Modeling Estimation of Tunnel Lining Pouring Volume by Borehole-blasting Method

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Key words: Drill-blasting method tunnel, Lining pour volume, Tunnel primary lining, Tunnel lining carts, Digital construction

1. SUMMARY

With the rapid development of big data, artificial intelligence and digital twin technology, tunnel construction is gradually moving towards the intelligent construction stage. However, the current tunnel lining construction still needs to rely on manual experience to adjust the lining cart and construction control, which has the problems of lack of precision and low efficiency. In this paper, we propose a multi-model combination method that integrates the tunnel lining model and lining cart model to meet the needs of intelligent construction in tunnel lining construction, and establish a model for estimating the amount of tunnel lining poured, with the aim of realizing accurate simulation and quantitative analysis of the lining construction process. The GTFS case study is used to obtain actual construction data, and the tunnel lining pouring process is modeled and verified. The results show that the method can effectively improve the digital level of tunnel lining construction, provide scientific basis for lining construction plan optimization and material scheduling, especially in the control of pouring volume, which can significantly save the construction materials, reduce the waste of resources, and improve the efficiency of resource utilization. At the same time, the study also expands the application scenarios of tunnel engineering in the digital construction of underground space, and provides more scientific construction guidance solutions for actual construction.

SUMMARY

随着大数据、人工智能及数字孪生技术的快速发展，隧道施工正逐步迈向智能化建造阶段。然而，当前隧道衬砌施工仍需依赖人工经验进行衬砌台车的调整与施工控制，且普遍存在超额消耗混凝土的问题。本文针对隧道衬砌施工中的智能化建造需求，提出一种融合隧道衬砌模型与衬砌台车模型的多模型组合方法，并建立隧道衬砌浇筑量的估算模型，旨在实现衬砌施工过程的精确模拟与量化分析。通过GTFS案例项目，获取实际施工数据，并对隧道衬砌浇筑过程进行模型化仿真与结果验证。研究结果表明，该方法可有效提升隧道衬砌施工的数字化水平，为衬砌施工方案优化与物料调度提供科学依据，尤其在浇筑量控制方面，可节约施工材料，提升资源利用效率。同时，研究也拓展了隧道工程在地下空间数字化建造中的应用场景，为实际施工提供更加科学的施工指导方案。

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2. Introduction

With the rapid development of big data, artificial intelligence, and digital twin technologies, tunnel construction is gradually moving towards the stage of intelligent construction (Apoji et al., 2023; Liu et al., 2024; Su et al., 2024; Ye et al., 2023; Yu et al., 2023; Zhu et al., 2019). However, current tunnel lining construction still relies heavily on manual experience for the adjustment of lining trolleys and construction control, which often leads to insufficient precision and low operational efficiency (Chen et al., 2025; Ha et al., 2021; Kavvadas, 2005). In particular, the lack of quantitative and model-based support in the lining construction process makes it difficult to achieve accurate control of construction parameters, especially the pouring volume of tunnel linings (Kong et al., 2023; Zhu et al., 2024).

In recent years, digital management approaches such as BIM–GIS integration have been applied to tunnel engineering to support information sharing and lifecycle-oriented management (Han et al., 2020; Kang et al., 2015; Liu et al., 2023; Wang et al., 2019; Zhu et al., 2022). Nevertheless, most existing studies focus primarily on construction organization and information management, while relatively limited attention has been paid to the construction process itself, especially the coupling relationship between tunnel lining structures and lining trolley operations (Chen et al., 2020; Sharafat et al., 2021; Zhang et al., 2019). In practice, tunnel lining construction is often characterized by excessive concrete consumption and a strong dependence on manual experience (Haas et al., 2020; Wang et al., 2024). Such experience-based decision-making is subject to individual variability and is not well suited to tunnel projects with complex alignments and geometries (Ninić et al., 2020). To address these challenges, it is necessary to introduce digital and model-based methods that explicitly describe the interaction between tunnel lining models and lining trolley models, thereby enabling quantitative analysis and accurate simulation of the lining construction process (Ninic et al., 2021; Sharafat et al., 2025; Tanoli et al., 2025). In particular, the establishment of a reliable model for estimating tunnel lining pouring quantities is essential for improving construction precision, optimizing construction plans, and enhancing material scheduling efficiency (Sharafat et al., 2021; Zhang et al., 2023). By analyzing pouring quantities at different construction stages, the material usage in tunnel lining construction can be simulated more accurately, providing a scientific basis for reducing material waste and improving resource utilization efficiency (Moosazadeh et al., 2018).

