross-sectional profile reconstruction, can reduce the influence of pipes, temporary facilities, and local clutter near the tunnel boundary. The reconstructed measured profile provides a stable geometric basis for comparison with the design contour and supports later overbreak and underbreak evaluation.

(3) Excavation quality cannot be represented well by a single deviation index alone. A more complete description can be obtained by combining profile comparison, overbreak and underbreak results, and segment-level quality indicators such as average overbreak depth, profile roughness, longitudinal variation, and TCI score. In engineering application, such results are useful for identifying segments with poorer contour control and for supporting follow-up lining work and construction quality inspection.

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