From a broader perspective, tunnels are key structural components of underground engineering. Advancing digital construction methods for tunnel lining processes not only supports intelligent construction at the project level but also expands the application scenarios of digital technologies in underground space engineering (Admiraal et al., 2020; Zhu et al., 2025). Therefore, this study proposes a multi-model combination method that integrates tunnel lining models and lining trolley models, together with a quantitative estimation approach for tunnel lining pouring volumes. A real tunnel project, referred to as GTFS, is used as a case study to obtain actual construction data, and the tunnel lining pouring process is modeled and verified. The results demonstrate that the proposed method can effectively enhance the digital level of tunnel lining construction and provide more scientific guidance for construction planning and on-site implementation.

3. Method

The research methodology proposed in this paper aims to bridge the gap between on-site construction data and digital models. A precise simulation of the entire lining construction process is achieved through the following three core steps: First, construction-oriented model construction is conducted to establish a solid foundation for geometric data. Second, multi-model integration and construction data calibration are performed to ensure synchronization between the simulated environment and the actual construction site. Finally, through tunnel lining pouring volume estimation, decision-making support is provided for construction plan optimization and material scheduling. The specific implementation workflow for each section is detailed as follows.

3.1 Model construction for drill-and-blast tunnels

3.1.1 Tunnel lining modeling

The primary lining of a tunnel serves as the fundamental data for researching concrete pouring volumes, and its refined modeling is a crucial step in estimating these volumes. The experimental data utilized in this chapter are obtained by extracting primary lining point cloud data using the extraction method (Zhao et al., 2024). The simplified results retain the hole boundary characteristics and morphological undulation features of the tunnel lining point cloud. However, the presence of holes in the primary lining point cloud remains the primary challenge in modeling.

When performing 3D reconstruction using primary lining point cloud data, the complexity of the tunnel construction environment often leads to obstructions from building materials, construction equipment, ventilation ducts, and power lines. This results in varying degrees of point cloud holes in the collected data. Since the estimation of lining pouring volume requires complete primary lining data, filling these point cloud holes is the research focus of primary lining modeling. As shown in Figure 1, starting from the spatial characteristics of the point cloud data and addressing the significant differences in hole morphology across different density regions. By dividing the primary lining point cloud into sparse and dense regions, different types of holes can be filled accordingly. This research begins with the surface features of the point cloud and fills the holes by adopting the conceptual framework of constructing Digital Elevation Models (DEMs).

Due to the overall irregularity and significant localized feature variations of the primary lining point cloud, it is difficult to fill the holes from a global perspective. To resolve this issue, a regional partitioning approach is required. Since the undulation morphology of the tunnel's primary lining is similar to topographical fluctuations, terrain representation methods can be used to construct the primary lining model. Drawing on the modeling logic of Digital Elevation Models, holes in the tunnel point cloud can be filled in a block-wise manner. Furthermore, the reference plane is the foundation for establishing the Digital Elevation Model of the primary lining. The design concept involves setting the longitudinal grid lines on the point cloud surface as the edges of polygonal prisms, and then configuring the number of edges for these prisms based on the specific conditions of different point cloud density regions. As illustrated in Figure 1, more grid lines can be set in dense regions, resulting in polygonal prisms with more edges; conversely, in sparse regions with less feature information, fewer grid lines can be used. Consequently, the reference plane of the primary lining surface is composed of a plane formed by transverse and longitudinal grid lines.

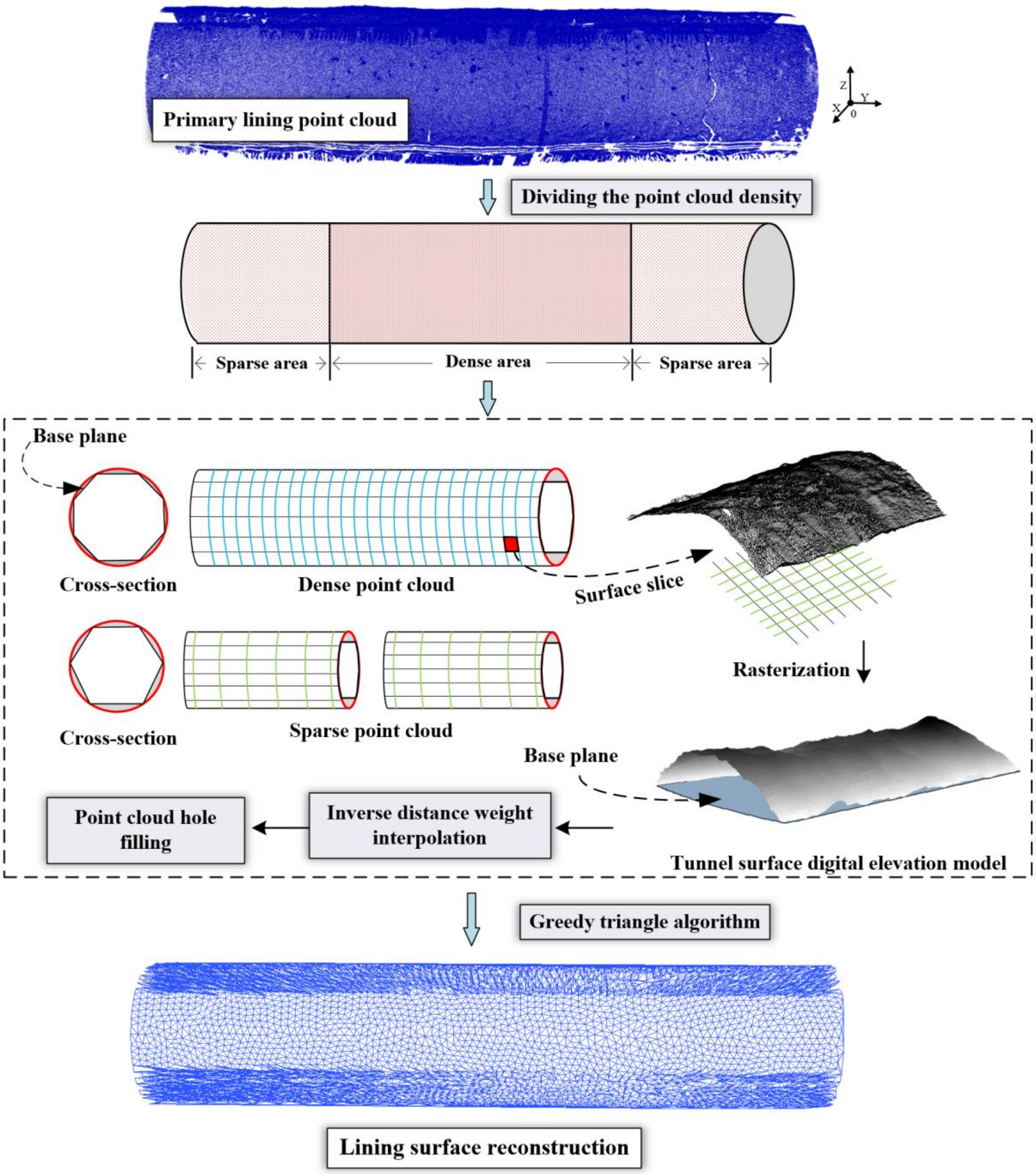


Figure 1 Modeling method of tunnel lining point cloud.

3.1.2 Tunnel lining trolley modeling

The tunnel lining trolley is the primary engineering equipment for secondary lining construction, used for pouring tunnel lining concrete. Following the completion of the tunnel's primary support structure (primary lining), the secondary lining construction commences. Before starting the secondary lining work, the trolley tracks must be laid. The tunnel lining trolley is then transported along these tracks to the designated chainage range. Once the position of the trolley is adjusted, the concrete pouring begins. The tunnel lining trolley is the central object of lining construction. The functional components that comprise the trolley primarily include the following:

(1) Gantry Assembly: The gantry assembly is the main component of the trolley, supported by the travel wheel frames and equipped with foundation jacks where it contacts the ground. During concrete pouring, the concrete load is transmitted through the gantry to the pouring windows (Figure 2). The gantry structure mainly consists of upper longitudinal beams, lower longitudinal beams, and gantry columns, with all components interconnected via bolts.

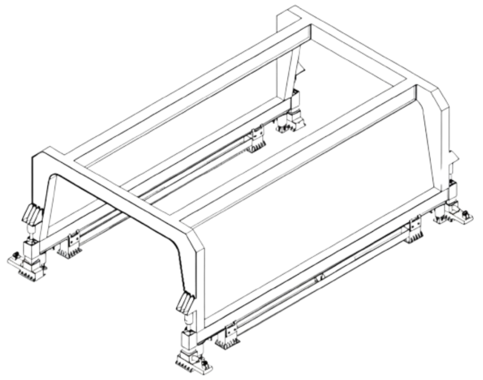


Figure 2 Illustration of tunnel lining trolley.

(2) Bracket Assembly: The bracket assembly is the internal framework of the lining trolley, designed to support the weight of both the concrete and the trolley formwork during secondary lining construction. The bracket assembly is supported by hydraulic cylinders located above the trolley tracks (Figure 3). Above the brackets, support jacks bear the weight of the formwork. The specific positions of the hydraulic cylinders and support jacks within the bracket assembly are adjusted based on specific engineering requirements.

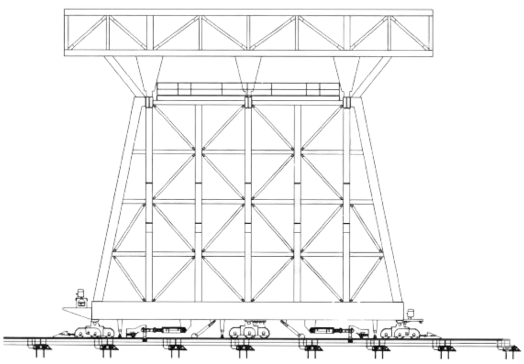


Figure 3 Illustration of lining trolley bracket.

(3) Formwork Assembly: The formwork assembly plays a vital role in the quality of tunnel construction and is a core functional component of the lining trolley. As shown in Figure 4, it primarily consists of the left side form, right side form, and top form. The dimensions of the side forms can be adjusted according to the tunnel cross-section. Additionally, multiple concrete pouring windows are regularly distributed across both side forms to control the pouring process. Besides the side forms, the top form is used for pouring the lining structure at the crown of the trolley. Once the side forms have been filled from bottom to top, construction begins on the section located at the top form. The formwork assembly is directly involved in the concrete pouring process; its surface quality and dimensional accuracy directly impact the final quality of the lining.

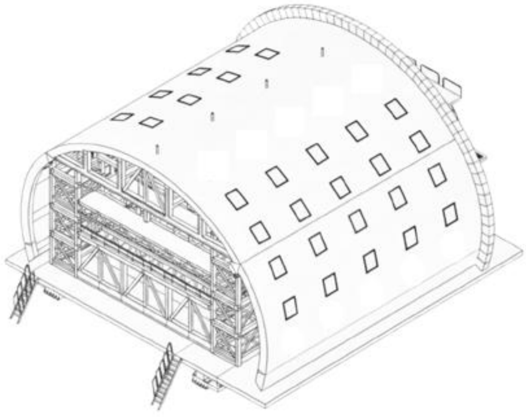
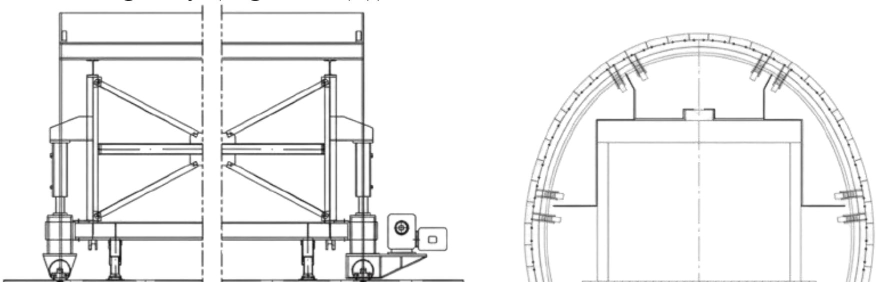


Figure 4 Illustration of lining trolley template.

(4) Hydraulic System: The hydraulic system is used to adjust the positions of the gantry, bracket, and formwork assemblies to facilitate the lining pouring work. It mainly consists of hydraulic cylinders and control circuits. As shown in Figure 5, the system includes hydraulic controls for the gantry, bracket, and formwork. The gantry and bracket hydraulics provide overall structural support and are located at the four corners of the trolley to synchronously adjust its elevation (Figure 5-(a)). Furthermore, the formwork hydraulics act as transmission devices distributed across the side and top forms. Lateral cylinders are positioned on both sides of the trolley, adjusting the elevation of the side forms to enable lateral movement of the formwork relative to the gantry (Figure 5-(b)).



(a) (b)

Figure 5 Illustration of hydraulic components of lining trolley.

Due to the numerous components of the tunnel lining trolley, it is necessary to design a modeling method tailored to the specific application objectives. This study aims to accurately estimate the concrete pouring volume of the secondary lining structure. Therefore, it is unnecessary to perform detailed modeling for every single part of the lining trolley; instead, only the components involved in the lining pouring process are modeled. By analyzing the construction process and component functions of the tunnel lining trolley, it is determined that the bracket assembly and the formwork assembly influence the positioning of the trolley and the quality of the concrete pouring. The positioning information of the lining trolley is a prerequisite for ensuring construction quality, particularly when pouring concrete on surfaces with a specific gradient. Furthermore, the formwork assembly is a critical component of tunnel lining construction, and modeling it establishes a direct link with the on-site construction activities. Consequently, establishing a tunnel lining trolley model that incorporates these two components can effectively represent the pouring process and facilitate the acquisition of accurate concrete pouring volumes.

When conducting modeling research on the tunnel lining construction process, it is necessary to collect data from the tunnel lining trolley under construction conditions for modeling purposes. However, during the data acquisition process, multiple instrument setups are required to obtain the point cloud data of the trolley. Furthermore, it is difficult to acquire information regarding the position of the trolley's top formwork during the lining construction process. Field investigations of the project indicate that the overall structure of the tunnel lining trolley is measured before each deployment to ensure there is no deformation on its surface and that the measurement results are consistent with the design values. Therefore, the tunnel lining trolley can be modeled based on its design drawings. The modeling method proposed in this paper involves modeling the bracket assembly and the formwork assembly separately based on the design drawings, thereby obtaining a simplified model of the tunnel lining trolley.

3.2 Multi-model integration for tunnel construction

To achieve a high-fidelity simulation of the secondary lining construction scenario, it is imperative to implement a sophisticated spatial integration of the primary lining model and the tunnel lining trolley model, ensuring the digital assembly strictly adheres to the physical constraints of the lining deployment process. The systematic methodology for synthesizing these construction models is detailed as follows: (1) Based on the high-precision tunnel alignment design parameters, the chainage data (mileage) along the tunnel’s central axis are systematically indexed. This stage establishes a crucial longitudinal reference framework, allowing for the precise synchronization of design requirements with actual site coordinates. (2) According to the specific chainage range corresponding to the primary lining, the spatial coordinates of the primary lining model are meticulously calibrated. By anchoring the geometric features of the primary support within the global coordinate system, a stable digital substrate is created for the subsequent model overlay. (3) Guided by the construction chainage data, the tunnel lining trolley model is sequentially embedded into the primary lining model along the predetermined central axis. This embedding process involves calculating the relative spatial posture of the trolley based on the axis mileage to ensure its alignment with the tunnel's curvature and gradient. The coordinates of the trolley model are then labeled and refined to reflect its exact positioning during the pouring phase. The finalized synthesis of the tunnel lining trolley and the primary lining models constitutes the integrated Tunnel Lining Construction Model, which provides a robust, multi-dimensional geometric foundation for the subsequent estimation of concrete pouring volumes and the analysis of structural interference.

3.3 Tunnel lining pouring volume estimation

The essence of calculating the concrete casting volume for the secondary lining is to determine the void volume between the primary lining surface and the secondary lining trolley model. However, the primary lining surface is an open curved surface rather than a closed solid model. Therefore, based on the established primary lining model and secondary lining trolley model, both models must be closed according to the chainage range defined along the tunnel centerline. For example, to calculate the concrete volume after the third construction cycle of the lining trolley, the chainage range corresponding to the first casting cycle is first identified, followed by that of the third cycle. The starting chainage of the first cycle and the ending chainage of the third cycle are then set as the start and end cutting planes of the lining construction. By combining these two boundary planes with the primary lining model and the secondary lining trolley model, two closed solid models are constructed. By calculating the Jacobian determinant, the integrand can be obtained, allowing the original triple integral to be converted into a double integral. The formula for calculating the model volume is as follows:

$$V = \frac{1}{3}\int_{u,v}\left(x(u,v)\frac{\partial(y,z)}{\partial(u,v)} + y(u,v)\frac{\partial(z,x)}{\partial(u,v)} + z(u,v)\frac{\partial(z,x)}{\partial(u,v)}\right)dudv\,, \tag{1}$$

Where V represents the grid volume, and x, y, and z denote the coordinate values on the grid surface. By calculating the volumes of the tunnel primary lining model and the tunnel lining trolley model, the result can be obtained.

4. Experiments and analysis

4.1 Experimental Data

The objective of this study is to estimate the concrete pouring volume of the tunnel lining, which requires the collection of tunnel lining data during the construction phase to support the research. To facilitate this study, the GTFS high-speed railway tunnel project, currently under construction in Guangdong Province, was selected as the case study. The geological environment of the GTFS project is described as follows: the project traverses a mountainous terrain with a relative elevation difference of approximately 60 m to 290 m and natural slopes ranging from 20° to 50°, indicating significant topographic fluctuations. The surface layer of the mountain where the tunnel is located consists of slope-residual silty clay. Furthermore, the rock mass within the main body of the tunnel is primarily situated in Cambrian gneiss strata, characterized by relatively fractured rock conditions.

The design specifications of the tunnel lining trolley for the GTFS project are predefined, whereas the primary lining point cloud data must be collected on-site to obtain the actual geometry within the specified chainage range. Additionally, to calculate the actual pouring volume of the tunnel lining, point cloud data for the secondary lining within the same chainage range were collected. By comparing the estimated values with the actual measurements, the proposed modeling method for tunnel lining pouring volume estimation can be evaluated. The equipment used for data acquisition is the Leica Nova MS60, a MultiStation that integrates high-speed laser scanning, GNSS connectivity, and digital imaging. This versatile instrument is suitable for various tasks such as topographic, architectural, and engineering surveying. It also functions as a high-precision 3D laser scanner, capable of scanning at speeds up to 30,000 points per second to capture large-scale 3D point cloud data. The layout of the traverse network must be determined based on site conditions. Given the relatively rough surface of the primary lining and the complexity of the construction environment, two principles for the placement of traverse points were established based on field experience: (1) Avoid obstacles near the traverse points that could obstruct the tunnel lining; (2) Ensure intervisibility between different traverse points.

After setting up the laser scanner, the scanning resolution parameters—including slope distance, horizontal interval, and vertical interval—were configured. For the two field measurements, the slope distance was set to 20 m, while both the horizontal and vertical intervals were set to 0.05 m. These scanning parameters were established in accordance with the project implementation plan to ensure the acquired point cloud data met the precision requirements for tunnel construction. By configuring these resolution parameters, the 3D laser scanner automatically captured the primary lining point cloud data. The data collected from multiple site visits are summarized in Table 1, consisting of three distinct data acquisition phases. The first phase obtained the primary lining point cloud data within a fixed chainage range (Area A), and the second phase captured the secondary lining point cloud data for the same range (Area A). Additionally, primary lining point cloud data were acquired during the excavation phase for a different section (Area B). In the third field measurement, the secondary lining point cloud data for that same section (Area B) were collected.

Table 1: List of Tunnel Point Cloud Data Acquisition for the GTFS Project

Data Acquisition Phase	Survey Area	Length (m)	Number of Points
First Acquisition	A	120	10,500,123
Second Acquisition	A	110	21,673,488
Second Acquisition	B	130	41,144,023
Third Acquisition	B	140	52,497,541

4.2 Results and Analysis

Following the assembly of the primary lining and lining trolley models, multiple trolley models must be spliced within the primary lining model. The splicing of the trolley models is conducted with a reserved overlapping area of 0.3m; the red banded zones represent the specific splicing regions for each trolley. Based on the total length of the primary lining, the corresponding number of lining trolleys is configured to simulate the actual construction process. The experimental results presented in Table 2 represent the numerical simulation of the pouring volume for Section A, which has a total length of 110m. In this context, the Design Value refers to the ideal volume of concrete required based on tunnel design specifications. The Simulated Value represents the concrete volume calculated using the estimation method proposed in this paper. The Actual Value is the actual volume of the secondary lining concrete used in real construction, obtained by calculating the interstitial volume between the primary lining model and the secondary lining model within the same chainage range.

Table 2:Statistics of Concrete Pouring Volume for Tunnel Lining Section A

Trolley No.	Chainage Range	Design Value (m^3)	Simulated Value(m^3)	Actual Value (m^3)
1	DK19+534 ~ DK19+522	152.6	199.45	196
2	DK19+546 ~ DK19+534	152.6	199.79	197
3	DK19+558 ~ DK19+546	152.6	209.79	208
4	DK19+570 ~ DK19+558	159.75	173.47	171.78
5	DK19+582 ~ DK19+570	159.75	166.57	163.89
6	DK19+594 ~ DK19+582	159.75	162.12	164.1
7	DK19+606 ~ DK19+594	182.61	187.57	188
8	DK19+618 ~ DK19+606	182.61	199.17	196
9	DK19+630 ~ DK19+618	182.61	186.52	184

As shown in Table 3, the numerical results correspond to the concrete pouring volume simulation for Section B, which spans a length of 130m. The tunnel lining trolleys utilized in this case study project have a standard length of 12m. According to project construction records, the dataset available for pouring volume estimation in Section A consists of 9 lining trolley operations, while Section B includes 10 lining trolley operations for estimation.

Table 3:Statistics of Concrete Pouring Volume for Tunnel Lining Section B

Trolley No.	Chainage Range	Design Value (m^3)	Simulated Value(m^3)	Actual Value (m^3)
1	DK19+90 ~ DK19+102	152.6	154.49	155
2	DK19+102 ~ DK19+114	152.6	158.29	155
3	DK19+114 ~ DK19+126	152.6	158.57	156
4	DK19+126 ~ DK19+138	152.6	155.53	155
5	DK19+138 ~ DK19+150	152.6	154.82	154
6	DK19+150 ~ DK19+162	152.6	156.40	155
7	DK19+162 ~ DK19+174	152.6	159.8	157
8	DK19+174 ~ DK19+186	152.6	179.17	178
9	DK19+186 ~ DK19+198	152.6	154.2	155
10	DK19+198 ~ DK19+210	152.6	156.97	159

To specifically estimate the concrete volume for each operation, the statistics are compiled incrementally as the number of lining trolleys increases. The trolleys in the statistics table are numbered sequentially based on the tunnel excavation chainage. The chainage range refers to the actual mileage data where each trolley was positioned during construction. Analysis of the concrete pouring results indicates that both the Actual Values and Simulated Values are generally higher than the Design Values. This discrepancy is primarily attributed to the deliberate expansion of the excavation face during the tunneling phase to prevent construction quality issues caused by under-excavation. Field investigations indicate that the error margin for concrete volume per trolley ranges from $3m^3$ to $5m^3$. A comprehensive analysis of the concrete pouring volume for each trolley across different regions demonstrates that the estimation results of this study meet practical application requirements. This validates that the proposed modeling-based method for estimating secondary lining volumes is applicable to real-world tunnel construction. Furthermore, by correlating the chainage range of each trolley with the relative position of the bracket assembly components, the specific chainage values for the center points of the outermost positioning columns of the bracket assembly are derived. The exact locations of these positioning columns on both the left and right sides are marked in lining trolley. The resulting positioning information provides a reliable reference for the specific setup of trolleys during lining construction and offers simulation data to predict subsequent concrete requirements.

5. Conclusions

This study, based on real-world cases of drill-and-blast tunnels, utilized 3D laser scanning technology to collect high-precision point cloud data from the construction site. By integrating the design specifications and geometric characteristics of the lining trolley, research was conducted on a high-precision point cloud-driven pose estimation method for tunnel lining trolleys. Utilizing the proposed data preprocessing, parametric modeling, and pose mapping algorithms, the study constructed a primary lining model reflecting the actual excavation profile and a geometric trolley model based on design drawings. By marking the range of key positioning components, the precise spatial localization and pose parameter estimation of the trolley model were achieved. The volume between the positioned trolley template surface and the primary lining point cloud surface was then calculated to achieve a quantitative simulation of the secondary lining concrete pouring volume. Comprehensive analysis demonstrates that the proposed pose estimation method and volumetric calculation model align with the accuracy requirements of tunnel lining construction, effectively identifying construction deviations and guiding material scheduling. Overall, this research introduces high-precision point cloud processing and spatial pose estimation algorithms into tunnel lining construction. It not only provides a more data-supported technical path for pouring volume estimation but also offers theoretical insights and methodological references for the digital monitoring and intelligent development of tunnel construction.

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